APPLICATIONS OF AUTONOMOUS VESSELS FOR OFFSHORE WIND DEVELOPMENT IN NEW YORK

FINAL REPORT

A Technical Study Produced for the New York Maritime Technical Working Group

MARCH 24, 2026

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NOTICE

LIST OF ACRONYMS AND ABBREVIATIONS

ABS	American Bureau of Shipping
BOEM	Bureau of Ocean Energy Management
COLREGs	International Regulations for Preventing Collisions at Sea
GOA	Government Accountability Office
IBN	IBN Environmental and Geomatics
IMO	International Maritime Organization
MARAD	United States Department of Transportation Maritime Administration
M-TWG	Maritime Technical Working Group
NYSERDA	New York State Energy Research and Development Authority
USCG	United States Coast Guard
VTS	Vessel Traffic Service

EXECUTIVE SUMMARY

The New York State Maritime Technical Working Group (M-TWG) is an independent advisory entity consisting of representatives from the maritime transportation sector, navigation community, and offshore wind developers. The M-TWG provides guidance and advice on responsibly implementing New York State's efforts to advance offshore wind energy development and achieve the state's clean energy and climate resilience goals. The M-TWG provides insights into offshore wind development's potential impacts to commercial shipping, navigational safety, and changes to supply chains. The feedback generated through the M-TWG increases knowledge sharing between diverse interested parties, strengthens relationships across industries, and facilitates awareness and engagement on offshore wind development efforts in the region.

In 2024, WSP USA Inc. (WSP) supported the M-TWG by updating its Shared Research Agenda, a compilation of potential research topics and questions useful for deepening shared learning and engagement. The purpose of the Shared Research Agenda is to enhance the depth of information made available to decision-makers on responsible development practices, port infrastructure upgrades, and navigation safety in the region. The topics are intended to identify unaddressed gaps in, and potential impacts to, key issues in vessel traffic and navigation.

One of the topics identified in the Shared Research Agenda was the need to learn more and understand the implications of emerging autonomous and unmanned vessel technologies for potential use in planning, development, construction, operations, and maintenance of offshore wind infrastructure. The M-TWG directed WSP to examine the current state of autonomous technologies used for maritime and offshore wind and explore their potential future use. The study intends to be a reference document for M-TWG members and their professional networks, to better understand this emerging technology and its potential applications and constraints within the region.

This study leverages comprehensive literature review, engagement from subject matter experts, and case study research to explore the current landscape and future potential of autonomous vessel technologies for offshore wind development in New York. The study highlights the emerging use of autonomous vessels in seabed surveys, asset inspections, logistics, and environmental monitoring; and explores improvements in safety, cost efficiency, and operational capability in demanding marine environments.

Despite these benefits, significant challenges remain, particularly regulatory uncertainty related to evolving United States Coast Guard (USCG) requirements, Jones Act compliance, and international maritime frameworks. The rapid pace of technological advancement is advancing beyond existing regulations, creating challenges for industry adoption. The report also points to the critical need for cybersecurity enhancements, port infrastructure upgrades, and workforce development to enable safe integration of autonomous systems into offshore wind operations.

Looking forward, the market for autonomous vessels is expected to grow substantially, driven by the promise of cost and operational efficiencies, and environmental sustainability. Realizing this potential will benefit from coordinated efforts among regulators, industry leaders, and educators to harmonize regulations, invest in essential infrastructure, and cultivate a skilled workforce. With these actions, autonomous vessel technologies can play a pivotal role in supporting New York's clean energy and offshore wind goals.

LITERATURE REVIEW

Introduction

WSP USA Inc. (WSP) produced a series of technical memos, the first was a literature review of current practices in autonomous and unmanned technologies for maritime and offshore wind development. The literature review encompasses a diverse range of sources, including peer-reviewed papers, industry reports, policy memos, and other relevant documents from government, intergovernmental agencies, nongovernmental organizations, and industry organizations, to provide a high-level overview of emerging technologies and their nascent implementation.

In the following sections, WSP provides an overview of different types of autonomous vessels and the varying degrees of autonomy they employ. The literature review includes nontechnical descriptions, supplemented with images and photographs, to explain differing categories of equipment and their applications. Surface and subsurface technologies are explored, providing an overview of existing uses and potential future applications in the offshore wind sector. The literature review also examines existing policies and regulations to better understand how governmental agencies are responding to the emergence of these new technologies and how best to regulate to ensure navigational safety and security. Last, the literature review summarizes current themes and key insights from subject matter experts on shifts in workforce development and training, logistics and supply chains, and new market opportunities for applying these technologies to different phases of offshore wind development.

Technology

Types and Classifications of Autonomous Vessels

For this literature review, there are three types of autonomous vessel technology:

- Autonomous surface vessel: a boat, ship, or device that operates independently on the surface of the water without the direction of a crew (Figure 1).

Figure 1: A saildrone, an example of an autonomous surface vessel, is a wind and solar-powered platform for collecting marine environmental data[1]

- Autonomous underwater vessel: an unoccupied device that operates independently underwater without continuous input from a human operator. Figure 2 provides an example of an autonomous underwater glider.

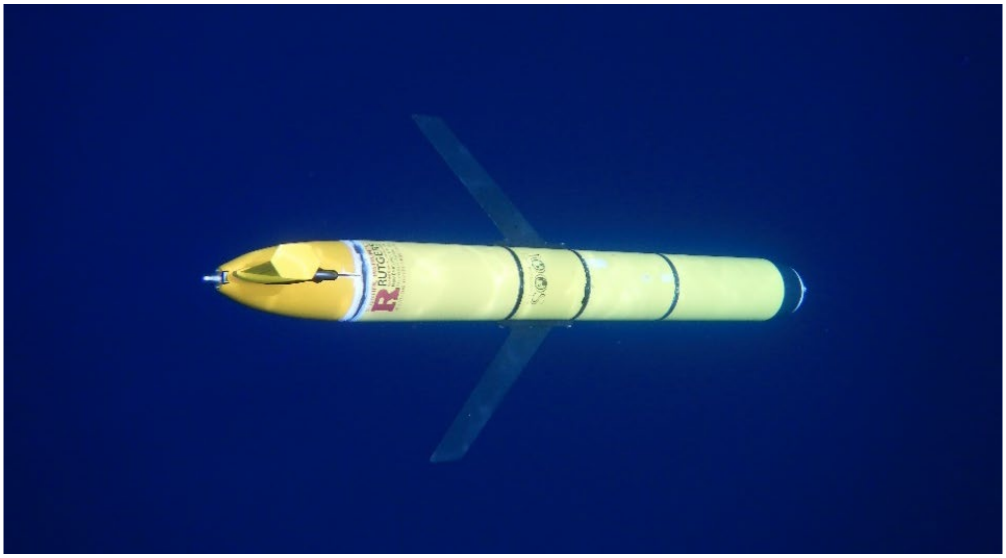


Figure 2: Submerged Underwater Glider[2]

- Remotely operated vehicle: an unoccupied device that operates, for this literature review, underwater while receiving continuous input and monitoring from a human operator. Figure 3 provides an example of a remotely operated vehicle used for benthic studies.

Figure 3: CRIS team with remotely operated vehicle used for benthic survey activities[3]

Autonomous vessels are equipped with varying degrees of autonomy. These vessels can range from less autonomous, including crewed ships with automated systems and decision support, to fully autonomous vessels capable of making decisions and taking actions independently without human input. These vessels are equipped with technologies that enable them to navigate independently, control their speed and direction, and communicate with other vessels.4 Each autonomous vessel operates within a preprogrammed decision framework (Perceive > Analyze > Decide > Act). Guardrails are embedded at every level, but the key behavioral constraints, those that determine how the vessel interprets and responds to its environment, reside in the analysis and decision layers. The vessel's autonomy is limited to its assigned mission parameters; if environmental or system variables exceed those parameters, built-in guardrails activate a safety protocol or human handover.[5]

The WSP team reviewed classification systems from several international organizations: The International Maritime Organization (IMO), the European Commission, Maritime UK, and Lloyd's Register.

- All systems classifications reviewed have similar designations for the first and last degrees of autonomy (human-operated to fully autonomous) but deviate when magnitudes of human intervention gradually decrease.
- The Maritime Safety Committee of the IMO established interim guidelines in 2019 detailing following four levels of autonomy for Maritime Autonomous Surface Ships:
  - "**Degree one**: ships with automated processes and decision support, which includes the automation of some unsupervised operations, but with a seafarer ready to take the control
  - **Degree two**: remotely controlled ships with seafarers on board, where the ships are operated from a remote location, but the seafarers can be available on board to take the control
  - **Degree three**: Remotely controlled ship without seafarers on board; hence, the ship is controlled and operated from another location
  - **Degree four**: fully autonomous ship controlled by an operative system"[6]
- Lloyd's Register, an industry leader in safety compliance across marine and offshore industries, references six levels of autonomy, while the European Commission references three levels of autonomy: "Remote Ship, Automated Ship, Autonomous Ship."[7]
- The Maritime Autonomous Surface Ships UK Code of Practice V2 includes six levels of autonomy, ranging from a typical manned vessel (Level Zero) controlled by operators, to autonomous (Level Five) (Table 1).

Level Zero	**Manned:** Vessel/craft is controlled by operators aboard.
Level One	**Operated:** All cognitive functionality is controlled by the human operator. The operator has direct contact with the unmanned vessel over, eg, continuous radio (R/C) and/or cable (eg, tethered UUVs and ROVs). The operator makes all decisions, directs and controls all vehicle and mission functions
Level Two	**Directed:** Some degree of reasoning and ability to respond is implemented into the unmanned vessel. It may sense the environment, report its state, and suggest possible actions to the operator, eg prompting them for information or decisions. However, the authority to make decisions is with the operator. The unmanned vessel will act only if commanded/ permitted to do so.
Level Three	**Delegated:** The unmanned vessel is now authorised to execute some functions. It may sense environment, report its state and define actions and report its intention. The operator has a set time in which to veto intentions declared by the unmanned vessel, if they do not, the unmanned vessel will complete the action. The initiative emanates from the unmanned vessel and decision-making is shared between the operator and the unmanned vessel.
Level Four	**Monitored:** The unmanned vessel will sense the environment and report its state. The unmanned vessel defines actions, decides, acts and then reports its action. The operator may monitor the events.
Level Five	**Autonomous:** The unmanned vessel will sense the environment, define possible actions, decide and act. The unmanned vessel is afforded a maximum degree of independence and self-determination within the context of the system capabilities. Autonomous functions are invoked by the onboard systems at occasions decided by the same, without notifying any external units or operators.

Table 1: Levels of Autonomy in Maritime Vessels[8]

Waterside and Landside Technology Considerations

Regardless of the type of autonomous vessel and the range of autonomy available, the following represent technological challenges and needs:[9]

- **Accurate, durable, and reliable sensors**: Vessels must incorporate a variety of different kinds of sensors (such as radar, lidar, and cameras) that can feed the operational systems. This equipment must function in harsh marine environments.
- **Collision avoidance and navigation systems**: These algorithms and systems are what allow vessels to navigate safely and ensure compliance with International Regulations for Preventing Collisions at Sea. This further includes the ability to handle complex and dynamic environmental conditions as well as monitoring sensor equipment to manage equipment issues.
- **Cybersecurity risks**: Autonomous vessels rely on digital systems that are at potential risk of attack. These systems must include sufficient security and encryption to prevent hacks that incorporate redundancies and fail-safe mechanisms.
- **Range and endurance**: Depending upon the uses, the equipment and systems described above may be tasked with long-ranging and/or long-lasting tasks. One builder of autonomous underwater vessels noted that range and endurance are two technological attributes that interest clients the most. Early autonomous underwater vessels could only operate for two to three days at a time, but now newer vessels (both underwater and

surface) can last for weeks, sometimes months, with a range exceeding 3,000 kilometers.[10,11] Common uses for these craft include geophysical surveys and pipeline and subsea cable inspections.

Another key aspect of autonomous marine technology is the landside technology requirements and infrastructure upgrades. These include the following items:[12,13]

- **Advanced Communication Systems**: It is recommended that ports implement robust communication networks to facilitate real-time data exchange between autonomous vessels and port authorities. This includes high-speed internet and secure communication channels.
- **Remote Operations Centers**: Establishing Remote Operations Centers is essential for monitoring and controlling autonomous vessels. These centers need to be equipped with advanced control systems and staffed by trained personnel.
- **Automated Docking Facilities**: Autonomous vessels can use automated docking systems to more quickly guide them safely into berths without human intervention or tugboat assistance. This involves the use of sensors, cameras, and artificial intelligence-driven docking algorithms.
- **Infrastructure Upgrades**: Physical infrastructure, such as piers and mooring systems, may need to be upgraded to handle the specific docking requirements of autonomous vessels. Electrical systems would likely need to be upgraded in tandem with other technologies to support ship charging, including mini power stations to support energy supply and battery/storage units to charge and discharge energy at will.[14]
- **Cybersecurity Measures**: Ports are encouraged to enhance their cybersecurity infrastructure to protect against potential cyber threats targeting autonomous vessels and port operations.
- **Environmental Monitoring**: It is suggested that ports consider implementing systems for continuous environmental monitoring to ensure that autonomous vessels comply with environmental regulations and minimize their impact on marine ecosystems.
- **Regulatory Compliance**: Ports need to stay updated with evolving regulations and standards for autonomous shipping, ensuring that their operations are compliant with international and national laws.

The advent of autonomous technologies within the maritime sector necessitates comprehensive reassessment and adaptation across all aspects of maritime operations on both land and water. These measures comprise an expansive communications network that constantly exchanges information to ensure safe autonomous maritime operations, regardless of levels of autonomy.

Use Applications

While still a nascent industry, there are several current and potential use applications for autonomous vessels.

For this study, autonomous vessel technologies have been organized into four categories that are currently applied in maritime environments, most relevant to this study: seabed surveys and mapping; asset inspection and maintenance; operations and logistics; and environmental monitoring. The same categorization is in later chapters of this study, including in the case studies.

Seabed Surveys/Mapping

Autonomous vessels can be equipped for hydrographic survey operations, particularly for environmentally sensitive areas or areas that are potentially risky for mariners and crew, including high depths or environments or regions with extreme physical conditions. Typical survey operations require two vessels, the survey craft and a standby rescue craft. Survey operations that utilize autonomous vessels typically require only one unmanned vessel. For example, Measurement Sciences Inc. completed pipe coverage surveys at four locations, using unmanned vessels in areas that would have been too dangerous for manned craft.[15]

From 2018 to 2019, Equinor Canada Limited, Wood Environment & Infrastructure Solutions, and Fugro GeoSurveys partnered to conduct a comprehensive coral and sponge survey in the Flemish Pass to document and map their locations in the event of future oil and gas exploration activities (Figure 4).[16] Developing and operating infrastructure for the offshore oil and gas industry is similar to the offshore wind industry because safe and reliable operations are needed in marine areas that are not easily accessible and may have sensitive environmental resources. During this survey, a side-scan sonar and a multibeam echo sounder were mounted on an autonomous underwater vessel to collect ultra-fine-scale resolution imagery of the seafloor and coral habitats.[17]

Figure 4: Echo Surveyor VI autonomous underwater vessel used for Flemish Pass benthic surveys[18]

Asset Inspection/Maintenance

Researchers from the Centre for Robotics & Intelligent Systems at the University of Limerick (CRIS) developed and tested a remotely operated vehicle to help inspect a floating turbine at WindFloat Atlantic, a semisubmersible floating offshore wind farm (Figure 5).[19] Regular inspections and maintenance are vital for the longevity of wind farms; therefore, technologies such as remotely operated vehicles and autonomous underwater vessels provide economical ways to conduct inspections and maintenance while reducing operational costs.[20] One of the challenges in inspecting a floating turbine is the movement of the structure. The University of Limerick team minimized risks by using an adaptive control system for the remote-operated vehicle, as well as customized machine vision algorithms in post-processing imaging. The survey produced "high-resolution, georeferenced 3D models of structure above and below the waterline."[21]

Figure 5: CRIS team with a remotely operated vehicle used for benthic survey activities[22]

Operations and Logistics

Many of the operations and logistics considerations related to autonomous marine vessels are examined throughout this document. At a high level, the following key issues are discussed.[23,24,25]

- **Navigational Safety**: Autonomous vessels must be able to safely operate in navigational waters with manned vessels and communicate with manned vessels to avoid collisions and allisions.
- **Cyber Safety and Security**: Ensuring the safety of autonomous vessels is important. This includes robust cybersecurity measures to protect against hacking and other cyber threats.
- **Regulatory Compliance**: Navigating the complex regulatory landscape is a significant challenge. International waters lack standardized regulations for autonomous vessels, requiring operators to comply with a varying mix of national and international laws.
- **Port Infrastructure**: Ports may need to upgrade their infrastructure to accommodate autonomous vessels. This potentially includes advanced communication systems, automated docking facilities, enhanced data exchange protocols, and on-site power stations and batteries capable of distributing energy for charging needs.[26] These systems should be supported by upgraded grid interconnections that enable a reliable power supply, bidirectional energy flow, and coordination with regional utilities. Strengthening the grid connection ensures ports can meet future electric and hybrid vessel charging demands while maintaining operational resilience.[27]

- **Remote Operations:** Establishing remote operations centers is crucial for monitoring and controlling autonomous vessels. These centers require skilled personnel and reliable communication networks.
- **Environmental Impact**: Autonomous vessels can optimize routes and speeds to reduce fuel consumption and emissions by actively analyzing environmental conditions and adjusting operations accordingly.
- **Operational Efficiency**: Automation can improve operational efficiency by reducing turnaround times and minimizing human errors. However, integrating autonomous vessels into existing logistics chains requires careful planning and coordination.
- **Emergency Response**: Developing protocols for emergencies, such as mechanical failures or pirate attacks, is essential. Autonomous vessels must be equipped with systems to handle such scenarios effectively. These systems include predictive maintenance, built-in redundancies for operating systems and equipment, remote monitoring and control, and surveillance networks.[28]

Environmental Monitoring

Autonomous technologies have been instrumental in environmental monitoring efforts because of the ability to collect information in areas where it is not safe or practical to send a vessel crew for extended periods. The following are documented uses for this type of technology in marine environments:

- Monitoring temperature, salinity, and density characteristics of surrounding water
- Detecting chlorophyll levels
- Measuring biological components such as oxygen, nitrate, and pH levels[29]
- Noise monitoring

Underwater gliders, a type of autonomous underwater vessel, are autonomous devices that can spend months in marine areas collecting data, including helping track environmental changes, ocean floor mapping, hurricane prediction, wildlife tracking, and geologic formations (Figure 6).[30] These vessels rely on buoyancy pumps to move through the water and rely on global positioning systems for navigation. Additionally, given the often-remote locations of where underwater gliders operate, there is generally less concern regarding interactions with other marine vessels.[31]

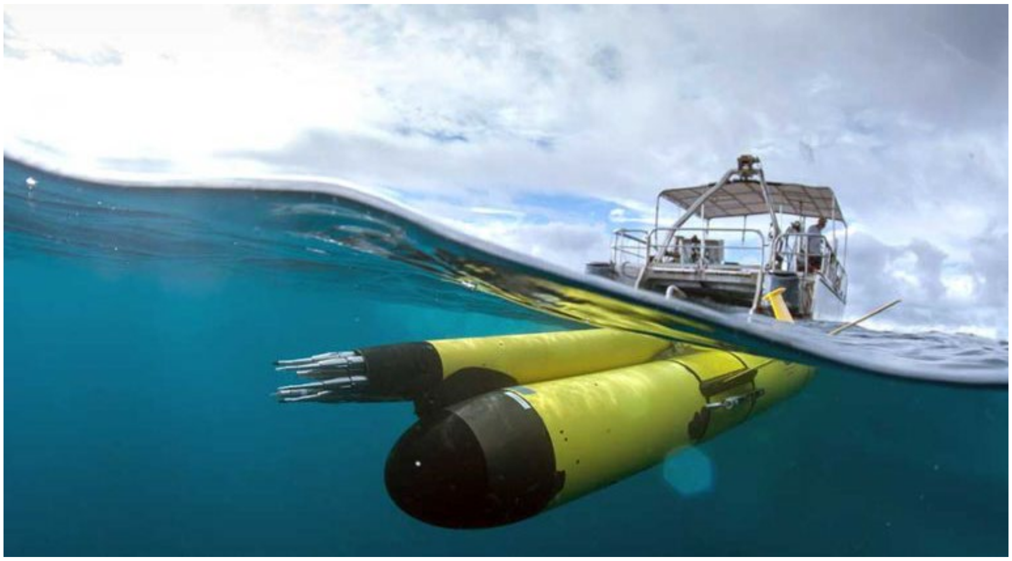


Figure 6: Submerged underwater glider[32]

Other Uses

Beyond the uses discussed above, there are several other potential uses. Safety considerations, environmental impacts, and labor concerns are often factors in identifying useful applications for unmanned vessels, which have already been used in the following ways:[33,34]

- Shipping (a 120 TEU autonomous vessel is operating between ports in Norway)[35]
- Commercial fishing
- Search and rescue operations
- Oil spills, such as outfitting an unmanned vessel with an oil collection skimmer
- Identification and/or disposal of unexploded ordnance
- Military use, including surveillance, advanced scouting, and asset escort and protection

Existing Policy and Regulatory Context

Jones Act

The Jones Act, a section of the Merchant Marine Act of 1920, is a federal law governing maritime trade as it pertains to US economic and security interests. It states that any commercial freight carried between US ports must be transported on vessels that are constructed, owned, and operated by US citizens or permanent residents.[36]

One of the primary requirements of the Jones Act is that vessels engaged in coastwise trade must be operated by US citizens or permanent residents. Autonomous vessels used primarily for survey, data collection, and asset management are classified typically as vessel equipment, and are not subject to Jones Act requirements. However, as increasing automation could reduce the need for human oversight and influence upon these vessels, autonomous vessel technologies could present challenges to comply with the Jones Act, particularly if there are situations where a fully autonomous vessel is carrying cargo with no direct human oversight. The regulatory landscape and related guidance to specific crew requirements are still developing. Currently, the United States Coast Guard (USCG) acknowledges that, "autonomous ship operations must comply with statutory crew requirements."[37] However, the USCG allows automated systems to be used on vessels to replace some crew members in compliance with certain conditions, depending on:

- Capabilities of the specified automated system
- The system's demonstrated reliability
- An existing maintenance program that ensures continued, reliable, and safe operation of vital vessel systems[38]

International Maritime Organization Policy and Regulations

This challenge is not limited to US policy but is evident in international policy as well. The IMO's Regulations for the Prevention of Collisions at Sea 1972, Rule Five, states:

> *"Every vessel shall at all times maintain a proper lookout by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and the risk of collision."*[39]

Additionally, Rule Two of these regulations dictates that all liabilities lie with the vessel, owner, master, or crew if any consequences arise from failure to abide by the rules.[40] The uncertainty that arises from this scenario is whether autonomous systems can legally replace an individual mariner that would otherwise fulfill a look-out position, and if so, who the liable party would be in the absence of mariners on autonomous vessels.

The IMO is beginning to develop broader regulatory frameworks for the integration of autonomous technologies for maritime uses, focusing on safety, training, and legal liability issues.[41] Developing these frameworks involves reviewing existing IMO conventions regarding maritime safety and security, and creating guidelines for evaluating autonomous vessels.[42] This process would generally follow similar IMO procedures, including having committees consisting of member states develop guidance and regulations with the guidance of IMO staff. The IMO itself does not directly develop or approve guidelines and regulations.[43]

From 2018 to 2022, various IMO committees, including the Maritime Safety Committee, the Legal Committee, and the Facilitation Committee, have been active in examining priority issues as they pertain to autonomous vessels, including the needs to clarify the roles and responsibilities of master of the ship and the crew, as well as the roles and responsibilities of individuals who are remotely operating ships and their classification as seafarers. The Maritime Safety Committee initially produced guidelines during regulatory scoping exercises that provided direction in managing safety risks, compliance issues, crew and certificate requirements, ensuring human involvement, and addressing cybersecurity risks.[44] After these scoping exercises, the Maritime Safety, Legal, and Facilitation Committee members agreed on the following:

- "Autonomous ships should have a human master, either onboard or remote who can take control of the ship as needed.
- A ship can have multiple masters on a single voyage, but only one remote operating center can be responsible for an autonomous ship at any one time.
- A master can be responsible for multiple ships under certain circumstances."[45]

This work by the IMO is expected to continue through 2032, with the following anticipated milestones along the way:[46]

- By May 2026, finalize and adopt the nonmandatory Maritime Autonomous Surface Ship code and consideration of treaty amendments and proposals and guidelines for new rules.
- By December 2026, develop a framework for an Experience-building phase post-adoption of the nonmandatory Maritime Autonomous Surface Ship code.
- By 2028, commence development of the mandatory Maritime Autonomous Surface Ship code, based on the nonmandatory code and the Experience-building phase results. Review new rules by relevant subcommittees and consider amendments to Safety of Life at Sea treaty, which sets out minimum safety standards in the construction, equipment, and operation of merchant ships.
- By July 2030, adopt the mandatory Maritime Autonomous Surface Ship code, for implementation in January 2032."[47]

United States Coast Guard Regulation and Guidance

In the US, various statutes used by entities such as the USCG require a minimum number of crew members onboard a vessel, and the USCG is generally not authorized to waive these requirements.[48] The United States Department of Homeland Security has recognized this inherent conflict as well, stating, "Current legal and regulatory frameworks support only limited remote and autonomous systems on board vessels, such as engine room automation and navigation controls that maintain a track line."[49]

Existing regulations are slow to respond to the pace of autonomous technology use and application for maritime operations, making it challenging for government and commercial entities to adapt. However, the USCG has implemented a multi-program autonomous technologies policy committee, "AutoPoCo," that regularly meets to discuss pertinent issues related to the increasing adoption of autonomous technologies.[50] It has also issued an initial application process for USCG review of potential autonomous vessel projects via a directive, *Policy Letter 22-01* published in 2022 and updated in April 2024, recognizing that, "Artificial intelligence and computer controls potentially provide the maritime industry with new and innovative tools to expand remote and autonomous systems beyond that permitted under current legal and regulatory structures."[51] Since the publishing of this letter, the USCG stated that it had received five inquiries for maritime autonomous vessel projects, though these inquiries seemed hypothetical in nature and beyond the scope of the letter.[52]

Internationally, it appears that conflicts and regulatory gaps are addressed through new regulations, but it remains to be seen whether the Jones Act in the US will be updated in tandem with international standards. The USCG is the leading US delegation of the IMO in addressing regulatory guidance on the use of autonomous ships.

Navigational Safety

Navigational safety with the advent of autonomous vessels is a concern for many operators within the maritime industry, particularly in safely implementing collision avoidance strategies and the ability to coordinate among different vessels that might all be operating with different degrees of autonomy.[53] With greater levels of autonomy, proponents believe ship navigation would be safer by mitigating human error and fatigue. However, subject matter experts interviewed for the United States Government Accountability Office also expressed concerns about safe operations of autonomous vessels, including:

- Technical challenges when a vessel's controls are transferred back and forth between on-site operators, remote operators, and integrated autonomous systems.
- The ability for autonomous vessels to navigate international waters with manned vessels.
- The safety of those within proximity to larger autonomous vessels, such as smaller fishing boats and human-powered boaters, that might not be entirely visible to onboard sensors and cameras.[54]

Rutgers University researchers raised a similar concern when examining potential collisions between maritime vessels and smaller autonomous underwater vessels off the New Jersey coast. They noted that smaller autonomous underwater vessels, such as underwater gliders that are often used for research, cannot sense and avoid vessels that might not see or sense them, necessitating the need for ship detection systems on autonomous underwater vessels.[55]

With the increasing prospect of fully autonomous vessels, a common and persistent concern among shipping industry leaders is the ability to maintain the safety of both the vessel and the crew when operating in the vicinity of other vessels that might have varying forms of autonomy. The ability, or inability, to communicate between these vessels in international waters is a key area worth addressing through technological and regulatory means by governments and entities like the IMO as ships gradually adopt more autonomous technologies.

Workforce and Training

According to a recent report by Drewry, the "officer supply shortfall has reached a record high and is not expected to improve." Further compounding the challenge is the anticipated growth of maritime commerce, stretching the labor market even tighter. The integration of autonomous marine vessels as a tool to support maritime operations and efficient port commerce raises the following workforce considerations for the commercial maritime industry:[56,57,58]

- **New Technical Skills and Workforce Transition**: The shift to autonomous vessels increases demand for new skill sets, including proficiency in artificial intelligence, robotics, and remote operations. Existing maritime professionals may need to retrain to learn new skills and adapt to new technologies. While a potentially challenging transition, new programs are arising to help with training. While traditional maritime training programs may not cover these areas adequately, some organizations are building such skills into their curriculums, including the following examples:
  - SUNY Maritime College's Offshore Wind Training, a joint program with RelyOn Nutec, offers five modules of offshore wind Basic Safety Training, certified by the Global Wind Organization[59]
  - A University of Southern Mississippi Uncrewed Maritime Systems Certificate Program[60]
  - A joint program between Embry-Riddle Aeronautical University and the US Naval Community College that offers an Associate of Science in Uncrewed and Autonomous Systems (covering both marine and aviation systems)[61]
  - SeaBot Maritime's Maritime Autonomous Surface Ship Certified Professional Training Scheme (based in the UK)[62]
  - An Autonomous Maritime Systems program at the Australian Maritime College[63]

- **Training Programs**: There is a need for specialized training programs that focus on the operation and maintenance of autonomous systems. This includes developing training programs for both onboard crew and personnel at remote operations centers.
- **Regulatory Compliance**: Ensuring that training programs meet international standards and regulations is crucial to ensure workers are trained in the safe and legal operations of autonomous vessels. The IMO is working on guidelines and recommends certification standards for training protocols. The USCG has been a key participant in this process as the lead agency in the US delegation to the IMO. The USCG, "…has led and assisted in aspects of the IMO Regulatory Scoping Exercise, specifically in the review of IMO conventions related to crew competence and certification, and prevention of collisions at sea, among other conventions."[64]
- **Safety and Reliability**: Training should emphasize the safe operation of autonomous vessels, including emergency response procedures and troubleshooting of cables, connectors, and other components of autonomous systems.
- **Attracting Talent**: There is an opportunity to promote the maritime industry as a high-tech field with diverse career opportunities, appealing to potential workers who might not have previously considered working in the field.

Collaboration between industry leaders, educational institutions, and regulatory bodies to develop comprehensive training programs and support the workforce transition would help address these challenges. An example of this kind of collaboration is the USM program, which has a formal partnership with the Naval Meteorology and Oceanography Command, along with working relationships with the National Data Buoy Center and private companies. Further, Department of Defense and National Oceanic and Atmospheric Administration employees qualify for in-state tuition regardless of their state of residency. Another endeavor is the Washington Autonomous Vehicle Cluster, located on the Kitsap Peninsula in Washington State, which focuses on autonomous maritime opportunities. This program is working with state and local economic development agencies as well as local businesses, educational institutions, and industry partners to provide training and educational programs for autonomous maritime systems (along with other policy, regulatory, and local economic development initiatives).

National Security

Autonomous technologies, and their increasing adoption, are generally viewed as imperative to safeguarding national security interests within marine environments by national entities such as the USCG. In its report *Unmanned Systems Strategic Plan*, the USCG stated its position on unmanned systems, stating, "Embracing and integrating [unmanned systems] will allow us to more effectively safeguard the American people and promote maritime safety and security in a complex and evolving environment."[65] The USCG views the use of unmanned systems as a means of maintaining safe commercial activity, explaining that this technology can be used to survey mooring areas, shipping channels, and the seafloor for potential threats.[66]

The increasing technological complexity that autonomous technologies present also introduces cybersecurity concerns. According to the Government Accountability Office, industry leaders are concerned about the potential for disruptions caused by hacking due to network vulnerabilities and reliance on connected technologies.[67]

Figure 7 depicts a typical communication network where information is exchanged to guide and operate autonomous vessels.[68] Between vessels, onshore control centers, satellites, and port communications, numerous potential points of failure leave vessels vulnerable to disruption. The IMO recognized these potential risks back in 2016, detailing potential cybersecurity risks that include disruption of "cargo handling and management systems; propulsion and machinery management and power control systems; access and control systems; and communication systems."[69]

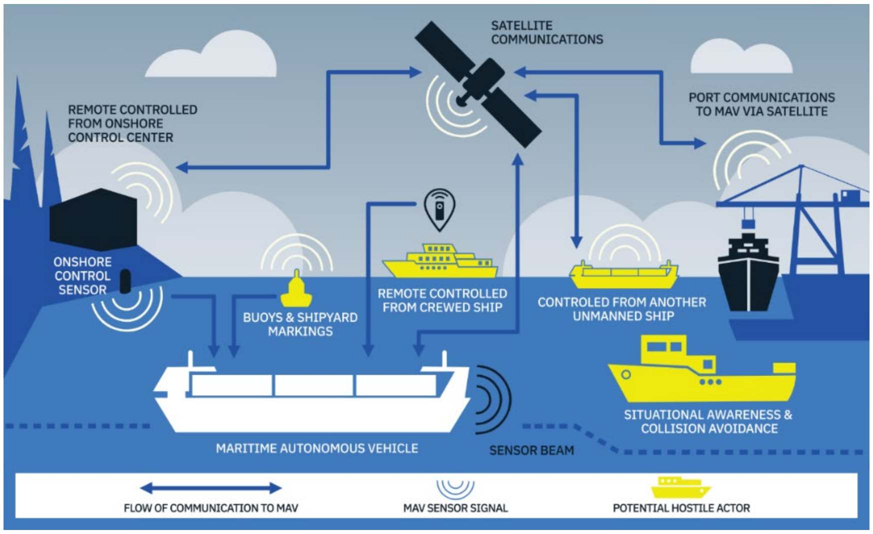


Figure 7: Typical communication network for a maritime autonomous vehicle[70]

As the network of communications associated with operating autonomous technologies becomes more intricate, there is a need to coordinate and adopt necessary security measures between government agencies, such as the USCG, port and maritime entities, as well as the shipping industry in general, to develop and implement security and communications operations that are resistant to potential hacks and external disruptions.

Market Opportunities

The market for autonomous marine vessels is growing rapidly, driven by advancements in artificial intelligence, machine learning, and sensor technologies. Global growth estimates have been estimated at 7.5 percent to 13.5 percent over the next 10 years.[71,72] The following are some key market opportunities:[73,74]

- **Cost Reduction**: Autonomous vessel adoption may result in lower overhead costs.
- **Green Shipping Solutions**: There is a growing demand for more environmentally sustainable shipping solutions. Autonomous vessels can optimize routes and speeds to reduce fuel consumption by actively assessing weather and environmental conditions and adjusting fuel consumption accordingly. This is supported by vessels that operate solely on electrical power, which would recharge at ports that offer the necessary upgraded infrastructure.
- **Safety and Reliability**: Automation can enhance safety by accessing areas that pose a safety risk to people and potentially reduce the number of accidents caused by human

error. However, there remain concerns about the interactions between autonomous and nonautonomous vessels.

- **Industry-Specific Applications**: Early adoption focuses on industry-specific applications such as offshore support (e.g., oil and gas exploration, marine construction, and maintenance activities) and short-sea shipping (i.e., short-distance commercial shipping activities within the same continent).

While regulatory frameworks continue to be developed, collaborative research and development partnerships between companies and research institutions are further advancing technological capabilities and addressing technical challenges.

In the US, a key growth driver is that the military deploys autonomous vessels for a variety of defense applications as the US military modernizes its capabilities, decreases reliance on manned vessels, and improves operational efficiency. The European market is driven more by offshore energy uses, including offshore exploration, drilling, maintenance, and environmental monitoring, in part driven by a desire to conduct continuous operations without the limitations of crew fatigue or safety concerns.[75]

INTERVIEWS WITH SUBJECT MATTER EXPERTS

Introduction

WSP USA Inc. (WSP) identified subject matter experts in the autonomous vessel industry and conducted a series of interviews to capture perspectives about the current and future uses of these emerging technologies. Subject matter experts included state and federal policy and regulatory leaders, industry leaders, technology leaders, and technology users.

The team interviewed subject matter experts with diverse perspectives and experiences with autonomous technologies in marine environments, including the categories presented below. These interview categories were chosen based on the variety of individuals who use and interact with autonomous vessels in maritime environments today and will influence the use of these emerging technologies in the future for offshore wind development, construction, and operations.

- **Autonomous Vessel User/Operator** – The team interviewed Justin Manley (Just Innovation, Inc.), a strategic adviser in ocean technology with experience consulting with clients developing marine and autonomous technologies by advising on issues including product development, market analyses, proposal writing, and other related tasks.
- **Technology Leader/Entrepreneur** – The team interviewed Mitch Johnson, who at the time of the interview worked as a Director at Beam, a UK-based offshore wind company developing autonomous vessels, remotely operated vehicles, and prototypes of autonomous vessels.
- **Regulatory Authority** - The team interviewed Christopher Rabalais, a commander in the US Coast Guard (USCG) who is part of the Office of Design and Engineering Standards, responsible for developing and implementing regulations and standards that support the design and construction of maritime equipment. The USCG advises the Bureau of Ocean Energy Management (BOEM) on project impacts to the nation's Marine Transportation System, navigation safety, vessel activities within waterways, and USCG missions.
- **New York/New Jersey Harbor Experts** - The team interviewed the Waterways Management Team of the USCG Northeast District: Matthew Stuck, Chief, Waterways and AtoN System Planning; Michele DesAutels, Waterways Management Specialist, Northeast Division Prevention; and Mark Cutter, Marine Transportation Specialist. As members of the USCG's Northeast District, their responsibilities include:
  - Promoting navigation safety
  - Integrating autonomous vessels into waterway planning
  - Ensuring that autonomous systems are visible and predictable to other mariners
  - Managing all aspects of USCG involvement for projects in its Area of Responsibility from the start of the NEPA process through construction and operations.

- **Offshore Wind Developers** – The team reached out to numerous offshore wind developers and other experts in the field, including Ørsted, Avangrid, Equinor, and Vineyard Offshore, to better understand applications of autonomous vessel technology for offshore wind projects. The team established contact with Cynthia Pyć, Principal and Founder of IBN Environmental and Geomatics. Cynthia has extensive experience with offshore wind infrastructure and autonomous vessels, having previously worked at:
  - RWE, Director or Permitting and Environment, Offshore Wind Americas
  - Avangrid, Director of Environment Offshore Wind
  - Vineyard Wind, Senior Manager of Environmental Affairs

Methodology

M-TWG members made recommendations for thought leaders in each of the above interview categories. The WSP team developed an Interview Guide to provide direction on outreach methods, interview format, and a list of guiding questions for each interview category. A copy of the Interview Guide is provided in Appendix A. Each interview was conducted virtually by video conference and was recorded and transcribed. Interviews took place between April and September 2025. The USCG's Office of Design and Engineering opted to provide written answers instead of participating in a recorded interview. Copies of the transcripts and written answers are provided in Appendix B.

WSP provided the list of guiding questions to each subject matter expert in advance of the interview. The questions were organized around a set of common themes to guide discussion and gain insights.

Common Themes and Questions for All Subject Matter Experts

The interview was designed to capture each interviewee's perspective as representative of a subject matter group. There was a set of common themes and questions for all interviews to create a common baseline of understanding across all subject matter groups. There was also a set of questions tailored for each specific group.

The goal was to elicit their respective understandings of the use of autonomous vessels in phases, from existing conditions and needs to shorter-term and longer-term uses. This helped the project team understand the steps and actions that it perceived as necessary to achieve that future, as well as risks, obstacles, and other concerns.

Common themes and questions are shown here, with preliminary targeted questions for each subject matter group provided in the Interview Guide (Appendix A).

Perspective: What is your organization's perspective on the use of autonomous vessels for offshore wind infrastructure and projects?

Vision: What is your organization's vision of the best outcome for the use of autonomous vessels in the short term (3–5 years) for the use of autonomous vessels for your work? Long term (15–30 years and beyond)?

Current Challenges: What challenges are your organization facing now in the more effective use of autonomous vessels?

Process: What are some steps needed to achieve that future condition?

Political and Institutional Issues and Impacts: How do political and/or institutional considerations play a role in how your organization makes decisions about using this technology for your work? For example, navigational safety, security, Jones Act compliance, workforce, and training.

Future Opportunities, Concerns, Constraints: What are other opportunities, constraints, risks, obstacles, and difficulties with achieving that future condition?

Collaboration and Research: What policy changes, research, and collaboration would help make the vision a reality? How can an organization like M-TWG help provide a forum to share information about the vision and the necessary changes?

Key Considerations and Takeaways Across Subject Matter Experts Interviewed

Similar Views

Interviewees generally expressed similar sentiments regarding some key issues, including uncertainty around regulations, the necessity for workforce development, as well as cybersecurity concerns. Just Innovation and BEAM expressed that the current regulatory landscape surrounding the use and implementation of autonomous vessels can be unclear because they are usually gauged on a case-by-case basis. Given no broad guidance on the use or testing of autonomous vessels, users and developers describe an obstacle to the investment in and use of autonomous technologies. Regulators, including the USCG Waterways Management Team, described the state regulation that contributes to this. These experts described slow regulatory inertia, uncertainty of compliance with the Jones Act, and technical obstacles such as the detection and staffing of unmanned vessels as elements that might make approval of using this technology more difficult.

The increasing prevalence of autonomous technologies necessitates the need for collaboration between regulators, commercial operators, and research academies to ensure a safe, efficient, innovative maritime domain. Interviewees stressed that ongoing evaluation, interagency coordination, and investment in shoreside infrastructure can help streamline the existing patchwork of regulatory and operational issues that interested parties engage with. Looking ahead, proof of concept, environmental impact assessment, and adaptation to evolving standards will determine the pace and scale of autonomous vessel adoption in harbor and offshore wind activities.

There is also a consensus among the interviewees that the region's strong Vessel Traffic Service infrastructure provides opportunities to understand how autonomous vessels operate across the harbor in conjunction with other maritime activities. However, autonomous technology developers and users cautioned that operational efficiency, safety, and public trust, especially regarding passenger transport, must be demonstrated before autonomous systems can be widely adopted.

Cybersecurity concerns and workforce development were additional themes of agreement among interviewees. Increasing autonomy is coupled with increasing cybersecurity concerns. For technology developers and users, this introduces financial and legal risks in the form of losing a vessel or damaging other property or life. For the USCG, the risk of an autonomous vessel hijacking for alternative purposes within their jurisdiction presents clear safety and security concerns.

Workforce development by training personnel in both maritime and technical skills can help minimize these risks. Increasing automation introduces the need for remote centers where operators control vessels from miles away, potentially with no individuals onboard the vessel itself. All interviewees recognize that ensuring successful operations and minimizing risks requires individuals who are proficient in areas including artificial intelligence, machine learning, as well as fundamental maritime knowledge that is required of those who work with or crew conventional vessels. Workforce development initiatives at institutions such as SUNY Maritime, United States Merchant Marine Academy, Mass Maritime, Maine Maritime, and Cal Maritime are considered essential for preparing maritime professionals to manage the growing intersection of marine and technical skillsets needed for maritime workers.

Different Views

Overall, there were no notable areas of disagreement between the subject matter experts. Technology developers/users would like to see more streamlined and transparent processes for testing and operating autonomous technologies. While the USCG examines these projects on a case-by-case basis, it recognizes that existing regulations and protocols have struggled to keep pace with this technology's advancement in recent years.

Perspectives of Each Subject Matter Expert Category

This section provides the perspective of each subject matter group, built around common themes, but also delves into the specific questions for each group.

Offshore Wind Developer – Cynthia Pyć, Founder and Principal, IBN Environmental & Geomatics

PERSPECTIVE

Cynthia Pyć is the principal and founder of IBN Environmental and Geomatics (IBN), a consultancy specializing in providing environmental and social impact and risk assessments, corporate governance services, regulatory policy, compliance, geospatial analysis, and project management. She has extensive experience with offshore wind infrastructure and autonomous vessels, having previously worked for RWE, Avangrid Renewables, and Vineyard Wind.

VISION

IBN anticipates a future where autonomous vehicles are widely adopted for monitoring and data collection in offshore wind projects. They believe that these technologies can significantly reduce environmental impacts, improve safety, and enhance the efficiency of cargo and maintenance operations.

CURRENT CHALLENGES

IBN noted the reluctance of regulatory agencies to approve autonomous technologies for monitoring, leading to the use of crewed vessels, which are noisier and pose a higher risk to marine life. This can negatively impact surveys that require documentation of wildlife. They also mentioned operational challenges, such as the loss of autonomous vehicles and data due to mishaps when autonomous and conventional vessels do not communicate effectively.

PROCESS

IBN reiterates the need for streamlined or structured regulatory approval for the use of autonomous technologies for offshore wind operations and marine operations in general. They mentioned that the development and, ultimately, the use of autonomous technologies is hindered by case-by-case evaluations. They also mentioned it is important to demonstrate the viability of these technologies in various contexts for greater adoption, not just offshore wind.

POLITICAL AND INSTITUTIONAL ISSUES AND IMPACTS

IBN points out that regulatory agencies like BOEM and NOAA have been more conservative in approving autonomous technologies compared to other jurisdictions. They suggest that establishing clear thresholds for technology readiness could help streamline the approval process and get autonomous vessels in the water.

- **Note**: While USCG is the primary authority over all autonomous maritime vessel operations, BOEM regulates autonomous vessel use tangentially through site surveys to protect marine life and compliance with the Endangered Species Act and Marine Mammal Protection Act. Similarly, the National Oceanic and Atmospheric Administration holds a role in consultative practices, mostly relating to internal uses. Neither holds entire authority over autonomous vessel regulations but do offer internal policy and recommendations for use.

FUTURE OPPORTUNITIES, CONCERNS, CONSTRAINTS

IBN sees significant opportunities for autonomous technologies in offshore wind, particularly in deep water and challenging marine environments. However, they also note the need for regulatory reforms and the development of more versatile autonomous vehicles that are accessible for a variety of uses.

COLLABORATION AND RESEARCH

IBN emphasizes the importance of collaboration between developers, regulators, and technology providers to advance the use of autonomous technologies. They also highlighted the need for ongoing research and trials to demonstrate the effectiveness of these technologies.

Autonomous Vessel Users/Operators – Justin Manley, Founder and Principal Consultant, Just Innovation, Inc.

PERSPECTIVE

Justin Manley is the Founder and Principal of Just Innovation, a strategic advisory firm focused on ocean technology, with unique experience in robotics, sensors, and offshore innovation. His work includes providing strategic consulting solutions for autonomous and maritime technologies, including product development, intellectual property strategies, market analysis, and other services.

VISION

Just Innovation views autonomous vessels as beneficial for the future of offshore wind, given their uses for offshore wind activities, including wind turbine inspections. The company emphasizes the need for new autonomous tools to perform functions traditionally done by on-site technicians in the fossil fuel offshore sector, including inspections, repairs, and equipment deliveries, due to the inherent dangers associated with offshore extraction.

CURRENT CHALLENGES

Just Innovation identifies capital risk, operational risk, and regulatory uncertainty as significant challenges for the widespread use of autonomous technologies in marine environments in the US.

Capital and operational risks with robotic systems arise from the absence of onboard personnel to address issues, which means an increasing reliance on remote operators to both diagnose and fix problems as they arise. Another challenge is adhering to the multitude of rules that differ across jurisdictions, creating potential difficulties in compliance and activities, including testing pilot projects in regulated waters as well as offshore wind development.

PROCESS

The industry needs to take specific steps to implement a detailed and layered, mission-specific best practices framework to manage operational risks when using autonomous vessels.

POLITICAL AND INSTITUTIONAL ISSUES AND IMPACTS

To make operations more seamless, Just Innovation advocates for the evolution of regulations toward international standards for operating unmanned systems, particularly if vessels move between different jurisdictions. The company also highlights supply chain security as an emerging concern, particularly when attempting to comply with the Jones Act. An example is aerial drones, for which the US has a “blue list,” meaning that government agencies can only work with drones that meet certain sourcing standards, particularly to limit Chinese-made components. This is a notable challenge because many rechargeable batteries are manufactured in China. With small drones, it might be feasible to build alternative supply chains, but for large underwater vehicles, which require much bigger, more powerful battery systems, tracing and controlling component content could become a real challenge.

FUTURE OPPORTUNITIES, CONCERNS, CONSTRAINTS

Just Innovation recognizes great potential in unmanned surface vessels, unmanned underwater vehicles, autonomous underwater vehicles, and seafloor vehicles. Just Innovation notes that XOCEAN has built its business around unmanned surface vessels and has performed extensive work for the offshore wind sector. However, the company cautions that operators will need to manage more complex workflows for small autonomous fleets, and skilled personnel will still be required to ensure quality control of the results.

COLLABORATION AND RESEARCH

Just Innovation emphasizes the importance of collaboration among industry, regulators, and vendors. Increased levels of cooperation and communication are essential for the successful proliferation of autonomous technology for services, including offshore wind inspections, equipment deliveries, and other services. The company also notes the significance of workforce development to help teach new skills to current maritime workers, as well as the involvement of the insurance industry to better protect technology developers and operators from potential liability issues.

Technology Leaders/Entrepreneurs – Mitch Johnson, Director, Beam

PERSPECTIVE

Mitch Johnson led US operations for Beam, a UK-based offshore wind company developing autonomous vessels and remotely operated vehicles. Based in New York, he focused on expanding Beam’s clean energy presence in the US. Beam operates about 60 percent of the offshore wind farms in the UK and typically runs between two and four remotely operated vessels at any given time. Johnson has joined another firm since WSP conducted the interview.

VISION

Beam sees autonomous vessels as transformative for offshore wind, reducing risks for maritime workers and overall costs. Automating offshore wind operations removes people from hazardous environments and speeds up maintenance and equipment delivery operations.

CURRENT CHALLENGES

Development costs, market acceptance, and client trust are key challenges for widespread and successful autonomous vessel use. Beam believes that cost and the adoption of new technology into maritime environments are notable concerns, particularly when compared to the UK, where regulations and more widespread use of autonomous technologies make the investment in and introduction of new technologies less risky. Liability is another issue, as clients may be nervous about autonomous vehicles in busy ports or harbors, not dissimilar to the introduction of autonomous cars on public roads.

PROCESS

Beam gradually integrates autonomy, starting with its proprietary camera system, SubSLAM. SubSLAM is a camera that creates real-time 3D models of vessel views. Johnson views this as Beam's gateway into full autonomy; taking the data captured and converting it into information that enables autonomous activities.

POLITICAL AND INSTITUTIONAL ISSUES AND IMPACTS

Beam emphasizes the need for regulatory clarity to support autonomous operations, specifically regulations that allow autonomous vessels to operate alongside other commercial vessels. This includes dictating how captains of commercial vessels communicate with and maneuver around autonomous vessels with no onboard personnel. Despite raising questions with the USCG, Johnson notes that there has been almost no guidance so far.

FUTURE OPPORTUNITIES, CONCERNS, CONSTRAINTS

Beam sees opportunities in New York Harbor and offshore areas but notes existing environmental and operational constraints, such as not interfering with fishermen or whale migration patterns. Ultimately, Johnson believes clients need proof of concept to be convinced that the technology will deliver the required data for desired activities, including bathymetric surveys, infrastructure inspections, deliveries, and other services.

COLLABORATION AND RESEARCH

Johnson highlights the importance of industry collaboration and workforce development. He stressed that it is up to all technology leaders to demonstrate the technology, explain its functionality and benefits, and deliver results when they secure a project. Supplier days and community events have been helpful, suggesting that if companies could collaborate to create mutually beneficial processes with other entities, it would create favorable conditions for autonomous technology.

Regulatory Authorities – United States Coast Guard Office of Design and Engineering Standards

PERSPECTIVE

Commander Christopher Rabalais, USCG Systems Engineering Division Chief at the Office of Design and Engineering Standards, provides a regulatory perspective. In this capacity, the USCG advises BOEM on project impacts to the Marine Transportation System, navigational safety, waterway uses, and USCG missions.

CURRENT CHALLENGES

Commander Rabalais notes that autonomous systems are still evolving and require careful oversight as they are evaluated on a case-by-case basis to ensure safety and regulatory compliance by the USCG. He also highlights the lack of explicit regulations governing the use of these technologies and the increasing need to be aware of cybersecurity threats that could threaten the operation and safety of autonomous vessels and those that interact with them.

VISION

Commander Rabalais explains that the USCG supports integrating autonomous technologies into USCG operations. He references the USCG's Unmanned Systems Strategic Plan and a pilot program for rocket recovery as examples. The USCG is actively engaged in this program to collect data and recognizes the regulatory and statutory challenges that autonomous technology developers might face as the technology becomes more widespread.

PROCESS

The USCG coordinates with unmanned system operators through local captains of the port to ensure the safety and security of operations in waterways within their respective jurisdictions.

POLITICAL AND INSTITUTIONAL ISSUES AND IMPACTS

Commander Rabalais emphasizes the USCG's leadership in international maritime regulation, explaining the USCG's role as the lead agency for the US delegations to the International Maritime Organization. He also notes that statutory requirements, such as manning of vessels and watchkeeping, may pose challenges regarding compliance with the Jones Act, as the Act has certain requirements for the presence of onboard crew members who are US citizens. This runs counter to the notion that increasing autonomy is coupled with a reduced onboard presence.

FUTURE OPPORTUNITIES, CONCERNS, CONSTRAINTS

Commander Rabalais acknowledges that regulatory frameworks are still developing for autonomous technologies both in the US and abroad. He also warns that with the increasing adoption of autonomous technologies, the risks, including cybersecurity and safety, to conventional and autonomous vessels could become more prevalent.

COLLABORATION AND RESEARCH

Commander Rabalais emphasizes the importance of interagency collaboration and informed regulation as the USCG considers proposals to provide flexibility for innovation while maintaining the safety of those operating within regulated waterways. He added that cybersecurity regulations under the Maritime Transportation Security Act may apply to some autonomous systems depending on their levels of autonomy, though there are no regulations explicitly addressing autonomous or remotely operated vessels at this time.

New York/New Jersey Harbor Experts – USCG Northeast District, Waterways Management Team

PERSPECTIVE

Matthew Stuck, Chief, USCG Waterways Management, oversees regulatory matters and operations within the waterways in the USCG Northeast District. Mark Cutter, a Marine Transportation Specialist with the Waterways Management Team at USCG Northeast District, focuses on navigation safety and integrating autonomous vessels into existing routing schemes. Specialist Cutter oversees autonomous vessel deployment safety and evaluates each situation individually.

Michele DesAutels, Chief, Maritime Energy and Marine Planning with USCG Northeast District, leads USCG's involvement in offshore energy projects located within the district.

VISION

Each USCG member anticipates that autonomous systems will play a larger role in the future of US ports, especially in busy environments such as New York Harbor. Chief Stuck and Specialist Cutter discussed the importance of early engagement between developers and the USCG to build best practices and ensure safe integration of pilot projects into the maritime environment. Chief Stuck highlights New York's strong regulatory infrastructure and interest in using unmanned systems for delivery as an alternative to roadways, including small packages and potentially larger cargo. Chief DesAutels points out that the UK is notably ahead of the US in deploying autonomous vessels for inspection and maintenance, a model that could soon be adopted in the US for environmental responses to oil spill monitoring and cleanup.

CURRENT CHALLENGES

A common concern among the USCG Waterways Management Team is the increasing number and small size of uncrewed, autonomous vessels in busy waterways. These types of vessels are often difficult to detect, raising the risk of collision, especially with larger vessels that may not notice them. The lack of onboard personnel means no human lookout, helm, or captain, requiring the USCG to pay more attention to maintain safe operations. Many operators are unaware that they should notify the USCG before testing autonomous technologies, highlighting an information gap that needs to be reconciled by establishing and publicizing protocols for pilot projects in marine environments. Reliance on automatic identification systems is another concern, as not all vessels are equipped with this technology, creating potential conflicts when interacting with fishing boats, wrecks, or ferries without autonomous capabilities. Subsurface autonomous vessels that surface unexpectedly to transmit data, introduce additional safety risks to vessels and crews, as they can surface with little to no warning within the path of a moving vessel. The USCG continues to learn about new vessel types as they emerge, but regulatory and operational burdens and uncertainty are evident.

PROCESS

The USCG currently relies on existing directives, such as captain of the port orders and navigation regulations, to manage autonomous operations within its jurisdiction. These protocols are generally reactive, though the Waterways Management Team emphasizes the importance of proactive coordination with contractors and local sector teams to minimize navigational risks. Marine safety information is advertised, and collaboration is encouraged to ensure vessels, both surface and subsurface, operate safely near other vessels.

POLITICAL AND INSTITUTIONAL ISSUES AND IMPACTS

The Waterways Management Team recognizes that the regulatory framework for autonomous vessels is evolving. The International Maritime Organization (IMO) sets international maritime standards, but has yet to fully address autonomous technology, leaving the USCG to interpret existing rules as best it can within its own jurisdiction. This creates ambiguities in vessel classifications, responsibility, and lookout functions, particularly regarding compliance with the Jones Act. Cybersecurity is a rising concern, especially for remotely controlled systems and autonomous vessels with no onboard personnel that could be vulnerable to hacking or misdirection.

FUTURE OPPORTUNITIES, CONCERNS, CONSTRAINTS

Autonomous vessel systems present significant opportunities for offshore wind, port logistics, and maritime domain awareness. However, the lack of existing comprehensive regulation in the United States creates gaps in safety and accountability for autonomous technology operators and those interacting with autonomous vessels. From a safety perspective, the operation of autonomous vessels mitigates the risk of impact on human life by minimizing the presence of onboard personnel in the event of an incident. However, autonomous vessels interacting with conventional vessels introduce new safety risks that need to be addressed via proactive protocols and domain awareness near busy ports.

COLLABORATION AND RESEARCH

The Waterways Management Team advocates early and ongoing collaboration between industry and regulators. Hybrid teams, those that combine licensed mariners and technical experts in coding, software, and artificial intelligence, have proven most effective in managing new autonomous technologies. Workforce development is essential, and maritime academies will need to train more professionals with both maritime and technical backgrounds as autonomous systems proliferate.

Opportunities for Future Study

These interviews provide three potential areas of further study: ongoing regulatory change, workforce development, and cybersecurity. Existing regulatory constraints and uncertainty, the emergence of new international regulations, and implications for US regulations to preserve the Marine Transportation System present the greatest barrier for advancing autonomous vessel technology in the US and creating effective regulatory systems for safe navigation. The maritime industry's future workforce has an opportunity to become proficient in new technologies, vessel operations, and skill training to mitigate potential navigational risks, including cybersecurity risks, to maintain safe and secure vessel operations in and around US ports. Future collaboration can help to better understand workforce development needs, particularly by engaging with existing maritime workers who have institutional maritime knowledge and are interested in developing additional technical skills.

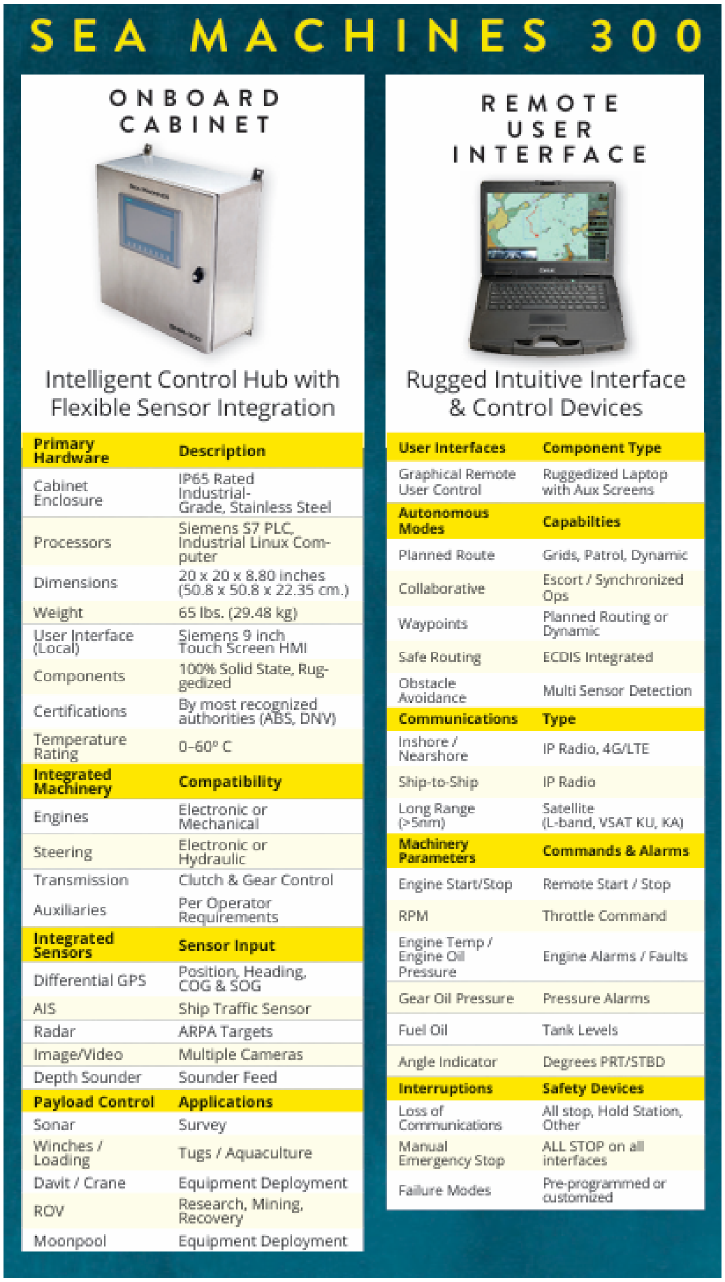
CASE STUDY: SEA MACHINES ROBOTICS – SM300 AUTONOMOUS COMMAND AND CONTROL SYSTEM

Sea Machines Robotics

Sea Machines Robotics, a Boston-based company in marine autonomy and advanced perception systems, specializes in developing autonomous command and control solutions for commercial and industrial maritime applications. Founded in 2017, the company has positioned itself as one of the leaders of maritime automation.

Sea Machines' most prevalent technology is the SM300 Autonomous Command and Control System, a modular autonomy solution designed to convert conventional crewed vessels into remotely operated or fully autonomous platforms. The SM300 system provides real-time situational awareness, autonomous navigation, and collision avoidance, allowing vessels to perform complex operations with minimal human intervention. The system integrates with radar, lidar, automatic identification systems, optical cameras, and remote communications (LTE, Iridium, Starlink) to ensure safe and efficient uncrewed operations.

Figure 8 provides an overview of the SM300 system and its specifications for achieving retrofit-ready technology.



Primary Hardware	Description
Cabinet Enclosure	IP65 Rated Industrial-Grade, Stainless Steel
Processors	Siemens S7 PLC, Industrial Linux Computer
Dimensions	20 x 20 x 8.80 inches (50.8 x 50.8 x 22.35 cm.)
Weight	65 lbs. (29.48 kg)
User Interface (Local)	Siemens 9 inch Touch Screen HMI
Components	100% Solid State, Ruggedized
Certifications	By most recognized authorities (ABS, DNV)
Temperature Rating	0-60° C
Integrated Machinery	**Compatibility**
Engines	Electronic or Mechanical
Steering	Electronic or Hydraulic
Transmission	Clutch & Gear Control
Auxiliaries	Per Operator Requirements
Integrated Sensors	**Sensor Input**
Differential GPS	Position, Heading, COG & SOG
AIS	Ship Traffic Sensor
Radar	ARPA Targets
Image/Video	Multiple Cameras
Depth Sounder	Sounder Feed
Payload Control	**Applications**
Sonar	Survey
Winches / Loading	Tugs / Aquaculture
Davit / Crane	Equipment Deployment
ROV	Research, Mining, Recovery
Moonpool	Equipment Deployment

User Interfaces	Component Type
Graphical Remote User Control	Ruggedized Laptop with Aux Screens
Autonomous Modes	**Capabilties**
Planned Route	Grids, Patrol, Dynamic
Collaborative	Escort / Synchronized Ops
Waypoints	Planned Routing or Dynamic
Safe Routing	ECDIS Integrated
Obstacle Avoidance	Multi Sensor Detection
Communications	**Type**
Inshore / Nearshore	IP Radio, 4G/LTE
Ship-to-Ship	IP Radio
Long Range (>5nm)	Satellite (L-band, VSAT KU, KA)
Machinery Parameters	**Commands & Alarms**
Engine Start/Stop	Remote Start / Stop
RPM	Throttle Command
Engine Temp / Engine Oil Pressure	Engine Alarms / Faults
Gear Oil Pressure	Pressure Alarms
Fuel Oil	Tank Levels
Angle Indicator	Degrees PRT/STBD
Interruptions	**Safety Devices**
Loss of Communications	All stop, Hold Station, Other
Manual Emergency Stop	ALL STOP on all interfaces
Failure Modes	Pre-programmed or customized

Figure 8: SM300 technology overview

SM300 System Deployment and Applications

The SM300 system has been deployed in multiple operational environments, demonstrating its capabilities in various offshore settings.

Key deployments include:

- **CT & NY – First Harvest Navigation:** Integrated with the cargo vessel Captain Ben Moore (63-foot by 21.3-foot aluminum catamaran), where the SM300 system enabled autonomous and remote-helm operation. The first hybrid cargo vessel to feature remote crew-assist technology in the US. The vessel operates between Norwalk, Connecticut, and Huntington, New York, transporting palletized produce and food across Long Island Sound (Figure 9).

- **Galveston Bay:** Used aboard DEA Marine Services' survey vessel Sigsbee, where it enabled a hybrid crewed/uncrewed hydrographic survey for NOAA, covering over 600 autonomous nautical miles (by 2021).
- **SELKIE 7 (Sea Machines Robotics, USA):** A 7-meter (m) uncrewed surface vessel designed for hydrographic surveys, offshore asset inspections, and environmental monitoring. Equipped with an under-keel sonar mount, Conductivity, Temperature and Depth (CTD) winch, and a cargo bay.
- **North Sea & Dutch Wadden Sea:** Integrated with Deep BV's survey vessel, Loeve (8 m/26.2-foot), where it enabled fully autonomous and remote-helm hydrographic surveys. This allowed for continuous operation in shallow waters and tidal environments, optimizing data collection accuracy while minimizing risks to personnel.
- **Netherlands/Denmark:** Nellie Bly (Machine Odyssey): An autonomous tug that completed a 129-hour voyage over 13 days (over 1,000 nautical miles), remotely commanded by US Coast Guard (USCG)-licensed mariners stationed 3,000 miles away in Boston. This demonstrated the SM300's capabilities in long-distance autonomous operations and successfully executed 31 collision avoidance and traffic separation maneuvers (Figure).
- **California – Foss Maritime:** Integrated with the tug Rachael Allen, where the SM300 system enabled autonomous transit and station keeping for tanker escort and ship assist operations. The system interfaces with Kongsberg-MTU propulsion controls, allowing for remote piloting trials from a shore-based command center.
- **Hawaii – USCG Research & Development Center:** Integrated with a Sharktech 29 Defiant autonomous vessel, developed in partnership with Metal Shark Boats. The SM300 system was tested in USCG-designated waters to evaluate autonomous surveillance, interdiction, and patrol capabilities.
- **Portland, Maine –** Marine Spill Response Corporation: Integrated with a Kvichak Marco skimmer boat, where the SM300 system enabled autonomous spill response operations. Conducted in August 2019 for the US Department of Transportation Maritime Administration (MARAD), this deployment showcased the world's first autonomous oil spill response vessel.

Figure 9: *Captain Ben Moore* Vessel

Figure 10: *Nellie Bly*

Challenges in Offshore Wind Vessel Operations

The offshore wind industry relies on a fleet of specialized vessels for offshore operations and faces significant challenges that impact project timelines, costs, and overall efficiency. These challenges stem from harsh environmental conditions, logistic complexities, high operational expenses, and increasing sustainability requirements (Table 2). Addressing these issues is critical for improving offshore wind farm development and optimizing long-term operations.

CHALLENGE	DESCRIPTION	IMPACT ON INDUSTRY
Crew Safety and Fatigue	Offshore wind operations require vessels to operate in harsh environments with long shifts, extreme weather, and physically demanding tasks.	Increased risk of accidents, fatigue-related errors, and crew injuries. Adverse weather can reduce workability windows, delaying projects.
High Operational Costs	Vessel operations require large crews, high fuel consumption, and frequent maintenance. The need for specialized vessels (SOVs, CTVs, and survey ships) further drives up expenses.	Increases CAPEX and OPEX, making offshore wind projects more expensive and dependent on vessel availability.
Survey Efficiency	Traditional survey vessels rely on human crews, are limited by shift durations, and may be prone to inconsistencies in data collection. Asset inspections often require divers or remotely operated vehicles deployed from crewed vessels.	Slower, costlier, and less precise seabed mapping and infrastructure monitoring, leading to longer permitting and maintenance cycles.
Environmental Sustainability	Maritime operators face pressure to reduce carbon emissions and fuel consumption.	Requires investment in low-emission technologies and hybrid/electric solutions.
Distance from Shore	As offshore wind farms move further offshore, vessel transit times increase, and traditional crewed operations become more challenging.	Longer travel distances reduce effective working hours, increase fuel consumption, and raise logistic challenges for maintenance, inspections, and crew rotations.

Table 2: Common Offshore Wind Vessel Operations Challenges

SM300 System Features

The SM300 system offers a scalable, adaptable solution for offshore vessel operations by enabling autonomous navigation, remote operations, and fleet coordination. Unlike many emerging maritime technologies, the SM300 is commercially available and can be installed on existing vessels in under a week in some cases, making it a practical option for enhancing autonomous capabilities in offshore environments.

Table 3 outlines how the SM300 system could address key operational challenges outlined in Table 2.

CHALLENGE	CHALLENGE ADDRESSED BY	KEY FEATURES ENABLING THE SOLUTION
Crew Safety and Fatigue	Autonomous Navigation and Collision Avoidance – The SM300 integrates artificial intelligence-	Autonomous Navigation and Collision Avoidance – artificial intelligence-driven perception systems provide situational

CHALLENGE	CHALLENGE ADDRESSED BY	KEY FEATURES ENABLING THE SOLUTION
	powered radar, lidar, optical cameras, and automatic identification systems, allowing vessels to navigate without constant human intervention. This reduces crew exposure to offshore hazards and minimizes fatigue-related incidents.	awareness, allowing vessels to detect and avoid obstacles with greater precision.
High Operational Costs	Remote-Helm Operation and Fleet Optimization – The SM300 enables vessels to be remotely commanded from a shore-based control center, reducing the need for large onboard crews.	Remote-Helm Control and Fleet Coordination – Wireless IP radio, LTE, Iridium, and Starlink connectivity enable centralized vessel command and fleet coordination, optimizing crew allocation.
Survey Efficiency	Continuous, High-Precision Surveying – SM300-powered vessels operate 24/7, enhancing seabed mapping, cable route planning, and infrastructure inspections with higher accuracy and efficiency.	Survey-Ready Automation – Preprogrammed mission execution, waypoint tracking, and precision control ensure high-quality data collection while reducing human error.
Environmental Sustainability	Sustainability and Emissions Reduction – By supporting hybrid and fully electric vessel operations, SM300-powered vessels lower carbon emissions and reduce fuel dependency.	Seakeeping and Adaptive Motion Control – Regulates vessel speeds and movements to optimize fuel efficiency, reduce emissions, and improve safety in rough sea conditions.

Table 3: SM300 System Features to Address Offshore Wind Vessel Operations Challenges

Navigational Safety and Security

Maritime navigation faces distinct challenges, including the presence of unregulated vessels, often referred to as “shadow fleets,” operating without proper oversight or communication. According to the International Maritime Organization (IMO), unregulated vessels operating without proper oversight or communication pose significant collision and environmental hazards, particularly in busy shipping lanes, such as those within New York Harbor and the surrounding area. Additionally, integrating autonomous technology heightens vulnerability to cyber threats, requiring robust cybersecurity measures.

Autonomous vessels equipped with Sea Machines' SM300 system address these navigational hazards by substantially reducing reliance on human judgment, thus minimizing risks associated with fatigue, poor visibility, and situational misjudgment. By continuously integrating data from radar, automatic identification systems, GPS, and computer vision, autonomous vessels enhance real-time situational awareness and collision avoidance capabilities. The SM300 system can swiftly detect and respond to vessels operating without proper identification, further mitigating potential navigational threats. Sea Machines' technology also conforms to international maritime collision regulations (COLREGs), ensuring regulatory compliance and effective hazard mitigation. Comprehensive cybersecurity features and continuous system monitoring protect against digital vulnerabilities, reinforcing both physical and cyber safety. This integrated approach enhances the overall security, safety, and resilience of maritime autonomous operations.

Infrastructure Requirements

Sea Machines' SM300 system integrates easily into existing vessels and port operations without specialized infrastructure. There are three main control configurations available for operating SM300-equipped vessels: shipboard control, shore-based control, and the portable beltpack.

- **Shipboard Control:** This configuration refers to direct control from the onboard wheelhouse. The vessel's captain or onboard crew operate the SM300 from familiar vessel consoles integrated with Sea Machines' system. This setup is beneficial when immediate onboard oversight and control are desired, particularly during operations that require advanced vessel handling or rapid response in challenging conditions.
- **Shore-Based Control:** This remote operation approach allows operators at onshore command centers to manage vessel navigation and mission execution via reliable communication networks, typically cellular or satellite. Shore-based control centers provide enhanced flexibility, enabling centralized supervision of multiple autonomous or semiautonomous vessels simultaneously. This configuration is preferable for users managing larger fleets, long-duration missions, or operations in high-risk or remote environments, reducing crew risk exposure and potentially lowering operating costs (Figure).
- **Beltpack Remote-Helm Device:** A portable, handheld wireless controller that enables short-range remote vessel operation. This option is useful for precision maneuvering during docking, cargo handling, or confined-water operations. It relies on short-range wireless communications similar to industrial wireless remote controls. The beltpack is preferable for mariners requiring greater mobility and direct visual oversight, making it ideal for harbor tugs, cargo transfer operations, or close-quarter maneuvers where precision and responsiveness are critical.

Overall, the choice between shipboard, shore-based, or beltpack control depends primarily on the end user's specific operational needs. Ports and vessel operators managing small-scale or precision-focused operations may prefer the beltpack or onboard control, whereas larger-scale commercial operations or fleets are more likely to utilize shore-based control for centralized fleet management and operational efficiency. Because of SM300's versatility, most ports can support autonomous vessels without significant infrastructure modifications beyond ensuring robust and reliable connectivity. In addition, use of shore-based or beltpack remote controls adds a layer of safety by reducing mariner exposure to potential collisions in high-risk situations.

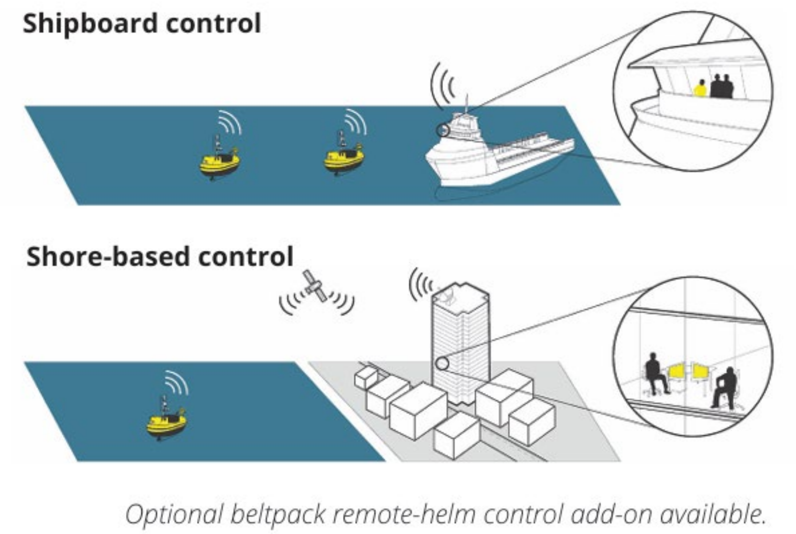


Figure 11: SM300 control interfaces

SM300 System - Training Approach and Skill Development

Based on publicly available information, no specific training applications or programs have been identified, as this technology has only been applied to a small number of project-specific deployments; however, Sea Machines generally provides both formal and informal guidance on operating and maintaining their autonomous control systems. While the SM300 system does not necessarily create entirely new maritime roles, Sea Machines recommends specialized training for mariners transitioning to using autonomous systems, including system calibration, remote monitoring and control, and managing cybersecurity protocols. It is anticipated that existing crew or shoreside staff will take on additional responsibilities related to remote command and control, data interpretation, cybersecurity, and software troubleshooting. This could involve cross-training mariners to become proficient in the SM300's user interface and emergency override procedures. Rather than introducing wholly new job types, Sea Machines' approach generally augments traditional mariner skill sets with a focus on technology, situational awareness, and continuous system monitoring.

Potential Offshore Wind Farm Support from the SM300 System

The SM300 Autonomous Command and Control System has the potential to enhance offshore wind operations by increasing efficiency, safety, and regulatory compliance. With its advanced autonomy, remote operation, and artificial intelligence-powered situational awareness, the system could optimize key offshore wind activities by reducing costs, improving data accuracy, and minimizing human exposure to hazardous environments.

While specific commercial deployments within offshore wind projects have not yet been publicly documented, Sea Machines highlights the SM300's potential suitability for offshore wind operations, citing use cases such as inspection and maintenance, logistics and supply chain management, and data collection and mapping. Sea Machines online blog posts have noted "Offshore energy plays a vital role in meeting global energy demands, contributing significantly to the production of renewable energy, oil, and gas. With the expansion of offshore energy projects worldwide, ensuring the efficiency, safety, and sustainability of operations becomes paramount. Unmanned vessels have emerged as integral tools in offshore energy operations, offering innovative solutions to challenges such as inspection, maintenance, and logistic support." Many of these use cases, including logistics and supply chain management, navigational support (e.g., collision avoidance), and data collection and mapping, are likely to be applicable to New York Harbor and their associated offshore wind installations.

Seabed Surveys and Mapping

The SM300 could be integrated with survey vessels to enable the autonomous collection of high-resolution bathymetric data for cable route planning, site selection, and permitting requirements. Equipped with multibeam sonars, sub-bottom profilers, and magnetometers, SM300-powered vessels could operate continuously without crew fatigue, ensuring faster and more cost-effective survey campaigns.

- **Hydrographic Surveys:** Mapping seabed features for offshore wind farm placement of vessels, assets, and navigation safety.
- **Geophysical Surveys:** Characterizing seafloor geology to support engineering design and installation.
- **Unexploded Ordnance Surveys:** Identifying potential hazards from historical munitions left on the seafloor.

Asset Inspection and Maintenance

The SM300 could enable real-time monitoring of subsea cables, turbine foundations, and offshore substations, ensuring early detection of structural wear, corrosion, or mechanical stress. By integrating with autonomous remotely operated vehicles and AUVs, SM300-powered vessels could conduct high-precision, automated inspections without divers or crewed vessels.

- **Proactive Maintenance:** Frequent inspections to prevent costly failures and reduce downtime.
- **Cable Protection Monitoring:** Detecting sand wave movement and evaluating the need for cable protection systems, such as rock dumping and concrete mattresses.
- **Extended Asset Lifespan:** Continuous monitoring enables predictive maintenance strategies, minimizing emergency repairs.

Operations and Logistics

The SM300 could support autonomous offshore logistics, including material transport and crew transfer operations. By enabling uncrewed operations, it could reduce reliance on expensive crewed support vessels, cutting fuel costs and improving operational efficiency.

- **CTV Support:** Autonomous navigation for crew transport and small-scale cargo deliveries during installation and maintenance phases.
- **Guard Vessels and Offshore Surveillance:** Autonomous patrols of offshore wind construction zones to prevent unauthorized vessel entry and enhance site security.

- **Buoy Deployment and Servicing:** Automating offshore marker buoy placement and maintenance to aid navigation and environmental monitoring.

Environmental Monitoring

By equipping autonomous vessels with hydrophones, passive acoustic monitoring systems, and environmental sensors, SM300-powered vessels could support comprehensive impact assessments and ecosystem monitoring.

- **Marine Mammal Observation:** Collecting autonomous data to assess the impact of wind farm construction on marine species and ensure endangered mammals are not within the defined area during installation.
- **Fisheries Studies:** Monitoring fish populations, seabed habitats, and benthic conditions to evaluate ecological effects.
- **Artificial Reef Research:** Evaluating turbine foundations' potential to support marine biodiversity.

The SM300 Control System presents an adaptable solution for offshore wind operations, with the potential to streamline surveying, maintenance, logistics, and environmental monitoring.

Regulatory Agencies for Autonomous Vessels

Autonomous vessels operating in US waters are subject to regulation by the agencies, regulatory bodies, and laws listed in this section.

United States Coast Guard (USCG)

The USCG is the federal agency responsible for regulating US waterways to ensure that they are safe and secure. The USCG acts as the lead agency within the US delegation to the International Maritime Organization (IMO).

Sea Machines has worked with the USCG to test and validate autonomous vessel operations, particularly in USCG-designated test zones such as Galveston Bay and Hawaii. The Sharktech 29 Defiant autonomous vessel, developed with Metal Shark Boats, underwent USCG-supervised trials to assess its performance in autonomous surveillance, patrol, and interdiction operations. These trials aimed to evaluate the viability of autonomous underwater vessels in maritime law enforcement and security applications.

International Maritime Organization (IMO)

The IMO is developing a regulatory framework for autonomous ships in commercial operation in international waters that addresses cross-cutting issues such as safety, training, and legal liabilities. It is generally expected to be adopted by member countries on a nonmandatory basis in 2025 and in force on a mandatory basis for member countries in 2032 by amending an existing IMO convention. Selected countries have approached the regulation of autonomous ships in various ways, including regulating them within the framework of existing laws and regulations, modifying regulations, and creating new regulations and policies.

The IMO has introduced Maritime Autonomous Surface Ship Guidelines, with which the SM300 system is fully compliant. These guidelines ensure that autonomous vessel operations adhere to existing safety and regulatory standards while paving the way for the gradual adoption of fully autonomous offshore wind logistics and maintenance vessels.

American Bureau of Shipping

The American Bureau of Shipping (ABS) is a US regulatory body and classification society that establishes and enforces safety, design, and operational standards for commercial vessels, including autonomous ships.

ABS has verified the SM300 system aboard Foss Maritime's tug *Rachael Allen*, marking a key regulatory milestone for autonomous vessel technology. The SM300 enables autonomous transit and station keeping, interfacing with Kongsberg-MTU propulsion controls for enhanced crew safety and operational efficiency. The collaboration between Sea Machines, Foss, and ABS underscores industry-wide efforts to integrate autonomy into commercial operations. *Rachael Allen* is currently deployed in California for tanker escort and ship assist operations.

Jones Act

Sea Machines' SM300 deployments within the US have consistently complied with Jones Act regulations, primarily because the system integrates seamlessly with domestically built and flagged vessels. As a retrofit solution designed to enhance the autonomous capabilities of conventional vessels, the SM300 generally does not impact a vessel's compliance status with the Jones Act. All Sea Machines deployment examples were either built and flagged in the US, operated domestically, or engaged in activities exempt from Jones Act requirements, further demonstrating the system's compatibility with existing US maritime regulatory frameworks. Operators aiming to implement autonomous technologies within US waters can leverage systems like the SM300 without requiring new builds or foreign vessel involvement, thereby simplifying regulatory compliance and enabling broader adoption in domestic maritime operations.

Lessons Learned

Through multiple deployments across different maritime environments, several lessons have been learned regarding the integration and operation of the SM300 system:

- Collaborative autonomy with manned mother ships expanded survey coverage and minimized downtime. Coordinated deployment of multiple autonomous vessels maximized data collection and significantly shortened survey durations.
- Remote operation capabilities reduced human exposure to hazardous offshore environments. The SM300 system mitigates risks associated with severe weather, vessel collisions, and crew fatigue, enhancing overall safety.
- Lower reliance on crewed vessels led to fuel savings and reduced carbon emissions. The SM300's ability to support uncrewed operations aligns with industry sustainability goals, decreasing environmental impact.
- While the SM300 meets key regulatory requirements, further standardization is needed. Full integration of autonomous vessels into commercial maritime operations requires continued development of industry-wide regulations.
- Autonomous operations remain reliable in challenging conditions. The SM300 enables vessels to continue working through poor visibility, extreme weather, and rough sea states.

Many of these lessons, including collaborative autonomy, remote operation safety benefits, reduced environmental impact, and regulatory standardization, apply broadly to autonomous maritime technologies beyond the SM300 system. Future efforts and industry recommendations should focus on standardizing protocols, ensuring operability between systems, and developing comprehensive training programs, thus supporting widespread adoption and integration of autonomous vessels into maritime operations.

CASE STUDY: FUGRO – AUTONOMOUS SURFACE VESSELS

Fugro is a global provider of geo-data acquisition, analysis, and interpretation, offering insights for infrastructure, environmental, and resource development. Fugro supports offshore wind projects globally, providing services from initial surveys through construction, operations, and maintenance.

In November 2023, Fugro acquired SEA-KIT International, its design partner for the Blue Eclipse XL-class vessel, strengthening its marine robotics capabilities.

Fugro's Autonomous Vessel Technology

Fugro has developed several unmanned surface vessel platforms, including Blue Essence, Blue Shadow, Blue Eclipse, and the conceptual Blue Prism. Fugro also deploys electric remotely operated vehicles, such as the Blue Volta and Blue Amp, for subsea inspections. These platforms enable offshore hydrographic, geophysical, environmental surveys, and subsea integrity assessments. They leverage advanced autonomous technologies to enhance operational safety, efficiency, and environmental responsibility.

Fugro Blue Essence

The Blue Essence is a 12-meter unmanned surface vessel developed with SEA-KIT International (Figure 12). It is equipped with multibeam echo sounders, lidar, Global Navigation Satellite System, optical imaging, and the Blue Volta electric remotely operated vehicle. The Blue Essence is operated from Fugro's Remote Operations Center.

Blue Essence provides real-time data, reduces exposure of personnel to hazardous marine conditions while reducing environmental impact, and achieves up to a 95 percent reduction in carbon emissions compared to traditional vessels for a typical deployment. Its modular design supports various marine applications, including offshore wind inspections, subsea monitoring, and hydrographic surveys.

A key capability of the Blue Essence is the remote deployment of the Blue Volta electric remotely operated vessel, providing detailed subsea inspections, cable tracking, and structural assessments, enhancing project safety and environmental sustainability of these project activities (Figures 12 and 13).

Figure 12: Fugro Blue Essence Vessel

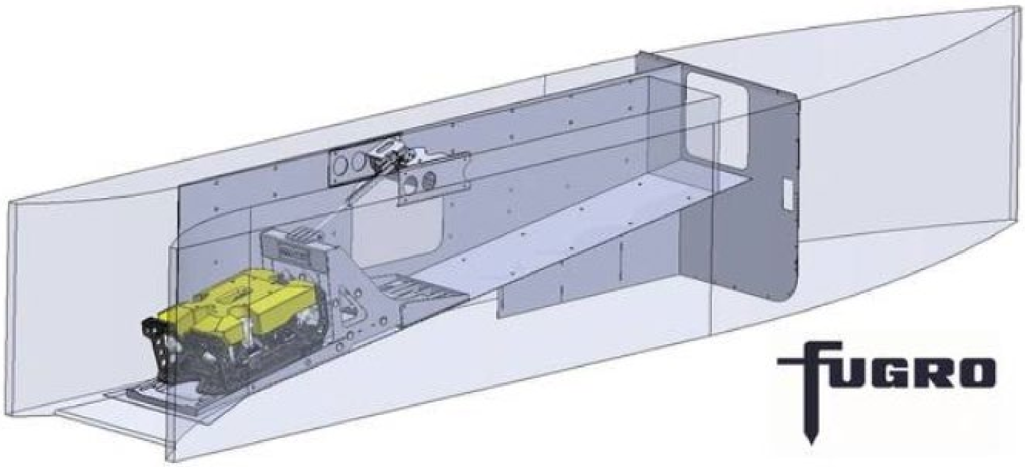


Figure 13: Blue Volta eROV deployed from Fugro Blue Essence Vessel

DEPLOYMENTS OF BLUE ESSENCE VESSELS AND APPLICATIONS

Aberdeen Offshore Wind Farm (North Sea, United Kingdom) – Blue Essence performed remote inspections of wind turbine foundations and seabed mapping, operated from Fugro's Remote Operations Center. In Aberdeen, the deployment, supported by Vattenfall and ORE Catapult, demonstrated reliable safety and environmental performance through remote operations.

Hollandse Kust Zuid Offshore Wind Farm (North Sea, Netherlands) – Blue Essence completed remote integrity inspections covering 140 wind turbines, two offshore substations, and extensive cable protection systems over 142 kilometers to ensure asset durability and reliability.

TAQA Offshore Assets (North Sea, Netherlands) – Fugro's first fully remote offshore integrity campaign for TAQA Netherlands involved inspecting two production platforms and 45 kilometers of pipelines.

Eni Energy Offshore Assets (North Sea, Netherlands) – Blue Essence remotely surveyed 282 kilometers of pipelines and performed inspections around 26 offshore platforms.

Rotterdam Port Authority (North Sea, Netherlands) – Operating in one of Europe's busiest ports, Blue Essence conducted remote inspections and surveys confirming the feasibility and safety of using unmanned surface vessels in congested maritime environments.

Fugro Pegasus (United Arab Emirates Operations) – Fugro Pegasus became the first unmanned surface vessel licensed for fully remote operations by the United Arab Emirates Ministry of Energy and Infrastructure and was deployed for subsea inspections and geophysical surveys.

Fugro Blue Shadow Class Vessels

The Blue Shadow is a 9-meter class unmanned surface vessel designed by Fugro for hydrographic mapping and bathymetric surveys (Figure 14). It features a wave-piercing hull and gondola-mounted sensors, providing stable data collection in challenging sea states. The vessel includes dynamic line planning, integrated radar, Automatic Identification System, Global Navigation Satellite System, multibeam echosounder, and 360-degree cameras to enhance data accuracy and situational awareness.

Blue Shadow operates in autonomous, semiautonomous, and direct remote-control modes, offering flexibility in various marine environments. The vessel also reduces greenhouse gas emissions compared to traditional survey methods due to the vessel's compact design, energy efficient propulsion systems, and optimized low-speed survey operations, which collectively minimize fuel consumption and emissions.

Figure 14: Fugro's Blue Shadow

DEPLOYMENTS OF BLUE SHADOW CLASS VESSELS AND APPLICATIONS

Middle East Deployment – Fugro deployed the Blue Shadow for high-precision hydrographic surveys supporting port expansions, coastal management, and offshore energy infrastructure.

United Kingdom Trials (Portchester Coast) – Blue Shadow conducted successful autonomous surveys in challenging conditions with waves up to 2 meters, where traditional survey vessels would often face operational limits.

Global Hydro spatial Surveys (Unspecified Region) – Blue Shadow has complemented larger survey vessels, improving geographic coverage and efficiency in large-scale hydrographic surveys.

Fugro Blue Eclipse Class Vessels

The Blue Eclipse is Fugro's larger unmanned surface vessel, designed for extended offshore operations (Figure 15). It is suited for deep water offshore wind farm support and floating wind applications. Blue Eclipse vessels have enhanced endurance, station keeping ability, and payload capacity, enabling subsea operations to depths of up to 650 meters. Equipped to deploy the Blue Volta electric remotely operated vehicle (Figure 16), it supports complex offshore site characterization, inspection, maintenance, and repair.

Currently, no publicly available deployment information is available; however, based on deployments for the Blue Shadow class of vessels, it is anticipated that the larger Blue Eclipse class of vessels would have the capability for deployment in northern and mid-Atlantic Ocean waters.

Figure 15: Fugro Blue Eclipse Vessel

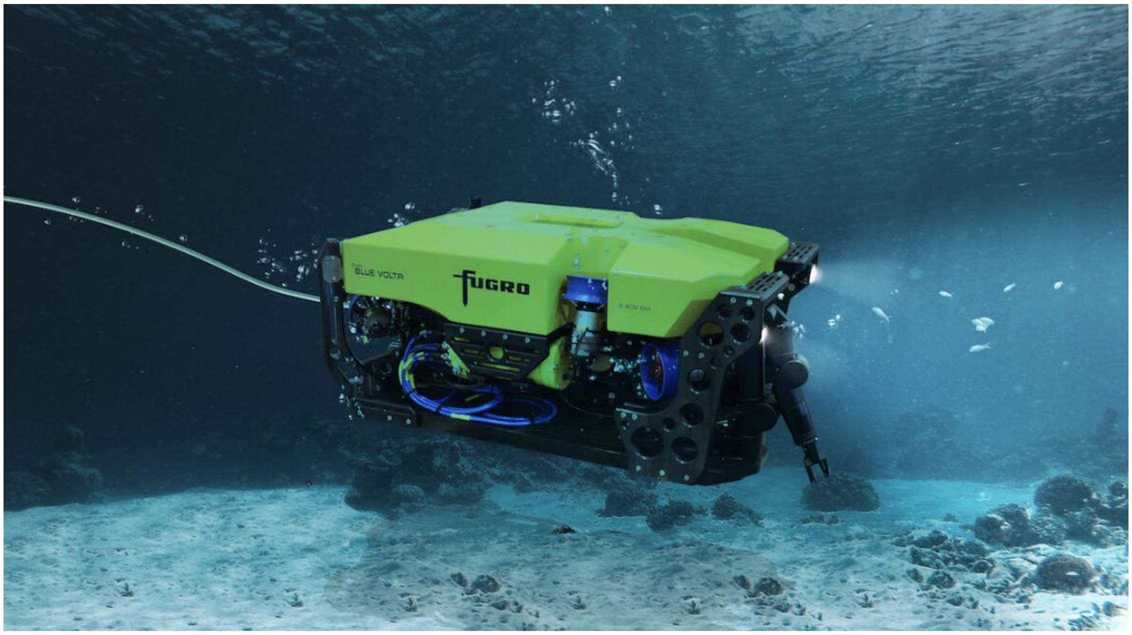


Figure 16: Blue Volta eROV

Fugro Blue Prism

Blue Prism is Fugro's next generation unmanned surface vessel, designed primarily for marine site characterization related to offshore energy projects (Figure 17). It features advanced geophysical survey equipment including sub-bottom profilers, a dual-head multibeam echo sounder, a side-scan sonar, and cable tracking technologies. Fugro is also considering future configurations to enable limited geotechnical sampling capabilities.

Blue Prism is currently in the development phase and has not yet been operationally deployed.

Figure 17: Fugro Blue Prism

Fugro's Autonomous Vessel Features

Table 4 describes Fugro's autonomous vessels that provide solutions to the common challenges of operating offshore wind vessels:

CHALLENGE	CHALLENGE ADDRESSED BY	KEY FEATURES ENABLING THE SOLUTION
Crew Safety and Fatigue	Offshore wind operations often expose crew to hazardous conditions, such as extreme weather and prolonged shifts, increasing accident risk. Fugro's unmanned surface vessels improve crew safety by reducing the need for onboard personnel in high-risk environments.	Shore-based control from Remote Operations Centers reduces crew exposure to offshore hazards, and a suite of autonomous navigation systems allows vessels to safely navigate with minimal human intervention.
Survey Efficiency	Shift limits, sea state, and weather conditions constrain crews on traditional survey vessels. Autonomous capabilities enable around-the-clock, real-time data collection and streaming.	Fugro's autonomous vessels operate continuously in varied conditions. This has been demonstrated by the Blue Shadow completing autonomous hydrographic surveys near Portchester, United Kingdom in waves up to 2 meters, which would have limited a traditional survey vessel.
Distance from Shore	As offshore wind farms extend farther offshore, crewed vessels face an increase in logistic challenges and transit times.	Fugro's autonomous vessels are designed to conduct extended range missions and are managed by Remote Operations Centers without on-vessel crew rotation, reducing supply requirements and simplifying logistics.

Table 4: Fugro's Autonomous Vessel Features to Address Offshore Wind Vessel Operations Challenges

Autonomous Fleet Development

Fugro continues to expand the capabilities of its autonomous vessel fleet by integrating advanced sensor and subsea payload technologies, improving mission endurance, and enhancing operational flexibility.

Navigational Safety and Security

Fugro's unmanned surface vessels employ advanced navigation and situational awareness systems to manage marine safety risks. These vessels operate in compliance with International Regulations for Preventing Collisions at Sea with real-time oversight from regional Remote Operations Centers.

Navigational safety protocols include redundant radar systems, Automatic Identification System transceivers, Global Navigation Satellite System, lidar for obstacle detection, optical cameras, sonar for submerged obstacle recognition, and proprietary computer vision software. Fugro simultaneously manages multiple vessels from regional Remote Operations Centers, with vessel operations continuously monitored for compliance and safety.

Cybersecurity measures feature encrypted communications, dedicated cybersecurity protocols, and proactive threat monitoring at Remote Operations Center facilities.

Infrastructure Requirements

Fugro's autonomous vessel operations can utilize existing port infrastructure with minimal modifications for berth and deployment requirements. Unmanned vessels can use standard refueling and data transfer facilities, and compact vessel designs facilitate easy transport via cranes, flat racks, or commercial shipping, simplifying mobilization and reducing project costs.

This operational model enables rapid deployment and scalability to meet project-specific demands without specialized infrastructure or transport requirements.

Training Approach and Skill Development

Fugro emphasizes upskilling existing personnel rather than replacing traditional maritime roles. Training includes the following elements:

- **Remote Operations Center Operator Training:** Staff are trained to manage multiple vessels simultaneously, monitor sensor feeds, and handle operational contingencies.
- **Payload Technician Training:** Personnel receive cross-training in remotely operating subsurface systems (e.g., Blue Volta), maintenance monitoring, and sensor calibration.
- **Cybersecurity and Communication Training:** Operators are trained in maintaining secure communication channels, identifying cybersecurity threats, and managing remote system protocols.
- **Situational Awareness Development:** Operators learn to integrate data from a variety of sensors for safe operations in dynamic maritime conditions.
- **Certification and Compliance:** Staff training includes familiarity with regulatory requirements from the USCG, International Maritime Organization, and the American Bureau of Shipping.

Application of Fugro's Unmanned Surface Vessels to Offshore Wind Operations

Fugro's unmanned surface vessels provide support across all phases of offshore wind farm development, including installation, operations and maintenance, and decommissioning.

Seabed Surveys and Cable Routing

Blue Essence and Blue Shadow are used to support seabed and cable routing surveys with 24/7 real-time data collection and streaming, comprehensive seabed mapping, and unexploded ordnance detection. The Blue Essence software includes adaptive line planning that adjusts survey coverage based on real-time depth data without requiring user review and input.

The unmanned vessels are also capable of identifying hazards and safe cable routes, mapping of sediment types, and assessing seabed stability.

Asset Inspection and Maintenance

The Blue Volta electric is a remotely operated vehicle that can be deployed from Blue Essence to conduct remote inspection of foundations, cables, mooring and anchoring systems, and other subsea assets. Cable monitoring is used to detect movement or exposure of protection layers, support the assessment of fatigue risks, and report burial depth compliance.

Data collection for asset inspection evaluation can be automated, but would still require user input and, in some cases, it may be more cost and schedule effective for asset inspection to be performed in real time by onboard crews that can make adaptations and assessments during the survey rather than during data review following the survey.

Environmental Monitoring and Compliance

Unmanned surface vessels can carry acoustic and environmental sensors for real-time monitoring during construction and operation, including marine mammals and turbidity. The vessels are also used to support habitat mapping and underwater noise measurements. These systems support compliance with the Marine Mammal Protection Act, Marine Strategy Framework Directive, and other regulatory frameworks.

Floating Offshore Wind Development

Blue Eclipse and Blue Prism have the capabilities to support floating offshore wind in deep, offshore waters, including mission durations over 14 days without refueling and operation in depths up to 650 meters, which would include sites beyond the 60-meter depth contour where the New York State Energy Research and Development Authority is planning for wind farm development. Use cases are expected to include monitoring of export cables, inspection of mooring and anchoring systems, and surveying sites for projects located 80 to 100 kilometers offshore, where conventional survey vessels may be cost prohibitive or operationally constrained.

Regulatory Agencies for Autonomous Vessels

Autonomous vessels operating in US waters are subject to regulation by the following agencies, regulatory bodies, and laws.

United States Coast Guard

The USCG is the lead federal agency overseeing maritime safety and security in US waters. It also represents the United States in the International Maritime Organization (IMO).

There is currently no publicly available information detailing Fugro's unmanned surface vessel activities or regulatory engagement with the USCG.

International Maritime Organization

The IMO is developing a regulatory framework for Maritime Autonomous Surface Ships, including safety standards, training, and legal responsibilities. Interim guidelines are in effect, with mandatory adoption by member states expected by 2032 through amendments to existing conventions.

Fugro has indicated alignment with these interim guidelines. In 2023, the Blue Essence unmanned surface vessel participated in the United Kingdom Maritime and Coastguard Agency's Smart and

Autonomous Vessel Code of Practice trials. These trials assessed autonomous navigation and compliance with the International Regulations for Preventing Collisions at Sea in congested waters.

In 2024, the Blue Essence unmanned surface vessel *Fugro Vaquita* received Category 0 approval from the United Kingdom Maritime and Coastguard Agency. This permits fully remote operations in unrestricted waters, indicating readiness to meet future international regulatory requirements.

American Bureau of Shipping

The American Bureau of Shipping (ABS) is a US-based classification society that sets safety and operational standards for commercial vessels, including autonomous craft.

There is no public record of Fugro's unmanned surface vessels receiving classification from the ABS. However, the vessels have obtained Uncrewed Marine System certification from Lloyd's Register in the United Kingdom. This certification reflects compliance with relevant design and operational safety standards for unmanned survey vessels in offshore wind applications.

Jones Act

The Jones Act requires vessels transporting goods or passengers between US ports to be US-built, owned, flagged, and crewed.

Fugro's unmanned surface vessels are engaged in survey and data acquisition tasks, not in transporting cargo or passengers; therefore, these vessels are likely to fall outside the scope of the Jones Act. However, this interpretation has not been formally confirmed by US regulatory authorities. Additional guidance from the USCG would clarify the applicability of these rules to unmanned surface vessel operations within US waters.

Lessons Learned

Fugro's operational use of unmanned surface vessels in offshore energy and marine infrastructure projects has provided practical insight into integrating autonomous systems into commercial maritime workflows.

- **Operational Continuity in Challenging Conditions** – Fugro's Blue Shadow unmanned surface vessel performed reliably in wave heights up to 2 meters during trials off the Portchester Coast in the United Kingdom, where conventional vessels would have been limited. Blue Shadow's wave-piercing hull enabled continuous data collection, helping reduce weather-related delays by an estimated 30 percent.
- **Efficiency Gains and Cost Reduction** – Unmanned surface vessels operated continuously without on-vessel crew shift limits at the Hollandse Kust Zuid site, where the Blue Essence completed inspections of 140 wind turbine foundations and 260 cable protection systems in 179 operational hours, reducing labor hours by an estimated 35,000 hours and contributing to a 20 percent reduction in total project costs.
- **Health, Safety, and Environmental Performance** – Remote operations from Fugro's Remote Operations Centers removed personnel from offshore risks such as heavy lifting, collisions, and severe weather. Blue Essence achieved up to 95 percent lower carbon dioxide output compared to conventional vessels (e.g., TAQA Netherlands), and Blue Shadow up to 90 percent in Middle East operations.

- **Standardization and Regulatory Engagement** – Experience from participating in regulatory initiatives, such as the United Kingdom Maritime and Coastguard Agency's Smart and Autonomous Vessel Code of Practice trials in 2023, emphasized the need for harmonized standards across vessel control, sensor integration, and cybersecurity. Blue Essence's Category 0 approval required detailed compliance, which may differ across jurisdictions, highlighting challenges in international operations pending full implementation of the International Maritime Organization's Maritime Autonomous Surface Ships Code.
- **Coordination and Transparency** – Engaging clients early and offering real-time visibility into operations increased trust and facilitated adoption. During a campaign for Eni Energy Netherlands, Fugro provided continuous data access and emergency override capabilities via its Remote Operations Centers. Clients monitored over 280 kilometers of subsea pipeline with full transparency, reporting high levels of confidence in the safety and quality of the data collected.
- **Scalability and Future System Integration** – Unmanned surface vessels acted as effective support platforms alongside larger vessels during a variety of hydro spatial surveys around the globe. However, scaling deeper water applications will require expanded infrastructure. Upcoming vessels such as Blue Eclipse and Blue Prism, with inspection capabilities to 650 meters, will require enhanced Remote Operations Center support and may benefit from integration with other autonomous systems, such as uncrewed aerial vehicles and remotely operated vehicles.

CASE STUDY: OCEAN INFINITY – ARMADA FLEET

Founded in 2017, Ocean Infinity, headquartered in Austin, Texas, and Southampton, United Kingdom, uses autonomous and remotely operated marine robotics for ocean and seabed data collection, serving energy, telecommunications, government, defense, and research sectors.

Ocean Infinity Autonomous Vessel Technology

Ocean Infinity operates the Armada fleet, a series of unmanned and minimal crewed vessels supported by a global network of Remote Operations Centers and an integrated portfolio of robotic subsea systems. The fleet includes vessels ranging in size from the 8-meter Armada A8 to the 86-meter Armada A86.

Armada vessels feature dynamic positioning, modular sensor suites (e.g., multibeam echo sounders, side-scan sonar, sub-bottom profilers), and remote control capabilities for survey, geotechnical, and maintenance tasks. Remote command and control functionality allows these vessels to conduct operations, including surveying, geotechnical sampling, and maintenance support, while reducing offshore personnel exposure and environmental footprint relative to conventional crewed vessels.

The Armada fleet operations include autonomous underwater vehicles, remotely operated vehicles, and modular geotechnical sampling systems.

Armada A8

The Armada A8 is Ocean Infinity's 8-meter unmanned surface vessel designed for a variety of coastal and shallow water offshore tasks (Figure 18). Designed for operations in nearshore conditions, the A8 is suited for flexible deployment and rapid mobilization.

The A8 has an endurance of up to seven days at typical survey speeds of 3 to 4 knots.

Typical applications include:

- Coastal and shallow water hydrographic surveys
- Environmental monitoring and sample collection
- Seabed inspection near offshore infrastructure
- Port and harbor activity monitoring

The A8 can operate as part of a larger multi-vessel campaign or as a stand-alone platform in constrained or remote environments.

Figure 18: Armada A8 unmanned surface vessel

Armada A21

The Armada A21 is Ocean Infinity's 21-meter unmanned surface vessel designed for offshore geophysical surveys and light subsea inspection (Figure 19). It includes an adaptable pop-top wheelhouse for crewed use if activities such as short harbor voyages or repositioning maneuvers are needed.

The Armada A21 is powered by twin 78-kilowatt-hour lithium-ion battery systems, with endurance ranging from 10 to 35 days depending on mission profile.

Typical applications include the following:

- Offshore wind farm site surveys
- Cable route and unexploded ordnance investigations
- Coastal infrastructure inspections
- Environmental baseline studies

Figure 19: Armada A21 unmanned surface vessel

Armada A36

The Armada A36 is Ocean Infinity's 36-meter optionally crewed surface vessel developed for offshore geophysical surveys, subsea inspections, and remote operations (Figure 20). The A36 is designed for use in moderate sea states, generally in waves up to about 2.5 meters high.

The A36 supports the integration of remotely operated vehicles, hosting an automated launch-and-recovery system onboard. Endurance is up to 35 days, depending on tasking.

Typical applications include the following:

- Offshore wind farm site characterization
- Pipeline and cable inspections
- Subsea asset monitoring
- Environmental and habitat mapping
- Unexploded ordnance surveys

Figure 20: Armada A36 OUSV

Armada A78

The Armada A78 is Ocean Infinity's 78-meter vessel designed for offshore survey, geotechnical sampling, and inspection, maintenance, and repair operations with capabilities for extended endurance (21–35 days) (Figure 21).

The A78 can be crewed with up to 16 personnel when required. A modular deck layout and moonpool-based launch-and-recovery system enable remote deployment of autonomous underwater vehicles, remotely operated vehicles, seabed drills, and cone penetration test tools.

Typical applications include the following:

- Deepwater geophysical and geotechnical site investigations
- Subsea infrastructure inspections
- Environmental and habitat surveys
- Unexploded ordnance detection and clearance

Figure 21: Armada A78 lean-crewed robotic vessel

Armada A86

The Armada A86 is Ocean Infinity's 86-meter multi-role vessel designed to expand the capabilities introduced by the Armada A78 (Figure 22). The A86 supports autonomous, remote, and limited-crew operations.

The vessel features hybrid propulsion, a modular deck layout, and a moonpool-fitted launch-and-recovery system for autonomous underwater vehicles, remotely operated vehicles, seabed drills, and cone penetration test tools.

The A86 can, if required, accommodate up to 16 crew members. Operational endurance ranges from 21 to 35 days, depending on configuration and mission type.

Key applications include the following:

- Offshore geophysical and geotechnical surveys
- Subsea inspection and maintenance
- Environmental and habitat mapping
- Unexploded ordnance surveys
- Support for offshore energy, defense, and telecommunications operations

Figure 22: Armada A86 lean-crewed robotic vessel

Vessel Deployments

Ocean Infinity's Armada fleet is designed to support a range of autonomous and remotely operated offshore activities. The following summarizes the deployment status of each vessel class as of May 2025, based on publicly available information. While the Armada A78 has documented field operations, details for the Armada A8, A21, A36, and A86 remain limited due to commercial confidentiality or ongoing development.

Armada A8 Deployment Status

Although the Armada A8 has been operational since 2017 or 2018, specific deployment records are limited, likely due to use in small-scale or confidential client projects. A confirmed deployment occurred during Project Seagrass in the Solent, United Kingdom, in 2021. During this project, Ocean Infinity's *SeaWorker 8,* an Armada A8-class vessel, conducted remotely operated bathymetric and side-scan sonar surveys covering approximately 10 square kilometers and supported marine habitat restoration efforts. It marked the first known fully remote seagrass survey in the region.

Armada A21 Deployment Status

As of May 2025, the Armada A21 class is reported to be under construction at Grovfjord Mekaniske Verksted in Norway, with initial deliveries expected in 2022. No confirmed public records verify active field operations.

Publicly available information suggests that the Armada A21 may have supported operations under Ocean Infinity's joint venture with Gregg Drilling, which focuses on geophysical and geotechnical surveys for offshore wind. Ocean Infinity stated that this venture will mobilize seabed drilling equipment onto vessels between 21 and 78 meters in length.

Armada A36 Deployment Status

As of May 2025, the Armada A36 is under construction in Norway. Public records confirm five vessels were ordered.. Some units are reported to be approaching commissioning or early operational phases; however, no commercial deployments have been publicly verified.

The Armada A36 has been used in a research and development context as part of the "Drone Swarm for Unmanned Inspection of Wind Turbines" project in the United Kingdom from 2022 to 2025. Funded by Innovate UK, the project involved launching autonomous aerial drones from a 36-meter Armada vessel, using 5G and satellite connectivity for remote operation and data transfer, serving as a mobile base for autonomous aerial systems.

Armada A78 Deployment Status

As of May 2025, documented deployments for the Armada A78 include the following:

SOUTHERN INDIAN OCEAN – MH370 SEARCH

In late 2024 and early 2025, three A78 vessels resumed seabed mapping in the search for Malaysia Airlines Flight MH370. These vessels conduct deepwater surveys using autonomous underwater vehicles under remote supervision with real-time data streaming for quality control.

CLARION-CLIPPERTON ZONE (PACIFIC OCEAN)

In early 2025, an Armada A78 performed environmental baseline studies and bathymetric mapping in the Pacific Ocean's Clarion-Clipperton Zone. The vessel also supported the United States Navy by recovering a Global Autonomous Reconnaissance Craft in San Diego Bay.

NORTH SEA AND NORWEGIAN SEA – SUBSEA PIPELINE & INFRASTRUCTURE SURVEY

An Armada A78 conducted pipeline and interconnector route surveys in the North Sea, including seabed imaging, unexploded ordnance detection, and shallow geotechnical investigations.

EAST OF TAIWAN – RYUKYU TRENCH DEEP-SEA SURVEY

An Armada A78 conducted deep-sea surveys near the Ryukyu Trench in the Pacific Ocean, including geological assessments and subsea cable corridor planning.

EUROPEAN WATERS – OFFSHORE WIND AND ENERGY SUPPORT

Multiple A78 vessels were used in the North Sea, Baltic Sea, and Atlantic Shelf to support offshore wind farm investigations, environmental surveys, and infrastructure inspections. Specific project names are not publicly available.

Armada A86 Deployment Status

As of May 2025, no confirmed public records note operational deployments of the A86. The vessel is expected to perform missions similar to those of the Armada A78 once fully operational.

Other Ocean Infinity Project Deployments (Unspecified vessels)

Several offshore projects conducted by Ocean Infinity have not identified specific vessels in public records; however, these deployments are summarized below.

OSSIAN FLOATING WIND FARM (SCOTLAND, 2023–2024)

Ocean Infinity conducted seabed-based geotechnical investigations for the Ossian Floating Offshore Wind Farm, located 84 kilometers southeast of Aberdeen. The project area spans 858 square kilometers with average depths of 72 meters. Ocean Infinity performed 90 cone penetration tests, 45 seismic cone penetration tests, and collected 20 vibracore samples.

MORRO BAY FLOATING WIND SURVEY (UNITED STATES WEST COAST, 2024)

Ocean Infinity conducted geophysical surveys for Equinor Wind US LLC offshore of the California coast. The operation involved the simultaneous deployment of multiple deepwater autonomous underwater vehicles across depths from 974 to 1,317 meters. The data supported Equinor's Site Assessment Plan and Construction and Operations Plan. While the vessel used was not disclosed, the depth and scale suggest potential use of an Armada A78-class vessel.

BALTICA 2 OFFSHORE WIND FARM SURVEY (POLISH BALTIC SEA, 2024)

In 2024, Ocean Infinity completed a survey campaign for Ørsted and PGE Baltica at the Baltica 2 project site. A multibeam echo sounder and ultra-high-resolution seismic system were used to map 540 kilometers of sub-seabed features. A limited-crew Armada vessel was reported, potentially an Armada A78, given the project profile.

STABROEK BLOCK OFFSHORE GUYANA – EXXONMOBIL SURVEY (2024)

Ocean Infinity conducted a geophysical and geotechnical survey for ExxonMobil in the Stabroek Block, covering 3,100 square kilometers in water depths from 70 to 2,150 meters. Multiple autonomous underwater vehicles were deployed simultaneously to acquire high-resolution data. The vessel was not identified, but the operational scale and water depth indicate potential use of an Armada A78-class platform.

Ocean Infinity's Autonomous Vessel Features

Table 5 describes Ocean Infinity's autonomous vessels features that address the common challenges of operating offshore wind vessels, as described above in Table 2:

CHALLENGE	CHALLENGE ADDRESSED BY	KEY FEATURES ENABLING THE SOLUTION
Crew Safety and Fatigue	By supervising Armada vessels from onshore control centers, Ocean Infinity enables offshore teams to focus on tasks such as data interpretation, system maintenance, and mission planning, while reducing their exposure to hazardous conditions. Ocean Infinity's Armada fleet is designed for continuous, remotely supervised operations, reducing reliance on offshore personnel and improving data acquisition rates. By acting as a force multiplier (multiple vessels deployed to support crewed vessels), unmanned surface vessels have been shown to double survey coverage and reduce time on site. For example, during the Ossian Floating Offshore Wind Farm campaign, Ocean Infinity remotely deployed the Infinity Cone Penetration Test 250 system for seabed sampling without sending personnel offshore.	Automated launch-and-recovery systems on larger vessels (such as those with moonpool launch-and-recovery systems on the Armada A78 and A86). Simultaneous deployment of autonomous underwater vehicles and remotely operated vehicles. Real-time data streaming to Remote Operation Centers, allowing quality control and mission adjustments without crew rotations.
High Operational Costs	Offshore vessel operations are typically influenced by crew, fuel, and idle time. The Armada fleet addresses high operational costs through a combination of remote operation, modularity, and hybrid propulsion.	Reduced personnel costs by optimizing crew complements (often fewer than 16), which allows for smaller accommodation modules, lower material and resource requirements, and streamlined onboard logistics. Lower fuel consumption than comparable vessels through efficient hull design and hybrid systems, with some vessels reporting fuel savings of up to 90 percent compared to conventional platforms.

CHALLENGE	CHALLENGE ADDRESSED BY	KEY FEATURES ENABLING THE SOLUTION
		Improved platform versatility by using modular payload bays and standardized power and data interfaces, enabling rapid swap out of equipment (e.g., replacing a geotechnical cone penetration test skid with a multibeam echosounder and sub-bottom profiler) within a single shift, eliminating extended downtime and reducing mobilization costs.
Survey Efficiency	Ocean Infinity's vessels operate continuously and are equipped with modular sensor systems, reducing changeover time between scopes. Real-time communications support data validation during acquisition, further reducing project timelines.	Dynamic payload control systems for rapid switching of survey equipment (e.g., multibeam echo sounders and sub-bottom profilers). Automated launch-and-recovery systems that reduce deployment time and improve equipment safety. Simultaneous multi-asset operations, especially on the Armada A78 and A86, where autonomous underwater vehicles and remotely operated vehicles are deployed in parallel. Real-time data streaming to Remote Operations Centers.
Distance from Shore	Ocean Infinity's Armada vessels are configured for extended range operations in remote and deepwater environments. Their endurance (typically 21 to 35 days) and global communication capabilities support missions far from shore without requiring frequent crew transfers.	Range and endurance: Armada A21 vessels can cover over 5,500 kilometers, Armada A36 over 10,000 kilometers, and Armada A78 and A86 vessels can remain at sea for up to 35 days. Reliable connectivity: Satellite and wireless links support command and data relay over long distances, as demonstrated in the Dr-SUIT project, where an Armada A36 maintained stable communication across a 10,000-kilometer operating area. Remote Operations Center integration: Facilities in Southampton (United Kingdom), Austin (Texas), and Australia provide global coverage for mission control and data oversight.

Table 5: Ocean Infinity's Autonomous Vessel Features to Address Offshore Wind Vessel Operations Challenges

Autonomous Fleet Development

Navigational Safety

Ocean Infinity applies safety protocols based on sensor integration, remote oversight, and regulatory compliance with the International Regulations for Preventing Collisions at Sea. The International Maritime Organization (IMO) adopted navigation rules governing vessel conduct to prevent collisions. Vessels are equipped with specific sensor systems for navigational safety, including sonar, multibeam echo sounders, automatic identification systems, and optical and infrared cameras.

Infrastructure Requirements

The Armada fleet requires minimal dependence on traditional port infrastructure.

The following are key infrastructure elements:

- **Remote operation by design:** Armada vessels do not require onboard bridge control.
- **Globally integrated Remote Operations Centers:** Facilities in the United Kingdom, United States, and planned sites in Asia manage mission control, vehicle deployment, and payload operations across locations.
- **Digital payload integration:** Ocean Infinity’s in-house systems connect vessel navigation, subsea deployment, and data collection, eliminating the need for separate support vessels.

Training Approach and Skill Development

Ocean Infinity's operational model emphasizes digital systems, remote mission management, and integrated team roles. The company employs cross-disciplinary teams comprising marine engineers, roboticists, data analysts, geotechnical specialists, and other experienced offshore roles.

Training methods include the following:

- Simulation-based onboarding: Operators are trained in virtual environments and through digital twins of vessels and operations, enabling rapid scaling without vessel access.
- Workflows: Teams are trained to manage the full survey chain remotely, including geophysical sensors, autonomous underwater vehicles, remotely operated vehicles, and seabed sampling tools.

Application of Ocean Infinity’s Uncrewed Surface Vessels to Offshore Wind Operations

Ocean Infinity’s Armada fleet is designed to support a range of offshore wind development activities. These include early site investigation, foundation and cable installation support, and long-term inspection and maintenance. The fleet addresses operational challenges associated with deeper water deployments, expanded lease areas, compressed construction schedules, and evolving decarbonization targets.

Seabed Surveys, Site Investigation, and Cable Routing

Armada vessels are equipped with multibeam echo sounders, side-scan sonar, sub-bottom profilers, and autonomous underwater vehicles, enabling high-resolution mapping of seabed and sub-seafloor conditions for turbine siting, foundation design, and export cable routing. Armada vessels can launch autonomous underwater vehicles, conduct remote geotechnical testing, and are used for unexploded ordnance detection.

Asset Inspection and Maintenance

After offshore wind infrastructure is installed, Armada vessels support regular condition monitoring using a combination of hull-mounted sensors and deployable subsea systems, including foundation inspections from remotely operated or autonomous underwater vehicles, sonar imaging of fixed and floating wind turbine foundations, and cable integrity monitoring.

Environmental Monitoring and Compliance

Armada vessels support environmental monitoring activities required for permitting and operational compliance, with a smaller offshore footprint compared to traditional crewed vessels. These operations include passive acoustic monitoring for marine mammals' presence, turbidity and sediment monitoring, benthic habitat surveys, and underwater noise monitoring.

Floating Offshore Wind Development

The Armada fleet is capable of extended endurance surveys, deepwater inspections using remotely operated and autonomous underwater vehicles (in depths up to 6,000 meters), and monitoring of dynamic assets such as mooring and anchor lines and export cables.

Regulatory Agencies for Autonomous Vessels

The use of unmanned surface vessels is governed by a range of national and international regulations designed to ensure safety, environmental compliance, and operational integrity. Key entities involved in this oversight include the USCG, International Maritime Organization, American Bureau of Shipping, and DNV (formerly known as Det Norske Veritas, a Norwegian-based international accreditation registrar). Additional regulatory constraints, such as the Jones Act, may also apply depending on vessel activities and locations.

United States Coast Guard

The United States Coast Guard (USCG) oversees vessel safety, cybersecurity, and maritime law compliance within US waters. For autonomous vessels, the USCG is developing guidelines in collaboration with the American Bureau of Shipping (ABS), DNV, and other maritime societies.

In a 2025 interview, USCG officials emphasized the importance of operator accountability, situational awareness, and early engagement with authorities when deploying unmanned systems, and noted that consistent oversight, real-time monitoring, and proactive risk management are essential to ensure safety for other mariners and the public. Agencies increasingly expect that autonomous operators maintain vigilance equivalent to onboard crews.

While no public information details Ocean Infinity's autonomous vessel operations in US waters, their 2024 Morro Bay survey for Empire Wind suggests potential engagement with the USCG for compliance. Managing Director of Armada Dan Hook notes the USCG's supportive stance, recognizing uncrewed vessels as a solution to offshore safety challenges, including avoiding personnel exposure to severe weather and high sea states, eliminating the hazards of helicopter or vessel transfers, reducing fatigue-related human errors on long watch cycles, and mitigating collision risks through advanced sensor-based navigation and automatic emergency stop functions.

International Maritime Organization

The IMO is developing an international regulatory framework for Maritime Autonomous Surface Ships, expected to become mandatory by 2032. This includes standards for navigation, safety, emissions, and legal responsibility.

Ocean Infinity participates in these regulatory efforts through its involvement in the International Maritime Organization Maritime Safety Committee. Operations such as the MH370 search have followed these emerging guidelines for uncrewed navigation and oversight.

American Bureau of Shipping (ABS)

ABS develops technical standards for vessel design, construction, and remote operation systems and serves as a recognized organization for the USCG and other flag states, supporting regulatory compliance and system verification.

DNV Classification Society

DNV provides vessel classification, statutory surveys, and verification services focused on safety, environmental performance, and system reliability. The organization has experience with autonomous technology and low-emission systems.

Ocean Infinity's Armada vessels, constructed in Norway and flagged in the United Kingdom, operate under certification from DNV. In 2021, Armada 78-03 received the first Statement of Compliance for remote operations under DNV-CG-0264, validating the safety and cybersecurity of Ocean Infinity's Remote Operations Center architecture.

DNV's certification supports operations involving Remote Operations Center oversight and hybrid propulsion systems. Armada vessels are also equipped with DNV-compliant ShipManager software for maintenance, procurement, and regulatory tracking.

Jones Act

The Jones Act requires vessels transporting goods or personnel between US ports to be built, owned, and operated by US citizens or permanent residents. It can affect mobilization and support operations for international unmanned surface vessels working in US waters. Ocean Infinity's smaller uncrewed vessels, such as the Armada A8, A21, and A36, are constructed in Norway and do not meet the US-built criteria. These vessels are primarily used for seabed mapping and offshore surveys and are not engaged in domestic cargo or passenger transport. As such, these vessels may fall outside the scope of Jones Act restrictions.

However, larger limited-crew vessels such as the Armada A78 and A86, which can carry payloads and limited personnel, may be subject to further review depending on their intended use. Ocean Infinity is in discussions with US shipyards to develop Jones Act-compliant vessels that would allow broader participation in US domestic operations. Additional clarification from the USCG may be required to confirm the status of uncrewed survey operations under the Jones Act framework.

CASE STUDY: XOCEAN UNCREWED SURFACE VESSEL CLASS

XOCEAN is an ocean data company headquartered in Carlingford, Ireland, established in 2017. It specializes in autonomous marine data collection using unmanned surface vessels to provide detailed seabed, water column, and environmental data to the offshore energy, marine construction, and environmental monitoring sectors. XOCEAN employs remotely operated vessels to enhance operational efficiency, minimize human risk, and reduce environmental impacts compared to traditional survey methods.

XOCEAN Autonomous Vessel Technology

XOCEAN maintains a fleet of unmanned surface vessels for oceanographic, hydrographic, and environmental data collection, including the XO-450, XO-250, XO-580 vessels, and the developmental XO-G2, each suited to different operational conditions. These unmanned surface vessels are monitored and controlled from Remote Operations Centers by trained personnel.

XOCEAN's unmanned surface vessels are utilized primarily for offshore wind farm site surveys and inspections, infrastructure monitoring, environmental assessments, marine spatial planning and habitat mapping, coastal erosion, and sediment studies.

XO-450

The XO-450 is XOCEAN's primary unmanned surface vessel and is designed for offshore survey operations (Figure 23). The vessel can conduct bathymetric surveys, environmental monitoring, pipeline inspections, and subsea assessments. It operates beyond visual line-of-sight using satellite communications for remote control and real-time data transfer.

The XO-450 has a catamaran hull and is capable of extended duration missions up to 18 days at sea and has a typical sensor payload that includes multibeam echo sounders, side-scan sonar, sub-bottom profiler, acoustic doppler current profiler, collision sensors, optical cameras, and acoustic monitoring instruments.

Key Specifications:

- Length: 4.5 meter | Beam: 2.2 meter | Draft: 0.5 meter
- Power: Hybrid system (solar, lithium-ion batteries, micro diesel generator)
- Navigation: Global Navigation Satellite System, Automatic Identification System, radar, collision avoidance, 360-degree high-definition cameras

Figure 23: XO-450

XO-250

The XO-250 is designed specifically for shallow water surveys and near-shore pipeline/cable landing assessments. It is smaller and lighter than the XO-450, facilitating operations in ultra-shallow waters (up to 1 meter depth) where shoaling or obstructions may pose risks to manned vessels. The vessel is optimized for bathymetric mapping, pipeline/cable inspections, and environmental monitoring of coastal ecosystems. The expected number of days the vessel can be at sea is not publicly stated.

XO-580

The XO-580 is a 5.8-meter unmanned surface vessel intended for extended period (potentially more than 20 days at sea) deepwater surveys, long-duration environmental monitoring, and geophysical surveys for buried pipeline detection (Figure 24).

Figure 24: XO-580

XO-G2

The XO-G2 is an unmanned surface vessel designed for longer-term offshore surveys (up to 3,000 nautical miles, 30-40 days at sea) and for towing underwater sensor arrays without requiring a support vessel, controlled remotely using secure over-the-horizon satellite communications.

XOCEAN Vessel Deployments

XOCEAN operates a fleet of 25 unmanned surface vessels (primarily the XO-450 model) and has conducted over 100 projects across 16 countries. The following sections summarize selected deployments.

Examples of unmanned surface vessel Deployments

TASMANIAN GAS PIPELINE (BASS STRAIT, AUSTRALIA)

In May 2025, the XO-450 unmanned surface vessel X-14 completed a periodic bathymetric and sub-bottom profiler inspection of the 300-kilometer Tasmanian Gas Pipeline across Bass Strait in the Southern Ocean and was mobilized from XOCEAN's technical center in Melbourne.

FISH POPULATION SURVEY (NORTH SEA, UK)

XO-450 unmanned surface vessel conducted the first-ever unmanned survey of fish populations around oil platforms off Scotland's northeast coast using sonar data to support environmental monitoring efforts.

HORNSEA ONE OFFSHORE WIND FARM (2021, NORTH SEA, UNITED KINGDOM)

XOCEAN conducted unmanned scour monitoring and cable burial depth surveys at the Hornsea One offshore wind farm in water depths up to 40 meters.

EAST ANGLIA ONE OFFSHORE WIND FARM (NORTH SEA, UNITED KINGDOM)

XOCEAN completed survey operations for ScottishPower Renewables' East Anglia One using multiple XO-450 unmanned surface vessels in water depths ranging from 20 to 50 meters.

OSSIAN FLOATING OFFSHORE WIND FARM (2022–2023, NORTH SEA, UNITED KINGDOM)

XOCEAN completed a series of geophysical surveys over a 13-month duration along a 420-kilometer export cable route for the proposed Ossian Floating Offshore Wind Farm using up to six XO-450 unmanned surface vessels operating simultaneously in water depths from the coastline to over 100 meters.

DOGGER BANK C AND D OFFSHORE WIND FARMS (NORTH SEA, UK)

XOCEAN supported the Dogger Bank Wind Farm, focusing on phases C and D. For Dogger Bank C, XOCEAN collaborated with Fugro to acquire geophysical data along the export cable route, deploying two XO-450 unmanned surface vessels in water depths of 18–36 meters and wave heights up to 2.5 meters. The unmanned surface vessels collected over 1,750 kilometers of multibeam echo sounders, sub-bottom profilers, side-scan sonar, and magnetometer data, providing bathymetry, topography, and subsurface soil conditions for cable installation planning. For Dogger Bank D, a fleet of eight unmanned surface vessels operated up to 230 kilometers from shore, gathering data to support consenting, geotechnical, and benthic campaigns. These operations took place alongside crewed vessels, including the BB Ocean support vessel, which served as the unmanned surface vessel mother ship. All XOCEAN vessels were mobilized from active ports (Scarborough and Hartlepool, United Kingdom) and transited through areas with regular maritime traffic. Formal Notices to Mariners requested that other vessels maintain safe separation and reduced speed, reinforcing the coordinated integration of unmanned and traditional vessels.

MORGAN AND MONA OFFSHORE WIND FARMS (2021–2023, IRISH SEA, UK)

XOCEAN conducted geophysical surveys for the Morgan and Mona offshore wind farms, covering 800 square kilometers in the Irish Sea, 30 square kilometers off the coast. Over four phases spanning two years, four XO-450 unmanned surface vessels completed 20,000 survey line kilometers in water depths of 0–35 meters, delivering 70,000 gigabytes of bathymetry, backscatter, and water column data. The project saved 35,000 kilograms of carbon dioxide compared to traditional vessels, via lower fuel consumption, smaller engine footprints, and optimized survey routes enabled by remote operations and autonomous navigation.

GREATER GABBARD OFFSHORE WIND FARM (NORTH SEA, UNITED KINGDOM)

XOCEAN has conducted multiple operations and maintenance surveys at SSE's 140-turbine Greater Gabbard wind farm, located 20 kilometers off Suffolk. XOCEAN's XO-450 unmanned surface vessels performed inter-array cable inspection surveys, assessing depth of burial along seven cables and two turbine locations while operating 24/7 in water depths of 2–30 meters.

SHERINGHAM SHOAL OFFSHORE WIND FARM (NORTH SEA, UK)

XOCEAN completed a routine operations and maintenance inspection for Equinor's Sheringham Shoal wind farm, 17–23 kilometers off Norfolk, on behalf of Reach Subsea. Three XO-450 unmanned surface vessels surveyed 88 wind turbine foundations and two 22-kilometer export cable routes in shallow, high-tide waters. Mobilized within 48 hours, the project was completed in nine days, with two unmanned surface vessels inspecting foundations and inter-array cables and a third focusing on export cables.

GREATER CHANGHUA 1 AND 2A OFFSHORE WIND FARMS (TAIWAN STRAIT, TAIWAN)

XOCEAN has conducted 160 seabed surveys at Ørsted's Greater Changhua 1 and 2a offshore wind farms. Covering a 108-kilometer site in water depths of 30–45 meters, XOCEAN's XO-450 unmanned surface vessels performed surveys around wind turbine generators and offshore substations during ongoing construction. A custom launch-and-recovery system facilitated the unmanned surface vessel deployment from a service operations vessel, enhancing operational flexibility. These surveys were conducted within an active construction environment and in proximity to various crewed installations and support vessels. XOCEAN's unmanned surface vessels operated within regulated offshore zones where coordinated traffic management was in place to ensure safe and effective survey execution alongside other ongoing marine operations.

SETANTA WIND PARK (FORMERLY BRAYMORE WIND PARK, IRISH SEA, IRELAND)

XOCEAN completed a seabed survey at the proposed Setanta Wind Park off Ireland's east coast. Using XO-450 unmanned surface vessels, the project acquired multibeam echo sounders, sub-bottom profilers, and side-scan sonar data to assess seabed conditions for wind farm development.

BP OFFSHORE WIND FARMS (GERMAN NORTH SEA, GERMANY)

XOCEAN delivered 1,000 kilometers of towed side-scan sonar and magnetometer data to support two wind farm developments in the German North Sea. Two XO-450 unmanned surface vessels, configured for towing, cleared seabed areas for geotechnical investigations, providing high-resolution data for project planning.

BEATRICE OFFSHORE WIND FARM (NORTH SEA, UK)

XOCEAN is set to commence nonintrusive subsea surveys of inter-array cables and turbine locations at SSE Renewables' operational Beatrice offshore wind farm. Using XO-450 unmanned surface vessels, the project will collect multibeam echo sounders, sub-bottom profilers, side-scan sonar data to monitor seabed conditions, supporting operations and maintenance activities.

UNSPECIFIED PROJECT (NEW YORK, UNITED STATES)

A publicly available image shows XOCEAN unmanned surface vessels operating off the coast of New York (Figure 25).

Figure 25: XOCEAN Unmanned surface vessels operating off the coast of New York.

Challenges in Offshore Wind Vessel Operations

The offshore wind industry relies on a fleet of specialized vessels for offshore operations and faces significant challenges that impact project timelines, costs, and overall efficiency. These challenges stem from harsh environmental conditions, logistic complexities, high operational expenses, and increasing sustainability requirements (Table 4). Addressing these issues is critical for improving offshore wind farm development and optimizing long-term operations.

XOCEAN Autonomous Vessel Solutions

Table 6 describes XOCEAN's autonomous vessel fleet solutions to common challenges faced by offshore wind operations, as described above in Table 2:

Challenge	Challenge Addressed By	Key Features Enabling the Solution
Crew Safety and Fatigue	Remote autonomous operations	No onboard crew, Remote Operations Centers, continuous monitoring, collision avoidance systems
High Operational Costs	Hybrid-powered, crewless unmanned surface vessels	Low fuel consumption, smaller vessels, reduced maintenance, minimal operational crews

Survey Efficiency	Autonomous, continuous operations	Real-time data transmission, rapid deployment, simultaneous multi-vessel operations
Environmental Sustainability	Low-emission hybrid systems	Solar, battery, micro diesel hybrid propulsion, reduced carbon emissions
Distance from Shore	Extended operational range	Up to 40 days continuous offshore endurance, satellite-enabled remote operations

Table 6: Solutions to Offshore Wind Vessel Operations Challenges

Autonomous Fleet Development

Remote Operations Centers

XOCEAN operates a global network of Remote Operations Centers and offices, including in the United States, that provide continuous oversight, control, and data management for its unmanned surface vessels. These land-based facilities are staffed by certified mariners and geophysical data specialists who monitor vessel navigation, system performance, and real-time data acquisition through secure satellite communication links. Each center can manage multiple vessels simultaneously, enabling safe and efficient survey operations across different regions. The Remote Operations Centers also allow for dynamic mission control, including the ability to adjust survey parameters in response to live data, environmental conditions, or evolving project requirements. This remote management model reduces offshore personnel exposure and increases operational flexibility.

Navigational Safety and Security

The USCG has identified automated lookout capabilities (e.g., combined radar, automatic identification systems, and visual sensors) as an area of growing relevance for enhancing situational safety. To support this mission, XOCEAN's unmanned surface vessels are equipped with standard maritime navigation systems, including global navigation satellite systems, radar, automatic identification systems, inertial navigation, and 360-degree cameras to support safe operation in accordance with International Maritime Organization regulations. These systems and technologies are intended to reduce the potential for navigational errors to enhance safety for the unmanned vessels, nearby vessels, and maritime users in shared waterways. All vessel movements and decisions are monitored in real time by qualified personnel at Remote Operations Centers.

Cybersecurity includes encrypted communications, access controls, and live threat monitoring. The vessels have compact vessel designs and anti-boarding features to reduce the risk of unauthorized physical access.

Infrastructure Requirements

XOCEAN's vessels can be transported using standard trailers or commercial containers and launched from a range of harbor types or from support vessels using a dedicated launch-and-recovery system. Remote operation is supported through a centralized control architecture combined with onboard autonomy for local navigation and hazard response. Data systems are designed to interface with third-party platforms using standard formats. XOCEAN is exploring vessels that currently use hybrid energy systems with future upgrades to incorporate alternative low-emission propulsion technologies.

Training Approach and Skill Development

The USCG members highlighted the growing need for personnel trained in both maritime operations and autonomous systems management. Therefore, XOCEAN maintains a structured training framework for staff involved in vessel oversight and mission support. Initial training includes hands-on instruction in the Cyberdeck control interface, simulation-based navigation, emergency procedures, and system diagnostics. Ongoing skill development is provided through scenario-based exercises, technical workshops, and updates on relevant regulations. Staff are cross trained in both vessel operations and data acquisition systems to ensure effective coordination across all mission components. Structured training programs support safer operations and help reduce the risk of technical failures that could pose hazards to mariners or coastal communities.

Application of XOCEAN Vessels to Offshore Wind Operations

Offshore wind development requires extensive marine data across all project phases, including site assessment, construction, operations and maintenance, and long-term monitoring. XOCEAN vessels are equipped with advanced sensors and collect high-resolution data for seabed surveys, environmental monitoring, construction oversight, and asset condition assessments.

Seabed Surveys and Site Investigation

XOCEAN unmanned surface vessels are equipped with multibeam echosounders, side-scan sonar, sub-bottom profilers, and magnetometers that are used to collect data during the early phases of offshore wind development. These surveys provide information necessary for bathymetric mapping, turbine siting, foundation design, and cable routing. They also help identify seabed conditions and potential geohazards that may influence engineering decisions or construction feasibility. Unmanned surface vessels can be deployed individually or in coordinated groups to survey large areas efficiently.

Geophysical Surveys

Unmanned surface vessels support offshore wind planning and permitting through the acquisition of high-resolution seabed and shallow subsurface data. Geophysical surveys conducted using these vessels contribute to site characterization and design studies and can also support the identification of unexploded ordnance and other potential obstacles along cable routes. The resulting datasets are used in regulatory submissions and in the development of mitigation measures for seabed risks.

Environmental Monitoring and Compliance

XOCEAN unmanned surface vessels are equipped with sensors to collect environmental data, including metocean and ecological parameters. These systems support baseline environmental studies, impact assessments, and long-term monitoring programs. Applications include measuring seabed and water column conditions, documenting habitat characteristics, and supporting environmental compliance during both construction and operations.

Asset Integrity

Unmanned surface vessels are used to inspect subsea infrastructure during the construction and operation phases of offshore wind projects. Typical tasks include surveying the burial depths of subsea cables, monitoring scour around turbine foundations, and evaluating general seabed conditions that may affect the stability or performance of installed assets. These surveys support proactive maintenance planning and contribute to long-term asset reliability.

Construction Monitoring

During offshore wind construction, unmanned surface vessels are used to gather data on seabed conditions before, during, and after installation activities. This includes monitoring foundation and cable installation to confirm alignment with design parameters and permit conditions. Unmanned surface vessels may also be used to survey landfall areas or cable routes in the nearshore environment. In some cases, these operations are coordinated with aerial or vessel-based data collection to provide a broader view of site conditions during critical construction phases.

Regulatory Agencies for Autonomous Vessels

The use of unmanned surface vessels is governed by a range of national and international regulations designed to ensure safety, environmental compliance, and operational integrity. Key entities involved in this oversight include the USCG, International Maritime Organization, American Bureau of Shipping, and DNV (formerly known as Det Norske Veritas). Additional regulatory constraints, such as the Jones Act, may also apply depending on vessel activities and locations.

United States Coast Guard

The United States Coast Guard (USCG) oversees vessel safety, cybersecurity, and maritime law compliance within US waters. For autonomous vessels, the USCG is developing guidelines in collaboration with American Bureau of Shipping (ABS), and DNV and other maritime societies.

In a 2025 interview, USCG officials emphasized the importance of operator accountability, situational awareness, and early engagement with authorities when deploying unmanned systems, and noted that consistent oversight, real-time monitoring, and proactive risk management are essential to ensure safety for other mariners and the public. Agencies increasingly expect that autonomous operators maintain vigilance equivalent to onboard crews.

While direct public records of regulatory engagement are limited, XOCEAN's operations in US waters suggest alignment with USCG expectations. The use of real-time oversight systems and onboard collision avoidance technologies reflects the type of controls evaluated by the USCG for safe autonomous operations.

International Maritime Organization

The IMO is developing an international regulatory framework for Maritime Autonomous Surface Ships, expected to become mandatory by 2032. This includes standards for navigation, safety, emissions, and legal responsibility.

XOCEAN's unmanned surface vessels operate in accordance with IMO navigation and environmental standards. Vessels are equipped with satellite communications and collision avoidance systems, consistent with interim guidance. Surveys conducted in international waters, including the Ossian Floating Wind Farm project, reflect operational practices aligned with emerging IMO protocols. The use of hybrid power and lightweight hulls is also consistent with the IMO's Carbon Intensity Indicator.

American Bureau of Shipping

ABS develops technical standards for vessel design, construction, and remote operation systems, and serves as a recognized organization for the USCG and other flag states, supporting regulatory compliance and system verification.

Although public certification details are not available, XOCEAN's unmanned surface vessel configurations align with ABS's focus areas, including hybrid power, remote operations, and digital control systems. Operations in US waters will require ABS review or coordination.

DNV Classification Society

DNV provides vessel classification, statutory surveys, and verification services focused on safety, environmental performance, and system reliability. The organization has experience with autonomous technology and low-emission systems.

Jones Act

The Jones Act requires vessels transporting goods or personnel between US ports to be built, owned, and operated by US citizens or permanent residents. The status of goods and personnel can affect mobilization and support operations for international unmanned surface vessels working in US waters.

XOCEAN's vessels are used exclusively for data collection and are not engaged in transporting merchandise between US ports, which exempts them from the Jones Act.

POTENTIAL IMPACTS, OPPORTUNITIES, AND CONSTRAINTS OF AUTONOMOUS VESSELS

Introduction

WSP USA Inc. performed a high-level evaluation of the integration and growth of autonomous vessel technology into offshore wind operations, with a special focus on New York Harbor. The primary objectives are to identify and analyze potential impacts, opportunities, and constraints associated with adopting this new technology, and to provide actionable insights for interested parties across the maritime industry. By examining essential themes, ranging from safety and workforce development to regulatory challenges and data management, the assessment aims to guide informed decision-making and support the responsible advancement of autonomous systems within the evolving offshore wind sector.

Methodology

The content in this report is drawn from the previous work completed for this study, including case studies, subject matter expert interviews, and a literature review. Key themes and areas of interest pulled from memos and notes associated with these tasks include:

- Safety and security
- Workforce and training
- Costs
- Data transfer and data management
- Policy and regulations
- Considerations for New York/New Jersey Harbor
- Qualitative risks

Safety and Security

The material gathered for this study summarizes the safety benefits, risks, and security implications associated with autonomous vessels in offshore wind operations. The key points are outlined below.

Safety Benefits and Risks

The following potential safety benefits are associated with using autonomous vessel technology:

- **Reduction in Human Risk:** Autonomous vessels can significantly reduce the risk to human life by removing personnel from hazardous offshore environments. This is particularly beneficial in offshore wind operations where conditions can be dangerous.
- **Operational Efficiency:** Autonomous vessels can operate continuously without breaks, leading to faster data collection and reduced project timelines. This efficiency can also translate into cost savings and minimize vessel crews working long shifts.
- **Enhanced Monitoring:** Autonomous vessels used for routine monitoring and inspections can improve the overall safety of offshore wind infrastructure by providing real-time data and reducing the need for human intervention.

However, in addition to potential benefits, there are potential safety risks as follows:

- **Navigational Hazards:** The proliferation of small, hard-to-detect autonomous vessels in busy waterways poses a risk of collision with larger, traditional, crewed vessels. The absence of onboard personnel means there is no human lookout, increasing the potential for accidents. This could be due to a conventional vessel operator's inability to communicate with an autonomous vessel. Further, recreational vessels that do not always carry radar and automatic identification systems are a potential risk of collision.
- **Regulatory Uncertainty:** The lack of clear regulatory guidance on the operation of autonomous vessels creates challenges in ensuring their safe integration into existing maritime operations. Numerous subject matter groups, including autonomous vessel developers, users, and regulators, have all expressed regulatory difficulties. This includes issues related to uncertainty with Jones Act compliance and other federal maritime laws (discussed later in this document).
- **Operational Risks:** Autonomous vessels may be more susceptible to operational failures due to the absence of personnel to address issues in real-time. This increases reliance on remote operators to diagnose and fix problems, which is also dependent upon sufficient, reliable high-bandwidth connectivity.

Security Implications and Measures

There are also concerns regarding the security of autonomous vessel technology, including both cybersecurity and operational security, highlighted below:

- **Vulnerability to Hacking:** Autonomous vessels, like other remote-controlled systems, are vulnerable to cybersecurity threats. The risk of hacking or misdirection is a concern for the United States Coast Guard (USCG), particularly as these technologies become more widespread. Security measures include encrypted communications, dedicated cybersecurity protocols, and proactive threat monitoring at Remote Operations Centers.
- **Regulatory Measures:** The USCG has recognized the need for robust cybersecurity protocols and recently established cybersecurity requirements for US-flagged vessels and facilities regulated under the Maritime Transportation Security Act, which may include some autonomous vessels. These measures aim to mitigate the risks associated with the dynamic cyber threat landscape.
- **Visibility and Predictability:** Ensuring that autonomous vessels are visible and predictable to other mariners is crucial for maintaining navigational safety. This includes the use of automatic identification systems and related technologies (such as navigation and remote

communications systems, echo sounding, and lidar) to make these vessels easily detectable.

- **Coordination with Local Authorities:** The USCG emphasizes the importance of early and ongoing collaboration between industry and regulators. This includes proactive coordination with local sector teams to manage navigational risks and ensure the safe operation of autonomous vessels.

It is important to delineate the different relationships within the USCG and operators. While the sector handles navigational risks and operations, big picture design regulations come from the Office of Design and Engineering Standards and the Marine Safety Center. Newer, more "novel" designs have more leeway at the sector level, before regulations are implemented. This may confuse operators because different sectors may have different standards, and "novel" design vessels may be able to operate in some sectors but not others.

A key factor in addressing these safety and security issues will be developing clear regulatory and policy changes at the state, federal, and international levels. This includes defining the master's responsibilities, ensuring proper lookout functions, and addressing the classification of these vessels under existing maritime laws. The USCG is actively engaged with the International Maritime Organization (IMO) to develop international standards for autonomous vessels, with a nonmandatory code expected in May 2026 and a mandatory code by July 2030. This collaboration aims to ensure that these technologies can be safely integrated into global maritime operations.

In summary, while autonomous vessels offer significant safety benefits by reducing human risk and improving operational efficiency, they also introduce new safety and security challenges. Addressing these challenges requires clear regulatory guidance, robust cybersecurity measures, and effective coordination between industry and regulatory authorities.

Workforce and Training

The material gathered for this study provides a comprehensive analysis of the potential impact of autonomous vessel technology on the workforce, the training requirements for operating and maintaining these vessels, and the opportunities for workforce development and industry support.

Existing Workforce Implications

- **Reduction in Human Risk:** Autonomous vessels can reduce the risk to human life by removing personnel from hazardous offshore environments or prolonged shifts. This is particularly beneficial in remote offshore wind operations where conditions can be dangerous.
- **Job Displacement Concerns:** There are concerns about job displacement, particularly among more traditional maritime workers. The introduction of autonomous vessels may reduce the need for certain roles, such as traditional vessel crew, divers, and manual operators of remotely operated vehicles.
- **Job Opportunities:** The development and deployment of autonomous vessels could drive economic growth by creating new job opportunities in technology, data analysis, system maintenance, and remote operations. Many of these roles will require training for new recruits or reskilling for those in the industry whose roles are shifting.

Training Requirements for Operating and Maintaining Autonomous Vessels

- **Technical Skills:** Operators of autonomous vessels need to have a strong understanding of both maritime operations and advanced technologies, including robotics, sensors, and artificial intelligence. As noted by a wide variety of subject matter experts, this requires a hybrid skill set that combines traditional maritime knowledge with technical expertise. Workforce development institutions such as State University of New York Maritime College, United States Merchant Marine Academy, Mass Maritime, Maine Maritime, and Cal Maritime are viewed as integral in preparing maritime professionals with these important skill sets.
- **Remote Operations:** Training in remote operations is essential. Operators need to be proficient in using remote control systems and understanding the data collected by autonomous vessels. This includes the ability to diagnose and fix issues remotely.
- **Regulatory Compliance:** Training programs must also cover regulatory compliance, including understanding the International Regulations for Preventing Collisions at Sea (COLREGs), lookout functions, and cybersecurity protocols.
- **Training Program Features:** Training programs will need to focus on remote operations, system calibration, cybersecurity protocols, and situational awareness. These programs should include hands-on instruction, simulation-based navigation, and ongoing skill development through scenario-based exercises.

Opportunities for Workforce Development and Industry Support

- **Hybrid Teams:** The development of hybrid teams that combine maritime and technical expertise is seen as essential across subject matter experts. This approach ensures that operators have both practical experience on the water and the technical skills needed to manage autonomous systems.
- **Industry Collaboration:** Collaboration between industry, regulators, and educational institutions is vital for workforce development. This includes creating training programs, sharing best practices, and ensuring that the workforce is prepared for the integration of autonomous technologies.
- **Government and Industry Support:** Government and industry support can facilitate maritime workforce development. This includes funding for training programs and incentives for companies to invest in workforce development.

In summary, while autonomous vessels offer significant benefits in terms of safety and efficiency, they also present challenges related to shifts in workforce requirements and the need for specialized training. Addressing these challenges requires a collaborative approach that involves industry, regulators, and educational institutions working together to develop the necessary skills to support for the workforce.

Costs

Cost will play a key role in determining the pace of adoption of autonomous technologies, including both initial capital costs and ongoing operations and maintenance costs.

Initial Investment and Operational Costs

- There is a significant initial investment required for developing and deploying autonomous vessels and technologies (including software development). While the technology is promising, the market conditions for offshore wind in the United States are currently challenging. Many offshore wind projects are paused or canceled, which impacts the private sector's willingness to invest in new technologies.
- The long-term operational costs, however, are generally lower compared to traditional manned vessels, due to lower fuel consumption, smaller crews, and continuous operations.

Maintenance Requirements and Sourcing of Replacement Materials

- Maintenance requirements for autonomous vessels may be lower than for manned vessels, according to XOCEAN, in part because they can utilize smaller vessels and are designed to operate with minimal human intervention.
- Maintenance requirements include regular system diagnostics, sensor calibration, and cybersecurity updates. This will require new tools and technologies to manage the larger areas covered by offshore wind farms compared to offshore oil and natural gas rigs.
- Replacement materials and parts may still be sourced through standard maritime supply chains. Sourcing replacement materials and parts, however, can be a challenge, especially for specialized components for a technology that is still developing and is in the early adoption stage.

Location of Services and Cost Implications

- **Regulatory Environment:** According to Justin Manly of Just Innovation, Inc., there are cost implications for operating in different locations, particularly the challenges of adapting to different regulatory environments and navigating varying compliance requirements. For example, in Canada, regulations require a human to monitor the data feed from an uncrewed vessel 24 hours a day, even if the robot is out at sea, whereas that is not the case for many Caribbean nations.
- **Climate Considerations:** In areas with good sunlight, solar-powered uncrewed surface vessels can operate continuously, reducing the need for frequent servicing. However, in regions with less sunlight or harsher environmental conditions, the operational efficiency may be reduced, leading to higher costs.
- **Remote Centers and Port Infrastructure:** Autonomous vessels can be operated from Remote Operation Centers, reducing the need for specialized port infrastructure. This operational model can reduce costs and enable rapid deployment and scalability to meet project-specific demands.
- **Strategic Locations:** Operating in New York is seen as a strategic location, providing the opportunity to position private firms well for the growing US offshore wind market and take advantage of a market with substantial capital and innovation. There is also a consensus among subject matter experts that the region’s strong USCG Vessel Traffic Service (VTS) infrastructure provides opportunities to understand how autonomous vessels operate across the harbor in conjunction with other maritime activities. Further, according to the USCG, VTS has built regulatory controls that help manage risk more effectively than in smaller ports.

- **Potential Cost Concerns:** To address potential cost concerns, it is helpful to build relationships with US suppliers. Just Innovation highlights supply chain security as an emerging concern, particularly when attempting to comply with the Jones Act. An example is aerial drones, for which the US has a "blue list," meaning that government agencies can only work with drones that meet certain sourcing standards, particularly limiting components manufactured in China. This is a notable challenge because so many rechargeable batteries are manufactured in China.

Operational Efficiency: Improvements in Operational Efficiency and Cost Savings

- Autonomous vessels can provide operational efficiency improvements, particularly in terms of enabling more affordable operations. Cost savings can come from the ability to operate smaller purpose-built vessels continuously in harsh conditions. Examples include companies like Ocean Infinity and Fugro that have successfully demonstrated cost savings when using autonomous vessels.[76,77]
- Operational efficiency gains from using autonomous vessels also help in terms of reducing project timelines and labor costs, especially as they can operate 24/7 without breaks. Beam noted that their SubSLAM camera system allows real-time data collection and decision-making that speeds up operations and reduces the need for additional mobilizations.[78]
- Autonomous vessels also tend to have greater fuel efficiency due to their modern fuel types and minimized downtime, further driving cost savings. However, the potential for alternative fuels and electrification on crewed vessels could make them comparable in fuel consumption.

Overall, there appears to be strong potential for autonomous vessels to reduce costs and improve efficiency in offshore wind operations, despite the initial investment and challenges related to maintenance and sourcing of replacement materials.

Data Transfer and Data Management

Data transfer and data management in the context of autonomous vessels and offshore wind operations have several implications, as discussed below.

Data Collection and Transmission Methods

- **Data Collection:** Autonomous vessels are equipped with various sensors and technologies to collect data. These include multibeam echo sounders, lidar, optical imaging, acoustic monitoring instruments, sonar, cameras, and other environmental monitoring tools. The collected data can include bathymetric surveys, core sampling, geotechnical surveys, and weather monitoring. The integration of multiple sensors, such as sonar and visual data, allows for comprehensive data collection even in low-visibility conditions.
- **Data Transmission:** Data collected by autonomous vessels is often transmitted in real-time to onshore centers for analysis and decision-making. Transmission methods include satellite communication, allowing for the remote operation and monitoring of vessels. Some autonomous systems are designed to transmit data periodically, surfacing during operations to send data before submerging again. Ports should implement robust communication networks to facilitate real-time data exchange between autonomous

vessels and port authorities. This includes high-speed internet and secure communication channels.

Data Security and Privacy Concerns

- **Cybersecurity:** Autonomous vessels are vulnerable to cybersecurity threats, including hacking and misdirection. The USCG has recognized the need for robust cybersecurity protocols and is working to establish minimum cybersecurity requirements for US-flagged vessels and offshore facilities. The dynamic nature of the cyber threat landscape presents both direct and indirect risks to autonomous and remotely operated vessels. Data security measures include encrypted communications, access controls, and live threat monitoring.
- **Data Privacy:** There are concerns about the ownership and use of incidental data collected by autonomous vessels. For example, environmental data collected during a survey may have secondary uses, such as weather prediction. Privacy concerns are addressed through strict data management protocols and compliance with regulatory standards.

Management and Utilization of Data

- **Data Management:** Effective data management is crucial to successfully operating autonomous vessels. This includes the storage, processing, and analysis of large volumes of data collected during operations. Remote Operations Centers typically oversee data acquisition, quality control, and mission adjustments. However, onboard processing and real-time decision-making using artificial intelligence are becoming more common, allowing for more efficient data management.
- **Utilization of Data:** The data collected by autonomous vessels is used for various purposes, including monitoring and maintaining offshore wind infrastructure, ensuring safe navigation, maintaining regulatory compliance, and conducting environmental assessments. The integration of data from multiple sensors allows for a comprehensive understanding of the marine environment, which can inform decision-making and improve operational efficiency.

While autonomous vessels offer significant benefits for data collection and transmission, they also present challenges related to data security, privacy, and management. Addressing these challenges requires robust cybersecurity measures, clear policies on data ownership, and effective data management practices.

Policy and Regulations

There is a wide variety of considerations for policy and regulations affecting autonomous vessels, particularly in the context of offshore wind operations. Key issues and themes are highlighted below.

Existing Regulations Affecting Autonomous Vessels

- The USCG is the principal federal regulator of the maritime industry, including autonomous vessels, although autonomous vessels are subject to regulations by the IMO and Classification Societies. The USCG's top priorities are ensuring safe navigation, efficiency, and security of the Marine Transportation System, safety of mariners and industrial personnel, and the ability to complete all USCG missions.

The USCG examines project proposals and advises the Bureau of Ocean Energy Management (BOEM) on projects that develop energy, mineral, and geological resources on the US Outer Continental Shelf and any potential impacts on the Marine Transportation System, navigational safety, traditional uses of the waterways, and USCG missions. The USCG also provides comments as Subject Matter Experts to BOEM or the United States Army Corps of Engineers regarding any necessary cable burial assessments and navigation safety risk assessments.

- The USCG works closely with traditional waterway users, other government partners, and developers to ensure that offshore energy projects and new technologies can safely coexist with other waterway uses.
- The USCG continues to explore how to handle the integration of autonomous technologies. Key questions include whether autonomous survey craft have the same privileges as a crewed vessel, whether it is recognized as a vessel, or only as a data-gathering device. There are also concerns about ensuring that autonomous systems follow the COLREGs and other navigational rules, such as right-of way crossing.
- Compliance with existing safety and operational standards is essential for regulatory approval.

Emerging Regulatory Landscape and the Evolving Compliance Environment

- The USCG is actively engaged in developing and promulgating national regulations and standards that govern the safe design and construction of ships and shipboard equipment, including autonomous vessels. The IMO is developing a regulatory framework for Maritime Autonomous Surface Ships, expected to become mandatory by 2032. Both organizations are supporting various committees to develop standards for autonomous and remote platforms.
  - The USCG is considering proposals for advanced automation, remote control, and autonomous systems on a case-by-case basis to provide flexibility for innovation without undue risk.
  - The USCG also has an Autonomous Technology Policy Council that consists of program leads from their headquarters and experienced field folks. They are working through challenges, with districts and local sectors sharing best practices along with the industry.
- New rules could address safety, training, and legal responsibilities for autonomous vessel operations. The dynamic nature of the cyber threat landscape presents both direct and indirect risks to autonomous and remotely operated vessels, and the USCG is working to identify and mitigate these threats.
- Some subject matter experts noted a preference for evolving rules toward international best practices rather than rigid technical standards. Perhaps best practices could distinguish between operating small, light systems versus large, heavy systems, and between different types of activities. It may also be helpful to develop performance standards tailored to specific missions, such as acoustic monitoring for marine mammal mitigation.

- Just Innovation suggested creating more "playpens" or designated areas where governments allow and encourage experimentation with autonomous vessels. This would accelerate hands-on experimentation and drive the dialogue needed to address longer-term policy questions. Increased experimentation on the water, coupled with more interactive discussions among diverse interested parties, could help establish best practices. Examples of this practice include a Navy test area in Gulfport, Mississippi, and a public test area in Plymouth, United Kingdom, run by the local harbor master.

Current Federal Policies and Regulations Affecting Autonomous Vessels

- The USCG's role includes enforcing applicable laws and regulations, including the Jones Act. The USCG is working with federal partners and across USCG programs to address the various challenges and opportunities that energy projects and autonomous vessels may bring. The USCG's *Unmanned Systems Strategic Plan* informs its approach to using autonomous technologies within its service.
- Statutory requirements associated with manning and watchkeeping may create challenges depending on the size and operational profile of the vessel. The USCG actively engages in a pilot program for the at-sea recovery of rockets by remotely operated vessels to gain data about these operations and understand the regulatory and/or statutory changes needed to safely manage remote and autonomous vessel operations.
- One subject matter expert’s analysis of current federal policies and regulations, they noted that there are no absolute “hard stops” in policy or regulation that prevent the advancement of autonomous vessel technology. However, regulators tend to be cautious and risk-averse when carrying out their mission to protect and preserve resources, which may slow down the adoption of new technologies.
- Another subject matter expert felt that the USCG could provide clearer guidance on the operation of autonomous vessels, with the lack of specific regulations seen as a significant hurdle. An additional potential difficulty is obtaining necessary documents such as insurance and licenses.
- Further regulatory challenges mentioned in interviews include the requirement for human oversight of robotic systems and the lack of clarity on how many vessels one person can monitor simultaneously. Some feel that the broader regulatory environment has not yet evolved to fully support the operation of autonomous vessels.

International Maritime Organization Standards: Review of IMO Standards and Their Implications

- Once vessels leave federal waters and enter the US Exclusive Economic Zone, they are under the oversight of the IMO.
- The USCG is the lead agency for the United States' delegations to the IMO and is actively engaged with various standards committees and classification society rule committees involved in developing standards for autonomous and remote platforms. The IMO is grappling with unresolved questions regarding the master’s responsibilities, rules of the road, definitions, and lookout functions for autonomous vessels.
- The IMO's *Maritime Autonomous Surface Ship Guidelines* ensure that autonomous vessel operations adhere to existing safety and regulatory standards. These guidelines pave the way for the gradual adoption of fully autonomous vessels.

- While the IMO has made progress in developing codes of conduct, some subject matter experts noted there is still room for improvement.

Implications of the Jones Act

- The Jones Act has implications for autonomous vessels. The USCG has a lead role in enforcing the Jones Act, including statutory requirements for manning and watchkeeping. The Jones Act requires vessels transporting goods or passengers between US ports to be US-built, owned, flagged, and crewed.
- The Jones Act's relevance to autonomous vessels includes ensuring that operators are licensed mariners and addressing job protections, training, and domestic vessel operations. However, autonomous vessels engaged in survey and data acquisition tasks possibly fall outside the scope of the Jones Act.
- Justin Manly, of Just Innovation, Inc., stated that "the Jones Act is very prescriptive when it comes to crews, vessels, and ports of call." He also noted that "while I haven't seen the Jones Act directly impact my own business yet, I have definitely seen how it drags on the broader industry in some cases—slowing innovation and creating challenges."[79]
- Interviewees noted that additional guidance from the USCG and US Customs and Border Protection could clarify the applicability of these rules to autonomous vessel operations.

Overall, the documents highlight the need for continued collaboration between the USCG, other federal agencies, and industry parties to develop and implement regulations that support both the maritime sector and safe and efficient use of autonomous vessels in offshore wind operations.

Other Considerations, Opportunities, Constraints in New York/New Jersey Harbor and Region

In addition to the broader issues discussed above, considerations, opportunities, and constraints related to the use of autonomous vessels in the New York/New Jersey Harbor and region, particularly in the context of offshore wind operations, were explored.

The New York/New Jersey Harbor is much larger than other northeastern ports, both in geographic scale and vessel traffic volume. The Harbor is dynamic in a way that demands control, with a mix of large commercial ships, several ferry operators traveling at fast speeds, and smaller recreational boats and human-powered boaters paddling around the harbor, as well as both nearshore and offshore environments, all in challenging environments with low visibility, dynamic currents, and highly urbanized coastal communities. Fortunately, VTS New York provides good tools for mariners. They have built-in regulatory controls that help manage risk more effectively than in smaller ports.

In addition to advantages (i.e., strong controls, well-established VTS) within the Harbor, it also has significant capital and innovation. There is local interest in using unmanned surface or aerial systems for delivery, including small packages and potentially even larger cargo runs across the Harbor. While not specific to offshore wind, other local uses and development of autonomous systems could help enable the broad adoption of autonomous vessels, which could then expand to include offshore wind uses.

Facilities within the Harbor have existing industrial infrastructure that is often not present, meaning these locations could be a strong candidate for becoming a more "wired" port (integrated automatic identification systems, networked radar, infrared, high-res cameras, real-time data streams).

The offshore wind industry is currently changing and experiencing a degree of uncertainty in the current market. Such changes have been researched in NYSERDA's Cumulative Ports Assessment. However, the USCG has already proposed expanding VTS New York to Albany/Troy, in part due to offshore wind and other energy development, as well as the Hudson River's status as a major maritime corridor, a spawning habitat for critical listed species, and a major cultural and environmental asset.

There are other environmental conditions to consider when operating a vessel in New York/New Jersey Harbor, such as making sure it does not interfere with fishermen or marine mammal migration patterns. It will be important for autonomous vessels to integrate into the existing harbor operations, allowing other uses and traffic to continue operating as they are accustomed.

Environmental Considerations

The research conducted highlights the potential environmental benefits of using autonomous vessels, particularly in reducing the carbon footprint and minimizing natural resource impacts. Autonomous vessels have the potential to operate more efficiently and with lower emissions than traditional manned vessels.

For example, solar-powered uncrewed surface vehicles from Open Ocean Robotics can operate continuously in areas with good sunlight, reducing the need for frequent servicing and minimizing environmental impacts.[80] Additionally, Fugro's Blue Essence vessel claims up to a 95 percent reduction in carbon emissions.[81]

Autonomous vessels also support environmental monitoring and compliance by collecting data on marine mammals, turbidity, and underwater noise, which helps in assessing and mitigating environmental impacts.

Technological Advancements: Innovations in Autonomous Vessel Technology and Their Potential Benefits

The materials reviewed discussed discuss several technological advancements in autonomous vessel technology and potential benefits. Innovations include the development of solar-powered uncrewed surface vehicles and advanced sensor suites and algorithms for hydrographic surveys, environmental monitoring, subsea inspections, navigation, and other forms of data collection. These technologies enable continuous, high-precision data collection, real-time data transmission, and remote operations, enhancing operational efficiency and safety.

Technical Challenges: Limitations and Technical Hurdles in Implementing Autonomous Technologies

Despite the potential benefits, there are several technical challenges and limitations in implementing autonomous technologies. These include the need for reliable communication and control systems (which require high-bandwidth connectivity), cybersecurity concerns, and the integration of autonomous vessels into existing regulatory frameworks. Additionally, retrofitting older vessels with autonomous systems can be costly and technically challenging.

The USCG is actively engaged in addressing these challenges and is considering proposals for advanced automation, remote control, and autonomous systems on a case-by-case basis to provide flexibility for innovation without undue risk. Additionally, the dynamic nature of the cyber threat landscape presents both direct and indirect risks to autonomous and remotely operated vessels, and key industry parties are working to identify and mitigate these threats.

Qualitative Risk Evaluation

Risk Identification: Key Risks Associated with Advancing Autonomous Technologies

There are several different types of risk that should be accounted for in the application of autonomous vessel technology, outlined below.

- **Operational Risks:** The primary operational risks include the potential for autonomous vessels to malfunction or encounter unforeseen obstacles, leading to accidents or collisions. The lack of human oversight on these vessels means that issues cannot be immediately addressed, increasing the risk of operational failures.
- **Regulatory and Compliance Risks:** The regulatory framework for autonomous vessels is still developing, and there are significant uncertainties regarding compliance with existing maritime laws and regulations. This includes the master's responsibilities, navigation rules, and lookout functions.
- **Cybersecurity Risks:** Autonomous vessels are vulnerable to cyber threats, including hacking and data breaches, which could compromise their operations and safety. The dynamic nature of the cyber threat landscape presents both direct and indirect risks to these vessels.
- **Environmental Risks:** There are concerns about the environmental impact of autonomous vessels, particularly in terms of their interactions with marine life and ecosystems. This includes the potential for these vessels to interfere with whale migration patterns and other natural resources.

Incidents that occur related to any of these risks could also then erode public trust in autonomous systems and make further deployment more difficult.

Risk Analysis: Qualitative Assessment of the Likelihood and Impact of Identified Risks

The following qualitative assessment synthesizes key risks of autonomous vessel operations, the likelihood of occurrence, and seriousness of impact. Together, these risks show the challenges of operating and regulating systems that rely on semi- and fully autonomous technology.

- **Likelihood of Operational Failures:** The likelihood of operational failures is a legitimate possibility, given the current state of autonomous technology and the lack of comprehensive regulatory oversight. Operational risks can arise when onboard personnel are not present to address issues as they arise, putting grater onus on the remote operator to diagnose and address an issue from miles away. The impact of such failures can be significant, leading to accidents, environmental damage, and financial losses.
- **Regulatory and Compliance Challenges:** The likelihood of encountering regulatory and compliance challenges is high, as the regulatory framework is still evolving. The impact of these challenges can be substantial, potentially delaying the deployment of autonomous vessels and increasing operational costs.

- **Cybersecurity Threats:** The likelihood of cybersecurity threats is high, given the increasing sophistication of cyberattacks and the reliance on digital systems for autonomous vessel operations. A lack of onboard personnel compounds the risks of vessels being co-opted for other purposes. The impact of a successful cyberattack can be severe, leading to operational disruptions, data breaches, and safety risks.
- **Environmental Impact:** The likelihood of environmental impact is difficult to predict but is possible, depending on the specific operations and locations of the autonomous vessels. The impacts could range from minor disturbances to significant harm to marine life and ecosystems.

Risk Mitigation: Strategies for Mitigating and Managing Risks

- **Enhanced Regulatory Framework:** Developing a comprehensive regulatory framework that addresses the unique challenges of autonomous vessels is crucial. This includes clear guidelines on the master's responsibilities master, navigation rules, and lookout functions.
  - Engaging with regulatory authorities early in the deployment process and adhering to international standards and guidelines can help mitigate regulatory risks.
- **Cybersecurity Measures:** Implementing robust cybersecurity measures to protect autonomous vessels from cyber threats is essential. This includes regular security assessments, encryption, live threat monitoring, and secure communication protocols.
- **Environmental Monitoring:** Conducting thorough environmental impact assessments and implementing measures to minimize the impact on marine life and ecosystems. This includes using sensors and monitoring systems to detect and avoid interactions with marine life.
- **Operational Oversight:** Ensuring that there is adequate human oversight and intervention capabilities for autonomous vessels. This includes having remote operators who can take control of the vessel in case of emergencies.
- **Workforce:** Providing training programs for remote operations, system calibration, and situational awareness development can help manage risks.

Overall, the materials reviewed highlight the need for a multifaceted approach to managing the risks associated with autonomous vessels, involving regulatory, technological, and operational measures to ensure their safe and effective deployment in offshore wind operations.

CONCLUSIONS

Autonomous vessels present both transformative opportunities and distinct challenges for offshore wind operations. The potential impacts span environmental, technological, and regulatory domains. Effective monitoring and mitigation can reduce harm to marine migration patterns and ecosystems. Technological advances offer increased operational efficiency, real-time risk management, and enhanced data collection. However, these are balanced by constraints such as regulatory uncertainty, cybersecurity vulnerabilities, and the necessity for skilled workforce adaptation.

The landscape examined in this study surfaces several keys areas for continued consideration as autonomous vessel technology advances in offshore wind operations:

- **Regulatory Environment**: Comprehensive, harmonized guidelines for the safe deployment and operation of autonomous vessels are increasingly recognized as essential. International consistency and clarity of jurisdictional roles represent critical gaps that the evolving regulatory landscape will need to address.
- **Industry Preparedness**: Robust cybersecurity frameworks, environmental monitoring systems, and remote operational oversight capabilities are emerging as foundational requirements for responsible autonomous operations. The development of reliable emergency intervention protocols is similarly gaining prominence as technology matures.
- **Workforce Adaptation:** As autonomous systems become more prevalent, targeted training in remote vessel operation, risk assessment, and system calibration represents a growing area of need. The development of such programs spans government agencies, maritime academies, and private industry, reflecting the breadth of the transition underway.
- **Research and Collaboration:** Sustained engagement among research institutions, industry, and regulatory bodies remains essential to resolving outstanding technical and operational risks, advancing innovation, and establishing shared best practices for risk mitigation and environmental stewardship.

In summary, the safe and effective integration of autonomous vessels into offshore wind operations points towards a holistic, adaptive approach, one that balances innovation with vigilance, and opportunity with responsibility. Collaborative engagement among regulators, industry, researchers, and the workforce can collectively shape a sustainable and resilient maritime future.

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