State-of-the-art sustainable energy efficiency technologies roadmap for waterborne transport towards the fit-for-55 guidance compliance

Project 101192661 - FLEETfor55

Deliverable D5.1 – GAP and risk assessment models

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Acronyms and Abbreviations	Meaning
ABS	American Bureau of Shipping
ACH	Air Changes per Hour
AiP	Approval in Principle
ALARP	As Low As Reasonably Practicable
ALS	Air Lubrication System
ARAFFF	Alcohol Resistant Aqueous Film Forming Foam
ARMS	Ammonia Release Mitigation System
BESS	Battery Energy Storage Systems
BOG	Boil-Off Gas
CFD	Computational Fluid Dynamics
CLT	Contracted and Loaded Tip
CMS	Cable Management System
CPP	Controllable Pitch Propeller
CRP	Contra-Rotating Propeller
DBB	Double Block and Bleed
DBT	Dibenzyltoluene
DME	Dimethyl Ether
DNV	Det Norske Veritas
DP	Dynamic Positioning
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EETs	Energy Efficiency Technologies
EEXI	Energy Efficiency Existing Ship Index
EMSA	European Maritime Safety Agency
ESD	Emergency Shutdown
ESS	Energy Storage System
ETA	Event Tree Analysis
FAME	Fatty Acid Methyl Esters
FC	Fuel Cell
FDR-AF	Frictional Drag Reducing Antifouling
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
GCU	Gas Combustion Units
GHG	Greenhouse Gas
HAZID	Hazard Identification
HAZOP	Hazard and Operability study
HP-EGR	High-Pressure Exhaust Gas Recirculation
HVAC	Heating, Ventilation, and Air Conditioning

Acronyms and Abbreviations	Meaning
HVO	Hydrotreated Vegetable Oil
HVSC	High Voltage Shore Connection
ICE	Internal Combustion Engines
IDLH	Immediately Dangerous to Life and Health
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IMO	International Maritime Organization
IP	Ingress Protection
ISO	International Organization for Standardization
JIT	Just In Time
KR	Korean Register
LED	Light Emitting Diode
LEL	Lower Explosive Limit
LFL	Low Flashpoint Liquid / Lower Flammability Limit
LH2	Liquid Hydrogen
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Petroleum Gas
LRM	Light Running Margin
MCR	Maximum Continuous Rating
NPT	New Profile Technology
ORC	Organic Rankine Cycle
PBCF	Propeller Boss Cap Fin
PEMFC	Proton Exchange Membrane Fuel Cell
P&ID	Piping and Instrumentation Diagram
PSPC	Performance Standard for Protective Coatings
PTI	Power Take-In
PTO	Power Take-Off
QRA	Quantitative Risk Assessment
RPN	Risk Priority Number
SCC	Stress Corrosion Cracking
SOFC	Solid Oxide Fuel Cell
SOLAS	Safety of Life at Sea
SRtP	Safe Return to Port
SSE	Shore Side Electricity
TCE	Tank Connection Enclosure
TCS	Tank Connection Space

Acronyms and Abbreviations	Meaning
VFD	Variable Frequency Drives
WAPS	Wind-Assisted Propulsion Systems
WHR	Waste Heat Recovery

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Executive Summary

Task 5.1 focuses on identifying regulations and previous studies related to the implementation of Energy Efficiency Technologies (EETs) on ships, while collecting and analysing essential data for subsequent Tasks 5.2, 5.3, and 5.4. This process ensures safety throughout the decarbonisation transition by evaluating the unique hazards associated with novel technologies such as hydrogen, ammonia, and wind-assisted propulsion. Specifically, technologies are classified based on maturity into those requiring Approval in Principle (AiP), proposing the use of methodologies like HAZID and CFD where existing regulations are lacking. Ultimately, this task identifies potential safety shortcomings and establishes specific mitigation strategies, providing a critical foundation for the detailed engineering development in WP4 and the remaining tasks within WP5.

To achieve this, the deliverable is structured into the following key sections:

• Chapter 1: Typical characteristics and hazards of alternative EETs: Outlines the physical properties, operational characteristics, and inherent safety risks (e.g., toxicity, flammability, structural stress) of various EET categories, including sustainable fuels, energy devices, and renewables.

• Chapter 2: Regulations, rules, standards, and guidelines: Maps the current frameworks provided by major classification societies (e.g., IMO, ABS, DNV, RINA) and explicitly identifies regulatory gaps where existing codes fail to sufficiently cover emerging technologies in ship design, material compatibility, and fire safety.

• Chapter 3: Safety challenges and current studies on EETs: Reviews recent qualitative and quantitative scientific literature to highlight how the industry currently models and manages complex safety scenarios, such as toxic gas dispersion and thermal runaway.

• Chapter 4: Overview of risk assessment to investigate the safety of EETs: This chapter defines the comprehensive risk assessment methodologies tailored to evaluate the safety of EET installations. It details the application of qualitative tools (HAZID, HAZOP, and FMEA) to systematically identify system deviations and operational hazards early in the design phase. This is complemented by Quantitative Risk Analysis (QRA) procedures, which utilise Computational Fluid Dynamics (CFD) to simulate the dispersion, combustion, and pressure consequences of hazardous scenarios.

• Chapter 5: Prioritisation of technologies for risk assessment and AiP: This final section categorises the investigated technologies to streamline the path toward commercialisation and regulatory compliance. It prioritises them into Tier 1, comprising high-priority, novel technologies that require formal risk assessment and an Approval in Principle (AiP) to bridge existing regulatory gaps. Conversely, Tier 2 consists of proven, standard compliance technologies that require only standard Plan Approval.

1 Typical characteristics and hazards of alternative EETs

This chapter provides a structured overview of the typical characteristics and inherent hazards associated with the Energy Efficiency Technologies (EETs) illustrated in Table 1 and Table 2.

Table 1. Categorization of ship related EETs

No.	EET category	Name of EET
1.	Carbon Capture Systems	Onboard Carbon Capture and Storage (CCS) Systems
2	Energy Optimized	Steam/heat plant improvements/optimization
		Advanced HVAC & cooling systems
		Waste heat recovery systems (WHRS)
3.	Hydrodynamic Efficiency Improvements	Hull Form Optimization (Streamlined Design for Efficiency)
		Air lubrication systems (ALS)
		Bulbous Bow Optimization
		Hull Openings and Skeg Shape Optimization
		Variation of block coefficient/lengthening (Inland)
4.	Power Conversion	Alternative Fuelled 2-S ICEs (Hydrogen)
		Alternative Fuelled 2-S ICEs (Methanol)
		Alternative Fuelled 2-S ICEs (Ammonia)
		Alternative Fuelled 4-S ICEs/Gensets (Hydrogen)
		Alternative Fuelled 4-S ICEs/Gensets (Methanol)
		Alternative Fuelled 4-S ICEs/Gensets (Ammonia)
		Alternative Fuelled 4-S ICEs/Gensets (Biofuels)
		PEM fuel cells
		SOFC fuel cells
		Shaft Generator PTI, PTO, PTI/PTO
5	Electrification	Energy storage systems (ESS) – lithium-ion batteries
		Energy storage systems (ESS) – redox flow batteries (RFB)
		Onshore Power Supply [OPS]
		Hydrofoil-Based Wave Energy Converters
		Heaving Oscillating Systems
		Full Electric Propulsion Concepts (e.g. dynafin, Superconducting electric motors)
		DC Grid technologies

No.	EET category	Name of EET
		SOLAR - Photovoltaic (PV) Panels for Ships
6.	Propeller ESDs	Post-swirl ESD Contra-rotating propellers (CRP)
		Pre-swirl ESD Wake Equalizing Ducts (WEDs)
		Pre-swirl ESD Fins
		Manoeuvring devices (e.g. Gate rudder)
		Propeller Nozzle (e.g. Kort)
		Post-swirl ESD PBCF (Propeller Boss Cap Fins)
		Post-swirl ESD Grim Vane Wheel
		Propeller-Retrofitting Advanced propeller Blade Sections (e.g. Winglets/kappel)
7.	Renewables	WAPSs - Soft Sails
		WAPSs - Flettner Rotors (Magnus Effect Rotors)
		WAPSs - Rigid Wing Sails
		WAPSs - Kite Propulsion Systems
		WAPSs - Suction Wings (Ventifoils)
8.	Sustainable, Climate-Neutral & Low-Emission Fuels	Fuel Reforming/Cracking
		Methanol
		Biomethane
		Ammonia
		Hydrogen
		Synthetic e-fuels

Table 2. Globally Applied EETs

Global Applied EETs		
No.	**EET category**	**Name of EET**
1.	Optimized Energy Systems	Variable Frequency Drive (VFD) for speed control (e.g. pumps, fans)
		Main Engine Tuning & Optimization
2	Hydrodynamic Efficiency Improvements	Hull Surface Coatings & Low-Drag Paints
		Trim & draft optimization
		Lightweight shipbuilding materials (composites, aluminium)
3.	Operations & Digital Optimization	Weather routing systems for voyage speed/fuel optimization
		Just-in-time (JIT) arrival strategies
		Cargo Load Factor Optimization

Global Applied EETs		
No.	**EET category**	**Name of EET**
4.	Electrification	LED lights application
5.	Sustainable, Climate-Neutral & Low-Emission Fuels	Biodiesel

The subsequent subsections within this chapter 1 will provide a detailed technical overview and hazards for the following categories:

- **Sustainable Climate Neutral Low Emission Fuels:** A summary of the physical properties (e.g., energy density, storage temperature) and primary hazards (e.g., toxicity, flammability) of fuels such as Ammonia, Methanol, and Hydrogen.
- **Power Conversion and Energy Devices:** An outline of the operational characteristics of fuel cells and battery energy storage systems, including risks related to high voltage and thermal instability.
- **Renewable Energy Sources:** An overview of wind-assisted propulsion (Flettner rotors, kites) and solar panels, focusing on their mechanical footprint and the structural hazards they may present.
- **Propeller Designs and Hydrodynamics:** A compilation of the technical features of advanced propulsion systems (e.g., Gate Rudders, Air Lubrication) and the associated maintenance or navigational considerations.
- **Operational and Engineering Approaches:** A review of how optimized energy management—such as "Just In Time" (JIT) arrivals and engine tuning—influences overall ship safety and efficiency.

1.1 Power Conversion / Electrification / Energy devices

Fuel Cells

Fuel cell technologies are at the forefront of the maritime industry's transition toward zero-emission shipping, with Hydrogen and Ammonia systems receiving the most significant research attention. Hydrogen-powered fuel cells, particularly Proton Exchange Membrane Fuel Cells (PEMFCs), are currently the most mature technology for maritime applications **[1]**. In parallel, Solid Oxide Fuel

Cells (SOFCs) are being evaluated for their high electrical efficiency and fuel flexibility, capable of utilising natural gas, methanol, or hydrogen, though experimental studies indicate that their performance is sensitive to the inclinations and accelerations characteristic of ship motions **[2]**. While these technologies offer environmental benefits, they introduce distinct hazard profiles; hydrogen presents significant explosion risks due to its wide flammability range and low ignition energy, where leakages in enclosed spaces can rapidly form explosive atmospheres that accumulate in upper areas due to buoyancy **[3]**. Ammonia fuel cells, while advantageous for fuel storage, introduce severe toxicity hazards that require rigorous detection and management protocols **[4]**. Furthermore, the integration of these systems necessitates complex safety architectures to manage voltage stability and prevent system failures that could lead to blackouts **[5, 6, 7]**.

Alternative Fuels Internal Combustion Engines (ICEs)

Alternative fuel Internal Combustion Engines (ICEs) represent an evolutionary decarbonisation strategy, leveraging established dual-fuel engine technologies to utilise Liquefied Natural Gas (LNG), methanol, and ammonia. These systems generally maintain power output and thermal efficiency comparable to conventional diesel engines, with LNG variants significantly reducing nitrogen and sulphur oxide emissions while offering the flexibility to switch between fuels based on availability. However, the operational requirements for these fuels introduce complex hazards; LNG necessitates cryogenic storage at approximately -162 °C, creating risks of cryogenic burns and asphyxiation, while the handling of methanol and ammonia involves severe toxicity and flammability concerns that demand corrosion-resistant materials and specialised bunkering systems **[8]**.

PTI / PTO (Shaft Generator)

Power Take-In/Power Take-Off (PTI/PTO) systems, commonly referred to as shaft generators, enhance vessel efficiency by enabling bidirectional power flow between the propulsion shaft and the ship's electrical grid. In PTO mode, the main engine drives the generator to produce electricity during steady-state cruising, thereby reducing the running hours of auxiliary generators, while in PTI mode, the system acts as a motor to provide propulsion power for low-speed manoeuvring or emergency operations. This dual functionality offers a critical safety redundancy; research has highlighted the capability of generator-electric motor systems to provide emergency propulsion in the event of a main engine failure, ensuring the vessel maintains manoeuvrability **[9]**. Despite these advantages, the mechanical coupling of the generator to the propulsion shaft introduces potential hazards related to vibration, misalignment, and bearing failures, which can compromise both propulsion integrity and electrical power quality.

Energy Storage Systems (ESS)

Energy Storage Systems (ESS), predominantly based on lithium-ion chemistry, are increasingly deployed in maritime sectors to facilitate peak shaving, load levelling, and hybrid or fully electric propulsion. Commercial exploitation of these systems has demonstrated their ability to optimise diesel generator loading and absorb regenerative energy, although operational data reveals that systems often deviate from their designed operational profiles, impacting longevity and safety **[10]**. The primary hazard associated with maritime BESS is thermal runaway, leading to fires and explosions that are difficult to extinguish. During such events, lithium-ion batteries release toxic gases, including hydrogen fluoride and carbon monoxide **[11]**. Additionally, the maritime environment introduces the specific risk of seawater immersion; accidental flooding can cause short circuits and the generation of hydrogen gas, leading to violent chemical reactions **[12]**. To mitigate these risks, safety and risk assessments are essential for identifying hazards and prioritising mitigation strategies **[13, 14]**.

Onshore Power Supply (OPS)

Onshore Power Supply, or High Voltage Shore Connection (HVSC), allows vessels to shut down onboard generators while in port and receive electrical power from the shore grid. The primary hazards associated with OPS are electrical, including the risk of arc flash and electric shock to personnel during the physical connection and disconnection processes **[15]**. Furthermore, the interconnection of ship and shore grounding systems creates complex technical challenges; improper bonding can result in dangerous circulating currents or interference with the vessel's cathodic protection systems **[16]**. To manage these risks, international standards mandate specific design requirements, such as the implementation of interlocks to prevent connection errors **[15]**.

1.1 Sustainable climate neutral low emission fuels

Hydrogen

Hydrogen is characterised by the highest gravimetric energy density among alternative fuels, yet it suffers from extremely low volumetric energy density in its gaseous form, necessitating storage solutions involving high-pressure compression typically between 350 and 700 bar or cryogenic liquefaction at -253 °C **[17]**. These physical properties fundamentally dictate its hazard profile;

hydrogen exhibits the widest flammability range of 4–75% by volume and an extraordinarily low minimum ignition energy of approximately 0.019mJ, making it highly susceptible to ignition from weak sources such as static electricity **[18, 19]**.

Despite these severe flammability characteristics, hydrogen's safety profile is nuanced by its buoyancy; being 14 times lighter than air, leaked hydrogen tends to disperse rapidly in open environments, which can mitigate the duration of explosive conditions compared to heavier fuels **[17]**. However, in confined spaces, this rapid accumulation can create severe explosion hazards, further complicated by the gas's colourless and odourless nature which hampers detection without specialised sensors **[20, 21]**.

Methanol

Methanol is a liquid fuel under ambient conditions, offering a volumetric energy density of approximately 3.3 kWh/L, which allows for its integration into existing liquid fuel infrastructure with relatively minor modifications **[22]**. Its physical behaviour contrasts sharply with hydrogen, as methanol vapours are slightly heavier than air and can travel along the ground to distant ignition sources, necessitating careful ventilation design **[19]**. While methanol exhibits a moderate flash point of 11–15.6 °C and flammability limits of 6–36.5%, posing standard fire risks, its most significant hazard lies in its toxicity **[23]**. Methanol exposure can occur through inhalation, ingestion, or skin absorption, leading to severe systemic effects including metabolic acidosis, permanent blindness, and death, which complicates handling procedures and requires comprehensive personal protective equipment **[24, 19]**. Furthermore, methanol fires are particularly hazardous because they burn with a pale, nearly invisible flame, making visual detection difficult during daylight emergencies **[18]**.

Ammonia

Ammonia is increasingly recognised for its potential as a carbon-free fuel, characterised by a high autoignition temperature of 650°C and a relatively narrow flammability range of 15–28%, which makes it significantly harder to ignite than hydrogen **[18, 25]**. From a storage perspective, ammonia is advantageous as it can be stored as a liquid at a moderate pressure of 10bar or at -33.4 °C, utilising conventional pressure vessel technology **[26]**.

However, the primary operational hazard of ammonia is its severe acute toxicity; it is corrosive to skin and eyes, and inhalation at concentrations as low as 300 ppm is considered immediately dangerous to life and health **[19]**. Unlike buoyant hydrogen, liquid ammonia releases result in dense vapour clouds that can linger at ground level, creating extensive toxic zones that pose risks to both crew and surrounding communities **[25]**. Additionally, the combustion of ammonia presents

environmental challenges, potentially generating higher levels of nitrogen oxides (NOx) than conventional fuels unless managed by advanced exhaust treatment systems **[26]**.

Biofuels

Biofuels are derived from various biomass feedstocks and are generally characterised by their compatibility with existing diesel and gasoline infrastructure, offering a renewable alternative with potentially lower lifecycle greenhouse gas emissions. Their toxicity and hazard profiles vary depending on the specific chemical composition, but biodiesel and similar biofuels generally demonstrate lower acute toxicity compared to conventional petroleum diesel **[24]**. While they share the general flammability risks of liquid hydrocarbon fuels, the environmental impact of spills is typically less severe due to higher biodegradability **[27]**. However, the combustion of biofuels still generates local air pollutants, and their specific emission profiles—such as aldehyde emissions from alcohol-based biofuels—require management to ensure air quality standards are met **[24]**.

LOHC (H_2 carrier)

Liquid Organic Hydrogen Carriers (LOHCs), such as dibenzyltoluene (DBT), represent a distinct approach to hydrogen storage, characterised by their stability as liquids at ambient temperature and pressure **[22]**. A defining safety characteristic of LOHCs is their classification as non-flammable under normal conditions, with flash points often exceeding 200 °C, which eliminates many of the fire and explosion hazards associated with compressed hydrogen or conventional fuels during storage and transport **[23]**. The primary hazards for LOHCs are introduced during the dehydrogenation process required to release the hydrogen; this step involves high temperatures and catalytic reactions that reintroduce flammability risks at the point of use **[22]**. While substances like DBT are generally considered non-toxic and non-mutagenic, data on the toxicity of various hydrogenated forms remains incomplete, necessitating further research to fully validate their safety profile **[23]**.

Ammonia (H_2 carrier)

When utilised as a hydrogen carrier, ammonia leverages its high volumetric hydrogen density and the existence of established global distribution infrastructure, making it a practical medium for transporting hydrogen over long distances **[26]**. The physical properties and storage requirements—liquefaction at -33.4 °C or moderate compression—are identical to its use as a direct fuel, offering a more energy-dense alternative to liquid hydrogen transport **[28]**. However, the safety challenges remain dominated by its toxicity; the large-scale transport required for hydrogen carriage increases

the potential magnitude of accidental releases, where the solubility of ammonia in water can lead to catastrophic impacts on aquatic ecosystems in the event of a maritime spill **[26]**. Furthermore, the process of cracking ammonia back into hydrogen at the destination introduces additional system complexity and thermal hazards similar to those found in chemical processing industries **[25]**.

Methane (synthetic methane/biomethane)

Methane, whether derived from synthetic sources or biomethane, shares the well-characterised physical properties of natural gas, with flammability limits of 5–15% and a minimum ignition energy of 0.28mJ **[25]**. Its established usage is supported by mature infrastructure and safety protocols, yet it presents specific hazards related to its density; being slightly lighter than air, it can still accumulate in enclosed spaces to form explosive atmospheres **[29]**. When handled as biomethane, methane introduces cryogenic hazards, including the risk of rapid phase transitions and pool fires upon release, as well as the potential for severe thermal injuries from vapour cloud explosions **[29]**. From an environmental perspective, methane slip—the leakage of unburned methane during production or combustion—poses a significant hazard due to methane's high global warming potential, which can offset the climate benefits of using biomethane **[28]**.

Ethanol Fuel (synthetic/biomass)

Ethanol exhibits physical and chemical characteristics similar to methanol, including a flash point near ambient temperature (approximately 13 °C) and miscibility with water, which allows for its use in internal combustion engines with minor modifications **[27]**. While it presents a moderate flammability risk comparable to conventional liquid fuels, ethanol is significantly less toxic than methanol, causing central nervous system depression rather than the severe systemic toxicity and blindness associated with methanol exposure **[24]**. The primary safety challenges in handling ethanol involve its flammability and the specific requirements for fire suppression; due to its water solubility, standard water-based extinguishing methods may be ineffective, necessitating alcohol-resistant foams **[18, 27]**. Environmental impacts from spills are mitigated by ethanol's biodegradability, although high concentrations can still cause acute toxicity to aquatic life and contaminate water sources **[24]**.

1.2 Renewables

WAPS-Flettner Rotors

Flettner rotors represent one of the most mature wind-assisted propulsion technologies, characterised as vertical rotating cylinders that generate lift via the Magnus effect. These systems typically consist of steel cylinders ranging from 15 to 30 metres in height and 3 to 5 metres in diameter, driven by electric motors with power ratings of approximately 80–90 kW to rotate at speeds up to 225 rpm **[30]**.

A critical design feature in modern implementations is the use of large endplates, which significantly improve aerodynamic efficiency by reducing tip vortex losses, allowing the rotors to achieve lift coefficients up to 9 and lift-to-drag ratios of approximately 4 **[31, 32]**. While these performance metrics enable substantial fuel savings of 5–30% depending on the route, the physical presence and operation of the rotors introduce specific hazards **[30]**. The generation of lift creates significant unsteady aerodynamic forces and moments that impose structural stress on the foundation and ship hull, particularly in turbulent wind conditions **[33]**. Furthermore, the height of the rotors creates air-draft constraints that jeopardise safe passage under bridges; while tilting mechanisms have been developed to mitigate this, the failure of such mechanical systems could lead to collisions or operational disruptions **[34]**. Additionally, the reliance on automated control systems to adjust rotation speed is safety-critical, as inappropriate operation during high winds could destabilise the vessel or result in net power losses **[35]**.

WAPS-Kite Propulsion Systems

Kite propulsion systems utilise large parafoils, typically ranging from 150 to 800 m^2, tethered to the vessel to harvest stronger and more consistent winds found at high altitudes. These systems operate dynamically, often flying in figure-eight patterns to maximise the towing force generated, and can be stowed at deck level when not in use, thereby avoiding the air-draft issues associated with fixed structures **[36, 37]**.

Despite their potential to reduce fuel consumption by 6–12%, kite propulsion systems are associated with high operational complexity and safety risks due to the substantial energy stored in the system **[37]**. The primary hazard involves the high-tension tether, which can experience loads of several hundred kilonewtons; a tether failure could result in dangerous snapback events, posing severe risks to crew and deck equipment **[36]**. Launch and recovery phases are particularly critical, as the kite passes through low-altitude zones where stability is reduced and the risk of collision with the ship's superstructure or entanglement is elevated **[37]**. Furthermore, the reliance on sophisticated automated control systems to manage flight stability is a significant risk factor, as control failure could lead to uncontrolled crashing or the generation of asymmetric loads that threaten vessel stability **[37]**.

WAPS-Suction Wings

Suction wings are a variant of rigid sail technology that incorporates active boundary layer control systems, using internal pumps or blowers to draw air through porous surfaces or slots on the suction side of the aerofoil. This active flow control delays flow separation, allowing the wing to achieve higher lift coefficients than passive rigid sails, though not as high as Flettner rotors **[32]**. The operational profile of suction wings is theoretically promising, yet the technology remains largely in the research and development phase with limited commercial deployment, which introduces significant uncertainty regarding its long-term reliability and safety **[38]**.

The primary hazard associated with suction wings is the potential failure of the active suction system; if the pumps fail while the wing is operating at high angles of attack, the airflow would suddenly separate, causing a stall that results in a rapid loss of propulsion and the generation of severe unsteady loads **[38]**. Additionally, the mechanical complexity of the ducting and pump systems increases the maintenance burden, and there is a risk that the marine environment could cause clogging of the suction slots with salt or debris, thereby degrading aerodynamic performance and compromising safety **[32]**.

WAPS-Rigid Wing Sails

Rigid wing sails, also known as wing sails, are fixed or articulated aerofoil structures constructed from steel, light alloys, or composites, designed to generate thrust through aerodynamic lift with high efficiency. Modern designs often feature automated trimming systems and may employ advanced profiles, such as crescent shapes or multi-element configurations, to optimise performance, achieving lift-to-drag ratios significantly higher than other wind propulsion technologies **[31, 39]**.

However, the large surface area and structural rigidity of these sails present distinct safety challenges. They are subject to significant unsteady aerodynamic loads, particularly flow separation effects and tip vortices, which can induce fatigue damage over the vessel's operational life **[39]**. Similar to Flettner rotors, rigid sails impose air-draft constraints that require reliable folding or retraction mechanisms for passing under bridges or entering ports; failure of these mechanisms constitutes a major operational hazard **[40]**. Furthermore, the inability to instantly "depower" a rigid structure during sudden storm conditions necessitates robust furling systems, as inadequate stowage during extreme weather can lead to catastrophic structural damage or dangerous heeling moments **[41, 31]**.

Solar Photovoltaic (PV) Panels

Solar photovoltaic (PV) panels in maritime applications are typically installed on available deck space to provide auxiliary electrical power, offering a complementary renewable energy source that can be integrated with other propulsion technologies. While standalone installations generally yield modest emission reductions of 2–5%, hybrid configurations combining solar with wind or fuel cells have demonstrated significantly higher efficiency improvements **[42]**.

The characteristics of marine solar installations are defined by the need to withstand a harsh corrosive environment while minimising interference with cargo operations. The primary safety and operational hazards stem from the environmental conditions; salt spray, humidity, and wave impacts can degrade electrical connections and panel integrity, potentially leading to electrical faults or structural failure of the mounting systems **[42]**. Additionally, the variability of solar power generation due to weather and latitude changes necessitates complex power management and storage systems to ensure voltage stability and prevent disruptions to the ship's electrical grid **[42]**. The low energy density of current PV technology also means that large surface areas are required to generate meaningful power, which can compete with deck space needed for cargo or safety operations **[42]**.

1.3 Propeller designs

Pre-Swirl Fins

Pre-swirl Fins function as stationary fin assemblies mounted on the stern boss immediately upstream of the propeller, designed to introduce controlled pre-swirl into the propeller inflow and recover rotational energy from the slipstream. These devices typically consist of three to five fins arranged asymmetrically to address circumferential wake variations caused by hull geometry and shaft inclination, thereby modifying the velocity distribution in the propeller disc plane to better match blade loading **[43, 44]**.

While mechanically straightforward compared to more complex energy-saving devices, the modification of inflow distribution introduces specific hydrodynamic hazards; poorly matched stator geometry can shift cavitation inception conditions or alter cavitation extent, potentially worsening hub or tip cavitation if interaction effects are not properly evaluated **[45]**. Furthermore, while optimised designs reduce wake harmonics, suboptimal configurations may increase vibratory forces at certain frequencies, leading to structural fatigue or passenger discomfort. The performance of these systems is also highly sensitive to scale effects, with observed differences between model-scale and full-scale cavitation behaviour necessitating conservative design approaches and validation through full-scale trials **[45]**.

Gate Rudder

Gate rudder systems represent distinct evolutionary paths in rudder design aimed at recovering rotational energy and improving propeller-rudder interaction. The rudder-bulb-fin combination typically features a twisted leading edge to align with local flow, a streamlined bulb to eliminate hub vortices, and horizontal fins to generate thrust from rotational flow, collectively offering efficiency improvements of approximately 2.3–3.3% **[46]**.

In contrast, the gate rudder system employs asymmetric wing sections flanking the propeller to create a duct effect, potentially yielding higher energy savings of 7–8% while improving manoeuvrability **[47]**. However, the aggressive modification of the flow field by these devices introduces significant risks; the gate rudder's location can adversely affect the propeller flow field, increasing the risk of cavitation and noise problems if not properly integrated **[47]**. For rudder bulbs, the primary hazard involves the concentration of stresses at fin-rudder connections and the potential for cavitation-induced erosion on the bulb or fins if the geometry creates adverse pressure gradients **[46]**. Additionally, gate rudder systems suffer from a lack of correlation data between model tests and full-scale performance due to their recent development, introducing uncertainty regarding their behaviour in extreme conditions or during manoeuvres **[47]**.

Post-swirl PBCF (Propeller Boss Cap Fins)

Propeller Boss Cap Fins (PBCF) consist of small fins attached to the propeller boss cap, equal in number to the propeller blades, designed to weaken or eliminate the hub vortex and recover rotational kinetic energy. This device has been widely adopted due to its ability to improve efficiency by 3–5% while simultaneously eliminating hub vortex cavitation, which reduces noise and the risk of rudder erosion **[48]**.

Despite these benefits, the installation of fins on the rotating boss cap introduces specific structural and hydrodynamic hazards. The fins impose additional centrifugal loads and bending moments on the boss cap structure, requiring rigorous fatigue analysis to ensure integrity over millions of revolution cycles **[48, 49]**. Furthermore, while the PBCF mitigates hub vortex cavitation, it modifies the pressure field in the hub region, which can alter blade loading distributions and potentially induce new cavitation sites on the inner portions of the propeller blades or on the fins themselves if not properly optimised using computational fluid dynamics **[50, 48]**.

Pre-swirl ESD Wake Equalizing Ducts (WEDs)

Pre-swirl ESD Wake Equalizing Ducts (WEDs), such as the Mewis duct, utilise a duct structure combined with inner fins positioned upstream of the propeller to regularise the wake flow and

reduce harmonic content. By making the axial wake flow more uniform, these devices reduce the angle of attack variation experienced by propeller blades, leading to more stable loading, improved efficiency of 6–8%, and reduced ship stern vibration **[51, 52]**.

However, the performance of wake equalising ducts is critically dependent on precise installation parameters, such as axial position and fin angle; turbulent changes in the wake flow field caused by poor design can paradoxically increase noise and exciting forces on the propeller **[51]**. Structural integrity poses a significant safety consideration, as the duct must withstand hydrodynamic loads and potential impacts; failure of the duct or its supports could result in contact with the propeller, leading to catastrophic damage **[51]**. Additionally, the duct surfaces themselves are prone to cavitation erosion and marine fouling, which can degrade performance and structural integrity over time if not regularly inspected and maintained **[52]**.

Propeller-Retrofitting Advanced propeller Blade Sections

Propeller retrofitting involves the replacement or modification of existing propellers with optimised designs, often incorporating advanced features like New Profile Technology (NPT) or Contracted and Loaded Tip (CLT) designs to match specific hull wake fields. This approach requires comprehensive hull-engine-propeller matching analysis, as changes to propeller characteristics alter the loading curve and must be compatible with engine operating characteristics to avoid off-design penalties **[53, 52]**. While well-designed retrofits can achieve efficiency improvements of 3–7%, they introduce risks related to structural compatibility and vibration; without proper validation, retrofit propellers can shift cavitation patterns in ways that increase hull pressure fluctuations or cause blade surface erosion **[44, 49]**. Furthermore, interaction effects between the hull wake, propeller, and any added devices are complex, and failure to account for these system-level interactions can lead to realised benefits falling short of predictions or even introducing operational penalties **[53]**.

Propeller Nozzle

Propeller nozzles, or ducts, are annular foil-shaped structures surrounding the propeller that generate additional thrust through lift forces, particularly for heavily loaded propellers operating at low advance ratios. While these devices can contribute significantly to total thrust and reduce vibration by constraining the propeller slipstream, their operation is associated with specific hydrodynamic hazards **[54, 55]**.

A primary risk is "thrust breakdown," a phenomenon where thrust suddenly decreases under heavy cavitation conditions, which can be dangerous during critical manoeuvres **[54]**. The duct itself is susceptible to cavitation on its surfaces, particularly at the leading edge or inner surface, leading to erosion and performance degradation **[54]**. Structurally, the duct must withstand significant steady

and unsteady hydrodynamic loads, and the maintenance of adequate radial clearance between the propeller tips and the duct is critical; contact due to shaft deflection or hull deformation could result in severe damage and loss of propulsion **[55]**.

Post-swirl Contra Rotating Propeller

Post-swirl Contra-Rotating Propeller (CRP) systems utilise two propellers mounted in tandem on concentric shafts rotating in opposite directions to recover the rotational energy lost in the slipstream of the forward propeller. This configuration offers substantial efficiency gains of 8–15% and can reduce propeller-induced pressure fluctuations and cavitation due to improved load distribution **[56, 57]**.

However, CRP systems introduce the highest level of mechanical complexity and associated hazards among energy-saving devices, requiring specialised epicyclic gearing or concentric shafting that increases the risk of mechanical failure **[56]**. A critical safety hazard is the risk of contact between the forward and aft propellers due to misalignment, shaft deflection, or bearing failure, which could cause catastrophic damage to the propulsion system **[56]**. Furthermore, the complex unsteady interaction between the two propellers requires careful design to avoid exciting hull structural modes, and the specialised components impose demanding maintenance requirements and the need for specific spare parts availability **[56, 57]**.

1.4 Operations

Cargo Handling Systems

Cargo handling systems encompass a diverse range of equipment and operational procedures tailored to specific vessel types, ranging from derrick rigs and deck cranes on conventional vessels to sophisticated pipeline networks on tankers. For liquid cargo operations, maintaining specific operational parameters is critical; for instance, crude oil pipelines are generally limited to flow velocities of 12 m/s, while light petroleum products are restricted to 7-8 m/s to mitigate safety risks **[58]**.

Chemical tanker operations are particularly complex, requiring stringent controls for loading, discharging, and tank washing due to the high toxicity and reactivity of the cargoes carried **[59]**. While modern systems increasingly incorporate automation to enhance efficiency, the primary hazards remain deeply rooted in physical and human factors. Fire and explosion risks are paramount, particularly regarding the generation of static electricity in pipelines if flow velocities exceed safe limits in explosive atmospheres **[58]**. Furthermore, chemical tankers face severe health hazards, classified on a 0-4 scale, where exposure to toxic substances can cause profound systemic injury or

death **[59]**. Crucially, human error remains a dominant risk factor, often stemming from high workloads and fatigue, which necessitates rigorous human reliability analysis and ergonomic engineering to prevent accidents resulting from error-fault chains **[59, 60]**.

Just-In-Time (JIT) arrival strategies

Just-In-Time (JIT) arrival is an operational efficiency strategy designed to transition maritime logistics from a "sail-fast-then-wait" model to a "sail-slow-and-save" paradigm, aimed at minimising port waiting times and reducing emissions **[61]**. This system relies on the precise coordination of vessel speed with berth availability, requiring sophisticated communication between ship and shore to optimise arrival windows.

While the potential for emission reduction is significant, the implementation of JIT arrival is fraught with commercial and legal hazards, particularly within voyage-chartered bulk shipping. The legal obligation of "due dispatch" in charter parties often conflicts with the intentional speed reduction required for JIT, creating liability risks for shipowners if delays occur **[61]**. Additionally, operational risks arise from inaccurate port information or sudden changes in berth availability, which can negate efficiency gains or result in commercial penalties. There are also safety implications, as the pressure to meet precise arrival slots may influence decision-making during adverse weather conditions or complicate crew fatigue management due to extended voyage durations **[61]**.

Weather Routing systems for voyage speed/fuel optimization

Weather routing systems utilise advanced computational fluid dynamics (CFD) and seakeeping analysis to optimise vessel routes and speeds based on high-resolution meteorological forecasts, aiming to minimise fuel consumption while ensuring vessel safety **[62]**. Modern systems integrate genetic algorithms to identify optimal paths, potentially offering fuel savings of roughly 4.9% when safety constraints are not the primary limiter **[62]**.

However, the pursuit of efficiency introduces distinct hazards related to environmental forces; without rigorous safety criteria, optimal routes may expose the vessel to dangerous slamming events, excessive roll, and high vertical accelerations that jeopardise hull integrity and cargo safety. Consequently, incorporating necessary safety constraints—such as limiting significant heave to 3.5 metres—may necessitate routes that consume more fuel and require longer transit times, highlighting an inherent trade-off between efficiency and safety **[62]**. Furthermore, the reliance on data-driven models introduces operational risks related to forecast accuracy, where errors in weather prediction can lead to suboptimal or hazardous routing decisions **[62]**.

Slow Steaming

Slow steaming operates on the cubic relationship between vessel speed and power requirements, where a reduction in speed yields disproportionately large fuel savings, potentially reducing consumption by up to 25% **[63]**. This practice varies from continuous slow steaming to flexible or super slow steaming, often requiring engine derating or operation with reduced numbers of engines to maintain efficiency.

Despite its effectiveness in fuel conservation, slow steaming introduces significant technical and operational hazards. Prolonged operation of main engines at low loads can lead to incomplete combustion, cylinder fouling, and reduced turbocharger efficiency, necessitating adjusted maintenance schedules and engine monitoring **[63]**. From a safety perspective, reduced speeds can compromise vessel manoeuvrability and increase stopping distances, which poses risks in high-traffic areas or adverse sea conditions. Additionally, extended voyage times exacerbate crew fatigue management challenges and expose the vessel to weather conditions for longer durations, potentially impacting cargo quality for time-sensitive shipments **[63]**.

Propeller-Retrofitting Advanced Propeller Blade Sections

Controllable Pitch Propeller (CPP) systems provide the operational flexibility to adjust propeller blade pitch to match varying loads and speeds, enabling the engine to maintain optimal efficiency across diverse conditions **[64]**. Advanced control strategies have evolved from static "combinator" curves to dynamic set point control, which continuously optimises the pitch and engine settings to reduce fuel consumption and emissions **[65]**.

However, the mechanical complexity of CPP systems introduces specific technical hazards not present in fixed-pitch propellers. The hydraulic systems governing blade pitch operate in harsh environments subject to vibration and pressure fluctuations, where failure can lead to a loss of pitch control and subsequent engine overload or loss of propulsion **[66]**. Furthermore, improper pitch settings, whether due to control system malfunction or operator error, can induce severe cavitation, leading to noise, vibration, and erosion of the blades and rudder **[67]**. The transition to dynamic control also increases the complexity of fault diagnosis, requiring sophisticated monitoring systems to track parameters such as shaft vibration and hydraulic pressure to prevent catastrophic failures **[66]**.

Trim and Draft Optimisation

Trim and draft optimisation involves the strategic adjustment of a vessel's floating position to minimise hydrodynamic resistance, recognised as one of the most cost-effective efficiency

measures with potential fuel savings of 0.5% to 5% **[63]**. This process utilises computational models or empirical data to recommend the optimal trim for a given displacement and speed, often requiring only standard ballast systems for implementation.

Despite its simplicity, improper execution of trim optimisation presents operational and safety hazards. Excessive trim can severely affect vessel stability and handling characteristics; for instance, significant forward trim increases the risk of slamming in head seas and can compromise bridge visibility **[63]**. Conversely, excessive aft trim may reduce bow freeboard, increasing the likelihood of deck wetness and green water ingress. Additionally, the alteration of longitudinal weight distribution affects hull structural loads, particularly bending moments, which must remain within design limits to prevent structural damage, especially in dynamic sea conditions **[63]**.

Propeller Performance Monitoring

Propeller performance monitoring systems are designed to continuously assess propeller efficiency by analysing data streams such as shaft torque, RPM, and thrust, facilitating the early detection of fouling or damage **[68]**. These systems allow operators to transition from fixed-interval maintenance to condition-based interventions, optimising the timing of cleaning to maintain hydrodynamic efficiency **[69]**.

The primary hazard associated with these systems lies in data quality and interpretation. Accurate assessment requires sophisticated filtering and correction for environmental factors like wind and waves; inadequate data processing can lead to false alarms regarding performance degradation or, conversely, the failure to detect actual issues **[70]**. Furthermore, reliance on defective sensors or improper calibration can result in erroneous performance indicators, leading to unnecessary maintenance costs or prolonged operation with degraded efficiency **[70]**. The complexity of analysing time-series data necessitates robust data handling infrastructure to ensure that the monitored parameters accurately reflect the physical condition of the propeller **[71]**.

Hull Monitoring

Hull monitoring systems function in parallel with propeller monitoring to assess the condition of the hull surface, specifically targeting resistance increases caused by biofouling and coating degradation **[72]**. By adhering to standards such as ISO 19030, these systems utilise operational data to track performance indicators, enabling the evaluation of coating systems and the optimisation of drydocking intervals **[73]**.

The operational impact of fouling is substantial, with heavy slime potentially increasing effective power requirements by over 30%, and calcareous fouling by over 100% **[73]**. However, technical

hazards arise from the difficulty of isolating hull resistance from other resistance components, such as air resistance and added resistance in waves. Inaccurate assessments can lead to inappropriate maintenance decisions; specifically, unsupervised or aggressive hull cleaning triggered by monitoring data can damage hull coatings, thereby accelerating future fouling and corrosion **[63]**. Consequently, the effectiveness of hull monitoring is heavily dependent on the precision of data analysis algorithms and the expertise of personnel interpreting the performance trends **[70]**.

1.5 Hydrodynamics improvements

Air Lubrication Systems

Air Lubrication Systems (ALS) function as a hydrodynamic drag reduction technology by injecting air bubbles into the boundary layer beneath a vessel's hull, thereby creating a thin air film that separates the hull's wetted surface from direct water contact. This mechanism, which can be implemented through active compressor-based systems or passive designs utilising natural pressure differentials, has demonstrated the potential to reduce viscous drag by up to 90% in laboratory settings and approximately 15-23% in full-scale applications **[74, 75, 76]**.

However, the operational viability of ALS is heavily constrained by environmental and technical hazards. The system's effectiveness is highly sensitive to sea states, where rough conditions can disrupt the stability of the air layer, potentially negating energy savings. Furthermore, the physical installation of interceptors required for passive systems adds approximately 5% to the bare hull resistance, creating a performance threshold that must be overcome to achieve net savings **[74]**. A significant operational risk arises when integrating ALS with alternative propulsion methods like hydrogen fuel cells, as the air generation process can cause load fluctuations that may lead to "starvation" events and damage sensitive fuel cell components **[76]**. Additionally, the technology entails high initial investment and operating costs, with economic returns remaining doubtful across a vessel's entire speed range **[77]**.

Bulbous Bow Optimization

Bow enhancement technologies, encompassing traditional bulbous bows and advanced designs like the Ulstein X-bow, are engineered to modify wave patterns and improve seakeeping performance. Bulbous bows are widely adopted to reduce wave-making resistance, particularly for inland and fishing vessels operating at specific speeds, while the inverted Ulstein X-bow design gently breaks waves to reduce pitch and heave motions, offering up to 11% resistance reduction **[78, 79]**.

Despite these hydrodynamic benefits, bow enhancements introduce distinct structural and operational hazards. In severe weather conditions, the interaction between the bow and waves can induce sharp pressure drops leading to the formation of large cavitation caverns; the subsequent collapse of these caverns generates destructive hydrodynamic loads capable of causing catastrophic structural failure **[80]**. Furthermore, the performance of bulbous bows is highly condition-dependent, creating a risk where a design optimised for one operational profile causes increased resistance under different loading conditions or speeds **[79]**. Modifications such as the X-bow may also require alterations to vessel length to maintain displacement, which can negatively impact manoeuvrability, a critical factor for fishing and offshore support operations **[78]**.

Hull Surface Coatings & Low-Drag Paints

Hull surface coatings & low-drag paints are essential for minimising skin friction and preventing biofouling, which can otherwise significantly increase power requirements. FDR-AF coatings utilising self-polishing copolymers with polyethylene glycol methacrylate have demonstrated the ability to reduce skin friction by up to 25% in laboratory tests and achieve approximately 11.7% power savings in full-scale applications **[81]**.

However, the application and long-term maintenance of these coatings present significant environmental and operational hazards. Historically, coatings containing tributyltin were banned due to toxicity, and even modern biocide-free or controlled-release formulations face scrutiny regarding their environmental impact and regulatory compliance **[82]**. Structurally, these coatings are susceptible to degradation; FDR-AF layers have been observed to peel off or suffer damage after prolonged service or berthing impacts, which compromises their drag-reducing properties **[81]**. Furthermore, the selection of an inefficient coating system for a specific route can lead to rapid biofouling growth, resulting in severe penalties in fuel consumption and greenhouse gas emissions **[82]**.

Optimisation of Water Flow Hull Openings

The optimisation of water flow hull openings focuses on minimising the hydrodynamic disturbances caused by through-hull penetrations, such as bow thruster tunnels, which are critical for manoeuvrability but create significant resistance. Computational Fluid Dynamics (CFD) analysis is employed to refine tunnel geometries and manage the interaction of protective grids, which are often the primary source of drag in these assemblies **[83]**.

While optimising these openings can reduce resistance—crucial for high-speed vessels where even minor drag penalties translate to substantial fuel costs—the process involves navigating complex safety and performance trade-offs. The protective grids, while detrimental to hydrodynamic

performance, are essential for preventing debris ingress that could damage thruster mechanisms; removing or altering them to improve flow can increase the risk of mechanical failure **[83]**. Additionally, for multi-hull vessels like fast catamarans, bow thruster openings can interfere with the complex flow field between demi-hulls, potentially amplifying resistance penalties in ways that are difficult to predict without advanced simulation **[84]**.

Lightweight shipbuilding materials

Lightweight shipbuilding materials leverages advanced materials, specifically carbon fibre composite sandwich structures, to achieve dramatic reductions in hull weight, thereby enhancing speed, payload capacity, and fuel efficiency. These structures, often composed of carbon fibre face sheets bonded to lightweight cores, offer high stiffness-to-weight ratios and have demonstrated excellent energy absorption capabilities during impact tests **[85]**.

However, the transition to these lightweight materials introduces unique safety and maintenance hazards compared to conventional steel construction. Despite their energy absorption properties, super light vessels remain vulnerable to catastrophic structural damage from major collisions with rocks or offshore structures, as the material behaviour differs significantly from ductile metals **[85]**. Fire safety is a critical concern, as the polymer matrices in composites can release toxic fumes and degrade rapidly at elevated temperatures. Furthermore, the long-term durability of these materials in marine environments is less proven, with risks of stiffness degradation due to moisture absorption or delamination, and repairs require specialised skills and facilities that may not be readily available **[85]**.

Aft-ship replacement (Inland)

Aft-ship replacement is a retrofitting strategy for inland waterway vessels involving the modification or complete replacement of the stern section to improve hydrodynamic performance and accommodate modern propulsion systems. This approach allows aging fleets to meet stricter environmental regulations and improve propulsive efficiency without the capital cost of newbuilding, utilising CFD to optimise flow in the aft region for shallow water operations **[86, 87]**.

The execution of such major structural modifications, however, carries significant technical and operational risks. The structural integration of a new stern with an existing hull requires precise engineering to avoid stress concentrations and ensure continuity, while poor hydrodynamic compatibility between the forward and aft sections can lead to flow separation and propeller cavitation **[87]**. Operational hazards are magnified by the restricted nature of inland waterways; changes to draft, trim, or manoeuvring characteristics resulting from the retrofit must be rigorously validated to ensure the vessel can safely navigate narrow channels and locks **[88]**.

Variation of Block Coefficient/Lengthening (Inland)

Variation of the block coefficient and vessel lengthening are fundamental optimisation strategies for inland vessels aimed at balancing cargo capacity with hydrodynamic efficiency. Increasing the block coefficient allows for greater deadweight within the strict dimensional limits of inland waterways, while vessel lengthening can reduce the length-to-beam ratio effect on resistance **[89]**.

These modifications, particularly for river-sea vessels, utilise parametric modelling to find optimal hull forms. However, these geometric changes introduce inherent hazards regarding seakeeping and stability. A high block coefficient, while beneficial for cargo volume, generally degrades seakeeping performance, leading to excessive pitch and heave motions that can be dangerous when river-sea vessels operate in coastal waters **[89]**. Furthermore, lengthening a vessel fundamentally alters its manoeuvring characteristics, typically increasing the turning radius, which poses a safety risk in confined inland waterways requiring frequent sharp turns. There is also a risk of structural discontinuity and increased longitudinal bending moments, necessitating careful reinforcement of the hull girder **[89]**.

1.6 Optimised engineering approach

Reduced Auxiliary Power Demand

The reduction of auxiliary power demand represents a foundational strategy in marine energy efficiency, primarily achieved through the systematic replacement of energy-intensive equipment with higher-efficiency alternatives such as LED lighting systems and high-efficiency motors. The integration of these technologies contributes to the overall vessel energy efficiency by lowering the base electrical load, which subsequently allows for more optimised operation of diesel generators and minimises the necessity for parallel generator operation during low-demand periods. When combined with other optimisation measures, such as variable frequency drives, the reduced baseline power demand can facilitate single diesel generator operation during sea-going conditions, maximising economic and environmental benefits **[90]**.

Despite the generally lower risk profile of these technologies compared to propulsion modifications, the transition to reduced auxiliary power systems introduces specific operational hazards related to the reliability of electronic components in harsh marine environments. LED driver electronics are susceptible to failure when exposed to vibration, humidity, salt spray, and temperature extremes, potentially leading to sudden lighting loss in critical areas. Furthermore, the electronic drivers

utilised in low-energy equipment can introduce harmonics into the ship's electrical system, posing a risk to sensitive navigation and communication equipment if power quality is not comprehensively assessed and filtered.

Variable Frequency Drive (VFD) for speed control

Auxiliary systems optimisation, particularly through the deployment of Variable Frequency Drives (VFD) for engine room ventilation fans and central seawater cooling pumps, allows for precise control of motor speed to match actual operational demand rather than running continuously at full capacity. Recent studies indicate that VFD-based process flow control can achieve significant reductions, with documented savings of 18.3% in annual energy consumption and 20.3% in diesel generator fuel consumption, while also providing benefits such as soft-starting capabilities and enhanced load shedding in complex applications like FPSO units **[90, 91]**.

However, the implementation of VFD technology introduces distinct electrical and mechanical hazards that must be managed to maintain system stability. The power electronic components within VFD systems can generate harmonic distortion that may overheat transformers and cables, while the interaction between multiple VFDs can create resonance conditions amplifying these frequencies. Mechanically, motors operated at low speeds via VFDs may suffer from reduced cooling fan effectiveness leading to thermal stress, and high-frequency switching can induce bearing currents that accelerate wear and precipitate unexpected motor failures. Moreover, control system failures in these critical auxiliary systems could result in the loss of essential cooling or ventilation, necessitating robust redundancy and fail-safe design features.

Main Engine Improvements

Modern main engine improvements rely on the synergistic integration of common-rail fuel injection, electronic engine control, and advanced engine tuning to enhance combustion efficiency and operational flexibility. Common-rail systems distinguish themselves from traditional injection by maintaining fuel at high pressures independent of engine speed, enabling precise control over injection timing and duration, while electronic control systems utilise sensor data to optimise parameters like turbocharger boost and exhaust gas temperatures in real-time **[92, 93]**.

While these technologies improve performance, they significantly elevate operational hazards due to the physical conditions required for their operation. The high-pressure fuel systems, often exceeding 2000 bar, create substantial risks of fuel leakage that can lead to fire and explosion hazards within the confined engine room space **[92]**. Additionally, the compatibility of these precision systems with sustainable fuels presents an emerging hazard; variations in fuel properties can affect injection performance and component durability, potentially leading to increased wear

and safety incidents if engine parameters are not appropriately adjusted **[94]**. Furthermore, the reliance on electronic control introduces cybersecurity vulnerabilities and complex failure modes, where a single sensor malfunction could lead to incorrect engine parameter adjustments, necessitating comprehensive failure mode, effects, and criticality analysis (FMECA) particularly for dual-fuel operations **[95]**.

Advanced HVAC & cooling systems

Improvements in HVAC and cooling systems are characterised by the adoption of absorption chillers and low-temperature energy recovery technologies, which utilise waste heat from engines to provide cooling, thereby drastically reducing electrical power consumption. Shipborne absorption refrigeration systems, often utilising water-lithium bromide or ammonia-water pairs, can reduce the electrical power demand for cooling by over **99%** compared to conventional compression systems, and are increasingly integrated with ice thermal storage to manage load fluctuations **[96, 97]**.

However, the operation of these systems introduces chemical and thermodynamic hazards unique to their working fluids and cycles. Ammonia-based systems present toxicity and flammability risks that require specialised detection and emergency procedures, while lithium bromide systems are prone to crystallisation if solution concentrations and temperatures are not strictly controlled, potentially blocking flow passages. A critical operational hazard involves thermal management and the potential for negative heat balance; relying solely on exhaust gas boilers during sea voyages can lead to insufficient steam generation or the need to cool condensate to prevent cavitation in boiler feed pumps, potentially compromising system reliability **[98]**.

Waste heat recovery systems (WHRS)

Waste Heat Recovery (WHR) systems that capture thermal energy from exhaust gases and cooling systems to generate steam or electricity via Rankine or organic Rankine cycles (ORC). These systems, including dual-pressure steam configurations and high-pressure exhaust gas recirculation (HP-EGR) integration, are capable of delivering fuel savings between 4% and 15% by maximising thermodynamic efficiency **[99, 100]**.

Despite their maturity, these systems are subject to significant operational hazards driven by the extreme conditions under which they operate. The continuous variation in engine loads induces thermal cycling and fatigue in heat exchangers and piping, which can lead to crack initiation and structural failure **[101]**. High-temperature and high-pressure steam leaks pose severe safety risks to personnel, while the internal environment of exhaust gas economisers is susceptible to sulfuric acid dew point corrosion. Furthermore, ORC systems introduce specific hazards related to organic

working fluids, many of which are flammable or toxic, requiring substantial safety equipment and precise control to prevent fluid degradation or freezing in condensers **[102, 103]**.

1.7 Summary

Table 3 below summarises the typical features and risks of various alternative EETs in maritime applications:

Table 3. Technical Characteristics and Hazard Analysis across Seven Categories

Technology	Typical Characteristics	Hazards
Fuel Cells	• **H_2 FC**: Zero-emission (PEMFC), uses compressed H_2; produces water byproduct. • **SOFC**: High efficiency, fuel flexible (LNG, Methanol), high operating temp (600-1000 °C). • **Ammonia FC**: Carbon-free, easier storage than H_2.	• **Explosion**: H_2 has wide flammability range (4-75%) and low ignition energy; leaks accumulate in upper spaces. • **Toxicity**: Ammonia is highly toxic and corrosive. • **Thermal**: Failure of thermal management in high-temp SOFCs causes stress/damage.
Alt. Fuels ICEs	• **Dual-Fuel**: Operates on gas (LNG) or liquid fuels; flexibility to switch based on availability. • **Efficiency**: Thermal efficiency comparable to diesel; significant NOx/SOx reduction.	• **Methane Slip**: Unburned methane contributes to GHG. • **Cryogenic/Toxic**: LNG requires -162°C storage (burns/asphyxiation); Ammonia/Methanol are toxic. • **Failure Modes**: Combustion instability and knocking.
PTI / PTO	• **Bidirectional**: Motor/Generator modes on shaft. • **Efficiency**: Utilises main engine for electricity (PTO) or aux engines for propulsion (PTI).	• **Mechanical**: Vibration, misalignment, and bearing failures due to coupling. • **Electrical**: Fault propagation to main switchboard; blackout risk from voltage instability.
Energy Storage Systems (ESS)	• **Li-ion**: High energy density; used for peak shaving, spinning reserve, and hybrid propulsion. • **Response**: Rapid load response, enables optimal engine loading.	• **Thermal Runaway**: Self-accelerating exothermic reaction leading to fire/explosion. • **Toxic Gas**: Release of HF, CO during fire. • **Seawater**: Immersion causes short circuits and H_2 generation.

Waste heat recovery systems (WHRS)	• **Recovery**: Captures exhaust/cooling heat (300-500 °C) for power. • **Efficiency**: Improves plant efficiency by 5-15%.	• **High Temp/Pressure**: Burn hazards, fire risk from leaks on hot surfaces. • **Complexity**: Increased engine room complexity and maintenance points.
Exhaust Gas Economizer	• **Steam Gen**: Uses exhaust gas to generate steam/hot water for ship services. • **Integration**: Located after turbocharger; reduces aux boiler use.	• **Soot Fire**: Accumulation of soot can ignite, causing rapid temp spikes. • **Corrosion**: Sulfuric acid dew point corrosion. • **Pressure**: Risk of steam leaks and vessel failure.
Onshore Power Supply (OPS)	• **Grid Connect**: Supplying shore power to ship while berthed to cut port emissions. • **High Voltage**: Typically 6.6 kV or 11 kV requiring frequency conversion.	• **Shock/Arc Flash**: High voltage handling risks during connection/disconnection. • **Grounding**: Potential for circulating currents and bonding issues affecting cathodic protection.
Hydrogen	• **Density**: High gravimetric but low volumetric energy density. • **Storage**: Compressed (350-700 bar) or Liquid (-253 °C).	• **Flammability**: Widest range (4-75%), extremely low ignition energy (0.019 mJ). • **Embrittlement**: Damages containment materials. • **Invisible Flame**: Hard to detect fires.
Methanol	• **Liquid**: Ambient storage, energy density ~3.3 kWh/L. • **Handling**: Uses existing liquid fuel infra with minor mods.	• **Toxicity**: Severe systemic effects (blindness/death) via ingestion/absorption. • **Vapor**: Heavier than air, travels to ignition sources. • **Fire**: Burns with invisible flame.
Ammonia	• **Carbon-free**: Zero CO_2 combustion. • **Storage**: Liquid at -33.4 °C or 10 bar; easier than H_2.	• **Toxicity**: Severe acute toxicity; IDLH at 300 ppm. • **Environment**: Highly soluble, aquatic toxicity if spilled. • **Combustion**: High NOx generation requiring abatement.
Biofuels	• **Compatibility**: Drop-in replacement for diesel/gasoline. • **Origin**: Derived from biomass; potentially lower lifecycle GHG.	• **Variable Properties**: Diverse chemical composition affects toxicity profiles. • **Environment**: Aquatic toxicity varies; oxidation stability issues.
LOHC (H_2 carrier)	• **Stability**: Liquid at ambient T/P (e.g., DBT); non-flammable storage.	• **Dehydrogenation**: Requires high temp (>200 °C) and catalysts to release H_2, reintroducing flammability risks at point of use.

	• **Transport**: Uses existing oil infrastructure.	• **Complexity**: Chemical processing required onboard.
Ammonia (H_2 carrier)	• **Density**: Higher volumetric H_2 density than liquid H_2. • **Infra**: Established global distribution network.	• **Cracking**: Requires energy/equipment to crack back to H_2. • **Leakage**: Large-scale transport increases potential for massive toxic release.
Methane (Syn/Bio)	• **Mature**: Established LNG infrastructure and safety protocols. • **Properties**: Cryogenic liquid or compressed gas.	• **Methane Slip**: High GWP if unburned gas escapes. • **Cryogenic**: LNG spill causes rapid phase transition, pool fires, and brittle fracture.
Ethanol	• **Liquid**: Ambient storage, water miscible. • **Toxicity**: Moderate (CNS depression), lower than methanol.	• **Flammability**: Flash point ~13 °C; requires alcohol-resistant foam for firefighting. • **Spills**: Soluble in water, difficult to contain.
Flettner Rotors	• **Magnus Effect**: Spinning vertical cylinders generate lift. • **Output**: 5-20% fuel savings; optimized at 1.0-3.0 spin ratio.	• **Structure**: High unsteady aerodynamic loads/vibration. • **Air Draft**: Clearance issues under bridges requiring tilting mechanisms. • **Stability**: Heeling moments in strong winds.
Kite propulsion systems	• **High Altitude**: Harvests stronger winds (150-800 m^2 kites). • **Dynamic**: Figure-8 flight path for max force.	• **Tether**: High tension (snapback risk), failure during launch/recovery. • **Control**: Loss of automated control leads to instability. • **Ops**: Restricted use in storms/light wind.
Suction Wing	• **Active Control**: Suction on aerofoil delays separation, increasing lift. • **Efficiency**: Higher lift coef. than passive sails.	• **System Failure**: Pump failure causes stall and sudden load loss. • **Maintenance**: Suction slots clogging with salt/debris. • **Maturity**: Low operational experience (R&D phase).
Rigid Wing Sails	• **Aerofoils**: Fixed/articulated wings (steel/composite). • **Performance**: High lift-to-drag ratio (~50); 9-30% savings.	• **Wind Load**: High structural stress; requires feathering/folding in storms. • **Visibility**: Large surface area can obstruct bridge view. • **Mechanisms**: Folding system failure risks.
SOLAR - Photovoltaic (PV) Panels for Ships	• **PV**: Photovoltaic arrays on deck for aux power. • **Output**: 2-5% emission reduction; weather dependent.	• **Environment**: Salt spray/corrosion degrades connections. • **Space**: Competes with cargo/deck space; susceptible to wave impact. • **Electrical**: Integration complexity with ship grid.

Pre-swirl Fins	• **Inflow Mod**: Stationary fins upstream of prop adjust wake. • **Gains**: 4-6% efficiency by recovering rotational energy.	• **Cavitation**: Poor design shifts cavitation inception, risking erosion. • **Vibration**: Suboptimal fin matching increases hull excitation forces.
Gate Rudder	• **Bulb**: Streamlined bulb with fins eliminates hub vortex. • **Gate**: Asymmetric twin rudders create duct effect (7-8% savings).	• **Structural**: Stress concentration at fin-rudder connections. • **Interaction**: Gate rudders may adversely affect prop inflow if misaligned. • **Erosion**: Cavitation risk on bulb/fins.
Post-swirl ESD PBCF (Propeller Boss Cap Fins)	• **Vortex**: Small fins on boss cap eliminate hub vortex. • **Efficiency**: 3-5% gain; reduced torque, increased thrust.	• **Structural**: Centrifugal loads on fins; fatigue failure risk. • **Cavitation**: May induce new cavitation roots on blade roots if not optimised. • **Installation**: Misalignment causes vibration.
Pre-swirl ESD Wake Equalizing Ducts (WEDs)	• **Flow Straightening**: Duct (e.g., Mewis) upstream regularises wake. • **Performance**: 6-8% savings; reduces vibration.	• **Drag**: Added resistance penalty if poorly positioned. • **Impact**: Risk of duct contacting propeller if supports fail. • **Erosion**: Duct surface cavitation.
Propeller-Retrofitting Advanced propeller Blade Sections	• **Optimization**: Replacing props with NPT/CLT designs for specific hull wake. • **Matching**: 3-7% gain via better hull-engine match.	• **Off-design**: Altered loading may mismatch engine map. • **Vibration**: New designs may shift cavitation patterns, increasing noise. • **Fatigue**: Blade root stress changes.
Propeller Nozzle	• **Nozzle**: Annular foil increases thrust for heavy loads (tugs). • **Thrust**: 20-30% gain at low speeds; protects blades.	• **Thrust Breakdown**: Sudden thrust loss under heavy cavitation. • **Cavitation**: Erosion on duct inner surface. • **Clearance**: Tip contact risk due to shaft deflection.
Post-swirl ESD Contra-rotating propellers (CRP)	• **Tandem**: Two props rotating in opposite directions on coaxial shafts. • **Efficiency**: 8-15% gain by recovering slipstream rotation.	• **Complexity**: High mechanical risk (gearing, bearings, seals). • **Contact**: Risk of prop-to-prop contact due to misalignment. • **Vibration**: Complex interaction pulses.

Cargo Handling Systems	• **Ops**: Loading/discharging logic specific to vessel (bulk/liquid). • **Safety**: Strict flow limits (12 m/s crude) to prevent static.	• **Human Error**: Fatigue/error leading to accidents. • **Static/Fire**: Explosion risk in liquid transfer. • **Stability**: Overloading causes hull stress/loss of seaworthiness.
JIT (Just In Time)	• **Optimisation**: "Sail-slow-and-save" to match berth availability. • **Goal**: Minimises port waiting time and emissions.	• **Commercial**: Charter party disputes (due dispatch vs. slow steaming). • **Safety**: Pressure to meet slots in bad weather; fatigue from longer voyages.
Weather Routing Systems	• **Avoidance**: Uses forecasts/CFD to optimise route/speed. • **Savings**: ~5% fuel saving; avoids storm damage.	• **Stability**: Parametric rolling/slamming if safety criteria ignored for efficiency. • **Data**: Reliance on inaccurate forecasts.
Slow Steaming	• **Law**: Cubic reduction in fuel vs. speed (up to 25% savings). • **Modes**: Continuous or flexible engine derating.	• **Engine**: Low-load fouling, turbocharger inefficiency, soot deposits. • **Manoeuvre**: Reduced steerage way/stopping power. • **Cargo**: Spoilage of time-sensitive goods.
Propeller Pitch Optimisation (CPP)	• **Dynamic**: Adjusts pitch/RPM to match load/sea state. • **Control**: Moving from combinator curves to dynamic setpoints.	• **Hydraulic**: Leakage/failure leads to loss of control. • **Overload**: Improper pitch overloads engine (thermal stress). • **Cavitation**: Off-design pitch induces face/back cavitation.
Trim and Draft Optimisation	• **Hydrodynamics**: Adjusts ballast for optimal floating position. • **Benefit**: 0.5-5% savings; low cost implementation.	• **Stability**: Excessive trim reduces stability/freeboard. • **Structure**: Increased longitudinal bending moments/shear forces. • **Slamming**: Forward trim increases bow slamming risk.
Prop Performance Monitoring	• **Analytics**: Tracks torque/thrust to detect fouling/damage. • **Condition**: Enables condition-based maintenance.	• **Data Error**: Inaccurate environmental correction leads to false alarms. • **Sensor**: Torque gauge calibration drift.
Hull Monitoring	• **Fouling**: Tracks resistance increase (ISO 19030). • **Impact**: Heavy slime adds >30% power penalty.	• **Maintenance**: Aggressive cleaning triggered by data may damage coatings.

		• **Analysis**: Difficulty separating hull/prop/weather resistance components.
Air Lubrication System	• **Microbubbles**: Injecting air reduces viscous drag by 15-23%. • **Types**: Active (compressors) or Passive.	• **Instability**: Performance loss in rough seas; bubble washout. • **Interference**: Air layer affects acoustic sensors/propeller inflow. • **Fluctuation**: Load spikes can damage hybrid fuel cells.
Bulbous Bow Optimization	• **Bulbous**: Reduces wave resistance (4-11% savings). • **X-Bow**: Inverted bow reduces pitch/heave.	• **Slamming**: Cavitation caverns collapse causing structural damage in storms. • **Manoeuvrability**: Extension may affect turning/docking. • **Range**: Penalties at off-design speeds/drafts.
Hull Coatings	• **Low Friction**: FDR-AF/Nanotech reduces drag by ~10-25%. • **Antifouling**: Self-polishing prevents roughness increase.	• **Environment**: Biocide/microplastic release concerns. • **Durability**: Peeling/damage from impact degrades performance. • **Application**: Sensitivity to humidity/temp during application.
Hull Openings Optimisation	• **Flow**: Optimising thruster tunnels/grids. • **Drag**: Reducing turbulence from penetrations.	• **Blockage**: Removing grids risks debris damaging thrusters. • **Structural**: Optimisations may weaken hull continuity. • **Interference**: Complex flow interaction in catamarans.
Lightweight shipbuilding materials	• **Composite**: Carbon fibre sandwich structures reduce weight. • **Capacity**: Increased payload/speed via weight savings.	• **Fire**: Resin matrix flammable/toxic fumes; rapid strength loss. • **Impact**: Brittle failure modes; hidden delamination damage. • **Repair**: Specialised skills required; difficult to repair at sea.
Aft-ship Replacement	• **Retrofit**: Replacing stern for better flow/propulsion (Inland). • **Efficiency**: Adapted for shallow water dynamics.	• **Integration**: Structural discontinuity stresses at join. • **Hydro**: Mismatch with forebody causing flow separation. • **Stability**: Change in LCG/buoyancy affects trim.
Block Coefficient /Lengthening	• **Capacity**: Maximize cargo (High C_b) or length for inland locks. • **Efficiency**: Lengthening reduces resistance-to-displacement ratio.	• **Seakeeping**: High C_b degrades pitch/heave response in coastal water. • **Strength**: Increased longitudinal bending moments. • **Handling**: Reduced manoeuvrability (turning radius).
Reduced Aux Power	• **Load Reduction**: LED lighting, high-eff motors reduce baseload.	• **Harmonics**: Electronic drivers introduce grid distortion. • **Reliability**: LED driver failure in vibration/heat.

	• **Ops**: Enables single generator operation at sea.	• **Emergency**: Backup power compatibility issues.
Variable Frequency Drive (VFD) for speed control	• **Variable Speed**: VFDs match pump/fan speed to demand. • **Savings**: ~20% fuel reduction; soft start capability.	• **Thermal**: Motor overheating at low speeds (reduced cooling). • **Electrical**: Harmonic distortion; bearing currents cause wear. • **Control**: VFD failure risks loss of critical cooling.
M/E Improvements	• **Electronic Control**: Common rail, auto-tuning for efficiency. • **Flexibility**: Optimises injection for varying loads/fuels.	• **Leakage**: High-pressure fuel (2000 bar) fire risk. • **Cyber**: Control system vulnerability/sensor failure. • **Complexity**: Higher maintenance/diagnostic skill required.
Advanced HVAC & cooling systems	• **Absorption**: Waste heat (LiBr/Ammonia) creates cooling. • **Storage**: Ice thermal storage for peak shaving.	• **Chemical**: Ammonia toxicity/flammability; LiBr crystallisation. • **Balance**: Negative heat balance at low engine loads. • **Pressure**: Vacuum/pressure vessel failure risks.
Waste heat recovery systems (WHRS)	• **WHR**: Turbines/ORC recover exhaust heat for power (4-15% gain). • **EGR**: Integrated high-pressure exhaust recirculation.	• **Steam**: High pressure leaks (scalding/visibility loss). • **Fatigue**: Thermal cycling causes pipe/exchanger cracks. • **Water Hammer**: Improper condensate management damages piping.

2 Regulations, rules, standards and guidelines

2.1 Power conversion/Electrification/Energy devices

Existing regulations such as the IGC Code and SOLAS have clear limitations in that they do not sufficiently reflect the characteristics of new technologies such as hydrogen, ammonia, fuel cells, and hybrid power systems. Consequently, major classification societies have developed their own Rules and Guides regarding Direct Current (DC) distribution, hybrid/electric propulsion, fuel cells, and the use of alternative fuels (LNG, LPG, LFL) to ensure the safety and design of these technologies.

• ABS (2022) - 'Requirements for Direct Current (DC) Power Distribution Systems for Marine and Offshore Applications'

• ABS (2024) - 'Requirements for Hybrid and All-Electric Power Systems for Marine and Offshore Applications'

• ABS (2020) - 'Guide for Hybrid Electric Power Systems for Marine and Offshore Applications'

• ABS (2019) - 'Guide for Fuel Cell Power Systems for Marine and Offshore Applications'

• DNV (2020) - 'Rules for Classification: Ships – Part 6 Additional class notations'

• RINA (2024) – 'Rules for the Classification of Ships – Part C Machinery, Systems and Fire Protection'

• RINA (2024) – 'Rules for the Classification of Ships – Part F Additional Class Notations'

2.1.1 Ship Design and Arrangement

Table 4 categorises critical design elements ranging from space layout and zoning to specific connection stations, highlighting the necessity of rigorous safety standards when adopting technologies like fuel cells, alternative fuel engines, shaft generators, and energy storage systems. A primary focus across these technologies is the mitigation of fire and explosion risks through strict physical separation and containment strategies. For instance, spaces housing fuel cells or batteries generally must be located aft of the collision bulkhead to minimise impact risks. Furthermore, the boundaries of these high-risk compartments, particularly those facing machinery spaces, control stations, or escape routes, require A-60 class fire integrity to prevent thermal propagation and ensure the safety of essential ship functions.

The arrangement of fuel containment and piping systems for alternative fuels such as LNG, hydrogen, and ammonia is governed by stringent geometric constraints to protect against collision and grounding damage. Fuel tanks must be positioned at a minimum distance of either B/5 or 11.5 metres, whichever is less, from the ship's side, and at least B/15 or 2.0 metres from the bottom shell. To prevent the migration of hazardous gases into safe zones, a minimum separation distance of 900 mm is required for cofferdams between fuel tanks and Category A machinery spaces. Additionally, piping systems routed through enclosed spaces must utilise double-walled constructions with dedicated gas-tight ducts, maintaining a minimum distance of 800mm from the shell to protect against external impact. These structural requirements extend to the ventilation design, where fuel preparation rooms and tank connection spaces must maintain a high ventilation rate of at least 30 air changes per hour (ACH) to ensure rapid dilution of any leaked gases.

Mechanical and electrical integration presents its own set of challenges, particularly for hybrid systems involving Shaft Generators (PTI/PTO) and Energy Storage Systems (ESS). For shaft generators, the design must account for substantial hydrodynamic propeller loads, requiring alignment calculations that extend to 30% of the MCR torque downward bending moment. Redundancy is a critical factor; vessels with Redundant Propulsion notations must separate these systems with A-60 bulkheads to ensure that a single fire or flooding event does not incapacitate the entire propulsion capabilities. Similarly, battery installations require specialised compartment safety designs to manage thermal runaway risks. This includes positioning exhaust duct intakes less than 400 mm from the ceiling to effectively capture buoyant off-gases and ensuring that doors are normally closed and self-closing. The thermal management of these spaces is further complicated on passenger ships, where battery rooms are strictly prohibited adjacent to essential emergency generator rooms or muster stations to protect passengers during evacuation scenarios.

Finally, Table 4 addresses the external interfaces and operational continuity of the vessel, specifically regarding WHR and OPS systems. WHR integration requires careful design of the exhaust uptake to prevent backpressure and soot accumulation, necessitating fail-safe fire dampers and relief valves that discharge at least 3 metres away from working areas. For shore power connections, the design must prevent ignition sources by locating connection points at least 1.5 metres away from hazardous zone boundaries and ensuring watertight integrity through hull doors. Underlying all these design considerations is the Safe Return to Port (SRtP) capability, which mandates that systems must be restorable within one hour using manual actions and must possess sufficient fuel and energy capacity to maintain a speed of 6 knots for 72 hours or the maximum duration of the voyage. This holistic approach ensures that the adoption of advanced energy efficiency technologies does not compromise the fundamental safety and seaworthiness of the vessel.

Table 4. Ship Design & Arrangement Matrix for Power Conversion EETs

Design Element	EET	Key Characteristics/ Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements/Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Space Layout & Zoning	**Fuel Cells** (PEM, SOFC)	**Hazards:** Hydrogen accumulation in ceilings, fire spreading to adjacent spaces, toxic gas (if ammonia). **Focus:** Simple geometrical shape to avoid gas pockets, gas-tight boundaries.	ABS FC Guide DNV Pt.6 Ch.2 Sec.3 RINA Pt. C	Prescriptive requirements for "Gas Safe" machinery spaces for Ammonia are newly developed (IMO CCC 11).	**Location:** Must be aft of collision bulkhead. **Boundaries: A-60 class** fire integrity required for boundaries facing machinery, control, or accommodation spaces. **Geometry:** Simple ceiling shape sloping up towards ventilation outlet to prevent gas pockets. **Separation:** Independent access (air locks) required if not on open deck.	**Passenger Ships:** Strict prohibition of direct access from accommodation spaces. **Ro-Ro/Ferries:** Protection from vehicle collision damage required for pipes on open decks.	**Arrangement:** Finding space for fuel preparation rooms that allows direct access to open deck. **Ventilation:** Deducting large volumes of air for negative pressure maintenance without affecting HVAC balance.
Tank & Piping Arrangement	**Alt. Fuels ICEs** (LNG/LPG/ H_2/NH_3)	**Hazards:** Cryogenic spill (hull fracture), toxic vapour dispersion, high-pressure gas rupture. **Focus:** Tank location (B/5), double-walled piping routing, cofferdams.	DNV Pt.6 Ch.2 Sec.5 (LNG) DNV Pt.6 Ch.2 Sec.6 (LFL)	LH_2 carriers require specific vacuum insulation arrangement and vent mast analysis which are distinct from LNG. TCE (Tank Connection Enclosure)	**Tank Distance:** Min **B/5 or 11.5 m** from ship side; **B/15 or 2 m** from bottom shell. **Cofferdams:** Min **900mm** separation between fuel tanks and high fire risk spaces. **Piping:** Distance from shell min **800 mm**.	**Tankers:** Fuel storage tanks cannot be located in the double bottom or adjacent to cargo tanks with incompatible cargoes. **Offshore Supply:** Aft/Fore peaks cannot be used as cofferdams.	**Structural Integration:** Integrating vacuum-insulated tanks (Type C) for H_2 which are significantly larger than LNG tanks. **Routing:** Routing double-walled piping through accommodation spaces requires dedicated gas-tight ducts.

				concepts for H_2 are new.	**Airlocks:** Min deck area **1.5m²**; door spacing **1.5m to 2.5 m**.		
Machinery Space Layout	**PTI / PTO** (Shaft Generator)	**Hazards:** Mechanical failure impacting propulsion, vibration transmission to hull. **Focus:** Shaft alignment, gear box integration, maintenance access.	ABS Hybrid Guide DNV Pt.6 Ch.2 Sec.10	Retrofitting PTI/PTO on existing vessels often faces space constraints around the main engine and shaft line.	**Alignment:** Shaft alignment calculations must account for hydrodynamic propeller loads (extended to **30% MCR** torque downward bending moment). **Redundancy:** For RP (Redundant Propulsion) notation, systems must be separated by **A-60** bulkheads to ensure one system survives fire/flooding.	**Single Screw Vessels:** Requires careful arrangement to ensure "Take Me Home" capability if main engine fails. **Ice Class:** Higher vibration/shock load standards for shaft components.	**Space:** Accommodating the large footprint of the shaft generator and frequency converter drive cabinets in the engine room. **Coupling:** Ensuring access for maintenance of clutches/couplings.
Compartment Safety	**ESS**	**Hazards:** Thermal runaway fire, explosive off-gas accumulation. **Focus:** Dedicated battery rooms, explosion relief, separation from heat sources.	ABS Hybrid Guide DNV Pt.6 Ch.2 Sec.1	Lack of standardised "Safe Return to Port" design criteria specifically for battery-only propulsion regarding compartment flooding.	**Location:** Aft of collision bulkhead. **Fire Safety: A-60** insulation towards machinery/cargo spaces. **Doors:** Normally closed, self-closing doors required. **Ventilation:** Exhaust duct intake **< 400 mm** from ceiling; Inlet near floor.	**Passenger Ships:** Prohibited from locating battery spaces adjacent to essential emergency generator rooms or muster stations. **Offshore:** ESS often placed in containers on deck; requires specific impact protection.	**Thermal Management:** Arranging cooling ducts and off-gas ducts (explosion relief) to open air without passing through other safe zones. **Access:** Ensuring safe egress routes for crew in case of gas release.

Exhaust & Ducting	**WHR / Exhaust Gas Economiser**	**Hazards:** Backpressure affecting engine, soot fire in uptake, high temperature surfaces. **Focus:** Uptake arrangement, bypass dampers, maintenance space.	ABS Marine Vessel Rules DNV Pt.6 Ch.2 Sec.4 RINA Pt. F	Complex integration with scrubbers or SCR systems within the limited funnel casing space.	• **Separation:** Combustion chambers and uptakes must be designed to prevent gas accumulation. • **Dampers:** Fire dampers must be fail-safe (close on loss of power). • **Venting:** Relief valves must discharge to safe locations (min **3 m** from working areas).	**Cruise Ships:** Funnel design is aesthetic but limits space for WHR boilers and bypass ducts. **LNG Carriers:** Integration with Gas Combustion Units (GCU) in the funnel stack.	**Volume:** WHR systems require significant volume in the engine casing; retrofits are often structurally difficult. **Support:** Structural reinforcement required for heavy boiler/economiser units high up in the ship.
Connection Station	**OPS**	**Hazards:** Cable handling, water ingress, arc flash at connection point. **Focus:** Location of Cable Management System (CMS), hull door arrangement.	ABS Hybrid Guide 3/35 DNV Pt.6 Ch.2 Sec.9 RINA Pt. F	Standardisation of connection location relative to varying port infrastructure (bow vs. stern vs. side).	• **Location:** Connection point must not face hazardous area boundaries (min **1.5 m** separation from hazardous zones). • **Ingress:** Hull doors/openings must maintain watertight integrity. • **Drainage:** Drip trays/drainage required to prevent water accumulation in connection locker.	**Container Ships:** Connection often required at specific container bays; impacts cargo loading capacity. **Tankers:** Connection station usually located aft of accommodation to avoid hazardous cargo zones.	**Routing:** High voltage cable routing from the ship's side connection point to the main switchboard (often deep in the ship) requires dedicated, protected cable ways.

2.1.2 Material

For hydrogen fuel cells and piping systems, the primary concern is the prevention of hydrogen embrittlement, which mandates the use of Austenitic Stainless Steel, specifically grade 316L, or equivalent materials that have been verified through ISO 11114-4 testing if data is unavailable. Conversely, ammonia systems require strict material compatibility controls due to the fuel's corrosivity; the use of Copper, Zinc, Cadmium, or their alloys is strictly prohibited in wetted parts to prevent rapid degradation and toxic leakage.

Cryogenic containment for alternative fuels like LNG and Liquid Hydrogen (LH_2) imposes rigorous standards on piping and structural materials to prevent brittle fracture at temperatures as low as -163 °C and -253 °C, respectively. Table 5 specifies that for design temperatures below -55 °C, only welding neck flanges are permitted, as slip-on or socket weld flanges pose a higher risk of leakage due to differential thermal contraction. Furthermore, secondary enclosures for these liquefied fuels must be constructed from materials capable of withstanding the cryogenic fluid temperature—down to -165°C for LNG—in the event of a primary barrier failure. For Liquid Hydrogen, the requirements are even more stringent, often necessitating vacuum-insulated piping where both inner and outer pipes are fully welded and verified for resistance to hydrogen embrittlement.

In the domain of mechanical power transmission, particularly for Shaft Generators (PTI/PTO), material selection is driven by the need to resist fatigue failure caused by torsional vibration and high torque loads. Table 5 highlights that aft propeller shaft bearings must generally be composed of a white metal alloy with tin (Sn) as the major constituent rather than lead-based alloys, particularly for shafts exceeding 400mm in diameter, to ensure superior fatigue strength under variable propulsion modes. Similarly, exhaust gas economisers and waste heat recovery systems face challenges related to high-temperature oxidation and sulfuric acid corrosion. For vessels fitted with scrubbers, discharge outlets require special acid-resistant coatings or high-grade stainless steel with a minimum pipe thickness of 15mm to resist the corrosive effects of acidic wash water. Electrical systems, including Energy Storage Systems (ESS) and OPS connections, require materials that ensure fire safety and conductivity. Battery enclosures must be constructed of steel or equivalent incombustible materials, and all system components must be flame-retardant in accordance with IEC 60092-101 to contain potential thermal runaway events. For shore power connections, the focus shifts to preventing galvanic corrosion and oxidation; plugs and connectors must often utilise silver or gold plating to ensure reliable conductivity, while outdoor enclosures require stainless steel or plastic construction rated to IP66 standards to withstand the marine environment. Across all these systems, proper electrical bonding is essential, with a maximum resistance requirement of 1 MΩ (10^6 Ohm) between piping or tanks and the hull to prevent static buildup and potential ignition. Finally, structural fire protection remains a universal requirement, with A-60 class

insulation materials mandated for boundaries of high-risk spaces such as fuel cell rooms and battery compartments.

Table 5. Material Design & Selection Matrix for Power Conversion EETs

Design Element	EET	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Fuel Piping & Containment	**Fuel Cells** (Hydrogen/ Ammonia)	**Hazards:** Hydrogen embrittlement (H_2), corrosivity to Copper/Zinc (NH_3), high temperature reforming. **Focus:** Material compatibility with specific molecule types.	ABS Fuel Cell Guide 2/2.2 DNV Pt.6 Ch.2 Sec.3 KR Fuel Cell Guide 204 RINA Pt. C	Qualification of new composite materials for high-pressure hydrogen storage. Standardisation of polymer liners for Type IV tanks.	**Hydrogen:** Materials must be resistant to hydrogen embrittlement (e.g., Austenitic Stainless Steel **316L**). ISO 11114-4 testing required if data is unavailable. **Ammonia:** Materials must not contain Copper, Zinc, Cadmium, or their alloys. Rubber/plastic must be verified. **Reformed Fuel:** Piping must be Austenitic Stainless Steel (e.g., 304, 316, 304L, 316L).	**Ro-Pax/Ferries:** Use of lightweight composite tanks to reduce displacement. **Gas Carriers:** Boil-off gas piping materials must match cargo tank specs.	**Compatibility:** Ensuring all downstream components (valves, seals, gaskets) are compatible with Ammonia to prevent toxic leaks. **Purity:** Preventing material leaching that could poison the fuel cell catalyst.
Cryogenic Containment	**Alt. Fuels ICEs** (LNG/LPG/ H_2)	**Hazards:** Brittle fracture at cryogenic temps (-163°C LNG, -253°C H2), thermal contraction stress. **Focus:** Charpy impact values, thermal expansion coefficients.	DNV Pt.6 Ch.2 Sec.5 (LNG) DNV Pt.6 Ch.2 Sec.6 (LFL)	Extremely limited material choices for Liquid Hydrogen (LH_2) due to -253°C requirement (mostly limited to specific Stainless Steels).	**Piping (-55°C limit):** For design temps < -55°C, only welding neck flanges allowed. **Piping (-165°C limit):** Secondary enclosures for liquefied fuel must withstand down to -165°C (LNG).	**LH_2 Carriers:** Vacuum insulation space requires specific materials to prevent outgassing and maintain vacuum stability. **LPG Tankers:** Tanks often use low-temperature carbon manganese steel (down to -50°C).	**Insulation:** Vacuum insulation materials must withstand oxygen-enriched environments (due to air condensation) in LH_2 systems. **Joints:** Minimising flanged connections to prevent leakage due to differential thermal contraction.

					H_2 Piping: Vacuum insulated pipe inner/outer pipes must be **fully welded** and verified for hydrogen embrittlement.		
Shaft & Bearings	**PTI / PTO** (Shaft Generator)	**Hazards:** Fatigue failure from torsional vibration, wiping of bearing material. **Focus:** Bearing alloy composition, shaft fatigue strength.	ABS Marine Vessel Rules Pt.4 Ch.3 DNV Pt.6 Ch.2 Sec.10	High-power PTI modes impose different torque characteristics than standard propulsion, affecting shaft material fatigue life.	**Bearing Material:** Aft propeller shaft bearings must be white metal alloy with tin (Sn) as the major constituent (Tin-based > Lead-based) for superior fatigue strength. **Shaft:** Material tensile strength determines the allowable stress (K factor) in alignment calculations.	**Ice Class Vessels:** Shaft materials must have higher toughness (Charpy V-notch) to withstand ice impact loads. **Single Screw:** Higher reliability required for bearing materials to prevent wiping.	**Lubrication:** Oil compatibility with bearing materials (especially environmentally acceptable lubricants - EALs). **Load:** Bearing material must withstand localised pressure peaks during turning operations.
Casing & Enclosure	**ESS**	**Hazards:** Thermal runaway containment, electrolyte corrosion, fire propagation. **Focus:** Flame retardancy, ingress protection (IP).	ABS Lithium-ion Battery Requirements DNV Pt.6 Ch.2 Sec.1	Standards for composite materials in battery casings to delay thermal propagation are still evolving.	**Fire Resistance:** Battery system materials must be flame-retardant. **Enclosure:** Enclosures must be constructed of steel or equivalent incombustible material. **Cooling:** Piping materials for liquid cooling must be corrosion-resistant and compatible with the coolant to prevent leakage.	**All Electric Ferries:** Weight reduction drives the use of aluminium/composite racks, requiring careful fire insulation application.	**Propagation:** Materials between modules/cells must prevent thermal propagation (thermal barrier materials like aerogels or mica). **Gas Tightness:** Ducting materials must withstand off-gas temperatures during failure.

Exhaust & Ducting	**WHR / Exhaust Gas Economiser**	**Hazards:** High-temperature oxidation, sulfuric acid corrosion (dew point), thermal cycling. **Focus:** Heat resistance, corrosion allowance.	ABS Marine Vessel Rules DNV Pt.6 Ch.2 Sec.5 RINA Pt. F	Material degradation when operating with new fuels (e.g., ammonia combustion byproducts) is not fully characterised.	**Piping:** Exhaust gas piping must be arranged to avoid accumulation of unburned gas (requires smooth internal surfaces). **Joints:** Expansion bellows must be prototype tested for fatigue and material durability. **Explosion Relief:** Bursting discs must be of specific yield strength material to rupture at precise pressures.	**Scrubber-fitted vessels:** Discharge outlets require special coating/materials (e.g., high-grade stainless or GRE) to resist acidic wash water (pH ~3).	**Corrosion:** Selecting materials for the "cold end" of the economiser to resist sulfuric acid corrosion if exhaust temps drop below dew point.
Connection Points	**Onshore Power Supply (OPS)**	**Hazards:** Galvanic corrosion, environmental degradation (salt mist), conductor oxidisation. **Focus:** Plating materials, insulation quality.	ABS Hybrid Guide 3/35 RINA Pt. F	Standardisation of contact materials to prevent fretting corrosion during long-term connection.	**Contacts:** Plugs/connectors must be labelled and listed for purpose (often involves silver/gold plating for conductivity). **Cables:** Insulation materials must be flame retardant and low smoke zero halogen (LSZH) in enclosed spaces. **Housing:** Socket/Inlet enclosures must be IP rated (e.g., IP66 for exterior) using marine-grade stainless steel or plastic.	**Container Ships:** Cable management systems (CMS) use drag chains requiring high-wear resistant polymers. **Tankers:** Ex-rated connectors required.	**Bonding:** Equipotential bonding conductors must be of sufficient cross-section and material (Copper) to handle fault currents.

2.1.3 Bunkering

The Bunkering and Charging Design Standards Matrix establishes a robust framework for the safe transfer of energy to vessels, addressing the distinct hazards associated with alternative fuels like LNG, hydrogen, and ammonia, as well as high-voltage shore connection systems.

The design of bunkering stations prioritises location and containment to mitigate risks such as toxic gas dispersion and cryogenic spills. Open deck locations are preferred to facilitate natural ventilation; however, when enclosed stations are necessary, they require mechanical ventilation systems capable of achieving at least 30 air changes per hour (ACH) to prevent the accumulation of hazardous vapours. Strict separation distances are enforced to protect vessel integrity and crew safety, with requirements that air intakes and openings be located at least 10 metres away from LNG hazardous zones and 3 metres from fuel cell outlets. Furthermore, structural protection measures, such as stainless steel drip trays with thermal insulation and water spray curtains, are mandated to shield the hull from brittle fracture caused by potential cryogenic leaks.

The transfer systems and piping arrangements are governed by rigorous pressure and material standards to prevent leaks during the high-risk bunkering operation. Bunkering lines typically require a design pressure of not less than 20 bar, while transfer hoses must withstand burst pressures of at least five times their working pressure. Operational safety is further reinforced through the requirement for double-walled piping, inerting arrangements for purging before and after transfer, and the use of dry-disconnect couplings that feature safety dry break-away capabilities. Control systems are integral to this process, necessitating an Emergency Shutdown (ESD) system linked between the ship and the shore facility. This system must be capable of closing automatic shutdown valves within a maximum of 5 seconds in the event of an emergency, supported by high-level alarms that trigger at 95% tank capacity to prevent overfilling.

For hybrid and all-electric vessels, Table 6 details specific safety protocols for electrical charging and OPS to manage hazards such as arc flashes and cable tension rupture. A critical safety feature is the equipotential bonding requirement where the earthing pole must be the "First to make, Last to break" during connection and disconnection procedures. Systems must also include automatic mechanisms to de-energise cables if they come under excessive tension or rupture. For offshore support vessels utilising dynamic positioning while charging, compliance with DPS-1 notation is required to ensure station-keeping reliability. Fire safety measures are specifically tailored to the chemical properties of the fuel; for instance, low flashpoint liquids like methanol require fixed fire extinguishing systems using Alcohol Resistant Aqueous Film Forming Foam (ARAFFF) with an application rate of 10 l/min/m², alongside specialised UV/IR flame detectors to identify invisible alcohol fires.

Table 6. Bunkering & Charging Design Matrix for Power Conversion EETs

Design Element	EET	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Bunkering Station Location	**Fuel Cells / Alt. Fuels ICEs** (LNG/LPG/ H_2/NH_3)	**Hazards:** Gas dispersion, pool fire, cryogenic spill, toxic release (Ammonia). **Focus:** Natural ventilation, separation from air intakes, drip trays.	ABS FC Guide 3/9.2 DNV Pt.6 Ch.2 Sec.5 [5.3] DNV Pt.6 Ch.2 Sec.6 [3.6] RINA Pt. C	Detailed toxicity zones for Ammonia bunkering are still under development (IMO CCC 11 draft). Standardisation of coupling interfaces for Hydrogen.	**Location:** Open deck preferred. Enclosed stations require mechanical ventilation (30 ACH). **Separation:** Air intakes/openings must not face the connection. **Spill Protection:** Stainless steel drip trays with thermal insulation required.	**Passenger Ships:** Bunkering station must not be visible/accessible to passengers; strict visibility analysis required. **Tankers:** Bunkering station located in cargo area simplifies hazardous zone management.	**Arrangement:** Ensuring sufficient natural ventilation to prevent gas accumulation. **Shielding:** Water spray curtains required for hull protection against cryogenic spills (LNG/LH_2).
Transfer System & Piping	**Fuel Cells / Alt. Fuels ICEs**	**Hazards:** Static electricity, trapped liquid expansion, hose rupture. **Focus:** Double-walled piping, inerting, self-draining lines.	ABS FC Guide 3/9.3 DNV Pt.6 Ch.2 Sec.5 [5.3.2] IMO News Flash (CCC 11) RINA Pt. C	Vacuum insulation failure scenarios for Liquid Hydrogen transfer lines (air condensation/ oxygen enrichment).	**Hoses:** Burst pressure min 5 times working pressure. **Inerting:** Arrangement for purging/gas-freeing required before/after transfer. **Valves:** Manually operated stop valve + Remote shutdown valve in series.	**Bunkering Vessels:** require specialised manifolds and emergency release couplings (ERC).	**Thermal Management:** Piping flexibility to handle thermal contraction (-163°C for LNG, -253°C for LH_2). **Identify:** All ammonia piping must be colour-coded/marked.

Control & Safety	**Fuel Cells / Alt. Fuels ICEs**	**Hazards:** Overfilling, breakaway during transfer, vapour return failure. **Focus:** Emergency Shutdown (ESD), tank level monitoring.	ABS FC Guide 3/9.6 DNV Pt.6 Ch.2 Sec.5 [5.3.3] KR FC Guide 506 RINA Pt. C	Unified standards for digital handshaking (ESD link) between ship and shore for new fuels like Hydrogen.	**ESD Time:** Shutdown valve closing time max 5 seconds. **Couplings:** Dry-disconnect type with safety dry break-away coupling. **Alarms:** High level (95%) and High-High level (shut-off) required.	**Gas Carriers:** Bunkering control often integrated with cargo control system.	**Integration:** Linked ESD systems between ship and bunker facility/truck. **Interlocks:** Prevention of operation if ventilation or inert gas pressure fails.
Electrical Charging (Connection)	**ESS / Onshore Power Supply** (Hybrid/All-Electric)	**Hazards:** Arc flash, cable tension rupture, phase sequence error. **Focus:** Cable Management System (CMS), equipotential bonding.	ABS Hybrid Requirements 3/35 ABS DC Power Guide 3/7 DNV Pt.6 Ch.2 Sec.1 RINA Pt. F	Standardisation of automated mooring and charging plugs for offshore charging stations.	**De-energisation:** Automatic means to de-energise if cable is under tension/rupture. **Contact:** Earthing pole must be "First to make, Last to break". **Interlock:** Cannot energise unless pilot loop confirms connection.	**Ferries:** Automated plug-in systems required for short turnaround times. **Offshore Support:** Dynamic Positioning (DP) capability required to maintain station during offshore charging.	**Handling:** Heavy high-voltage cables require mechanical handling systems (CMS). **Safety:** Prevention of drive-off while connected (interlock with propulsion).
Fire Safety	**Methanol / Ethanol / LFL**	**Hazards:** Invisible flame (Methanol), re-ignition, solubility in water. **Focus:** Alcohol-resistant foam, flame detection.	ABS FC Guide 4/3.4 DNV Pt.6 Ch.2 Sec.6 [4.3] RINA Pt. C	Optimisation of firefighting media for Ammonia (toxicity vs. flammability).	**Fixed System:** Alcohol Resistant Aqueous Film Forming Foam (ARAFFF) required for bunkering station.	**Ro-Pax:** Bunkering stations often recessed into side shell; requires specific deluge/foam coverage.	**Detection:** Smoke detectors combined with IR/UV flame detectors (essential for invisible alcohol fires).

					Portable: Dry chemical powder extinguisher (5 kg min) located near entrance. **Coverage:** Foam application rate 10 l/min/m² (horizontal).		

2.1.4 Fuel supply systems

Table 7 establishes a comprehensive safety framework for the handling and distribution of alternative fuels, addressing the complex physical and chemical hazards associated with LNG, hydrogen, ammonia, and low flashpoint liquids like methanol. A fundamental requirement across these systems is the containment of high-pressure and hazardous fluids; piping routed through enclosed spaces, such as engine rooms, must invariably utilise a double-walled arrangement with mechanical under-pressure ventilation in the annular space capable of achieving at least 30 air changes per hour (ACH). To protect these critical supply lines from external impact, particularly in the event of a collision, the matrix mandates that fuel piping maintain a minimum distance of 800mm from the ship's side. Furthermore, structural integrity is prioritised through requirements for fully welded piping where practicable and automatic isolation mechanisms at tank boundaries to prevent uncontrolled fuel release.

The specific properties of emerging fuels necessitate distinct design mitigation strategies. For liquid hydrogen (LH_2), the extreme cryogenic temperature of -253°C requires vacuum-insulated piping to prevent liquid air condensation and oxygen enrichment on pipe surfaces, alongside vent outlets positioned at least 10 meters (or B/3) above the weather deck to facilitate safe dispersion. Conversely, ammonia systems focus heavily on toxicity management; unlike LNG, ammonia piping must be double-walled in machinery spaces regardless of the operating pressure, and direct venting is prohibited in favour of an Ammonia Release Mitigation System (ARMS) that treats vapours before discharge. Material compatibility is also strictly regulated, with copper, zinc, and cadmium prohibited in ammonia systems to prevent corrosion, while methanol systems require stainless steel wetted parts and dedicated, gas-tight pump rooms equipped with drip trays and independent ventilation.

Operational control and emergency response are governed by rigorous valve and detection standards. The fuel supply to consumers must be protected by a Double Block and Bleed (DBB) valve arrangement and a Master Gas Valve located outside the machinery space, with automatic shutdown valves required to close within a maximum of 5 seconds in the event of a fault. Safety thresholds are precisely defined, with gas detection systems triggering alarms at 20% of the Lower Explosive Limit (LEL) and initiating automatic shutdown at 40% LEL. To ensure vessel reliability, redundancy measures are enforced, such as the requirement for service tanks to hold a capacity for 8 hours of continuous rating for essential services, and for ventilation fans in hazardous spaces to maintain at least 50% capacity upon a single failure.

Table 7. Fuel Supply Systems Design Matrix for Power Conversion EETs

Design Element	EET	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Piping Arrangement & Containment	**Fuel Cells / Alt. Fuels ICEs** (LNG/LPG/ Methane)	**Hazards:** High-pressure gas leakage, fire/explosion, cryogenic embrittlement. **Focus:** Double-walled piping, ventilation of annular space, separation from safe zones.	DNV Pt.6 Ch.2 Sec.5 [5.1] DNV Pt.6 Ch.2 Sec.13 [5.1] KR Fuel Cell Guide Ch.2 RINA Pt. C	Complexity in retrofitting double-walled piping in existing tight engine rooms.	**Double-Wall:** Gas piping in enclosed spaces must be double-walled with annular space ventilation (30 ACH). **Distance:** Fuel piping min 800mm from ship side. **Isolation:** Automatic isolation at tank boundary required. **Welding:** Piping must be fully welded as far as practicable.	**Gas Carriers:** Cargo boil-off gas (BOG) can be used as fuel; requires specific compressor room safety. **Ro-Pax:** Piping passing through ro-ro spaces requires impact protection.	**Routing:** Avoid passing through accommodation/service spaces. If unavoidable, must use dedicated gas-tight ducts. **Flexibility:** Piping must absorb thermal contraction without excessive stress.
Fuel Preparation & Processing	**Fuel Cells** (Reformers)	**Hazards:** High temperature surfaces (> self-ignition temp), toxic byproducts, gas accumulation. **Focus:** Reforming equipment isolation, process control.	ABS Fuel Cell Guide 2/2.2 KR Fuel Cell Guide Ch.2 RINA Pt. C	Standardisation of "Ex" zones for high-temperature solid oxide fuel cells (SOFC) inside machinery spaces.	**Automation:** Reformers must operate automatically; manual operation not permitted. **Purging:** Automatic purging with inert	**Passenger Ships:** Strict noise and vibration limits for fuel prep machinery.	**Thermal Management:** Insulation required for surfaces > **220°C** (or fuel specific self-ignition temp). **Integration:** Reformer often integrated into the FC module, requiring complex hazardous area classification.

					gas required after shutdown. **Separation:** Fuel prep rooms must be gas-tight towards other spaces.		
Low Flashpoint Liquid Supply	**Alt. Fuels ICEs** (Methanol/ Ethanol)	**Hazards:** Toxicity (Methanol), corrosivity, invisible fire, low flashpoint (<60°C). **Focus:** Leak detection (liquid/vapour), pump segregation.	DNV Pt.6 Ch.2 Sec.6 [3.3] IMO IGF Code	Lack of unified standards for converting existing tanks (e.g., ballast tanks) to methanol storage due to coating compatibility.	**Pump Room:** Dedicated pump room required; must be gas/water-tight and vented (**30 ACH**). **Drip Trays:** Required below all possible leak points (valves, filters). **Connections:** Non-permanent connections (hoses) restricted; must use double barriers.	**Chemical Tankers:** Cargo can be used as fuel; requires segregation from other cargo systems. **Offshore Supply:** Fuel tanks prohibited in aft/fore peaks.	**Material:** Stainless steel required for wetted parts (no aluminium/galvanised steel). **Identification:** All LFL piping must be colour-marked.
Cryogenic & High Pressure Supply	**Hydrogen** (Liquefied/ Compressed)	**Hazards:** Hydrogen embrittlement, tiny molecule leakage, extreme cryogenic temp (-253°C), high pressure rupture. **Focus:** Vacuum insulation, vent mast location, material selection.	IMO News Flash (CCC 11 Draft Guidelines) ABS Fuel Cell Guide 3/4.3	Vacuum insulation failure scenarios leading to liquid air condensation/oxygen enrichment are critical safety gaps being addressed (Part D of Guidelines).	**Insulation:** Vacuum insulated piping required for LH_2 to prevent air condensation. **Venting:** Vent outlets must be **10m** (LNG) or higher from	**H_2 Carriers:** Boil-off management is critical (active cooling or usage). **Ferries:** Frequent bunkering cycles require robust coupling designs.	**Leakage:** H_2 leaks are hard to detect (odourless, invisible flame); requires specialised wide-spectrum sensors. **Joints:** Minimising flanged connections is critical to prevent leaks.

			DNV Pt.6 Ch.2 Sec.5 [4.2.16] RINA Pt. C		openings; specific dispersion analysis required for H_2. **Enclosure:** Tank Connection Enclosure (TCE) required for compressed H_2 valves, maintained under inert atmosphere.		
Toxic Fuel Supply	**Ammonia** (ICEs / Fuel Cells)	**Hazards:** High toxicity (fatal at low ppm), corrosivity to copper, low flammability. **Focus:** Toxic release mitigation, double-walled piping everywhere.	IMO News Flash (CCC 11 Draft Guidelines) KR Fuel Cell Guide RINA Pt. C	Determination of "Safe Haven" requirements for crew in case of massive ammonia release.	**Piping:** Gas-tight double-walled piping required in machinery spaces regardless of pressure (unlike LNG). **Release:** Ammonia Release Mitigation System (ARMS) required to treat vented gas; direct venting prohibited except in emergencies. **Material:** Prohibited materials: Copper, Zinc, Cadmium.	**Ammonia Carriers:** Cargo as fuel allowed; "Gas Safe" machinery space concept is mandatory.	**Detection:** Toxic gas detection takes precedence over flammable gas detection. **Purging:** Purge lines must be routed to the ARMS, not directly to the mast.

Valve & Isolation System	**All Fuels** (Gas/Liquid)	**Hazards:** Fuel uncontrolled flow, backflow, overpressure. **Focus:** Master Gas Valve, Double Block and Bleed (DBB).	ABS Fuel Cell Guide 4/4 DNV Pt.6 Ch.2 Sec.5 [5.1.6]	Reliability of fast-acting valves for high-pressure hydrogen service (embrittlement risk).	**Master Valve:** Automatic shut-off valve required outside the machinery space. **DBB:** Double Block and Bleed valve arrangement required for gas supply to consumers. **Closing Time:** Automatic shutdown valves must close within **5 seconds** (LNG/LFL).	**DP Vessels:** Valve failure must not cause total loss of propulsion (split fuel supply systems).	**Redundancy:** Single failure in the fuel supply system must not lead to unacceptable loss of power (requires redundant supply lines/tanks).

2.1.5 Fire safety

Table 8 establishes a comprehensive framework for protecting vessels utilising advanced power conversion technologies, emphasising the containment of high-risk hazards such as hydrogen jet fires, thermal runaway in batteries, and toxic smoke from alternative fuels. A cornerstone of this safety architecture is structural fire protection; boundaries of fuel cell spaces and battery rooms facing machinery spaces, control stations, or escape routes must be constructed with A-60 class divisions to prevent thermal propagation to essential vessel functions. This containment strategy is further reinforced by the requirement for automatic fail-safe fire dampers in ventilation ducts, which must close immediately upon fire detection to seal the space before any extinguishing agent is released. Additionally, high-risk zones such as fuel preparation rooms must be separated from other fire-risk spaces by a cofferdam with a minimum width of 900mm equipped with A-60 insulation.

Suppression strategies are tailored to the specific chemical and physical behaviours of the energy source. For Lithium-ion Energy Storage Systems (ESS), the primary objective is to manage thermal runaway and prevent re-ignition; consequently, water-based systems must be capable of discharging fresh water for 30 minutes to provide cooling, followed by a switch to sea water. If a gas-based extinguishing system is utilised for spaces with a capacity exceeding 100 kWh, regulations mandate two independent charges (2 x 100%) to ensure sufficient suppression capability remains after the initial discharge. In contrast, alternative fuels like methanol and ethanol require suppression media that address their solubility and invisible flames; fixed systems using Alcohol Resistant Aqueous Film Forming Foam (ARAFFF) are required for deck tanks, while bunkering stations must be equipped with dry chemical powder systems capable of discharging at a rate of 3.5 kg/s for a minimum of 45 seconds.

Detection and external cooling protocols are equally critical, particularly for fuels with invisible flames or high toxicity. Hydrogen installations necessitate the use of specialised UV/IR flame detectors combined with smoke and heat sensors to identify invisible fires instantly and trigger an automatic shutdown of fuel supply and ventilation. For external protection during fire events, water spray systems are mandated for cooling fuel tanks and bunkering stations, requiring an application rate of 10 l/min/m² for horizontal surfaces and 4 l/min/m² for vertical surfaces. These protective measures are integrated into the broader Safe Return to Port (SRtP) standards, which require that a fire be contained within its space of origin and that essential systems, such as fire mains and lighting, remain operational for 3 hours to support orderly evacuation scenarios.

Table 8. Fire Safety Design Matrix for Power Conversion EETs

Design Element	EET	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Structural Fire Protection	**Fuel Cells** (PEM, SOFC)	**Hazards:** High temperature surfaces (>300°C), hydrogen jet fire (invisible), explosive atmosphere. **Focus:** Containment of fire within the FC space to prevent spread to essential machinery.	ABS Fuel Cell Guide Section 4 DNV Pt.6 Ch.2 Sec.3 KR Fuel Cell Guide Ch.2 Sec.3 RINA Pt. C	Determining fire resistance for novel materials used in lightweight fuel cell modules. Lack of standardised testing for "internal" stack fires.	**Boundaries:** Fuel cell spaces must be separated by **A-60 class** divisions from machinery spaces of Category A, control stations, and escape routes. **Dampers:** Automatic fail-safe fire dampers required for ventilation ducts; must close before extinguishing release.	**Passenger Ships:** SRtP (Safe Return to Port) rules require that a fire in one FC space must not impair the redundancy of the propulsion system.	**Containment:** Designing the FC space to withstand a local gas explosion without affecting the integrity of adjacent spaces. **Isolation:** Minimizing penetrations in A-60 bulkheads.
Fire Extinguishing	**ESS**	**Hazards:** Thermal runaway (self-oxygenating fire), re-ignition, toxic off-gas, high heat release. **Focus:** Cooling capability (Water) vs. Oxygen displacement (Gas).	ABS Lithium-ion Battery Requirements ABS Hybrid Guide 3/29 DNV Pt.6 Ch.2 Sec.1	Determining the optimal extinguishing medium; water is best for cooling but damages equipment; gas requires sealing and may not stop thermal runaway propagation.	**Water-based:** System must discharge fresh water for **30 minutes** (then switch to sea water). **Gas-based:** If used, requires two independent charges (2 x 100%) for spaces with capacity ≥ 100 kWh. **Activation:** Fixed system must be suitable for the	**Ferries:** High energy density in small spaces increases thermal load; requires robust water-mist or deluge systems.	**Media Selection:** Balancing the need to cool the battery modules (prevent propagation) with the need to protect electrical components from water damage. **Release:** Automatic release of extinguishing agent for thermal propagation prevention.

					specific battery chemistry.		
Fire Suppression	**Alt. Fuels ICEs** (Methanol/ Ethanol/ LPG/NH_3)	**Hazards:** Invisible fire (Methanol), toxic smoke (Ammonia), pool fires, jet fires. **Focus:** Alcohol-resistant foam, dry chemical powder for bunkering.	ABS Fuel Cell Guide 4/3.4 DNV Pt.6 Ch.2 Sec.6 DNV Pt.6 Ch.2 Sec.5	Effective firefighting strategies for Ammonia are still under development due to toxicity of the smoke/vapour and reaction with water.	**Foam:** Fixed system with Alcohol Resistant Aqueous Film Forming Foam (ARAFFF) required for methanol tanks/bunkering on deck. **Powder:** Dry chemical powder system with capacity 3.5 kg/s for 45 seconds required for bunkering stations. **Water Spray:** Coverage of 10 l/min/m² (horizontal) and 4 l/min/m² (vertical) for cooling tanks/boundaries.	**Tankers:** Cargo deck foam system may cover fuel tanks if compatible. **Gas Carriers:** Integration with cargo fire protection systems.	**Detection:** Methanol fires are invisible; requires specialised UV/IR flame detectors. **Coverage:** Ensuring foam coverage reaches under tank structures and into spill trays.
Fire Detection	**Hydrogen** (Fuel Cells/ ICEs)	**Hazards:** Invisible flame, low ignition energy, rapid flame propagation. **Focus:** Specialised flame detectors, rapid response.	IMO News Flash (CCC 11) ABS Fuel Cell Guide 4/4 RINA Pt. C	Standard smoke detectors are ineffective for hydrogen fires. Difficulty in detecting hydrogen flames in bright daylight.	**Detectors:** Must use Hydrogen-specific flame detectors (UV/IR) combined with smoke/heat detectors. **Placement:** Detectors located at ventilation outlets and high points where gas accumulates. **Response:** Detection must automatically shut	**Ro-Pax:** Sensors must differentiate between hydrogen flames and other heat sources (e.g., vehicle exhausts).	**Speed:** System must react instantly to hydrogen ignition to isolate fuel sources. **Integration:** Linking fire detection to the Emergency Shutdown (ESD) system.

					down fuel supply and ventilation.		
Machinery Space Safety	**PTI / PTO** (Shaft Generator)	**Hazards:** Generator winding fire, oil mist ignition (if gearbox involved), high voltage arc. **Focus:** Local application firefighting (water mist).	ABS Marine Vessel Rules DNV Pt.6 Ch.2 Sec.2	Fire protection for permanent magnet machines (rare earth materials) presents specific toxicity risks.	**Detection:** Smoke and heat detectors required in machinery spaces. **Extinguishing:** Fixed total flooding system (CO_2 or Water Mist) required for Category A machinery spaces. **Oil Mist:** Detectors required for gearboxes/engines to prevent crankcase explosions.	**Single Screw Vessels:** Fire in the main engine room disabling the shaft generator results in loss of all propulsion/power generation unless redundant separation exists.	**Separation:** Segregating the shaft generator from the main engine with a cofferdam or shield if oil leakage is a risk.
Connection Safety	**Onshore Power Supply (OPS)**	**Hazards:** Cable insulation fire, connector overheating, arc flash in connection locker. **Focus:** Temperature monitoring, fixed extinguishing in locker.	ABS Hybrid Guide DNV Pt.6 Ch.2 Sec.9 (Implied) RINA Pt. F	Standardisation of fire protection requirements for cable management system (CMS) rooms.	**Enclosure:** Connection room/locker must be A-60 separated from high fire risk spaces. **Extinguishing:** Fixed fire extinguishing system recommended for enclosed connection spaces. **Interlock:** High temperature alarm in the connection box triggers breaker trip.	**Cruise Ships:** Connection is often near passenger areas; strict smoke containment required.	**Containment:** Preventing smoke from a cable fire entering the vessel's accommodation or ventilation intakes.

2.1.6 Ventilation

Table 9 provides a crucial safety architecture for managing the atmospheric hazards associated with Power Conversion Energy Efficiency Technologies (EETs), specifically addressing the risks of toxic gas accumulation, explosion potential, and thermal runaway. The design framework is governed by strict regulatory standards from bodies such as DNV, ABS, and IMO, which mandate precise airflow rates and pressure regimes to maintain vessel integrity. For high-risk areas such as fuel preparation rooms and Tank Connection Spaces (TCS) utilising alternative fuels like LNG, ammonia, or hydrogen, the matrix enforces a minimum ventilation rate of 30 ACH to ensure rapid dilution of any leaked vapours. These hazardous enclosed spaces must typically be maintained at a negative pressure relative to adjacent compartments to prevent the migration of dangerous gases into safe zones, whereas airlocks and safe access spaces are kept at a positive overpressure to create a pneumatic barrier.

Redundancy and reliability are central to the ventilation strategy for critical power systems. Fuel cell spaces and gas turbine enclosures require a robust 2 x 100% capacity fan arrangement supplied by separate electrical circuits, ensuring that ventilation remains fully operational even in the event of a single component failure. This redundancy requirement extends to general hazardous spaces, where the system capacity must not drop below 50% upon a fan failure. Furthermore, the design of the distribution network for hazardous fuels mandates the use of double-walled piping; the annular space between the inner and outer pipes must be continuously ventilated at a minimum of 30 ACH under negative pressure, with active flow or pressure monitoring to detect inner pipe ruptures immediately.

Distinct ventilation strategies are applied to Energy Storage Systems (ESS) and high-voltage power electronics to address their unique thermal and chemical risks. For Lithium-ion battery rooms, the ventilation system serves a dual purpose: rejecting normal operational heat and extracting toxic, explosive off-gases during a thermal runaway event. The regulations specify a minimum rate of 6 ACH, with a critical design constraint that exhaust inlets be positioned less than 400mm below the ceiling to effectively capture buoyant hot gases, while air inlets are placed near the floor to facilitate circulation. Conversely, for Shaft Generators (PTI/PTO) and converter rooms, the primary focus is on managing significant heat loads and preventing the ingress of salt mist or contaminants that could compromise high-voltage insulation, necessitating filtered air intakes and interlocks that shut down equipment upon loss of cooling airflow.

The physical arrangement of ventilation infrastructure is also strictly regulated to prevent cross-contamination and ignition. Hazardous exhaust outlets must be located in the open air, maintaining a minimum safety distance of 3 metres from any ignition sources or openings, while non-hazardous air intakes must be separated by at least 1.5 metres from hazardous boundaries. To prevent mechanical sparks from becoming ignition sources within the airflow,

fans serving hazardous zones must utilise non-sparking construction, such as non-ferrous impellers with ferrous housings, and maintain specific tip clearances. Additionally, ducts serving these high-risk spaces must be structurally independent and constructed of steel to meet SOLAS requirements, ensuring that the ventilation system itself does not become a conduit for fire or gas spread.

Table 9. Ventilation Design Matrix for Power Conversion EETs

Design Element	EET	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Space Ventilation	**Fuel Cells** (PEM, SOFC)	**Hazards:** Hydrogen/Ammonia accumulation, toxic/explosive atmosphere. **Focus:** Negative pressure maintenance, redundancy, flow direction (low to high for H_2).	DNV Pt.6 Ch.2 Sec.3 [5.3] KR Fuel Cell Guide Ch.2 RINA Pt. C	Determining ventilation rates for Ammonia: balancing toxicity dilution vs. dispersion risks (CCC 11 notes 45 ACH proposal vs. existing IGC). Vacuum insulation failure scenarios for LH_2.	**Redundancy:** 2 x 100% capacity fans required; separate circuits. **Rate:** Sufficient to dilute gas below LEL; Fuel Prep Rooms min **30 ACH**. **Interlock:** Automatic shutdown of fuel supply upon loss of ventilation. **Air Inlet:** Non-hazardous area, min 1.5m from hazardous boundaries.	**Passenger Ships:** Ventilation outlets must be located to prevent toxic gas (Ammonia) ingress into accommodation/muster stations.	**Pressure Balance:** Maintaining negative pressure in FC spaces relative to adjacent spaces to prevent leakage. **Ducting:** Dedicated ducts required; no cross-over with other spaces.
Hazardous Zones	**Alt. Fuels ICEs** (LNG/LPG/ Ammonia/H2)	**Hazards:** Gas pockets in tank connection spaces (TCS) or fuel prep rooms. **Focus:** Extraction type, spark-proof fans, airlocks.	ABS Marine Vessel Rules Pt.5C Ch.13 DNV Pt.6 Ch.2 Sec.5 [6.1]	Hydrogen Tank Connection Enclosures (TCE) require inerting rather than	**Rate:** Tank Connection Space (TCS) & Fuel Prep Room: Min 30 ACH. **Airlocks:** Mechanical ventilation to	**Tankers:** Cargo pump room ventilation (30 ACH) often serves as a reference for fuel pump rooms. **Ro-Pax:** Ventilation outlets must be clear of vehicle deck openings.	**Stack Effect:** Designing duct runs to avoid gas accumulation (vertical ascent for lighter-than-air gases like LNG/H_2; low-level extraction for LPG).

			DNV Pt.6 Ch.2 Sec.6 [3.5]	mechanical ventilation (IMO CCC 11).	maintain overpressure relative to hazardous zone. **Fan Type:** Non-sparking construction (impeller/housing material compatibility).		
Annular Spaces	**Double-Walled Piping** (Gas/Low Flashpoint)	**Hazards:** Inner pipe rupture leading to gas migration. **Focus:** Under-pressure maintenance, flow monitoring.	DNV Pt.6 Ch.2 Sec.5 [6.1.4] KR Fuel Cell Guide	Leak detection sensitivity in high-flow ventilation of annular spaces for very small H_2 molecules.	**Rate:** Min 30 ACH for secondary enclosures. **Pressure:** Maintained at less than atmospheric pressure. **Monitoring:** Flow or pressure monitoring required (running signal of fan motor insufficient).	**Gas Carriers:** Ventilation of fuel supply lines passing through accommodation (using double ducts) requires strict independence.	**Integration:** Designing concentric pipe ventilation that does not compromise the structural integrity or flexibility of the fuel piping.
Off-Gas Management	**ESS**	**Hazards:** Thermal runaway off-gas (explosive/toxic). **Focus:** Extraction arrangement, gas density consideration.	ABS Lithium-ion Battery Requirements DNV Pt.6 Ch.2 Sec.1 [2.3]	Quantifying off-gas volume for specific chemistries to determine precise ACH	**Rate:** Min 6 ACH (or calculated based on cell count/gas volume). **Arrangement:** Exhaust inlet <	**Ferries:** High capacity banks require robust ventilation to handle massive heat/gas release potential.	**Temperature Control:** Ventilation must also handle normal heat rejection to keep batteries within optimal temp range (often <30°C).

				beyond minimums.	400mm from ceiling; Inlet near floor (to circulate air). **Ducting:** Independent system required; integrated off-gas ducts must have ex-proof fans.		
Cooling & Heat Rejection	**PTI / PTO** (Shaft Generator / Converters)	**Hazards:** Overheating of power electronics, reduced efficiency. **Focus:** Heat load calculation, filtered air intake.	ABS DC Power Guide ABS Hybrid Guide	Managing salt mist ingress in high-volume ventilation for air-cooled converters.	**Cooling:** Design must comply with 4-8-3/8.5.8 of Marine Vessel Rules (liquid or air). **Interlock:** Shutdown upon loss of cooling medium/airflow.	**All-Electric Vessels:** Large converter rooms require significant ducting space for heat rejection.	**Air Quality:** ensuring ventilation air is clean/dry to prevent creepage/short circuits in high voltage equipment.
Safety Enclosures	**Gas Turbines**	**Hazards:** Gas leakage within acoustic enclosure. **Focus:** Rapid dilution, high redundancy.	DNV Pt.6 Ch.2 Sec.5 [10.2.2]	Noise attenuation baffles restricting airflow.	**Redundancy:** 2 x 100% capacity fans from different electrical circuits required for the enclosure. **Rate:** Dilution of gas to below LEL.	**High Speed Craft:** Weight/space constraints for large ventilation ducts.	**Acoustics vs. Safety:** Balancing the need for large airflow for safety with the need to seal the enclosure for noise reduction.

2.2 Sustainable climate neutral low emission fuels

The IGF Code currently serves as the foundational regulation for ships using low-flashpoint fuels; however, it includes detailed prescriptive requirements primarily for natural gas (methane). Recognising that the Code does not yet fully address the specific hazards of emerging fuels such as hydrogen, ammonia, and methanol, the IMO is actively developing interim guidelines. To bridge these regulatory gaps and support the "Alternative Design" process, major classification societies, as well as agencies like EMSA, have published specific requirements, guides, and white papers to ensure the safe application of these alternative energy technologies.

• ABS (2023) - 'Requirements for Hydrogen Fueled Vessels'

• ABS (2022) - 'Guide for Methanol and Ethanol Fueled Vessels'

• ABS (2021) - 'Requirements for Ammonia Fueled Vessels'

• ABS (2020) - 'Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels'

• Bureau Veritas (2022) - 'Alternative Fuels Outlook for Shipping'

• DNV GL (2020) - 'Rules for Classification: Ships – Part 6 Additional class notations'

• DNV (2025) - 'Methanol Fuel in Shipping: Barriers and pathways to low-GHG methanol as a marine fuel'

• EMSA (2023) - 'Safe Bunkering of Biofuels'

• RINA (2024) – 'Rules for the Classification of Ships – Part C Machinery, Systems and Fire Protection'

2.2.1 Ship Design and Arrangement

Table 10 outlines a comprehensive framework for the design and arrangement of ships utilising alternative marine fuels, categorising the requirements by specific EETs such as ammonia, hydrogen, methanol, methane, and biofuels. The primary objective of these standards is to address the unique physical and chemical hazards associated with each fuel type, necessitating distinct architectural and engineering approaches to ensure the safety of the vessel and crew.

For ammonia fuel, the central design focus is mitigating high toxicity and corrosivity, which mandates strict separation of fuel spaces from accommodation and machinery areas to prevent toxic exposure. Regulations stipulate that the "ESD machinery space" concept is not permitted for ammonia; instead, only "Gas Safe" concepts utilising double-walled piping are allowed, and airlocks are required for access between non-hazardous and hazardous zones. A critical design constraint for ammonia involves the establishment of toxic zones, requiring a minimum distance of 25 metres from vent masts to air intakes and openings, and 10 metres from other release sources like tank outlets.

Hydrogen fuel introduces a different set of challenges centred on its wide flammability range, low ignition energy, and buoyancy, which requires design strategies that prevent gas accumulation in enclosed spaces. To address the risk of gas pockets, spaces are required to have simple geometries with smooth ceilings and exhaust ventilation located at the highest point, contrasting with heavier-than-air fuels. Furthermore, hydrogen tanks located on open decks must maintain a minimum clearance of 800 mm from the vessel's side, and the hull requires protection against embrittlement and liquid air formation caused by the extreme cold of liquid hydrogen.

In the context of methanol and ethanol, the design priority shifts toward fluid containment and toxicity management, as these fuels are liquid at ambient temperatures but possess invisible flames and toxic properties. Integral tanks for these fuels must be surrounded by protective cofferdams, typically with a minimum width of 600 mm for fire integrity, to ensure effective segregation from machinery and accommodation spaces. Unlike hydrogen, methanol vapours are heavier than air, necessitating that vents be located at least 10 metres away from air intakes or openings to accommodation areas to prevent the ingress of toxic vapours.

Methane (LNG) and biofuels present their own specific arrangement criteria, with methane requiring collision protection distances of B/5 or 11.5 metres from the ship side and rigorous boil-off gas management due to its cryogenic nature. Biofuels, while often treated as drop-in replacements, require careful verification of material compatibility for seals and gaskets, as components like FAME can act as solvents that loosen sediments and dissolve rubber, potentially clogging filters or causing leaks. Collectively, these standards highlight that there is no one-size-fits-all approach to ship design for alternative fuels; rather, the arrangement must be tailored to the specific toxic, cryogenic, or flammable characteristics of the energy source employed.

Table 10. Comprehensive Design and Arrangement Standards for Alternative Marine Fuels

Design Element	EET (Alternative Fuel)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Location & Separation	**Ammonia Fuel (NH_3) & Ammonia (H_2 Carrier)**	**Hazards:** High toxicity (IDLH 300 ppm), corrosivity, and flammability. **Focus:** Strict separation of fuel spaces from accommodation and machinery spaces to prevent toxic exposure.	ABS Requirements for Ammonia Fuelled Vessels RINA Pt. C	**Gap:** Lack of mature technology for Ammonia Release Mitigation Systems (ARMS). **Barrier:** Determining safe distances for toxic vents requires complex gas dispersion analysis.	**Toxic Zones:** Minimum 25m distance from vent masts to air intakes/openings; 10m from other release sources (e.g., tank outlets, bunker manifolds). **Gas Safe Machinery Space:** "ESD machinery space" concept is not permitted; only gas safe concepts (double-walled piping) are allowed. **Airlocks:** Required for access between non-hazardous and hazardous areas.	**Gas Carriers:** Cargo can be used as fuel. **Tankers:** Fuel tanks in cargo area must be dedicated.	**Toxic Zones:** Designing vent masts and relief systems to ensure toxic vapours do not reach manned areas, muster stations, or air intakes. **Segregation:** Ensuring gastight separation of fuel preparation rooms from machinery spaces.
Location & Separation	**Hydrogen Fuel (Liquid/Gas)**	**Hazards:** Wide flammability range (4-75%), low ignition energy (0.017 mJ), cryogenic (-253°C for liquid), hydrogen embrittlement.	ABS Requirements for Hydrogen Fuelled Vessels RINA Pt. C	**Gap:** Prescriptive regulations were lacking until recent	**Tank Location:** Tanks on open deck must be minimum 800mm	**Ferries/Short-sea:** Often use Fuel Cells; require specific	**Ventilation & Buoyancy:** Designing spaces so hydrogen (lighter than air) cannot get

		Focus: Preventing accumulation in enclosed spaces and managing cryogenic risks.		CCC 11 developments. **Barrier:** High volume requirements due to low energy density.	from the vessel's side. **Ventilation:** Spaces must have simple geometry/smooth ceilings to prevent gas pockets; exhaust ventilation at the highest point. **Gas Safe:** Machinery spaces must be gas safe (double-walled piping).	hydrogen storage volume management. **Gas Carriers:** Liquefied Hydrogen carriers have specific vacuum insulation requirements.	trapped; intakes must be low, exhaust high. **Cryogenic Protection:** Hull protection against liquid air formation and embrittlement due to extreme cold.
Location & Separation	**Methanol Fuel** & **Ethanol Fuel** (Synthetic/ Biomass)	**Hazards:** Toxic (ingestion/contact), low flashpoint (approx. 10°C for Methanol), invisible flame. Liquid at ambient temp. **Focus:** Fluid containment (cofferdams) and toxicity barriers.	ABS Guide for Methanol/Ethanol RINA Pt. C	**Gap:** Mature compared to H_2/NH_3, but toxicity management in confined spaces remains critical. **Barrier:** Invisible flame detection requires specific sensor placement.	**Tank Distance:** Fuel tanks located on deck must be minimum 800mm from the vessel's side. **Cofferdams:** Integral tanks must be surrounded by protective cofferdams (min 600mm for fire integrity, generally 900mm for segregation). **Vents:** Vents must be minimum 10m	**Container Ships:** High uptake; specific focus on maximising cargo space while fitting cofferdams. **Passenger Ships:** Strict separation of hazardous zones from passenger areas.	**Containment:** Designing cofferdams around integral tanks to prevent leakage into machinery/accommodation. **Spill Management:** Drip trays and holding tanks essential due to toxicity/flammability.

					from air intakes or openings to accommodation.		
Location & Separation	**Methane Fuel** (Synthetic/ Biomass)	**Hazards:** Cryogenic (-162°C for LNG), flammability. **Focus:** Cryogenic containment and boil-off gas management.	DNV Rules Pt.6 Ch.2 Sec.5 RINA Pt. C	**Barrier:** Methane slip management and boil-off gas handling for long voyages.	**Tank Location:** Fuel tanks located B/5 or 11.5m (whichever is less) from the ship side to protect against collision. **Ventilation:** Tank connection spaces require 30 air changes per hour. **Airlocks:** Required for access to hazardous spaces from non-hazardous areas.	**Gas Carriers:** Often use cargo boil-off as fuel. **RoPax/Cruise:** LNG is common; strict bunkering safety zones required.	**Cryogenic Protection:** Protecting hull structure from brittle fracture in case of leaks. **Boil-off Gas:** Designing systems to handle pressure build-up (re-liquefaction or combustion).
Location & Separation	**Biofuels** (FAME/HVO)	**Hazards:** Solvent properties (FAME), cold flow issues, microbial growth. Flashpoint usually >60°C (safer). **Focus:** Material compatibility and storage conditions.	EMSA Guidance. RINA Pt. C	**Gap:** Lack of specific international bunkering procedures; often treated simply as "drop-in" without reviewing material compatibility.	**Material:** Compatibility verification for seals/gaskets (FAME dissolves rubber, copper/zinc not recommended). **Heating:** Heating coils may be required due to higher cloud points	**All Ships:** Considered drop-in, but older vessels need seal/gasket verification. **Ice Class:** Cold flow properties are critical design constraints.	**Sediment Management:** FAME acts as a solvent; tank design must facilitate cleaning/drainage to prevent filter clogging from loosened sediments.

					(e.g., FAME cloud point -5 to 20°C).		
Location & Separation	**LOHC** (H_2 Carrier)	**Hazards:** Chemical toxicity, thermal management for hydrogenation/dehydrogenation. **Focus:** Chemical handling and heat integration.	ABS Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels.	**Gap:** Regulatory framework for LOHC as a fuel is less developed than for compressed/liquid H_2.	**Certification:** Storage and systems generally follow chemical tanker standards (IBC Code concepts) or Alternative Design. **Heat Integration:** Dehydrogenation requires significant heat input, impacting machinery space arrangement.	**Tankers/Cargo:** Likely early adopters for transport.	**System Complexity:** Integrating the release units (dehydrogenation) within the ship's machinery spaces safely.

2.2.2 Fuel containment system

The design and engineering of fuel containment systems for alternative marine fuels require a rigorous approach tailored to the distinct physical and chemical characteristics of each energy carrier, ranging from extreme cryogenic requirements to specific material compatibilities. For hydrogen fuel, the primary challenges involve managing its liquid state at -253°C and its propensity for causing hydrogen embrittlement in metallic structures. Consequently, containment systems for liquid hydrogen typically utilise vacuum-insulated tanks, such as Type C or membrane systems, to prevent the liquefaction or solidification of surrounding nitrogen and to minimise heat ingress. Materials in direct contact with hydrogen must be qualified to resist embrittlement, and tanks located on open decks are mandated to observe a minimum safety distance of 800 mm from the ship's side to mitigate collision risks. Furthermore, strict protocols are required to detect any loss of vacuum in the insulation spaces, which could lead to dangerous oxygen enrichment or thermal failure.

Ammonia presents a different set of containment challenges, primarily driven by its toxicity, corrosivity to yellow metals, and risk of stress corrosion cracking (SCC). To ensure safety, the use of mercury, cadmium, copper, zinc, and their alloys is strictly prohibited in ammonia piping and tank systems. Containment designs must incorporate secondary barriers depending on the tank type, with specific welding and material selection processes—such as the use of carbon manganese and nickel steels—required to mitigate SCC. Additionally, ammonia systems must be capable of holding boil-off gas for a minimum of 15 days without venting to the atmosphere, and pressure relief valve outlets must be positioned at least 25 metres away from air intakes to prevent toxic exposure.

In the case of methanol and ethanol, which are liquid at ambient temperatures, the design focus shifts towards fluid containment and fire safety due to their low flashpoints and corrosive interaction with materials like aluminium and galvanised steel. Unlike cryogenic fuels, methanol can be stored in integral tanks, provided they are surrounded by protective cofferdams to ensure segregation from machinery and accommodation spaces. These tanks require inerting systems to maintain oxygen levels below 8% during harbour stays, and specific coating systems must be selected to withstand the solvent properties of alcohols. Similarly, biofuels such as FAME require careful material verification, as they can dissolve natural rubber and loosen sediments in older tanks; storage is generally recommended to be limited to six months to prevent oxidation and degradation.

Methane (LNG) and LPG containment systems focus heavily on thermal management and pressure control. LNG tanks utilise thermal insulation to handle temperatures of -163°C and must be located at a minimum distance of B/5 or 11.5 metres from the ship's side to protect against collision damage. Like ammonia, LNG systems require a 15-day holding time for boil-off gas. For LPG and Bio-DME, which are heavier than air, independent Type C tanks are

common, and design emphasis is placed on low-level extraction ventilation and ensuring pressure relief valves discharge vertically upwards from the highest point of the tank. Finally, Liquid Organic Hydrogen Carriers (LOHC) generally utilise standard chemical tanker containment standards but introduce complexity regarding heat integration for the dehydrogenation process.

Table 11. Design Standards and Regulatory Frameworks for Alternative Marine Fuel Containment Systems

Design Element	EET (Alternative Fuel)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Containment Structure & Materials	**Hydrogen Fuel (Liquid/Gas)**	**Hazards:** Hydrogen embrittlement, extreme cryogenic temperature (-253°C for LH_2), high pressure (CGH_2). **Focus:** Material suitability and vacuum insulation integrity.	ABS Requirements for Hydrogen Fuelled Vessels RINA Pt. C	**Gap:** Lack of standardised testing for LH_2 vacuum insulation loss scenarios. **Barrier:** Very high volume required (5-7 times MGO) impacting cargo capacity.	**Material:** Containment system must be resistant to hydrogen embrittlement. **Tank Type:** LH_2 tanks typically require vacuum insulation (Type C or Membrane) to prevent nitrogen liquefaction/solidification. **Location:** Tanks on open deck must be minimum 800mm from ship side.	**Liquefied Hydrogen Carriers:** Membrane-type containment systems must maintain vacuum in insulation spaces; emergency inerting (Helium) required if vacuum is lost.	**Vacuum Maintenance:** Designing systems to detect and manage loss of vacuum in insulation spaces to prevent oxygen enrichment and heat ingress. **Embrittlement:** Ensuring all metallic materials in contact with H_2 are qualified to resist embrittlement.
Containment Structure & Materials	**Ammonia Fuel (NH_3)**	**Hazards:** Stress corrosion cracking (SCC), toxicity, corrosivity to copper/zinc. **Focus:** Secondary barriers and material selection to prevent SCC.	ABS Requirements for Ammonia Fuelled Vessels RINA Pt. C	**Gap:** Limited data on SCC in large-scale marine fuel tanks under sloshing loads.	**Secondary Barrier:** Required based on tank type (Membrane/Type A = Complete; Type B = Partial; Type C = None). **Material Ban:** Mercury, cadmium, copper, zinc, or their alloys are strictly prohibited.	**Ammonia Carriers:** Cargo tanks used as fuel tanks must follow IGC Code; prohibited to use toxic cargoes as fuel generally, but allowed for Ammonia under specific guidelines.	**SCC Prevention:** Selection of materials and welding procedures to minimise stress corrosion cracking. **Toxic Relief:** PRV vent exits must be minimum 25m from air intakes/openings (B or 25m whichever is less).

					SCC Mitigation: Specific measures for carbon manganese and nickel steels required. **Holding Time:** 15 days pressure control capacity required without venting.		
Containment Structure & Materials	**Methanol Fuel / Ethanol Fuel**	**Hazards:** Corrosive to aluminium/galvanised steel, low flashpoint (~10-12°C), water solubility. **Focus:** Integral tanks with cofferdams and inerting.	ABS Guide for Methanol/Ethanol Fuelled Vessels RINA Pt. C	**Gap:** Long-term effects of methanol/ethanol on certain coating systems in integral tanks.	**Tank Type:** Integral tanks allowed but must be surrounded by protective cofferdams (except shell plating below waterline). **Inerting:** Inert gas must be available to keep tanks inerted for 2 weeks in harbour; Oxygen content max 8%. **Material Ban:** Galvanised steel, aluminium, lead, magnesium, or alloys prohibited. **Filling Limit:** Maximum 98% at reference temperature.	**Chemical Tankers:** Often carry methanol as cargo; specific considerations for using cargo as fuel regarding segregation and contamination.	**Cofferdam Design:** Ensuring gas-tight separation (cofferdams) between fuel tanks and machinery/accommodation spaces. **Coating compatibility:** Selecting tank coatings compatible with alcohol to prevent degradation.
Containment Structure & Materials	**Methane Fuel (LNG)**	**Hazards:** Cryogenic (-163°C), boil-off gas (BOG). **Focus:** Thermal insulation and BOG management.	DNV Rules Pt.6 Ch.2 Sec.5 RINA Pt. C	**Barrier:** Methane slip from pressure relief valves during BOG accumulation.	**Location:** Fuel tanks located at a minimum distance of B/5 or 11.5m (whichever is less) from the ship side.	**LNG Carriers:** Membrane tanks common; fuel is boil-off gas. **Container/RoPax:**	**Thermal Stress:** Protecting hull structure from brittle fracture (cryogenic spills) using drip trays and water spray.

					Holding Time: 15 days holding time required without venting. **Tank Type:** Independent tanks (Type A, B, C) or Membrane tanks allowed.	Type C tanks common due to pressure build-up capability.	**BOG Management:** Designing re-liquefaction or combustion units to handle boil-off.
Containment Structure & Materials	**Biofuels (FAME/HVO)**	**Hazards:** Solvency (dissolves rubber/sediments), hygroscopic (absorbs water), cold flow issues (waxing). **Focus:** Material compatibility and heating.	EMSA Safe Bunkering of Biofuels. RINA Pt. C	**Gap:** Lack of unified international standard for material compatibility testing for various FAME blends.	**Material Compatibility:** For B100 (FAME), avoid copper, bronze, brass, zinc, lead, tin, and natural rubber. Carbon steel, aluminium, and stainless steel are compatible. **Heating:** Heating coils may be required as Cloud Point can range from -5 to 20°C. **Storage Life:** Recommended max 6 months storage to prevent degradation/oxidation.	**All Ships:** Drop-in fuel, but requires tank cleaning prior to first loading to prevent filter clogging from dissolved sediments.	**Sediment & Water Management:** Tank design must facilitate draining of water (hygroscopic nature) and cleaning of sediments dissolved by FAME.
Containment Structure & Materials	**LPG (Bio-DME/LPG)**	**Hazards:** Pressurised or refrigerated storage, heavier than air gas (accumulation in low spots). **Focus:** Pressure vessel design and leak detection in low areas.	DNV Rules Pt.6 Ch.2 Sec.13 EMSA Safe Bunkering of Biofuels.	**Gap:** Specific regulations for Bio-DME are less developed than for LPG; often treated as LPG equivalent.	**Tank Type:** Independent Type C tanks are common for pressurised storage. **Relief Valves:** PRVs connected to the highest part of the tank; discharge must be unobstructed and vertically upwards.	**LPG Carriers:** Cargo used as fuel. **Gas Carriers:** Specific requirements for reliquefaction to control tank pressure.	**Low Temperature Protection:** Hull protection against low temperature leaks is required (drip trays/insulation). **Ventilation:** Extraction from low points due to gas density > air.

					Secondary Barrier: Not required for Type C tanks.		
Containment Structure & Materials	**LOHC** (H_2 Carrier)	**Hazards:** Chemical handling, thermal management for release. **Focus:** Standard chemical tank storage.	ABS Guide for Gas Ready Vessels. BV Alternative Fuels Outlook	**Gap:** Regulatory framework for onboard dehydrogenation process integration is developing.	**Tank Type:** Similar to chemical tankers; standard liquid fuel tanks often sufficient but requires certification for the specific chemical carrier. **Process:** Requires heat integration for the release of H_2, affecting tank arrangement and proximity to heat sources.	**Tankers:** Likely initial application.	**Heat Management:** Efficient heat supply to the dehydrogenation reactor and safe storage of the "spent" carrier liquid.

2.2.3 Material

Material selection and compatibility for alternative marine fuels are governed by the specific chemical and physical hazards of each energy carrier, ranging from extreme cryogenic embrittlement to solvent-induced degradation of seals. For hydrogen fuel systems, the primary engineering challenges are hydrogen embrittlement and the containment of liquid hydrogen at -253°C, which necessitates the use of austenitic stainless steels such as 304 or 316L to prevent brittle fracture. Materials directly exposed to high-pressure hydrogen must be qualified to recognised standards like ISO 11114-4, and strict welding procedures are required to minimise hardness and residual stress, while non-metallic materials must be selected to resist permeation due to the small molecular size of hydrogen.

Ammonia fuel demands a strict prohibition of "yellow metals" including copper, zinc, cadmium, mercury, and their alloys (such as brass and bronze), as these materials are highly susceptible to rapid corrosion in ammonia environments. Furthermore, to mitigate the risk of Stress Corrosion Cracking (SCC) in carbon-manganese steels, regulations mandate the use of Post Weld Heat Treatment (PWHT) or the selection of steels with a controlled yield strength of 355 N/mm² or less. Similarly, methanol and ethanol fuels act as solvents that can dissolve standard rubber seals and corrode specific metals; consequently, aluminium, galvanised steel, lead, and magnesium are prohibited, and PTFE (Teflon) seals are recommended over butyl or nitrile rubber, which are prone to swelling and degradation.

Biofuels present distinct compatibility profiles depending on their type; while Hydrotreated Vegetable Oil (HVO) acts as a drop-in fuel compatible with existing systems, Fatty Acid Methyl Esters (FAME) possess solvent properties that can mobilise old sediments and degrade natural rubber or copper-containing fittings. To prevent oxidation and acidity that attack materials, it is recommended that FAME storage be limited to a maximum of six months. Finally, systems utilising Bio-DME share similar solvent risks with methanol, requiring PTFE seals to ensure integrity, alongside the use of low-temperature steels capable of withstanding -55°C to prevent brittle fracture in hull structures

Table 12. Material Selection and Compatibility Standards for Alternative Marine Fuels

Design Element	EET (Alternative Fuel)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Material Selection & Compatibility	**Hydrogen Fuel** (Liquid/Gas)	**Hazards:** Hydrogen Embrittlement (severe loss of ductility/toughness), Permeation, Extreme Cryogenic temp (-253°C). **Focus:** Preventing brittle fracture and leakage through materials.	ABS Requirements for Hydrogen Fuelled Vessels Sec 7 RINA Pt. C	**Gap:** Limited data on fatigue life of materials in high-pressure H_2 marine environments. **Barrier:** High cost of high-grade stainless steels required for all piping.	**Allowed:** Austenitic stainless steels (e.g., 304, 316, 316L) are generally suitable. **Testing:** Materials directly exposed to H_2 must be qualified for resistance to embrittlement according to recognised standards (e.g., ISO 11114-4). **Weld:** Strict welding procedures to minimise hardness and residual stress.	**Fuel Cells:** Proton Exchange Membrane (PEM) FCs are sensitive to impurities; piping material must not contaminate the fuel stream.	**Embrittlement:** Preventing catastrophic failure of high-strength steels. **Permeation:** H_2 molecules are very small; materials (especially non-metallics) must be selected to minimise gas diffusion through pipe walls/seals.
Material Selection & Compatibility	**Ammonia Fuel** (NH_3)	**Hazards:** Corrosive to Copper/Zinc (Yellow metals), Stress Corrosion Cracking (SCC), Toxicity. **Focus:** Chemical compatibility and SCC prevention.	ABS Requirements for Ammonia Fuelled Vessels Sec 7. RINA Pt. C	**Gap:** Standardisation of elastomer materials (gaskets/seals) specifically for marine ammonia service is evolving.	**Prohibited:** Mercury, cadmium, copper, zinc, or alloys of these (e.g., brass, bronze) are strictly prohibited. **SCC Mitigation:** Carbon-manganese steel requires Post Weld Heat Treatment (PWHT) or controlled yield strength (min. yield stress < 355 N/mm^2) to prevent SCC.	**Existing Ships (Retrofit):** Existing fuel systems often contain brass valves/fittings which must be completely replaced.	**SCC Prevention:** Managing welding residual stresses in carbon steel. **Component Sourcing:** Finding standard marine auxiliary components (gauges, valves) that do not contain prohibited yellow metals.

					Compatibility: Rubber/plastics must be proven resistant to ammonia aging.		
Material Selection & Compatibility	**Methanol Fuel / Ethanol Fuel**	**Hazards:** Corrosive to aluminium/galvanised steel/lead. Solvent properties (dissolves rubber/plastic). **Focus:** Seal integrity and corrosion protection.	ABS Guide for Methanol/Ethanol Fuelled Vessels Sec 7 RINA Pt. C	**Barrier:** Identifying legacy materials in existing ship systems during retrofits (e.g., coatings in tanks, pump seals).	**Prohibited:** Galvanized steel, aluminium, lead, magnesium, and their alloys. **Allowed:** Stainless steel (austenitic/duplex) and carbon steel are acceptable. **Seals:** Butyl rubber and nitrile are generally not to be used; PTFE (Teflon) is recommended.	**Chemical Tankers:** Often already compatible, but fuel supply systems to engines (gaskets) need verification.	**Solvency:** Methanol acts as a solvent; it can degrade standard fuel system elastomers (swelling/dissolving), leading to leaks. Coating compatibility in integral tanks is critical.
Material Selection & Compatibility	**Biofuels** (FAME)	**Hazards:** Solvency (dissolves sediments), acidity (corrosion), oxidation. **Focus:** Elastomer compatibility and preventing filter clogging.	EMSA Safe Bunkering of Biofuels RINA Pt. C	**Gap:** Variability in FAME feedstock implies varying levels of acidity and solvency effects.	**Prohibited/Not Recommended:** Copper, bronze, brass, zinc, lead, tin (accelerates oxidation/sedimentation). **Elastomers:** Natural rubber, nitrile rubber, and polypropylene are often incompatible (degrade rapidly). **Allowed:** Carbon steel, stainless steel, aluminium, Teflon, Viton.	**Older Vessels:** High risk of seal failure and filter clogging (mobilisation of old deposits) when switching from fossil diesel to FAME.	**Solvency Effect:** FAME cleans existing tanks/pipes; loosened sediments can clog filters immediately. Material compatibility of seals in fuel pumps must be verified.

Material Selection & Compatibility	**Biofuels** (HVO)	**Hazards:** Very similar to MGO/MDO. Minimal material issues compared to FAME. **Focus:** Drop-in compatibility.	EMSA Safe Bunkering of Biofuels RINA Pt. C	N/A (Drop-in fuel).	**Compatibility:** HVO is a paraffinic diesel (non-polar) and is generally compatible with existing marine fuel system materials, seals, and gaskets.	**All Ships:** True drop-in fuel; usually requires no material changes.	**Cold Flow:** While materials are compatible, viscosity/cold flow properties must be matched to the system design temperatures.
Material Selection & Compatibility	**LPG / Bio-DME**	**Hazards:** Low temperature (embrittlement), solvency (DME). **Focus:** Low-temp toughness and chemical resistance.	DNV Rules Pt.6 Ch.2 Sec.13 EMSA Safe Bunkering of Biofuels	**Gap:** Bio-DME specific interactions with certain new synthetic seals need verification.	**DME Incompatibility:** DME is a solvent; it attacks certain elastomers (similar to Methanol). PTFE/Teflon is required for seals. **LPG Materials:** Low-temperature steel (killed carbon steel or nickel steel) required for tanks/pipes exposed to low temps (down to -55°C).	**LPG Carriers:** Cargo systems usually compatible, but fuel supply piping to engine room needs specific material selection.	**Seal Integrity (DME):** DME causes swelling/softening of rubber; improper seal selection leads to immediate leakage. **Low Temp:** Prevention of brittle fracture in hull structures via drip trays/insulation.

2.2.4 Bunkering

The bunkering operations for alternative marine fuels necessitate distinct safety protocols and infrastructure designs tailored to the specific chemical and physical hazards of each energy carrier, ranging from high toxicity to cryogenic embrittlement. For ammonia fuel, the primary design focus is the management of toxic release zones and the prevention of aquatic contamination. Regulations mandate that bunkering manifold valves be positioned at a minimum distance of 10 metres from non-hazardous area openings and air intakes to prevent the ingress of toxic vapours into accommodation spaces. Furthermore, the system must be designed as a closed loop to prevent any venting to the atmosphere under normal conditions, and bunker stations require water spray protection and spill containment measures to manage releases without discharging toxic runoff directly to the sea.

Hydrogen bunkering introduces rigorous controls over temperature and leak management due to the risks of explosion and cryogenic material failure. Operational standards stipulate that fuel tank temperatures must not exceed 85°C during transfer operations to ensure structural integrity. To mitigate leak risks, the design requires the use of break-away couplings or self-sealing quick-release devices, alongside a robust Ship-Shore Link (SSL) that integrates Emergency Shutdown (ESD) systems to stop fuel flow immediately upon hazard detection. Additionally, any enclosed or semi-enclosed bunkering spaces must feature gas-tight bulkheads and remote monitoring capabilities to handle high-pressure interactions safely.

For liquid fuels with low flashpoints such as methanol and ethanol, safety measures prioritise spill containment and the management of hazardous vapours. The bunkering interface requires dry-disconnect couplings and dedicated vapour return connections to facilitate vapour balancing between the ship and the supplier, preventing the release of flammable gases. Due to the toxicity of these fuels upon contact or ingestion, safety showers and eyewash stations must be located in close proximity to the bunkering station to provide immediate first aid in the event of accidental exposure.

Methane (LNG) and LPG transfers focus heavily on protecting the vessel structure from cryogenic brittle fracture and managing pressurised gases. Design standards require the installation of water distribution systems below shore connections to provide a protective water curtain for the hull in case of low-temperature spills. To minimise the volume of a potential release, automatic shutdown valves are required to have a closing time of no more than 5 seconds. While biofuels like FAME and HVO are often treated as drop-in replacements, they present specific operational challenges regarding material compatibility; hoses and gaskets must be verified for resistance to FAME to prevent degradation, and systems must be managed to prevent filter clogging caused by the solvent properties of the fuel loosening accumulated sediments.

Table 13. Design Standards and Safety Requirements for Alternative Fuel Bunkering Systems

Design Element	EET (Alternative Fuel)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Bunkering Station & Manifold	**Ammonia Fuel (NH_3)**	**Hazards:** High toxicity, corrosivity, flammability. Risk of release during connection/disconnection. **Focus:** Toxic area management, water spray protection, and preventing any venting.	ABS Requirements for Ammonia Fuelled Vessels Sec 8, Sec 11, Sec 12 RINA Pt. C	**Gap:** Lack of standardised international bunkering procedures specifically for ammonia fuel transfer.	**Location:** Bunkering manifold valve must be at least **10m** away from non-hazardous area openings and air intakes. **Protection:** Bunker station must be protected with a water spray system. **System Design:** Designed to prevent venting under all normal operating conditions; no discharge to air allowed. **Gas Detection:** Permanently installed gas detectors for flammability and toxicity required.	**Gas Carriers:** Cargo handling systems often used for bunkering; strict separation required if not.	**Toxic Zone Design:** Ensuring the 10m safety distance is maintained from air intakes. **Spill Containment:** Designing drip trays and water spray curtains to manage toxic releases without discharging directly to sea (aquatic toxicity).
Bunkering Station & Manifold	**Hydrogen Fuel (Liquid/Gas)**	**Hazards:** Explosion, cryogenic spills (-253°C), hydrogen embrittlement.	ABS Requirements for Hydrogen Fuelled Vessels Sec 8	**Gap:** Lack of established infrastructure and	**Tank Temp:** Fuel tanks must have a maximum	**Ferries:** Fast bunkering requirements may	**ESD Integration:** Ensuring the Ship-Shore Link (SSL) effectively triggers Emergency Shutdown

		Focus: Leak prevention, ESD integration, and temperature control.	RINA Pt. C	standardised couplings for liquid hydrogen bunkering.	temperature of no more than 85°C (185°F) during bunkering operations. **Enclosures:** If enclosed/semi-enclosed, bulkheads must be gas tight. **Couplings:** Break-away couplings or self-sealing quick release devices required. **Control:** Remote operation from a safe location required, monitoring tank pressure/temp.	necessitate specialised high-pressure connection designs.	(ESD) on both sides immediately upon leak detection.
Bunkering Station & Manifold	**Methanol Fuel / Ethanol Fuel**	**Hazards:** Toxicity (ingestion/contact), low flashpoint (~10°C), invisible flame. **Focus:** Spill containment, vapor return, and personnel protection.	ABS Guide for Methanol/Ethanol Fuelled Vessels Sec 8 RINA Pt. C	**Gap:** Standardisation of bunkering couplings to ensure compatibility between different ports/barges.	**Couplings:** Dry-disconnect type with additional safety dry break-away coupling/self-sealing quick release. **Vapour Return:** Connections for vapour return lines are to be provided. **Protection:** Showers and eye wash stations	**Chemical Tankers:** Often act as bunker vessels; require specific manifold arrangements for fuel vs. cargo transfer.	**Drip Tray Capacity:** Sizing drip trays to handle the maximum credible spill during disconnection. **Vapour Management:** Managing displaced vapours from the fuel tank back to the supplier (vapour balancing).

					must be located in close proximity. **Valve:** Remote shutdown valve must be fail-closed.		
Bunkering Station & Manifold	**Methane Fuel (LNG)**	**Hazards:** Cryogenic spill (-163°C) causing brittle fracture, flammable gas release. **Focus:** Cryogenic protection (hull) and boil-off gas management.	DNV Rules Pt.6 Ch.2 Sec.5 RINA Pt. C	**Barrier:** Methane slip during disconnection if purging is not effective.	**Hull Protection:** Water distribution system required below shore connections to provide a low-pressure water curtain. **Valve Speed:** Closing time of the shutdown valve shall not be more than 5 seconds. **Lines:** Bunkering lines must be double-walled if passing through enclosed spaces.	**LNG Carriers:** Boil-off gas management is standard; bunker stations often integrated.	**ESD Compatibility:** Ensuring Ship-Shore Link (SSL) compatibility (electric/pneumatic/fibre optic) for ESD transmission.
Bunkering Station & Manifold	**Biofuels (FAME/HVO)**	**Hazards:** Environmental spill (similar to oil), solvency (FAME). **Focus:** Material compatibility and contamination prevention.	EMSA Safe Bunkering of Biofuels. RINA Pt. C	**Gap:** Lack of specific international safety regulations for biofuel bunkering; relies on conventional oil standards.	**Documentation:** Biofuel product name must be on the Bunker Delivery Note (BDN) (Port of Singapore).	**All Ships:** Drop-in fuel; standard oil bunkering procedures generally apply.	**Cross-Contamination:** Preventing mixing with incompatible fuels in the bunkering manifold/lines. **Filter Blocking:** FAME's solvent properties can loosen sediments in bunker lines, clogging ship filters.

					Compatibility: Hoses and gaskets must be verified for resistance to FAME (e.g., FKM/Viton).		
Bunkering Station & Manifold	**LPG Fuel (Bio-DME)**	**Hazards:** Low temperature release, heavier than air gas (accumulation in low spots). **Focus:** Leak detection in low areas and hull protection.	DNV Rules Pt.6 Ch.2 Sec.13; WLPGA Guide.	**Gap:** Lack of dedicated bio-DME bunkering standards; relies on LPG/chemical gas codes.	**Water Curtain:** Water distribution system required under shore connections for hull protection. **Line Drainage:** Bunkering lines must be arranged as self-draining towards the tank. **Couplings:** Dry-disconnect type with break-away coupling.	**LPG Carriers:** Cargo used as fuel.	**Low Zone Ventilation:** Ensuring any leaked gas (heavier than air) is extracted from the bottom of the bunker station/manifold area.

2.2.5 Fuel supply systems

The design and engineering of fuel supply systems for alternative marine fuels must address a diverse array of physical and chemical hazards, ranging from the extreme toxicity of ammonia to the cryogenic challenges of hydrogen. For ammonia fuel, the primary safety imperative is the prevention of toxic exposure, which dictates that the "ESD machinery space" concept is strictly prohibited; instead, machinery spaces must adhere to the "Gas Safe" concept, requiring continuous gas-tight double-walled piping regardless of operating pressure. To mitigate environmental and safety risks, these systems must be designed to prevent direct venting to the atmosphere during normal operations, utilising Ammonia Release Mitigation Systems (ARMS) to ensure exhaust gas ammonia content does not exceed 10 ppm, and triggering automatic shutdowns if concentrations in fuel preparation rooms reach 150 ppm.

Hydrogen fuel supply systems face unique challenges related to hydrogen embrittlement, permeation, and the need to prevent the liquefaction of air on cryogenic surfaces. Consequently, vacuum-insulated double-wall piping is mandatory for liquid hydrogen lines on open decks to ensure that exposed surface temperatures remain above -183°C, thereby preventing dangerous oxygen condensation. Similar to ammonia, hydrogen systems generally require gas safe machinery spaces, and compressed hydrogen configurations necessitate the use of Tank Connection Enclosures (TCE) to isolate valves and fittings from the surrounding environment.

For low-flashpoint liquids like methanol and ethanol, the engineering focus shifts to leak detection and ventilation within enclosed spaces. Fuel piping in these areas must be double-walled, with the annular space subject to mechanical under pressure ventilation providing a minimum of 30 air changes per hour (ACH) to ensure rapid removal of vapours. The outer barriers of these piping systems are robustly designed to withstand the maximum working pressure or a minimum built-up pressure, often specified as 10 bar, to contain leaks effectively while liquid leak detectors monitor the annular space.

Operational compatibility and material maintenance are critical for biofuels and LPG derivatives. While HVO serves as a seamless drop-in replacement, FAME poses challenges due to its solvent properties, which can loosen accumulated deposits in tanks and clog filters, as well as its tendency to oxidise if exposed to copper or zinc fittings or excessive heat. Similarly, fuel systems for LPG and Bio-DME must maintain sufficient pressure to keep the fuel in a liquid state and address low viscosity issues that risk pump leakage; this often requires the use of PTFE seals, as standard rubber components are susceptible to dissolution by DME.

Table 14. Design Standards and Regulatory Requirements for Alternative Fuel Supply Systems

Design Element	EET (Alternative Fuel)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Fuel Distribution & Piping	**Ammonia Fuel (NH_3)**	**Hazards:** High toxicity, corrosivity to copper/zinc, risk of release in machinery spaces. **Focus:** "Gas Safe" machinery space concept and preventing any release to atmosphere (ARMS).	ABS Requirements for Ammonia Fuelled Vessels Sec 9 RINA Pt. C	**Gap:** Lack of mature technology for Ammonia Release Mitigation Systems (ARMS) to handle normal operation venting.	**Gas Safe Concept:** Machinery spaces must be “Gas Safe”; the "ESD machinery space" concept is not permitted. **Piping:** Continuous gas-tight double-walled piping required in machinery spaces regardless of pressure. **Identification:** Fuel piping must be clearly marked/color-coded. **Valve Closing:** Master fuel valve must close automatically	**Gas Carriers:** Cargo can be used as fuel but specific toxicity barriers required. **Passenger Ships:** Prohibited from using toxic cargoes as fuel under IGC, but allowed under IGF with alternative design.	**Release Management:** Designing systems to prevent venting during normal operation; any release must go to a treatment system (ARMS), not directly to the mast. **Material Selection:** strictly prohibiting copper/zinc alloys in piping/valves.

					upon safety system activation.		
Fuel Distribution & Piping	**Hydrogen Fuel (Liquid/Gas)**	**Hazards:** Hydrogen embrittlement, extremely wide flammability range, permeation, liquefaction of air on cold surfaces. **Focus:** Vacuum insulation for LH_2 and leakage containment.	ABS Requirements for Hydrogen Fuelled Vessels Sec 9, Sec 7 RINA Pt. C	**Gap:** Limited availability of certified high-pressure hydrogen components (valves/compressors) for marine use.	**Insulation:** Insulation must maintain exposed surface temperatures above -183°C to prevent oxygen condensation **Machinery Space:** Only Gas Safe machinery spaces permitted. **Piping:** Vacuum-insulated double-wall piping mandatory for LH_2 on open decks. **Tank Connection Enclosure (TCE):** Required for compressed H_2 systems to enclose valves.	**Fuel Cell Vessels:** Piping often requires higher cleanliness standards. **Ferries:** Frequent startup/shutdown cycles require robust automated purging sequences.	**Vacuum Integrity:** Maintaining vacuum in double-walled LH_2 pipes to prevent heat transfer and air liquefaction. **Permeation:** Selecting materials that prevent H_2 molecules from diffusing through pipe walls.
Fuel Distribution & Piping	**Methanol Fuel / Ethanol Fuel**	**Hazards:** Solvency (attacks gaskets/seals), low flashpoint (~10-12°C), toxicity.	ABS Guide for Methanol/Ethanol Fuelled Vessels Sec 9	**Gap:** Standardisation of fuel pump durability with low-lubricity fuels like methanol.	**Double Barriers:** Fuel piping in enclosed spaces must be double-walled.	**Chemical Tankers:** Often easier integration due to existing hazardous zone designs.	**Leak Detection:** Installing liquid leak detectors in the annular space of double-walled pipes.

		Focus: Double-walled piping in enclosed spaces and leak detection.	RINA Pt. C		**Ventilation:** Annular space of double-walled pipes requires mechanical under pressure ventilation of minimum 30 air changes per hour (ACH). **Design Pressure:** Outer pipe of double-wall systems must withstand max working pressure or built-up pressure (min **10 bar** often applied).	**Container Ships:** High uptake; long fuel lines require careful thermal expansion management.	**Pump Protection:** Pumps must be protected against running dry.
Fuel Distribution & Piping	**Biofuels (FAME)**	**Hazards:** Solvency (dissolves deposits), hygroscopic (water absorption), oxidation/degradation.**Focus:** Filter maintenance and material compatibility.	EMSA Safe Bunkering of Biofuels RINA Pt. C	**Gap:** Lack of real-time onboard monitoring for oxidation stability or microbial growth.	**Filtration:** System must handle loosened deposits; finer filtration may clog easily. **Heating:** Heating may be required to maintain viscosity, but overheating (>60°C for long	**All Ships:** Drop-in nature allows use in existing engines, but requires gasket upgrades in older vessels.	**Deposit Management:** FAME acts as a solvent; initial switch-over can strip old tank/pipe deposits, clogging filters instantly.

					periods) accelerates oxidation. **Materials:** Avoid copper, brass, zinc in piping and fittings.		
Fuel Distribution & Piping	**HVO (Renewable Diesel)**	**Hazards:** Minimal; similar to MGO. **Focus:** Drop-in replacement.	EMSA Safe Bunkering of Biofuels RINA Pt. C	N/A (High compatibility).	**Compatibility:** Fully compatible with existing diesel fuel supply systems, pumps, and injectors. **Cold Flow:** Check Cloud Point/CFPP for Arctic operations (though often better than FAME).	**All Ships:** No specific modifications typically required.	**Cost vs. Benefit:** Purely economic/supply chain decision rather than technical system design.
Fuel Distribution & Piping	**LPG Fuel (Bio-DME)**	**Hazards:** Low viscosity (leakage risk), lubricity issues, material incompatibility (seals). **Focus:** Sealing and pressure maintenance to keep liquid state.	EMSA Safe Bunkering of Biofuels DNV Rules Pt.6 Ch.2 Sec.13	**Gap:** Durability of fuel injection equipment with low-lubricity LPG/DME.	**State Maintenance:** Pressure in fuel manifold must be sufficient to maintain fuel in liquid state. **Viscosity:** Low viscosity (<1 cSt) requires tight	**LPG Carriers:** Cargo used as fuel. **RoPax:** DME used in converted diesel engines.	**Lubricity:** DME has very low lubricity; lubricity additives or specialised fuel pumps are required to prevent seizure.

					tolerances in pumps/valves to prevent leakage. **Seals:** PTFE/Teflon seals required; DME dissolves standard rubber.		

2.2.6 Fire safety

Fire safety strategies for alternative marine fuels must be fundamentally adapted to address specific hazards that differ significantly from conventional hydrocarbon fires, such as invisible flames, toxic vapour dispersion, and thermal runaway. For ammonia fuel, the primary safety concern is its high toxicity rather than flammability alone; consequently, fire protection systems utilise water sprays designed not merely for cooling but specifically for vapour absorption and containment to mitigate toxic cloud spread. This approach introduces a secondary challenge regarding environmental protection, as the resulting runoff is toxic to aquatic life and must be contained in sizable drain tanks rather than discharged overboard.

In contrast, hydrogen and methanol fuels present the unique danger of invisible flames, which renders standard smoke detection ineffective and necessitates the mandatory installation of specialised Infrared (IR) or Ultraviolet (UV) flame detectors to ensure early identification. For hydrogen fires, which are characterised by high burning velocities and low radiant heat, the primary mitigation strategy is often to isolate the fuel source and allow for a controlled burn while applying copious water spray to cool surrounding structures and prevent steel failure. Methanol fires require a chemical-specific approach; because alcohols destroy standard fire-fighting foams, the use of Alcohol-Resistant (AR) foam is strictly required, alongside water spray application rates of 10 l/min/m² for horizontal surfaces to manage heat and vapours.

Methane (LNG) safety protocols focus heavily on protecting the vessel's hull from cryogenic embrittlement caused by liquid spills, utilising water curtains to shield steel structures, while dry chemical powder systems are mandated at bunkering stations to extinguish jet fires. Biofuels like FAME introduce a risk of spontaneous combustion in soaked insulation or rags, requiring rigorous housekeeping and the potential use of AR foam for effective pool fire suppression. Finally, lithium-ion battery fires pose the risk of thermal runaway, a process that generates its own oxygen and cannot be easily smothered by gas suppression systems; therefore, the design focus is on aggressive cooling using water-based systems to prevent heat propagation between cells.

Table 15. Fire Protection and Detection Standards for Alternative Marine Fuels

Design Element	EET (Alternative Fuel)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Fire Protection & Extinguishing	**Ammonia Fuel (NH_3)**	**Hazards:** High toxicity, lower flammability than hydrocarbons but toxic smoke/vapours. Ammonia dissolves in water (exothermic reaction). **Focus:** Water spray for vapour absorption/containment and cooling.	ABS Requirements for Ammonia Fuelled Vessels Sec 11 RINA Pt. C	**Gap:** Efficacy of standard fire-fighting agents on large ammonia fires is still under study; risk of contaminated runoff water (aquatic toxicity).	**Water Spray:** Required for fuel tanks, bunkering stations, and manifolds to absorb vapours and cool. **Extinguishing Media:** Fixed fire-extinguishing system required for machinery spaces; media must be proven suitable for ammonia. **Containment:** Ammonia is extremely harmful to aquatic life; direct discharge of spray water to sea should be avoided where possible.	**Gas Carriers:** Water spray systems often integrated with cargo safety systems. **Passenger Ships:** Containment of toxic fire-fighting run-off is critical to prevent passenger exposure.	**Vapor Absorption:** Designing water spray systems not just for cooling (like LNG) but for vapour absorption. **Run-off Management:** Sizing drain tanks to hold contaminated water preventing overboard discharge.
Fire Protection & Extinguishing	**Hydrogen Fuel (Liquid/Gas)**	**Hazards:** Invisible flame, extremely high burning velocity, low radiant heat (hard to feel until close), risk of explosion if extinguished prematurely (re-ignition/explosion).	ABS Requirements for Hydrogen Fuelled Vessels Sec 11 RINA Pt. C	**Barrier:** Lack of effective extinguishing agents for large H_2 fires; strategy is often to let it burn while cooling	**Water Spray:** Coverage required for fuel tanks and all exposed fuel piping on deck. **Extinguishing Media:** Dry powder or Carbon Dioxide	**Ro-Pax:** Strict separation of H_2 vent masts from passenger muster stations due to thermal radiation risk during fire/venting.	**Flame Visibility:** Hydrogen flames are invisible in daylight; reliance on thermal imaging/UV detectors is mandatory.

		Focus: Cooling and controlled burn.		surroundings to prevent explosion.	(CO_2) recommended for machinery spaces. **Isolation:** System must allow isolation of fuel source to stop the fire (starvation).		**Cooling Capacity:** High water rates required to prevent steel failure from jet fires.
Fire Protection & Extinguishing	**Methanol Fuel / Ethanol Fuel**	**Hazards:** Invisible flame (without smoke), water soluble, re-ignition risk. **Focus:** Alcohol-Resistant foam and flame detection.	ABS Guide for Methanol/Ethanol Fuelled Vessels Sec 11 RINA Pt. C	**Gap:** Standard foams break down on contact with alcohols; logistics of ensuring specific AR-foam supply availability globally.	**Foam:** Fixed fire-fighting system must use Alcohol-Resistant (AR) foam; standard foam is ineffective. **Water Spray:** Application rate of 10 l/min/m² for horizontal surfaces and 4 l/min/m² for vertical surfaces. **Portable Extinguishers:** Dry chemical powder required near bunkering stations.	**Chemical Tankers:** Often already equipped with AR-foam; easier integration. **Container Ships:** Deck fire-fighting systems must cover fuel tanks located below container stacks.	**Invisible Flame:** Designing detection systems (UV/IR) because smoke detectors are ineffective for pure methanol fires. **Foam Compatibility:** Ensuring all foam systems (fixed and portable) use alcohol-resistant concentrate.
Fire Protection & Extinguishing	**Methane Fuel (LNG)**	**Hazards:** Cryogenic spill causing brittle fracture, high radiant heat pool fires. **Focus:** Hull protection and dry powder.	DNV Rules Pt.6 Ch.2 Sec.5 RINA Pt. C	**Barrier:** Managing jet fires from high-pressure gas injection systems.	**Water Spray:** Required for cooling fuel tanks and protecting hull structures; rate similar to methanol (10 l/min/m²). **Dry Powder:** Dry chemical powder system required for bunkering stations to extinguish gas fires.	**LNG Carriers:** Extensive existing standards apply. **Cruise Ships:** Water curtain design critical for protecting life-saving appliances (lifeboats).	**Cryogenic Shielding:** Water spray curtains to protect steel from shattering under liquid LNG contact. **Rapid Shutdown:** Fire detection must trigger ESD to stop fuel flow immediately.

Fire Protection & Extinguishing	**Biofuels (FAME)**	**Hazards:** Spontaneous combustion (soaked rags/insulation), higher flashpoint (>100°C) makes pool fires harder to ignite but persistent. **Focus:** Housekeeping and compatible foam.	EMSA Safe Bunkering of Biofuels RINA Pt. C	**Gap:** Misconception that standard diesel fire procedures are perfectly adequate; FAME requires specific foam types for optimal extinction.	**Foam:** Alcohol-Resistant (AR) foam or water mist is recommended over standard foam for pool fires. **Spontaneous Ignition:** Rags/materials soaked in FAME must be stored in closed metal containers to prevent auto-oxidation and fire.	**All Ships:** Retrofitting old vessels requires checking if existing foam systems are effective against FAME.	**Housekeeping:** Strict procedures to prevent accumulation of FAME on hot surfaces or insulation (lagging), which leads to auto-ignition.
Fire Detection	**Hydrogen & Methanol**	**Hazards:** Flames are invisible to the naked eye. Smoke detectors may not trigger early. **Focus:** Specialised flame detectors.	ABS Guide for Methanol Sec 11 ABS Hydrogen Guide Sec 11. RINA Pt. C	**Barrier:** Cost and maintenance of UV/IR sensors compared to standard smoke detectors.	**Detector Type:** Detectors must detect IR (Infrared) or UV (Ultraviolet) signatures specific to hydrogen/methanol flames. Smoke detectors alone are not considered sufficient. **Location:** Detectors required in machinery spaces, fuel prep rooms, and bunkering stations.	**All Ships:** Positioning sensors to avoid blind spots is critical due to the lack of visible smoke.	**Sensor Technology:** Selecting sensors that do not false alarm from sunlight or welding but reliably detect clear flames.
Fire Protection & Extinguishing	**ESS**	**Hazards:** Thermal runaway, toxic off-gas, oxygen generation (cannot be smothered). **Focus:** Cooling and gas extraction.	DNV Rules Pt.6 Ch.2 Sec.1.	**Gap:** Ineffectiveness of standard CO_2/gas suppression on thermal runaway (which generates its own oxygen).	**Extinguishing:** Water-based systems (e.g., water mist) recommended for cooling.	**Ferries:** High capacity battery rooms require robust, independent fire suppression systems.	**Thermal Management:** The primary goal is cooling to prevent propagation between cells, rather than oxygen starvation.

					Gas Suppression: If gas is used, two independent releases are often required (2 x 100%). **Detection:** Combined smoke and heat detectors required.		

2.2.7 Ventilation

Ventilation design for ships utilising alternative fuels must be rigorously adapted to the specific buoyancy, toxicity, and flammability characteristics of each energy carrier to ensure the effective removal of hazardous vapours. For ammonia fuel, the paramount concern is toxicity, which dictates a high standard ventilation rate of 30 air changes per hour (ACH) in fuel preparation rooms, increasing to 45 ACH for emergency gas evacuation systems upon detection of leaks. To prevent toxic plumes from re-entering accommodation spaces or muster stations, exhaust outlets must be positioned at least 10 metres away from air intakes and openings, and 4 metres above the open deck, while the system requires 100% fan redundancy to maintain continuous under pressure in hazardous areas.

In contrast, hydrogen fuel systems must address the risk of lighter-than-air gas accumulation, requiring exhaust extraction points to be located at the highest point of the space rather than the floor. Design standards for hydrogen mandate smooth ceilings to prevent the formation of gas pockets and require the use of non-sparking fans with motors certified for Group IIC environments; furthermore, recent guidelines indicate a growing preference for inerting or vacuum systems over simple mechanical ventilation in fuel preparation rooms. Conversely, for heavier-than-air fuels such as methanol, ethanol, and LPG, ventilation pickups must be located at low points like bilges to effectively scavenge settling vapours. These systems also require the use of airlocks that maintain overpressure in non-hazardous spaces relative to the fuel preparation rooms, with air inlets for safe zones separated by a minimum of 1.5 metres from hazardous boundaries.

Methane (LNG) ventilation adheres to the 30 ACH standard for ESD-protected machinery spaces but places specific emphasis on the integrity of ventilation ducts passing through safe areas, often requiring them to be gas-tight and maintained at negative pressure. Finally, ventilation for lithium-ion battery rooms is designed to mitigate thermal runaway events by removing explosive off-gases, which typically include hydrogen; this requires exhaust at the highest point and flow rates calculated based on battery energy capacity or a minimum of 6 ACH.

Table 16. Ventilation Design Standards and Regulatory Requirements for Alternative Marine Fuels

Design Element	EET (Alternative Fuel)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Space & Duct Ventilation	**Ammonia Fuel (NH_3)**	**Hazards:** High toxicity (IDLH 300 ppm), corrosivity, risk of gas accumulation. Vapours can be heavier than air due to hygroscopic nature. **Focus:** Rapid dilution of toxic vapours and safe dispersion away from manned areas.	ABS Requirements for Ammonia Fuelled Vessels Sec 13 RINA Pt. C	**Gap:** Uncertainty in dispersion modelling for toxic plumes; CCC 11 suggests validating effectiveness via CFD analysis.	**Rate:** Minimum **30 air changes per hour (ACH)** for fuel preparation rooms and tank connection spaces; 45 ACH for emergency gas evacuation systems in fuel prep rooms. **Distances:** Exhaust outlets must be at least **10m** from air intakes/openings and 4m above the open deck. **Pressure:** Spaces maintained at under pressure relative to surrounding areas.	**Passenger Ships:** Critical to ensure toxic plumes do not reach muster stations or accommodation air intakes even under emergency venting.	**Dispersion Design:** Designing exhaust outlets to direct discharge upward and away from decks; requiring high-velocity discharge to dilute toxicity. **Redundancy:** Fans must have 100% redundancy (capacity not less than 100% if one fan fails).
Space & Duct Ventilation	**Hydrogen Fuel (Liquid/Gas)**	**Hazards:** Lighter than air (accumulates in ceilings), wide flammability range (4-75%), low ignition energy.	ABS Requirements for Hydrogen Fuelled Vessels Sec 13	**Gap:** Lack of standardised criteria for "simple geometry" to	**Rate:** Minimum 30 ACH for fuel preparation rooms and tank connection spaces.	**Ferries:** Frequent bunkering/operations increase risk of leakage; ventilation systems must	**Buoyancy Management:** Smooth ceilings required to prevent hydrogen pocketing; ventilation must sweep the entire ceiling area.

		Focus: Preventing gas pockets in high points and rapid dilution.	RINA Pt. C	prevent ceiling pockets. **Barrier:** Large duct sizes required to handle high volume flow for dilution.	**Inlet/Outlet:** Inlets positioned low; Exhausts at the highest point (opposite to LPG/Methanol). **Pressure:** Hazardous spaces at under pressure; Fuel piping ducts require **30 ACH**. **CCC 11 Update:** Preference for **inerting or vacuum** in fuel prep rooms; mechanical ventilation requires Explosion Risk Analysis (ERA).	be robust and continuously monitored.	**Fan Safety:** Fans must be non-sparking and motors certified for Hydrogen (Group IIC).
Space & Duct Ventilation	**Methanol Fuel / Ethanol Fuel**	**Hazards:** Heavier than air vapours (accumulate in bilges/low points), toxic, flammable. **Focus:** Extraction from low points and airlock protection.	ABS Guide for Methanol/Ethanol Fuelled Vessels Sec 13 RINA Pt. C	**Gap:** Detection of vapours in complex bilges/double bottoms can be difficult.	**Rate:** Minimum **30 ACH** for fuel preparation rooms and double-walled piping ducts. **Flow:** Extraction from **low points**; Inlets high. **Airlocks:** Required for access from non-hazardous spaces; must maintain **overpressure** relative to the hazardous space.	**Ro-Pax:** Ventilation outlets must be carefully located to avoid passenger decks, as methanol vapours sink/spread along decks.	**Low-Level Extraction:** Ensuring ventilation pickups are located in bilges and low spots where vapours settle. **Airlock Control:** Managing pressure differentials to prevent hazardous gas ingress into engine rooms.

					Distance: Air inlets for non-hazardous spaces must be at least **1.5m** from hazardous area boundaries.		
Space & Duct Ventilation	**Methane Fuel (LNG)**	**Hazards:** Lighter than air (at ambient T), cryogenic spills. **Focus:** ESD protected machinery spaces and ducting.	DNV Rules Pt.6 Ch.2 Sec.5; IGF Code.	**Barrier:** Managing large ventilation ducts through accommodation spaces.	**Rate:** Minimum **30 ACH** for ESD protected machinery spaces, tank connection spaces, and ducting. **Redundancy:** Fan capacity must not drop below **50%** (DNV) or **100%** (ABS) upon single failure depending on class notation. **Pressure:** Hazardous spaces at **under pressure**; Pipe ducts at **under pressure** (usually).	**Gas Carriers:** Cargo compressor rooms use similar standards. **Cruise Ships:** ESD machinery spaces allow gas piping in engine rooms if ventilated at 30 ACH.	**Duct Integrity:** Hazardous ventilation ducts passing through safe spaces must be gas-tight and often require negative pressure to ensure no leakage outward.
Space & Duct Ventilation	**LPG Fuel**	**Hazards:** Heavier than air, settles in low areas. **Focus:** Bottom extraction and gas pocket prevention.	DNV Rules Pt.6 Ch.2 Sec.13.	**Gap:** Ensuring effective sweep of large flat tank tops/bilges.	**Rate:** Minimum **30 ACH** for pump rooms and fuel storage hold spaces. **Fans:** Fans must be non-sparking; motors not located in the air	**LPG Carriers:** Cargo machinery spaces follow similar rules.	**Low Point Scavenging:** Designing suction points to effectively remove heavy gas from the lowest parts of the room (e.g., below floor plates).

					stream unless certified. **Operation:** Ventilation must be in operation when pumps/fuel treatment equipment are working.		
Space & Duct Ventilation	**ESS**	**Hazards:** Thermal runaway off-gas (explosive/toxic hydrogen, CO, organics). **Focus:** Removing explosive gases and cooling.	DNV Rules Pt.6 Ch.2 Sec.1.	**Gap:** Defining the "worst case" gas release volume for sizing fans is complex and varies by cell chemistry.	**Rate:** Calculation based on battery capacity; often 6 ACH minimum or specific formula based on cell volume. **Arrangement:** Exhaust at the highest point (hydrogen evolution); inlet low. **Safety:** Ventilation must start automatically upon gas detection; Exhaust must lead directly to open air.	**All-Electric Ferries:** High capacity banks require dedicated, robust ventilation trunks to safe areas.	**Off-Gas Ducting:** Integrating battery rack exhaust directly into a ventilation system vs. room ventilation. Protecting fans from high-temperature off-gases.

2.2.8 Fuel tank location

For hydrogen fuel, the design priority is the mitigation of leak accumulation and explosion risks, necessitating that tanks located on open decks maintain a minimum clearance of 800 mm from the vessel's shell plating to protect against collision damage. When placed within enclosed spaces, hydrogen tanks require gas-tight enclosures and typically utilise vacuum insulation to manage the extreme cryogenic temperatures of liquid hydrogen, while ensuring strict separation from passenger muster stations on Ro-Pax vessels to prevent exposure during venting events.

In the context of toxic and low-flashpoint liquids like methanol and ethanol, the configuration relies heavily on the use of integral tanks surrounded by protective cofferdams—typically 600 mm in width—to isolate fuel from machinery and accommodation spaces. Similar to hydrogen, methanol tanks positioned on open decks must adhere to the 800 mm minimum distance from the ship's side, and integral designs must avoid location within Category A machinery spaces to minimise fire risks. Ammonia fuel introduces even more stringent spatial constraints due to its high toxicity; regulations mandate the establishment of extensive toxic zones, requiring pressure relief valve outlets to be positioned at least 25 metres from air intakes or openings, and 10 metres from other release sources.

Methane (LNG) and LPG storage strategies are fundamentally driven by collision protection and thermal management, requiring tanks to be situated inboard at a distance of at least B/5 or 11.5 metres from the ship's side to prevent breach during impact. Furthermore, LNG tanks require specific bottom clearances of B/15 or 2.0 metres, and their placement often competes with valuable cargo space due to the preference for avoiding enclosed machinery spaces. Finally, biofuels such as FAME generally utilise drop-in tank arrangements but require specific provisions for heating coils to maintain temperatures above the cloud point and strict material exclusion of copper and zinc to prevent oxidation and sediment accumulation.

Table 17. Alternative Fuel Tank Arrangement and Siting Standards

Design Element	EET (Alternative Fuel)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Tank Arrangement & Siting	**Hydrogen Fuel (Liquid/Gas)**	**Hazards:** High flammability, hydrogen embrittlement, cryogenic liquid (-253°C), buoyancy of gas (accumulates in ceilings). **Focus:** Open deck location preferred to prevent accumulation in enclosed spaces.	ABS Requirements for Hydrogen Fuelled Vessels Sec 5 RINA Pt. C	**Barrier:** High volume requirement (5-7 times MGO) competes with cargo space.	**Deck Distance:** Fuel tanks located on deck must not be located less than 800mm from the vessel's side. **Protection:** Tanks on open decks must be protected against mechanical damage and surrounded by coamings (for liquid). **Enclosed Spaces:** Tanks in enclosed spaces require gas-tight enclosures and vacuum insulation is typically required.	**Ferries:** Often place tanks on top decks for safety and easy venting. **Ro-Pax:** Strict separation from passenger muster stations required.	**Mechanical Protection:** Ensuring tanks located on open decks are protected from collision and cargo handling damage. **Ventilation:** Preventing gas pockets in overheads if tanks are in semi-enclosed spaces.
Tank Arrangement & Siting	**Methanol / Ethanol Fuel**	**Hazards:** Toxicity, low flashpoint (~10-12°C), corrosive to certain metals. **Focus:** Integral tanks with cofferdams.	ABS Guide for Methanol/Ethanol Fuelled Vessels Sec 5 RINA Pt. C	**Gap:** Optimising cofferdam arrangement to minimise lost cargo volume in integral tank designs.	**Deck Distance:** Fuel tanks located on deck must not be located less than 800mm from the vessel's side.	**Chemical Tankers:** Cargo tanks often used as fuel tanks; requires specific connection logic.	**Cofferdam Design:** Designing cofferdams (typically 600mm width) to separate fuel from machinery and accommodation.

					Integral Tanks: Integral fuel tanks must be surrounded by protective cofferdams (except surfaces bound by shell plating below the lowest possible waterline). **Separation:** Tanks must not be located within accommodation spaces or Category A machinery spaces.	**Container Ships:** Integral tanks often located between cargo holds with cofferdams.	**Corrosion:** Applying zinc silicate or equivalent coatings compatible with methanol.
Tank Arrangement & Siting	**Ammonia Fuel (NH_3)**	**Hazards:** High toxicity, stress corrosion cracking. **Focus:** Strict physical separation from personnel areas and preventing toxic ingress.	ABS Requirements for Ammonia Fuelled Vessels Sec 5, Sec 6 RINA Pt. C	**Barrier:** Large safety zones (toxic areas) reduce available deck space for operations.	**Toxic Zones:** Fuel tank PRV vent exits must be at least B or 25 m (whichever is less) from air intakes/openings. **Separation:** Fuel containment systems must be separated from Category A machinery spaces and high fire risk areas. **Protection:** Tanks on open deck must be protected by water spray systems.	**Gas Carriers:** Ammonia cargo used as fuel; specific restrictions on location relative to accommodation. **Tugs/Workboats:** High toxicity makes tank location on small vessels challenging due to distance requirements.	**Distance Management:** Maintaining the **25 m** safety distance from vent masts to accommodation intakes. **Containment:** Ensuring secondary barriers for Type A/B tanks to prevent hull cooling in case of leak.

Tank Arrangement & Siting	**Methane Fuel (LNG)**	**Hazards:** Cryogenic (-163°C), flammable gas. **Focus:** Collision protection and boil-off management.	DNV Rules Pt.6 Ch.2 Sec.5, RINA Pt. C	**Barrier:** "Not in enclosed spaces" preference often forces tanks to valuable cargo deck areas.	**Collision Protection:** Fuel tanks must be located at a minimum distance of B/5 or 11.5 m (whichever is less) inboard from the ship side. **Bottom Clearance:** Lowermost boundary must be above the minimum distance of B/15 or 2.0 m (whichever is less). **Location:** Tanks should not be located within machinery spaces of Category A.	**Cruise Ships:** Large Type C tanks often located in deep holds requiring large void spaces. **Container Ships:** Membrane tanks often utilised to maximise volume efficiency.	**Space Efficiency:** Balancing the B/5 collision protection requirement with cargo capacity. **Heat Ingress:** Minimising heat transfer to keep boil-off gas within manageable limits.
Tank Arrangement & Siting	**LPG / Bio-DME**	**Hazards:** Heavier than air gas (accumulates low), flammability. **Focus:** Low-point leak detection and containment.	DNV Rules Pt.6 Ch.2 Sec.13 RINA Pt. C	**Gap:** Lack of specific "drop-in" tank rules for Bio-DME; usually follows LPG rules.	**Collision Protection:** Similar to LNG, tanks must be located B/5 or 11.5 m inboard. **Location:** Fuel tanks should not be located within machinery spaces or accommodation spaces. **Containment:** Independent tanks (Type A, B, C) are required; Type C is most common.	**LPG Carriers:** Cargo used as fuel; tanks already compliant. **RoPax:** Tanks often on deck to mitigate heavy gas accumulation risks in holds.	**Heavy Gas Management:** Designing tank rooms so that heavier-than-air gas does not accumulate in bilges; requires physical separation from machinery spaces.

Tank Arrangement & Siting	**LOHC** (H_2 Carrier)	**Hazards:** Chemical toxicity, thermal management. **Focus:** Integration with heat sources for dehydrogenation.	ABS Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels.	**Barrier:** High volume required and proximity to waste heat sources (engines) for efficiency.	**Tank Type:** Standard liquid tanks (coated) generally suffice, similar to product tankers. **Location:** Proximity to the release unit (reactor) is critical for system efficiency but must maintain safety segregation.	**Tankers/Cargo:** High volume tanks fit well in hull.	**Heat Integration:** Designing tank location to facilitate heat transfer from engine exhaust/jacket water to the fuel release system.

2.3 Renewable Energy Integration

The integration of Wind Assisted Propulsion Systems (WAPS) and alternative fuels into the maritime industry is guided by a framework of technical standards and reports. The provided sources include classification rules, as well as comprehensive reports. These documents establish the requirements for structural integrity, safety systems, and environmental compliance for technologies such as rotor sails, wing sails, and alternative fuels like ammonia and hydrogen.

• ABS (2022) - 'Requirements for Wind Assisted Propulsion System Installation'

• DNV (2020) - 'Rules for classification: Ships — Part 6 Additional class notations, Chapter 2 Propulsion, power generation and auxiliary systems'

• EMSA (2023) - 'Potential of Wind-Assisted Propulsion for Shipping'

• DNV (2025) - 'WIND-ASSISTED PROPULSION SYSTEMS (WAPS): How WAPS can help to comply with GHG regulations'

• KR (2024) - 'Guidance for Prevention System of Pollution from Ships (GC-36-K)'

Table 18 highlights that for Flettner Rotors, the primary engineering challenge lies in the foundation design, which must accommodate the significant weight of the unit—often constituting approximately 30% of the total system mass—while transferring thrust forces and withstanding vibrations caused by rotation speeds that can reach 180 rpm for a standard 30 by 5-metre unit. These structural considerations extend to the vessel's hull, where materials typically must be steel or equivalent to handle static and dynamic loads, including those from green seas, requiring rigorous load analysis as mandated by classification guidelines.

Beyond structural mechanics, the implementation of foil-based technologies such as Rigid wing sails and Wing Sails introduces critical stability and clearance challenges. The large lateral windage area of these systems necessitates a careful reassessment of both intact and damage stability, as current regulatory criteria may not fully account for dynamic stability failures or excessive accelerations induced by large sails. To mitigate the risk of collision with overhead obstacles like bridges and gantry cranes, these systems generally require foldable or tiltable stowage positions, a design focus that is particularly pertinent for container ships and Ro-Ro vessels where air draft is a limiting factor. Furthermore, the aerodynamic interaction between multiple units must be optimised, as seen with suction wings

(VentoFoils), where improper spacing can lead to thrust reductions of up to 16% due to interaction effects.

Navigational safety remains a paramount regulatory concern, specifically regarding the obstruction of bridge visibility and radar interference caused by deck-mounted units. Compliance with SOLAS Chapter V Regulation 22 is strictly monitored, requiring that radar blind sectors do not exceed 10 degrees individually or a total arc of 20 degrees, a standard that often necessitates the installation of additional cameras or radar systems to compensate for visual impairments. This issue is most acute on General Cargo and Bulk Carriers where the bridge is located aft, creating significant forward visibility challenges that designers must address through strategic arrangement planning to ensure navigation lights and critical sectors remain unblocked. Additionally, safety zones for operations such as helicopter landings must be maintained, typically requiring a clearance area of twice the helideck diameter or specific distances ranging from 16 to 22 metres depending on the aircraft type.

Operational and environmental resilience further dictates the design parameters of these technologies. Active systems like Suction Wings are designed to operate within specific wind windows, reaching maximum fan revolutions at wind speeds between 14 and 17 m/s and transitioning to a weathervaning mode for survival when speeds exceed 22 m/s. Electrical integration for these active systems poses its own set of hazards, including the risk of overheating and harmonic distortion from Variable Frequency Drives (VFDs), necessitating independent emergency stops and certification for motors exceeding 100 kW. Finally, environmental factors such as ice accretion and lightning strikes must be managed through dedicated protection systems, such as ice-prevention modes where rotors idle at 30 rpm to shed ice, and robust lightning protection measures per IEC standards, ensuring the vessel's safety in diverse climatic conditions ranging from -20°C to 50°C.

Table 18. Comprehensive Design and Regulatory Matrix for Marine Renewable Energy Technologies (WAPS & Solar)

Design Element	EET (Technology)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Structure & Foundations	**Flettner Rotors (Rotor Sails)**	**Characteristics:** Spinning vertical cylinders utilising the Magnus effect to generate thrust. **Hazards:** High rotation speeds (e.g., 180 rpm for 30x5m unit) cause vibration and noise. Large windage area increases structural load. **Focus:** Foundation strength to transfer thrust forces to the hull.	ABS Guide Sec 2/2.1 DNV-ST-0511 KR Guidance Ch 5	**Gap:** Lack of customised load determination requirements for different WAPS types in some class rules. **Barrier:** Retrofitting requires significant steel work for foundations.	**Requirement:** Foundation structure must withstand static and dynamic loads including green sea loads. **Standard:** Materials for support structure generally must be steel or equivalent (ABS Part 2).	**Tankers/Bulk Carriers:** Well-suited due to ample deck space. **Passenger Ships:** Noise/vibration analysis required for passenger comfort (Comfort Class).	**Challenge:** Foundation weight is significant (approx. 30% of total unit weight). **Focus:** Drains in the foundation to handle condensation/water ingress.
Stability & Air Draft	**Rigid wing sails**	**Characteristics:** Foil-like structures with high lift-to-drag ratio. **Hazards:** Large lateral windage area affects intact and damage stability. High air draft poses collision risk with bridges/cranes.	ABS Guide Sec 3/3 KR Guidance Ch 5 307.	**Gap:** Current criteria do not fully address dynamic stability failures (e.g., excessive acceleration) caused by large sails. **Barrier:** Adverse heeling moment may require reassessment of damage stability.	**Requirement:** WAPS must have a stowage position (foldable/tiltable) for adverse weather or port operations. **Standard:** Evidence of sufficient intact stability under worst load cases required.	**Container Ships:** High air draft may interfere with gantry cranes; typically lack deck space. **Ro-Ro:** Potential for stability issues due to high vertical centre of gravity.	**Challenge:** Balancing aerodynamic efficiency with stability limits. **Focus:** Systems often designed to be tiltable to reduce air draft and stability risks in storms.

Aerodynamics & Operations	**Suction Wing (VentoFoil)**	**Characteristics:** Wing-shaped with internal fans using boundary layer suction for high lift. **Hazards:** Fan failure reduces lift. Interaction between multiple wings can reduce thrust by up to 16%.	DNV-ST-0511 KR Guidance Ch 5.	**Gap:** Lack of standardised full-scale sea trial verification methods. **Barrier:** Operational restrictions in narrow channels or when pilot is onboard.	**Requirement:** Fans must be IP66 rated for marine environment. **Standard:** System designed to withstand wind speeds of 14-17 m/s at max revs, weathervaning at >22 m/s.	**General Cargo:** Highly suitable; often installed as retrofits. **Fishing Vessels:** Successfully installed on smaller vessels.	**Challenge:** Suction fans require continuous power supply. **Focus:** Optimal spacing to minimise aerodynamic interaction losses.
Deployment & Safety	**Kite propulsion systems**	**Characteristics:** Tethered aerofoil flying at high altitude (dynamic or passive). **Hazards:** Launch/recovery failure in high winds. Line snapping. Entanglement with ship structures.	DNV-ST-0511	**Gap:** EEDI calculation is difficult due to dynamic nature. **Barrier:** Cannot be used in head winds; reliance on specific wind angles.	**Requirement:** Emergency release system required. **Mitigation:** Automated launch/retraction systems to minimise crew risk.	**Bulk Carriers:** Suitable due to open deck for launch. **Vessels with limited deck space:** Alternative option where deck units don't fit.	**Challenge:** Route optimisation is critical as kites operate best at specific wind angles. **Focus:** Bow reinforcement for tether attachment point.
Machinery & Electrical	**Flettner Rotors & Suction Wings**	**Characteristics:** Active systems requiring electrical power for rotation/suction. **Hazards:** Overheating of motors. Harmonics from Variable Frequency Drives (VFD). Electrical fire.	ABS Guide Sec 2/3.2 KR Guidance Ch 6 303.	**Gap:** Clarification needed on "hybrid propulsion" definition for EEDI exemptions.	**Requirement:** Electrical motors >100 kW must be certified. **Standard:** independent emergency stop from navigation bridge and engine control room.	**Tankers/Gas Carriers:** Electrical equipment in hazardous areas must be EX-rated/certified safe type.	**Challenge:** Integrating high-power demands into existing board net. **Focus:** Electrical load analysis to ensure sufficient power availability.
Environmental & Weather	**All WAPS (Rotors, Sails, Wings)**	**Hazards:** Ice accumulation affects stability and adds weight. Green sea loads damage bearings/structure. Lightning strike risk.	ABS Guide Sec 3/2.2.3 KR Guidance Ch 5 304.	**Gap:** MPP (Minimum Propulsion Power) guidelines may need updating to account	**Requirement:** Ice prevention mode (e.g., Rotors spin at 30 rpm idle to shed ice).	**Ice-Class Vessels:** Must verify stability with ice accretion on WAPS.	**Challenge:** Designing for survival conditions (e.g., 55 m/s wind static load).

				for windage area in adverse conditions.	**Standard:** Lightning protection per IEC 60092-401.	**North Atlantic Trade:** Design must account for severe wave loads.	**Focus:** De-icing systems or coatings.
Auxiliary Power	**Solar Panels**	**Characteristics:** Can be mounted on hard sails to generate extra power. **Hazards:** Reflection/glare affecting bridge visibility. Damage from green water/weather.	ABS Part 4 Ch 8).	**Gap:** Specific regulations for solar propulsion on large commercial vessels are limited in the provided texts compared to WAPS.	**Requirement:** Integration with onboard power supply must follow standard electrical load analysis.	**All Ship Types:** Supplementary power generation; generally not primary propulsion.	**Challenge:** Limited surface area on sails versus power generation needs. **Focus:** Weight addition to the sail structure affects stability calculations.

2.4 Propulsion and Hull Technologies

Major classification societies have developed comprehensive rules covering propulsion systems, machinery, and specific notations for alternative fuels and energy storage.

• ABS (2018) - 'Rules for Building and Classing Marine Vessels, Part 4 Vessel Systems and Machinery'

• DNV (2020) - 'Rules for Classification: Ships, Part 6 Additional class notations, Chapter 2 Propulsion, power generation and auxiliary systems'

• DNV (2011) - 'Rules for Ships / High Speed, Light Craft and Naval Surface Craft, Part 4 Chapter 2 Newbuildings Machinery and Systems – Main Class - Rotating Machinery, General'

• MAN Energy Solutions (2023) - 'Basic principles of ship propulsion: Optimisation of hull, propeller, and engine'

• RINA (2024) – 'Rules for the Classification of Ships – Part B Hull and Stability'

• RINA (2024) – 'Rules for the Classification of Ships – Part C Machinery, Systems and Fire Protection'

• RINA (2024) – 'Rules for the Classification of Ships – Part F Additional Class Notations'

Technologies designed to condition the flow entering the propeller disc, such as pre-swirl fins and wake equalising ducts, primarily focus on aligning the wake field to reduce rotational losses and flow separation. While pre-swirl fins can offer power savings between 3-5%, their design must be intricately matched to the specific hull wake field to ensure that the added wetted surface resistance does not negate the efficiency gains. Similarly, wake equalizing ducts are particularly effective for fuller hull forms like bulkers and tankers where uneven wake fields are common, potentially yielding savings of 3-8% provided the structure can withstand substantial hydrodynamic loads without inducing fatigue.

Addressing losses at the propeller hub and slipstream is another critical area of intervention where devices like Propeller Boss Cap Fins (PBCF) and gate rudders target the elimination of the low-pressure hub vortex. PBCFs are noted for their ease of retrofit and potential savings of 2-5%, though material compatibility—specifically matching the fin material to the propeller's bronze or stainless steel—is essential to prevent galvanic corrosion. Gate rudders serve a similar hydrodynamic function by streamlining the transition from the hub to the rudder, which is particularly beneficial for Controllable Pitch (CP) propeller vessels where the larger hub diameter ratio, typically 0.22-0.30, otherwise incurs significant efficiency penalties.

For vessels requiring fundamental changes to meet EEXI compliance, propeller retrofitting involves replacing existing units with optimised designs, often necessitating a careful re-evaluation of the Light Running Margin (LRM). A recommended LRM of 4-7% is standard to account for fouling and sea margins, though this may extend to 10% in special cases to prevent engine overloading during heavy weather. More complex propulsion arrangements like Contra-Rotating Propellers (CRP) offer higher efficiency gains of 4-7% by recovering rotational energy through coaxial shafts, yet they introduce significant engineering challenges regarding shaft sealing and torsional vibration management. Alternatively, for vessels requiring high thrust at low speeds such as tugs, propeller ducts or nozzles utilise annular aerofoil rings to augment thrust, requiring precise blade tip clearance and robust structural design to mitigate cavitation erosion and hydrodynamic forces.

All these hydrodynamic modifications are bound by strict mechanical and safety constraints to ensure structural integrity and operational safety. For instance, keyless propeller fittings require a safety factor against slip of at least 2.8 at 35°C, while shaft alignment must ensure relative misalignment slopes do not exceed 0.3×10^{-3} rad to protect bearings. Furthermore, bearing loads are strictly regulated, with white-metal lined bearings limited to a nominal pressure of 0.80 N/mm² to ensure operational reliability under the altered load conditions introduced by these energy-saving devices.

Table 19. Comprehensive Design and Regulatory Analysis of Propeller-Based Energy Saving Technologies (EETs)

Design Element	EET	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Hydrodynamics & Flow Optimization	**Pre-swirl Fins**	**Characteristic:** Devices placed before the propeller to reduce rotational losses in the propeller slipstream. **Hazard:** Potential vibration if not matched to propeller inflow. **Focus:** Aligning flow to improve propeller efficiency.	ABS Pt.4 Ch.3 Sec.3 MAN Energy Solutions	Specific structural strength rules for the fins themselves are often generic hull appendage rules rather than specific machinery rules.	**Performance:** Capability to provide **3-5%** power saving. **Integration:** Must be evaluated against added wetted surface resistance.	**Container Ships/Bulkers:** Effective for optimising flow on slower, full-form ships or high-speed liners.	**Wake Interaction:** Must be designed based on the specific wake field of the hull; savings cannot simply be added to other devices.
Hub Efficiency & Vortex Control	**Propeller Boss Cap Fin (PBCF)**	**Characteristic:** Fins attached to the propeller hub cap to reduce hub vortex losses. **Hazard:** Mechanical failure of attachment bolts. **Focus:** Eliminating low pressure behind the hub.	ABS Pt.4 Ch.3 Sec.3 MAN Energy Solutions	Limited specific regulation on the fin geometry itself; relies on general propeller fitting standards.	**Material:** Must match propeller material (e.g., bronze/stainless steel) to prevent galvanic corrosion. **Efficiency:** Potential savings of **2-5%**.	**All Vessels:** Simple, maintenance-free solution applicable to most screw propellers.	**Retrofit:** Easy to retrofit, but must ensure secure attachment to the existing hub to prevent detachment.
Rudder & Slipstream Integration	**Gate Rudder**	**Characteristic:** Bulb on the rudder aligned with the propeller hub to reduce hub vortex losses.	ABS Pt.4 Ch.3 Sec.4 MAN Energy Solutions	Interaction between gaterudder and propeller removal procedures	**Clearance:** Must maintain adequate clearance from propeller hub.	**CP Propeller Vessels:** A gate rudder significantly reduces the efficiency difference between	**Integration:** Reduces efficiency loss caused by the larger hub diameter of CP propellers (typically 0.22-0.30 hub/diameter ratio).

		Focus: Streamlining the transition from propeller hub to rudder.	RINA Pt. C	(clearance for shaft withdrawal).	**Efficiency:** Potential savings of 2-5% (Gate rudder) or 2-6% (Efficiency Rudder).	Fixed Pitch (FP) and Controllable Pitch (CP) propellers.	
Wake Flow Management	**Wake Equalising Duct (Grothues Spoilers)**	**Characteristic:** Duct placed upstream of the propeller to equalise wake flow and reduce separation. **Focus:** Improving inflow to the propeller.	MAN Energy Solutions	High loads on duct attachments due to flow forces; requires robust structural integration.	**Performance:** Potential savings of 3-8%. **Structure:** Must withstand hydrodynamic loads without vibration or fatigue failure.	**Bulkers / Tankers:** Works best for ships with large block coefficients where wake fields are uneven.	**Drag vs. Thrust:** Potential savings must be evaluated against the added resistance of the duct structure itself.
Propulsion Efficiency & Redundancy	**Contra-Rotating Propellers (CRP)**	**Characteristic:** Two propellers rotating in opposite directions on coaxial shafts to recover rotational energy. **Focus:** Hydrodynamic efficiency and shaft sealing.	ABS Pt.4 Ch.3 Sec.9 MAN Energy Solutions RINA Pt. F	Complexity of shafting (inner/outer) and sealing limits widespread adoption; high maintenance requirements.	**Vibration:** Torsional vibration calculations required for both shafts (coupled and isolated modes). **Seals:** Effective means to prevent water access between inner/outer shafts. **Alarms:** Audible/visual alarms for inner/outer shaft RPM and bearing temp.	**Ro-Pax / Ferries:** Suitable for high-speed vessels or those requiring redundancy. **High Power:** Beneficial for highly loaded propellers.	**Shaft Alignment:** Evaluation must consider relative inclining angle between inner and outer shafts. **Efficiency:** Potential savings of **4-7%**.
Thrust Augmentation	**Propeller Duct (Nozzle / Cort or Rice)**	**Characteristic:** Annular aerofoil ring around the propeller to increase thrust at low speeds.	ABS Pt.4 Ch.3 Sec.5 RINA Pt. B	Cavitation erosion on the inner surface of the nozzle can be a maintenance issue.	**Blade Thickness:** Wide-tip blades in nozzles have specific thickness formulas: t0.35 calculation must	**Tugs / Trawlers:** High thrust at low speed (bollard pull).	**Tip Clearance:** Maintaining precise clearance between blade tips and nozzle to maximise thrust without contact.

		Focus: Blade tip clearance and structural strength.			account for distinctive coefficients. **Strength:** Duct must resist hydrodynamic forces.		
Modifications & Upgrades	**Propeller Retrofitting**	**Characteristic:** Replacing existing propellers with optimised designs (e.g., larger diameter, fewer blades). **Focus:** Matching engine torque limits and shaft alignment.	DNV Pt.4 Ch.2 Sec.10 MAN Energy Solutions RINA Pt. C	Retrofitting a larger/heavier propeller changes shaft dynamics, potentially requiring new vibration analysis.	**Torque Limit:** Engine torque limitation prevails; retrofit must not overload the engine. **Lubrication:** Forced lubrication may be omitted for retrofits unless damage history exists. **Power Limit:** Power limitation (EPL/Shaft Power Limit) often required to protect engine/shaft.	**EEDI/EEXI Compliance:** Used to improve efficiency for EEXI compliance. **Slow Steaming:** Optimising for lower operating speeds.	**Light Running Margin (LRM):** Retrofit often reduces LRM; recommended margin 4-7% (up to 10% special cases) to allow for heavy weather.

2.5 Operational Strategies

The provided source highlights the IMO development of safety guidelines for alternative fuels like ammonia and hydrogen, alongside the implementation of energy efficiency measures such as SEEMP. Concurrently, classification societies are establishing frameworks for hull condition monitoring to ensure structural integrity and operational safety under these new conditions.

• ABS (2020) – 'Guide for Hull Condition Monitoring System'

• RINA (2024) – 'Rules for the Classification of Ships – Part C Machinery, Systems and Fire Protection, Chapter 2 Electrical installations'

• RINA (2024) – 'Rules for the Classification of Ships – Part F Additional Class Notations'

In the domain of cargo and machinery systems, a primary focus lies on the optimisation of discharge operations where pumps and fans have historically operated at full load regardless of actual demand, leading to significant energy waste and equipment risk. To mitigate the hazards of cavitation and excessive energy consumption, the implementation of Variable Frequency Drives (VFD) is essential, as reducing pump speed by just 10% can yield power savings of approximately 27% according to affinity laws. Design considerations for these systems are increasingly influenced by the emergence of alternative fuels; for instance, ammonia cargo systems require rigorous risk assessments and safety protocols that differ from LNG standards, specifically necessitating gas detection alarms at 30% of the Lower Flammability Limit (LFL) and automatic shutdown at 60% LFL.

Operational efficiency is further enhanced through navigation and logistics strategies such as Just In Time (JIT) arrival and speed optimisation, which rely on adaptive algorithms to manage voyage profiles. These systems address the inefficiency of RPM fluctuations, which can cause propulsion energy losses of 4.7%, by smoothing operations to reduce losses to approximately 1%. For container vessels specifically, the sensitivity to fuel costs is so high that the payback period for such optimisation software can be less than two months. Parallel to speed management, weather routing systems are critical for avoiding heavy seas where energy loss can exceed 50% in waves greater than 10 metres. The design of these systems requires precise instrumentation, including accelerometers with an uncertainty of ±0.01g and wave radars that calculate statistical sea state parameters over 20 to 30-minute intervals to ensure the vessel remains within approved scantling limits.

In the engine room, propulsion operations such as slow steaming and controllable pitch propellers (CPP) present specific design challenges regarding engine health and power generation. Extended slow steaming, while effective for fuel reduction, risks engine fouling

and prevents standard shaft generators from functioning if the vessel drops below the design RPM. Consequently, modern designs must incorporate VFDs on shaft generators to enable power production over a wider speed range and utilise electronic governors with dedicated slow modes. Similarly, for vessels with CPP, running in "combinator mode" (variable RPM) rather than constant RPM is crucial to prevent turbulence and high fuel consumption, necessitating torque monitoring systems to identify the optimal pitch angle.

Finally, the hydrodynamic performance of the vessel is maintained through rigorous trim optimisation and comprehensive hull and propeller monitoring. Dynamic trim optimisation software, which can generate propulsion energy savings of up to 5%, is required to replace insufficient static tables by accounting for real-time changes in speed and draft. To sustain these efficiencies over the vessel's life, propeller performance monitoring using non-contact torque metres with stability better than 0.5% over ten years is recommended. This is complemented by hull monitoring systems that utilise long base strain gauges with an uncertainty of ±5 microstrain to track structural fatigue and biological fouling, the latter of which can impose a power penalty of approximately 30% if not managed through timely cleaning based on accurate data analysis.

Table 20. Operational Energy Efficiency Technologies and Hull Monitoring Systems

Design Element	EET (Operational Measure)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Cargo & Machinery Systems	**Cargo Handling Systems (Discharge Operation)**	**Characteristics:** Pumps/fans often run at 100% load continuously even when requirements are lower (e.g., 40%). **Hazards:** Cavitation in pumps due to over-dimensioning. Ammonia toxicity/flammability during handling. **Focus:** Variable Frequency Drives (VFD) to match motor speed to actual demand.	ABS Guide Hull condition	**Barrier:** Non-financial barriers such as split incentives and lack of cooperation between actors limit uptake.	**Ammonia Safety:** Risk assessment required for fuel system. Alarm at 30% LFL, Shutdown at 60% LFL (LNG) vs Risk Assessment based for Ammonia. **VFD:** 10% speed reduction = **27%** power saving (Affinity laws).	**Tankers:** Chemical/Product tankers with multiple cargo pumps. **Bulk Carriers:** Monitoring inner bottom structure during loading.	**Pumps:** Avoid cavitation damage to impellers caused by throttling; VFD reduces this risk. **Ammonia:** Double-walled piping required in machinery spaces; no openings permitted.
Navigation & Logistics	**JIT (Just In Time Arrival) / Speed Optimization**	**Characteristics:** Adjusting speed to meet ETA without anchoring, reducing fuel consumption. **Focus:** Software advising optimal RPM/speed profiles based on route and weather.	ABS Guide Hull condition	**Gap:** Fluctuations in RPM can cause 4.7% losses in propulsion energy; optimization can reduce this to 1%.	**Data:** Utilisation of adaptive algorithms to forecast ETA and fuel consumption. **Integration:** Link to loading computer for actual displacement data.	**Container Vessels:** High sensitivity to speed/fuel costs; payback time for optimisation can be < 2 months.	**Voyage Planning:** Must balance ETA requirements with weather forecasts to avoid "rushing and waiting".

Navigation & Safety	**Weather Routing**	**Characteristics:** Avoiding heavy weather (waves/wind) to reduce added resistance and ensure safety. **Focus:** Motion monitoring and forecasting systems.	ABS Guide Hull condition	**Gap:** Lack of real-time data on hull response to specific sea states.	**Sensors:** Accelerometers (uncertainty ±0.01g), Wave radar. **Calculation:** Statistical parameters calculated over 20-30 minutes.	**Heavy Lift Vessels:** Critical for crane operations/DP capability. **Container Ships:** Prevention of parametric roll.	**Energy Loss:** In heavy weather (e.g., >10m waves), >50% of energy can be spent fighting nature. **Safety:** Warning levels must reflect approved scantlings.
Propulsion Operations	**Slow Steaming**	**Characteristics:** Operating at reduced speed to significantly lower fuel consumption. **Hazards:** Low load operation causes engine fouling; Shaft generators may not function if fixed to engine RPM.	ABS Guide Hull condition RINA Pt. C	**Gap:** Fixed Pitch Propellers (FPP) with shaft generators cannot produce power if RPM drops below design point.	**Technology:** VFD on shaft generator enables power production over wider RPM range. **Governor:** Electronic governors with slow mode function.	**Oceangoing Vessels:** 2-stroke engines with FPP. **Container Ships:** Often have WHRS which requires >40% engine load to function.	**Engine Health:** Extended low load operation (<50%) requires specific engine tuning (VIT) to maintain efficiency and prevent damage.
Propulsion Control	**Propeller Pitch Optimization (CPP)**	**Characteristics:** Optimising the combination of RPM and blade pitch for Controllable Pitch Propellers. **Focus:** Moving from "Constant RPM" to "Combinator Mode" or variable speed.	ABS Guide Hull condition RINA Pt. C	**Gap:** Constant RPM mode (for shaft generators) causes high fuel consumption and propeller cavitation at low speeds.	**Control:** VFD allows shaft generator use during combinator mode (variable RPM). **Feedback:** Torque monitoring to identify optimal pitch.	**RoPax/Ferries:** Frequent manoeuvring and speed changes.	**Hydrodynamics:** Fast rotating propeller with low pitch creates significant inefficiency and turbulence/cavitation.
Hydrodynamics	**Trim and Draft Optimisation**	**Characteristics:** Adjusting ballast to achieve the optimal floating position for minimal resistance.	ABS Guide Hull condition	**Gap:** Optimal trim changes with speed and draft; static tables are often insufficient.	**Savings:** Potential up to **5%** of propulsion energy. **Data:** Must separate trim effects from wind/wave resistance.	**Container Vessels:** High sensitivity to trim due to hull form.	**Real-time Analysis:** Requires adaptive self-learning algorithms to advise crew based on current conditions, not just design point.

		Focus: Dynamic trim optimisation software (e.g., EMMA).					
Propulsion Monitoring	**Propeller Performance Monitoring**	**Characteristics:** Continuous measurement of shaft torque, power, and RPM. **Focus:** Shaft torque metres (e.g., Torductor).	ABS Guide Hull condition	**Gap:** Lack of accuracy in older systems prevents meaningful trend analysis.	**Sensor:** Non-contact transducers recommended. Free shaft length required: 250 mm. **Accuracy:** Better than 0.5% stability over 10 years.	**All Vessels:** Critical for EEOI reporting.	**Vibration:** System must detect torsional vibration (sampling 30 times/sec) to identify engine misfiring.
Structure & Hull	**Hull Monitoring (Fouling & Stress)**	**Characteristics:** Monitoring biological fouling (resistance) and structural stress/fatigue. **Focus:** Strain gauges, accelerometers, and performance algorithms.	ABS Guide Hull condition RINA Pt. F	**Gap:** Hull fouling resistance grows linearly with time; hard to separate from weather effects without advanced data.	**Sensors:** Long base strain gauges (uncertainty ±5 microstrain). **Locations:** Midships (port/starboard), 25% length from bow, 25% length from stern.	**Large Vessels:** Tankers/Bulk Carriers >200m recommended for stress monitoring. **Membrane LH_2 Carriers:** Vacuum monitoring required.	**Maintenance:** Hull fouling can cause **~30%** power penalty; determining exact cleaning time is critical. **Fatigue:** Bin size for fatigue counting 50 microstrain.

2.6 Engineering Optimisation

Major classification societies are developing rules and guidelines for alternative arrangements, carbon capture, and specific machinery systems. These documents provide the necessary safety standards and classification criteria for adopting new technologies, alternative fuels, and pollution prevention equipment in marine applications.

• ABS (2024) - 'Rules for Alternative Arrangements, Novel Concepts and New Technologies'

• ABS (2023) - 'Requirements for Onboard Carbon Capture and Storage'

• DNV (2020) - 'Rules for Classification: Ships - Part 6 Additional class notations - Chapter 2 Propulsion, power generation and auxiliary systems'

• DNV (2016) - 'Rules for Classification: Ships - Part 4 Newbuildings Machinery and Systems - Main Class - Chapter 6 Piping systems'

• KR (2024) - 'Guidance for Prevention Systems of Pollution from Ships'

• RINA (2024) – 'Rules for the Classification of Ships – Part C Machinery, Systems and Fire Protection, Chapter 2 Electrical installations'

• RINA (2024) – 'Rules for the Classification of Ships – Part F Additional Class Notations'

Regarding Main Engine (M/E) improvements, specifically the adoption of common rail and electronic engine controls, the design priority shifts toward managing the risks associated with precise high-pressure fuel injection. Regulatory standards explicitly mandate that high-pressure pipes be jacketed and equipped with leakage alarms to prevent fire hazards, while fuel oil pressure must be continuously monitored with low-pressure alarms to safeguard engine availability. For specific vessel types such as tankers, safety measures are intensified, requiring fuel tanks located on open decks to be protected by water spray systems with a capacity of 10 l/min/m², and structural design must ensure fuel tanks maintain a minimum separation distance of B/5 or 11.5 metres from the ship side to mitigate collision risks.

In the realm of auxiliary systems optimisation, the implementation of variable speed drives for pumps and fans introduces specific requirements for flow control, redundancy, and system stability. While these systems optimise flow via RPM control, regulations stipulate that fuel feed rates to separators must be directly controlled by pump frequency and that manual bypass means must be available to ensure continuous operation if the frequency control fails.

Furthermore, fluid dynamic requirements remain stringent regardless of energy optimisation; bilge pumps must maintain a water velocity of at least 2 m/s to ensure effective drainage, and redundancy protocols require that any loss of function in critical systems be restorable within 15 minutes.

The optimisation of HVAC and cooling systems frequently involves the use of alternative refrigerants like Ammonia (R717) or CO_2 (R744), necessitating rigorous management of toxicity, flammability, and high-pressure hazards. Design standards dictate that refrigeration machinery rooms must be separated by steel bulkheads and equipped with high-capacity ventilation systems capable of 30 air changes per hour to disperse potential leaks. Safety protocols for ammonia are particularly granular, requiring multi-tiered alarm systems triggering at thresholds ranging from 150 ppm for initial detection to 5000 ppm for automatic shutdown, alongside strict material compatibility rules that prohibit the use of copper with ammonia to prevent catastrophic corrosion.

Thermal energy management through steam plant optimisation requires detailed stress analysis and insulation strategies to handle high-temperature operations safely. Systems operating with steam temperatures exceeding 400°C necessitate thermal stress analysis to prevent structural failure, while piping must be designed to absorb expansion without developing substantial stresses. To prevent fire hazards in machinery spaces, surfaces exceeding 220°C must be insulated to prevent the ignition of leaked oil, and drainage systems must be configured to avoid water pockets that could lead to dangerous water hammer effects.

Finally, efforts to reduce auxiliary power demand through lighting and electrical load optimisation must not compromise the availability of essential services or safety systems. Regulations enforce the division of lighting in hazardous areas into at least two branch circuits to prevent total darkness during a fault, and specific load analyses must account for all future consumers. For passenger vessels, safety requirements are paramount, mandating that lighting along escape routes remains operational for three hours following a casualty to ensure safe evacuation.

Table 21. Regulatory Requirements and Design Considerations for Optimised Engineering Systems

Design Element	EET (Energy Efficiency Technology)	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
M/E Improvements	**Common Rail / Electronic Engine Control**	**Characteristics:** Precise fuel injection control. **Hazards:** Leakage from high-pressure pipes; Loss of control power; Failure of electronic components. **Focus:** Fuel oil pressure, viscosity, and temperature control.	DNV Pt.6 Ch.2, DNV Pt.4 Ch.6 Sec.5 KR Ch.2	Not explicitly detailed in provided sources regarding tuning algorithms.	**Leakage Protection:** Jacketed high-pressure pipes with leakage alarms are required. **Monitoring:** Common rail fuel oil pressure must be monitored (Low Alarm required). **Automation:** Automatic fuel changeover systems must be monitored to ensure continuous availability.	**Gas Fuelled/Dual Fuel Ships:** Requires inerting of fuel tanks (oxygen content < 5%). **Tankers:** Fuel tanks located on open deck must be protected by water spray (10 l/min/m² for horizontal surfaces).	**Separation:** Fuel tanks must be located at a minimum distance of **B/5 or 11.5m**, whichever is less, from the ship side. **Redundancy:** One single failure in the fuel supply system shall not lead to total loss of fuel supply (for LFL-only engines).
Auxiliary Systems Optimisation	**Pumps & Fans (Variable Speed/Frequency Control)**	**Characteristics:** Optimisation of flow via RPM control. **Hazards:** Loss of cooling/lubrication due to pump failure; vibration; fire. **Focus:** Capacity, redundancy, and pressure control.	DNV Pt.4 Ch.6 Sec.4, Sec.5 KR Ch.2	Specific VFD energy saving metrics are not detailed in safety rules.	**Flow Control:** Fuel feed rate to separators shall be controlled by means of rpm (frequency) of feed pump. **Redundancy:** Time lag to restore lost	**Passenger Ships:** Must have at least three branch bilge suctions.	**Control Stability:** Interfaces to other ship systems must prevent backflow. **Availability:** If frequency control fails, manual operation or bypass means must be available to ensure continuous operation.

					function shall not be more than 15 minutes. **Capacity:** Bilge pumps must provide water velocity of at least 2 m/s.		
HVAC & Cooling Systems	**Refrigeration & Cooling Improvements**	**Characteristics:** Use of R717 (Ammonia) or R744 (CO_2). **Hazards:** Toxicity (Group 2 refrigerants), flammability, suffocation, high pressure. **Focus:** Leakage detection and ventilation.	DNV Pt.4 Ch.6 Sec.6, DNV Pt.4 Ch.6 Table C3	Absorption chiller specific performance standards not detailed.	**Ventilation:** Refrigeration machinery rooms require 30 air changes per hour. **Leakage** Detection (R717): Alarms at 150 ppm (initial), 350 ppm (access dangerous), and 5000 ppm (automatic shutdown). **Pressure (R744):** Low pressure alarm required above triple point (approx. **5.2 bar**).	**Fishing Vessels:** Specific rules for refrigerated cargo spaces. **Vessels < 65m:** R717 systems with < 25 kg filling may be located in engine room if hood/water spray provided.	**Material Compatibility:** Copper must not be combined with ammonia; zinc must not be combined with ammonia or fluorinated hydrocarbons. **Separation:** Refrigeration machinery rooms must be separated by steel decks/bulkheads.
Steam / Heat Plant	**Steam Piping & Heating Optimisation**	**Characteristics:** High-temperature steam distribution.	DNV Pt.4 Ch.6 Sec.9 DNV Pt.4 Ch.6 Sec.4,	Waste heat recovery efficiency metrics not detailed.	**Thermal Stress:** Analysis required for steam temperatures exceeding 400°C.	**Tankers:** Steam coils in cargo tanks have specific corrosion allowance (2 mm).	**Expansion:** Piping must absorb thermal expansion/contraction without developing substantial stresses.

		Hazards: Thermal expansion stress, water hammer, hot surface ignition. **Focus:** Thermal stress analysis and insulation.			**Insulation:** Surfaces > 220°C must be insulated to prevent ignition of leaked oil. **Drainage:** Water pockets must be avoided to prevent water hammer; drain cocks required.		**Monitoring:** Pipes > 450°C may require calibrated gauge lengths for creep checking.
Reduced Auxiliary Power	**Lighting & General Electrical Loads**	**Characteristics:** Reduction of electrical load. **Hazards:** Blackout, loss of emergency lighting. **Focus:** Availability and hazardous area safety.	DNV Pt.6 Ch.2 Sec.2 DNV Pt.4 Ch.6 Sec.5	Specific "Low Energy" (LED) standards not detailed in sources.	**Emergency Lighting:** Portable rechargeable battery lighting accepted if charging capability provided. **Hazardous Areas:** Lighting in hazardous areas must be divided between at least two branch circuits.	**Passenger Ships:** Lighting along escape routes must remain operational for 3 hours after a casualty (SRtP).	**Load Analysis:** Electrical load analysis must include all future consumer loads (e.g., scrubber pumps). **Dimming:** Alarm indicators on bridge cannot be dimmed below visibility in normal daylight.

2.7 Hydrodynamics

Major classification societies have established comprehensive guidelines to address structural integrity through coating maintenance and to enhance vessel performance via innovative technologies. These documents provide the necessary criteria for adopting air lubrication systems to reduce carbon emissions.

- ABS (2017) - 'Guidance Notes on Maintenance and Repair of Protective Coatings'
- ABS (2019) - 'Air Lubrication Technology'
- RINA (2024) – 'Rules for the Classification of Ships – Part B Hull and Stability'
- RINA (2024) – 'Rules for the Classification of Ships – Part E Service Notations'
- RINA (2024) – 'Rules for the Classification of Ships – Part F Additional Class Notations'

Table 22 offers a comprehensive analysis of Hydrodynamic EETs, predominantly focusing on Air Lubrication Systems (ALS) and the associated structural and material considerations necessary for their implementation. The central technology analysed is the air lubrication system, which functions by injecting air beneath the hull to generate bubble, air layer, or partial cavity drag reduction. This technology is particularly significant for low-speed displacement vessels where frictional resistance constitutes up to 85% of total resistance, offering potential net energy savings ranging from 4% to 10%. However, the realisation of these benefits is technically demanding, as the generation of optimal micro-bubbles smaller than 0.1 mm is difficult to achieve on full-scale ships and less effective at lower speeds due to buoyancy effects.

From a regulatory and safety perspective, the installation of ALS and related hydrodynamic systems is governed by a framework involving IMO circulars, such as MEPC.1/Circ.815, and specific classification society guideline like ABS. A critical design focus identified in the table is vessel stability; the added weight of compressors and piping necessitates a mandatory stability re-evaluation if the lightship displacement changes by more than 2% or if the longitudinal centre of gravity shifts by more than 1.0% of the length between perpendiculars. Furthermore, safety standards dictate that air supply piping must be treated with the same rigor as compressed air piping, requiring independent systems, galvanic corrosion prevention for distance pieces, and sufficient ventilation in machinery spaces.

The structural integration of these technologies presents specific challenges regarding the optimisation of water flow hull openings. Creating penetrations for air dispensers introduces risks of stress concentration and structural integrity compromise. Consequently, design standards mandate that such openings incorporate sufficient corner rounding and reinforcement, especially

when located forward of the collision bulkhead, to maintain the hull girder section modulus. To prevent flooding, the design must ensure watertight integrity through the use of non-return valves or loops in the air piping, alongside valves that feature open/close indicators and manual operation capabilities for failure modes.

Complementing mechanical interventions, the matrix highlights the role of hull coatings in hydrodynamic efficiency. While ALS reduces the wetted surface density, coatings are essential for reducing skin friction, and the combination of superhydrophobic surfaces with air layers can significantly improve the economy of drag reduction. The maintenance of these coatings is strictly regulated under standards like the PSPC to prevent corrosion, which increases roughness and drag. Requirements for coating application are stringent, necessitating salt contamination limits of 80 mg/m² and environmental controls where steel temperature must remain 3°C above the dew point. Finally, the design process involves trade-offs, such as balancing the hydrodynamic gains of bow enhancements or ALS against the weight penalties that conflict with Super Light Ship design goals.

Table 22. Hydrodynamic Energy Efficiency Technologies (EET) Design

Design Element	EET	Key Characteristics/Hazards and Primary Design Focus	Regulation & Guidance References	Regulatory Gaps / Barriers	Key Requirements / Mitigation Standards	Specific Ship Type/Service Considerations	Design Considerations/Challenges (Primary Design Focus)
Hydrodynamics / Machinery	**Air Lubrication System (ALS)**	**Characteristics:** Reduces frictional resistance by pumping air beneath the hull (Bubble Drag Reduction, Air Layer Drag Reduction, Partial Cavity Drag Reduction). Frictional resistance can reach 85% of total resistance for low-speed displacement vessels. Net energy savings reported range between 4% to 10%. **Hazards:** Potential loss of stability due to changes in lightship weight. Structural stress concentrations at air dispenser openings.	ABS Guide Air lubrication system RINA Pt. F	**Barriers:** Micro-bubbles (less than 0.1 mm) are efficient but difficult to produce on full-scale ships and less effective at low speeds due to buoyancy. Net savings are difficult to determine as older sea trial data were not collected for EEDI compliance.	**Stability:** Stability re-evaluation is required if lightship displacement changes by > 2% or LCG changes by > 1.0% of LBP. **Piping:** Air supply piping is treated as compressed air piping. Distance pieces connecting to air chambers must follow Rules Pt 5, Ch 6, 301.2. **Safety:** Fail-safe design required for control/alarm systems. Remote and local emergency stop means required.	**Applied Vessels:** Cruise ships (e.g., *Quantum of the Sea*, *AIDAprima*), Heavy Cargo Carriers, LNG Carriers, Ferries, Bulk Carriers, Chemical Tankers. **Considerations:** For low-speed displacement vessels, frictional resistance is dominant (85%), making ALS highly effective. Cruise ships recently delivered (2015-2018) frequently install ALS.	**Structural:** Installation of air dispensers requires hull openings; local stress concentrations must be reassessed. Openings must have sufficient corner rounding (KR Rules Pt 3, Ch 4, 701). **System Integration:** Air piping must be independent of other systems. Galvanic corrosion prevention required for distance pieces. Ventilation in ALS machinery spaces must be sufficient (ISO 8861:1998). **Power:** Generator capacity must account for ALS power load (compressors).
Hydrodynamics / Structure	**Optimisation of Water Flow Hull Openings**	**Characteristics:** Refers to openings created for air dispensers or air chambers in ALS to facilitate air injection.	ABS Guide Air lubrication system RINA Pt. B	**Barriers:** Openings affect the longitudinal strength members used in hull	**Structural Reinforcement:** Openings must have sufficient rounded	**All Ship Types with ALS:** Applicable to any vessel installing air lubrication	**Design Focus:** Minimising stress concentration around air chambers. Ensuring watertight integrity via non-return valves or

		Hazards: Structural integrity compromise due to shell plating penetration. Water ingress risk through air piping.		girder section modulus calculations.	corners and appropriate reinforcement. If located forward of the collision bulkhead, must meet specific Class Rules (Pt 3, Ch 14, 201). **Valves:** Air injection valves must have open/close indicators. Power-operated valves must have manual operation means for failure modes.	requiring hull penetrations (e.g., MALS, Silverstream, SAVER systems).	loops in air piping. Distance pieces must be corrosion-resistant or coated.
Hydrodynamics / Materials	**Hull Coatings**	**Characteristics:** Air Lubrication reduces wetted surface area/density; Coatings reduce skin friction. Superhydrophobic surfaces (SHS) combined with air layers can significantly reduce required air flux. **Hazards:** Corrosion if coatings fail (PSPC focuses on tank protection, but principles apply to steel preservation).	ABS Guide Maintenance and repair RINA Pt. E	**Barriers:** Coating breakdown allows rust/corrosion, increasing roughness and drag. "POOR" condition is defined as breakdown of coating or rust penetration ≥ 20% of area or hard scale ≥ 10%.	**Maintenance Standards:** Target useful life of 15 years in "GOOD" condition. Salt contamination must be removed (limit 80 mg/m² NaCl) before repair coating. Dew point control: Steel temp must be 3°C (5°F) above dew point during application.	**Tankers/Bulk Carriers:** Specific focus on ballast tanks and crude oil tanks for PSPC. Hydrodynamic coatings (external) are critical for all ships to maintain speed/fuel efficiency.	**Design Focus:** Combining air layers with superhydrophobic surfaces to improve ALDR economy. Ensuring compatibility between original and repair coatings. Stripe coating on edges/welds to prevent premature failure.
Hydrodynamics / Structure	**Lightweight shipbuilding materials**	**Characteristics:** Reduction of lightweight to improve efficiency. ALS installation adds	ABS Guide Air lubrication system	**Barriers:** Added weight of energy efficiency equipment	**Stability Thresholds:** Re-evaluation of stability is required if:	**All Ship Types:** Particularly sensitive for vessels with tight	**Design Focus:** Managing the weight penalty of additional machinery (compressors, piping,

		weight (piping, compressors), necessitating lightship re-evaluation.		(like ALS) counteracts lightship design goals.	1. Lightship displacement change > 2%. 2. LCG change > 1.0% of Length Between Perpendiculars (LBP).	stability margins installing heavy retrofit equipment.	air chambers) against the hydrodynamic drag reduction benefits. Updating stability booklets for existing ships (retrofit).

3 Safety challenges and current studies on EETs

3.1 Risk from previous qualitative analysis

Table 23 aggregates thirty-two research papers published between 2014 and 2025, offering a comprehensive overview of the safety, reliability, and efficiency challenges. The literature reveals a distinct shift in focus from optimising conventional heavy fuel oil systems to managing the complex risks of alternative fuels like hydrogen, ammonia, methanol, and lithium-ion batteries, as well as adopting energy efficiency technologies such as wind-assisted propulsion and waste heat recovery.

A significant portion of the research is dedicated to the unique hazards of low-flashpoint and toxic fuels. Hydrogen propulsion systems are frequently analysed for risks regarding high-pressure leakage, wide flammability ranges, and material embrittlement. Ammonia is scrutinised primarily for its severe toxicity and corrosiveness, necessitating robust safety barriers and hazard identification studies to protect crew and the environment during storage and bunkering. Similarly, research on methanol highlights its toxicity and flammability, focusing on the adequacy of safety barriers during bunkering and the need for improved technical guidelines to mitigate fire and explosion risks.

Table 23 also highlights the growing concern over fire safety in the transport and use of lithium-ion batteries. The primary hazard identified is thermal runaway, which can lead to fires that are difficult to suppress and release toxic off-gases. To address these dynamic risks, researchers have moved beyond simple checklists to advanced probabilistic methods, such as Fault Tree Analysis combined with Bayesian Networks or Game Theory, to model fire scenarios in battery shipping containers and energy storage systems.

In the realm of energy efficiency, the research focuses on Waste Heat Recovery (WHR) and Wind-Assisted Ship Propulsion (WAPS). Studies on WHR, particularly Organic Rankine Cycle systems, prioritise thermodynamic optimisation and economic analysis to reduce fuel consumption, while also considering the flammability of organic working fluids. Research into wind propulsion, including Flettner rotors and suction wings, addresses the uncertainty of performance data and the challenges of integrating these systems into regulatory frameworks to ensure reliable emission reductions.

Table 23. Risk from previous qualitative analysis

No.	Published Year	Titles	Key risks/hazards	Fuels	System	Addressed challenges	Risk assessment techniques	Links
1	2025	Fire Risk Assessment of Lithium-Ion Power Battery Shipping Containers in Maritime Transportation Scenarios	Thermal runaway, fire, ventilation blockage, inspection omission	Lithium-ion Battery	Power battery shipping containers	Failure of initial emergency response, lack of analysis on full transportation process	Fault Tree (FT), Bayesian Network (BN), Attack–Defence Game Theory	https://doi.org/10.3390/fire8120453
2	2025	Reliability and Risk Assessment of Hydrogen-Powered Marine Propulsion Systems Based on the Integrated FAHP-FMECA Framework	Hydrogen leakage, valve leakage, inverter overload, membrane electrode degradation	Hydrogen	Hydrogen-powered marine propulsion (PEMFC, storage, cooling)	Uncertainty, multi-factor coupling, harsh marine environments	Fuzzy Analytic Hierarchy Process (FAHP), FMECA	https://doi.org/10.3390/jmse13112115
3	2025	Towards Safe Maritime Decarbonization: Safety Barriers of Methanol Fuel	Toxicity, flammability, explosivity, tank explosions	Methanol	Methanol bunkering, storage, and handling	Lack of technical guidelines, human error reduction	Hazard-based coding system, qualitative analysis (MAXQDA), Gap analysis	https://doi.org/10.3390/su17114896
4	2025	Ship Bunkering Operations Risk Assessment using Rule-Based Fuzzy Failure Mode Effect Analysis (FFMEA)	Lack of control mechanisms, incorrect valve operations, ineffective communication	Bunker Fuel (General)	Ship bunkering operations	Dynamic complexity, human/mechanical failures, environmental impact	Rule-Based Fuzzy FMEA (FFMEA), Fuzzy Risk Priority Numbers (FRPNs)	https://doi.org/10.4274/jems.2025.94546
5	2025	Review of Wind-Assisted Propulsion Systems in Maritime Transport	Uncertainty in fuel savings, hidden costs	Wind	WAPS	Lack of credible performance data, regulatory compliance (CII)	Literature Review, Comparative Analysis	https://doi.org/10.3390/en18040897
6	2025	State of the Art in Wind Assisted Ship Propulsion for Maritime Decarbonisation and Sustainable Shipping: A Systematic Review	Lack of operational data	Wind	WAPS	Quantifying CO_2 reductions, lack of consistent research methodologies	Systematic Literature Review	https://doi.org/10.5957/jst/2025.10.1.258
7	2024	Waste Heat Utilization in Marine Energy Systems for Enhanced Efficiency	Material degradation, corrosion, high temperatures	Fossil Fuels (WHR source)	WHR technologies (Heat exchangers, ORC, TEG, CHP)	Space constraints, compatibility, fouling, maintenance	Thermodynamic Analysis, Economic Evaluation, Review	https://doi.org/10.3390/en17225653

8	2024	A Comprehensive Review of the Establishment of Safety Zones and Quantitative Risk Analysis during Ship-to-Ship LNG Bunkering	Gas leaks, fire, explosion, cryogenic damage to steel	LNG	Ship-to-Ship (STS) LNG bunkering	Establishing safety zones, lack of detailed international codes	Quantitative Risk Analysis (QRA), CFD simulations	https://doi.org/10.3390/en17020512
9	2024	A Comprehensive Analysis of Risks and Safety Measures in the Maritime Industry's Transition to Sustainable Fuels	Leaks, spills, fires, collisions, toxicity, cryogenic burns	HFO, LNG, Methanol, Hydrogen, Ammonia, Batteries	Propulsion systems using alternative fuels	Transition to sustainable fuels, lack of regulations, technical factors	Risk analysis of accidents, review of safety measures	https://hdl.handle.net/11250/3156922
10	2024	A Prominent Future Fuel: Methanol & Risk Assessment of Methanol Fuel System of Tanker as a Case Study	Toxicity, flammability, explosiveness, corrosiveness	Methanol	Methanol fuel system of an oil/chemical tanker	Regulatory gaps, need for design improvement	FMECA (Failure Modes, Effects, and Criticality Analysis)	https://commons.wmu.se/all_dissertations/3403
11	2024	Evaluating the Impact of Wind-Assisted Propulsion Systems on Ship Energy Efficiency	Impact of side forces (drift, rudder resistance)	Wind	Flettner Rotor, eSAIL systems	Compliance with IMO Minimum Propulsion Power, manoeuvrability in adverse weather	Theoretical modelling (wind forces, wave resistance), computational trials	https://dspace.lib.ntua.gr/xmlui/bitstream/handle/123456789/61130/DIPLOMA%20THESIS.pdf?sequence=6
12	2023	Fire Accident Risk Analysis of Lithium Battery Energy Storage Systems during Maritime Transportation	Fire, thermal runaway, high temperature, vibration, humidity	Lithium-ion Battery	Lithium battery energy storage system (LBESS)	Dynamic risk factors in maritime transport, unsuitable firefighting systems	Fault Tree Analysis (FTA), Bayesian Network (BN), Fuzzy set theory	https://doi.org/10.3390/su151914198
13	2023	Hazard Identification of Hydrogen-Based Alternative Fuels Onboard Ships	Flammability, explosion, embrittlement, toxicity (ammonia), cryogenic hazards	Hydrogen carriers, Ammonia, Methanol	Onboard fuel storage and usage systems	Lack of specific safety definitions/regulations for hydrogen carriers	Hazard Identification (Qualitative based on GHS), pairwise comparison, fuzzy set theory	https://doi.org/10.3390/su152416818
14	2023	A Priority-based Failure Mode and Effects Analysis (FMEA) Method for Risk Assessment of Hydrogen Applications Onboard Maritime Vessels	Wide flammability range, high risk of ignition, high pressure storage	Hydrogen	Onboard hydrogen storage, handling, and refuelling	Low volumetric energy density, lack of specialised risk approaches	Priority-based FMEA (AIAG-VDA method), Action Priority (AP) rating	http://instance.metastore.ingenta.com/content/conference5871
15	2023	Research on the Operational Performance of Organic Rankine Cycle System for Waste Heat Recovery from Large Ship Main Engine	(Performance focused)	Main engine exhaust	Basic ORC (BORC) and Preheated ORC (PORC)	Enhancing waste heat utilisation, Carbon emission reduction	Thermodynamic simulation model	https://doi.org/10.3390/app13148543

16	2022	Maritime Safety in the Era of Decarbonization: A Safety Barrier Analysis	Toxicity, corrosiveness, flammability, leakage	Ammonia	Ammonia fuel onboard (bunkering, storage, piping)	Lack of regulations for ammonia as fuel, occupational health	Hazard Identification (HAZID), Bowtie method (Barrier analysis)	https://doi.org/10.3850/978-981-18-5183-4_S16-04-479-cd
17	2022	Safety Considerations of Hydrogen Application in Shipping in Comparison to LNG	Wide flammability range, embrittlement, cryogenic hazards	Hydrogen, LNG	Fuel storage and usage systems	Lack of specific IMO regulations for hydrogen	Fuzzy set theory, pairwise comparison	https://doi.org/10.3390/en15093250
18	2022	Analysis on the Development of Wind-assisted Ship Propulsion Technology and Contribution to Emission Reduction	(Technology focus)	Wind	WAPS (Rotors, towing kites, wing sails)	CO_2 peaking, carbon neutrality, constraints of wind-aided navigation	Analysis of development and emission reduction contribution	https://doi.org/10.1088/1755-1315/966/1/012012
19	2022	How is Electrification Affecting the Onboard Fire Safety?	Thermal runaway, explosive/toxic off-gases, re-ignition	Lithium-ion Battery	Battery propulsion (Hybrid/Electric)	Lack of specific SOLAS regulations, fire suppression difficulties	Qualitative interviews, literature review	https://odr.chalmers.se/bitstreams/beb7f6f5-b3b9-433a-9175-f6a2ccaf6ea5/download
20	2022	Hazard Analysis of Hydrogen Fuel Cell Ships Using Land Based Accidents Data and Elicitation of Experts	Leakage, ignition sources, permeation, flooding	Hydrogen	Hydrogen Fuel Cell (HFC) ships	Lack of maritime regulations, lack of accident data in maritime	HAZID (based on eMARS database), Delphi method, Barrier Analysis	https://commons.wmu.se/all_dissertations/3072
21	2021	Safety Design and Engineering Solution of Fuel Cell Powered Ship in Inland Waterway of China	Hydrogen leakage, explosion in enclosed spaces	Hydrogen	Fuel cell power system, DC-bus power system	Area classification for explosive atmospheres, ventilation in enclosed spaces	IEC 60079-10-1 algorithm (quantitative calculation)	https://doi.org/10.3390/wevj12040202
22	2021	Safety and Reliability Analysis of an Ammonia-Powered Fuel-Cell System	Toxicity, flammability, leakage, control system failure	Ammonia	Ammonia fuel-cell-powered plant (storage, feeding, SOFC)	Toxicity to crew, lack of specific regulations	HAZID, Functional-based modelling (FBM), FTA, FMECA	https://doi.org/10.3390/safety7040080
23	2021	Wind Assisted Ship Propulsion Technologies – Can they Help in Emissions Reduction?	Lack of real-life results leading to doubt	Wind	WAPS (Rigid/soft sail, wing sail, kite, Flettner rotor)	Lack of wide acceptance, implementation dependency on design	Review/Progress analysis	https://doi.org/10.17818/NM/2021/2.6
24	2021	Study on Risk Assessment of Methanol Fueled Ship	Leakage, ignition sources, permeation, flooding	Methanol	Methanol fuelled ship (storage, supply, engine)	Lack of specific rules/regulations, toxicity, low flash point	Delphi method, Risk matrix analysis, Fuzzy comprehensive evaluation	https://commons.wmu.se/msem_dissertations/1301

25	2020	Comparison and Verification of Reliability Assessment Techniques for Fuel Cell-Based Hybrid Power System for Ships	Subjectivity in evaluation, system failures (MCFC, battery)	Hydrogen, Diesel, Battery	Fuel cell based hybrid power system	Ambiguous evaluation criteria in conventional RPN, subjective factors	Rule-based Fuzzy FMEA, Kendall's concordance coefficient	https://doi.org/10.3390/jmse8020074
26	2020	Investment Analysis of Waste Heat Recovery System Installations on Ships' Engines	Investment risk, volatile fuel prices	Marine Fuels (MDO/HFO)	Waste Heat Recovery System (WHRS)	Economic assessment under volatile market conditions	Capital budgeting (NPV), Real-Options Approach (ROA)	https://doi.org/10.3390/jmse8100811
27	2019	Influence of EEDI on Ship–Engine–Propeller Matching	CO_2 emissions (environmental risk)	Diesel	Ship–Engine–Propeller system	Meeting EEDI regulations, GHG emission reduction	System matching platform, regression analysis	https://doi.org/10.3390/jmse7120425
28	2019	Improving the efficiency of a gas-fueled ship power plant using a Waste Heat Recovery metal hydride system	High energy consumption of compressor	LNG	WHR metal hydride system, gas fuel compressor drive	Reducing primary energy consumption of gas fuel supply system	Mathematical modelling	https://doi.org/10.17402/346
29	2017	Waste Heat Recovery from Marine Gas Turbines and Diesel Engines	(Efficiency focus)	Gas/Diesel	COGAS, Combined Diesel and Steam	Increasing energy conversion efficiency, reducing weight/size	Mathematical modelling, simulation	https://doi.org/10.3390/en10050718
30	2015	Thermodynamic and Environmental Analysis of Low-Grade Waste Heat Recovery System for a Ship Power Plant	Flammability of working fluids (R601a, R601)	Marine Fuels	Organic Rankine Cycle (ORC)	Energy efficiency, GHG emissions	Thermodynamic analysis, environmental/economic analysis	https://doi.org/10.12783/IJES.2015.0501.04
31	2015	Calculation of Efficiencies of a Ship Power Plant Operating with Waste Heat Recovery through Combined Heat and Power Production	Efficiency focus	HFO, MDO	Combined Heat & Power (CHP) plant, ORC	Increasing thermal efficiency, reducing fuel consumption	Thermodynamic analysis	https://doi.org/10.3390/en8054273
32	2014	Thermodynamic Analysis of a Ship Power Plant Operating with Waste Heat Recovery through Combined Heat and Power Production	Thermodynamics focus	HFO	Supercritical ORC, Steam Turbine	Efficiency optimisation	Thermodynamic analysis	https://doi.org/10.3390/en7117368

3.2 Risk from previous quantitative analysis

Table 24 presents a multi-faceted approach to maritime decarbonisation, emphasising safety assessments for alternative fuels and hydrodynamic efficiency improvements. A major area of focus involves the safety of ammonia as a marine fuel, where computational fluid dynamics (CFD) simulations are extensively used to model leakage, dispersion, and explosion risks in confined spaces such as fuel preparation rooms and engine rooms. These studies highlight that ignition location profoundly influences explosion characteristics, with ceiling-level ignitions often producing the highest overpressures, and suggest that ventilation optimisation is critical for mitigating toxicity and flammability hazards. Similarly, hydrogen safety is rigorously examined, with specific attention paid to the effects of ship motion on gas dispersion; findings indicate that the kinetic movements of a vessel, such as rolling and pitching, significantly accelerate hydrogen spread compared to stationary conditions, necessitating dynamic risk assessment models for fuel cell compartments.

In the realm of propulsion efficiency and hull design, researchers are leveraging advanced numerical methods to reduce resistance and fuel consumption. This includes the optimisation of ship hull forms using parametric modelling and surrogate-based optimisation algorithms to minimise wave and viscous resistance. Air lubrication systems (ALS) are a prominent subject, with studies investigating the stability of air cavities and air layers to reduce frictional drag, identifying specific air loss mechanisms that must be managed for effective implementation. Furthermore, propulsion technologies are being advanced through the analysis of composite propellers, where fluid-structure interaction simulations predict performance changes under cavitating conditions due to blade deformation.

The integration of renewable energy sources is also a key theme, as demonstrated by assessments of wind power generation ships that combine rigid wing sails with underwater turbines to harvest energy. Additionally, combustion strategies for dual-fuel engines are being optimised, such as the use of methane-hydrogen blends and ammonia injection intensification, to balance energy efficiency with the reduction of harmful emissions like NOx and greenhouse gases. Collectively, these studies demonstrate a heavy reliance on high-fidelity CFD and numerical simulations to solve complex engineering challenges associated with the transition to zero-carbon shipping.

Table 24. Risk from previous quantitative analysis

No.	Published Year	Titles	Key risks/hazards	Fuels	Addressed challenges	Risk assessment techniques	Links
1	2025	Research on Hydrogen Leakage Risk Control Methods in Deck Compartments of Hydrogen Fuel Cell-Powered Ships Based on CFD Simulation and Ventilation Optimization	Hydrogen leakage, diffusion, accumulation near ceiling, explosion risk	Hydrogen	Leakage location effects, ventilation optimisation for risk control	CFD simulation (FLUENT)	https://doi.org/10.3390/fire8100400
2	2025	Research on Control of Ammonia Fuel Leakage and Explosion Risks in Ship Engine Rooms	Ammonia toxicity, leakage, explosion	Ammonia	Diffusion behaviour in complex engine rooms, ventilation optimisation	CFD simulation (ANSYS Fluent)	https://doi.org/10.3390/fire8070271
3	2025	Quantitative Analysis of Explosion Characteristics Based on Ignition Location in an Ammonia Fuel Preparation Room Using CFD Simulation	Explosion overpressure, rapid pressure rise, toxic exposure	Ammonia	Influence of ignition location on explosion severity	CFD simulation (FLACS)	https://doi.org/10.3390/app15126554
4	2025	Numerical Study on Ammonia Dispersion and Explosion Characteristics in Confined Space of Marine Fuel Preparation Room	Toxicity, flammability, overpressure, corrosive properties	Ammonia	Leakage detection, emergency planning, structural safety reinforcement	CFD (FLACS-CFD), TNO Multi-Energy method	https://doi.org/10.3390/jmse13071235
5	2025	An integrated qualitative–quantitative risk assessment for defining toxic and hazardous zones on hydrogen-fuelled ships with ammonia cracking systems	Toxicity, fire/explosion, gas dispersion	Hydrogen (fuel), Ammonia (carrier)	Impractical hazardous zones for small vessels, defining leak points	HAZID, CFD (FLACS, STAR-CCM+), Probabilistic risk assessment	https://doi.org/10.1016/j.oceaneng.2025.122475
6	2025	Simulation Study on a fuel cell/battery hybrid electric propulsion system for ships	Thermal load management, system power balance	Hydrogen (PEMFC)	Cooling system regulation, fast response to load changes	MATLAB Simulink simulation	https://doi.org/10.5916/jamet.2025.49.3.206

7	2025	Safety Studies for Approval of Green Ammonia Bunkering Terminals – How Best to Apply CFD Modelling	Toxicity (fatal at 1%), odour, dispersion dynamics	Green Ammonia	Siting studies, leak rate evaluation, terrain effects	CFD modelling (limited use), Phast/Safeti (implied)	https://doi.org/10.3303/CET25116038
8	2024	Optimization of Combustion Cycle Energy Efficiency and Exhaust Gas Emissions of Marine Dual-Fuel Engine by Intensifying Ammonia Injection	N_2O formation (GHG), NOx emissions, Ammonia slip (toxicity)	Ammonia, Diesel (Dual-fuel)	Combustion duration, high auto-ignition temperature, emission trade-offs	Numerical simulation (AVL FIRE M)	https://doi.org/10.3390/jmse12020309
9	2024	Simulation Analysis of a Methanol Fueled Marine Engine for the Ship Decarbonization Assessment	CO_2 emissions (fossil vs. green), lower efficiency than NG	Methanol	Lack of fuel consumption data, engine-propeller matching	Matlab-Simulink simulation (0D/1D)	https://doi.org/10.3390/en17112498
10	2024	Advanced Simulation and Environmental Impact Assessment of Combustion in Maritime Energy Systems	NOx, SOx, soot emissions, environmental pollution	Diesel, Methanol	High emissions from diesel, combustion performance optimisation	CFD (ANSYS Fluent)	https://doi.org/10.4031/MTSJ.58.3.3
11	2024	Aerodynamic Analysis of Rigid Wing Sail Based on CFD Simulation for the Design of High-Performance Unmanned Sailboats	Sail breakage, structural stability, low lift coefficient of flexible sails	Wind (Rigid Wing Sail)	Power consumption, harsh ocean environment adaptation	CFD simulation (ANSYS Fluent)	https://doi.org/10.3390/math12162481
12	2024	Safety evaluation on ammonia-fueled ship: Gas dispersion analysis through vent mast	Toxicity, high fatality risk	Ammonia	Dispersion from vent mast, regulatory gaps	CFD (FLACS)	https://doi.org/10.1016/j.ijhydene.2024.08.027
13	2023	The Effect of Ventilation on the Hazards of Hydrogen Release in Enclosed Areas of Hydrogen-Fueled Ship	Leakage, accumulation, fire, explosion	Hydrogen	Ventilation strategy (inlet/outlet position), sensor placement	FLACS-CFD, Event Tree Analysis (ETA)	https://doi.org/10.3390/jmse11091639
14	2023	Numerical validation of a hydrogen leakage and dispersion experiment considering ship kinetic characteristics	Fire, explosion, gas accumulation due to motion	Hydrogen	Effect of roll/pitch motion on dispersion, sensor placement	CFD (ANSYS Fluent), Experimental validation	https://doi.org/10.5916/jamet.2023.47.6.352
15	2023	Numerical Analysis of Dual Fuel Combustion in a Medium Speed Marine Engine Supplied with Methane/Hydrogen Blends	Increased NOx with H_2, uncontrolled ignition, knock	Methane, Hydrogen	Reducing CH_4 slip, controlling combustion timing	0D/1D modelling, 3D CFD (ANSYS Forte)	https://doi.org/10.3390/en16186651

16	2023	Future Ship Emission Scenarios with a Focus on Ammonia Fuel	Ammonia slip (toxicity), N_2O emissions, NOx	Ammonia, LNG	Decarbonisation targets, unburnt fuel slip, engine technology comparison	Modular Ship Emission Modelling System (MoSES)	https://doi.org/10.3390/atmos14050879
17	2023	Optimizing Energy Management and Case Study of Multi-Energy Coupled Supply for Green Ships	Energy inefficiency, high operating costs	Wind, Solar, Fuel Cell, Battery	Energy management optimisation, cost reduction	Dynamic planning, Optimisation model	https://doi.org/10.3390/jmse11071286
18	2022	Numerical Analysis of the Effects of Ship Motion on Hydrogen Release and Dispersion in an Enclosed Area	Leakage, fire/explosion, rapid dispersion due to motion	Hydrogen	Detection time lag, effect of ship motion (roll/pitch) on gas behaviour	CFD (ANSYS Fluent)	https://doi.org/10.3390/app12031259
19	2022	Performance Prediction of Composite Marine Propeller in Non-Cavitating and Cavitating Flow	Cavitation inception, noise, structural deformation	N/A	Analysing deformation effects on cavitation/noise	Coupled CFD-FEM (FSI analysis)	https://doi.org/10.3390/app12105170
20	2022	Numerical prediction of cavitation phenomena on marine vessel: Effect of the water environment profile on the propulsion performance	Cavitation, performance loss, erosion	N/A	Environmental effects (temp/salinity) on cavitation	CFD (ANSYS CFX), Zwart/Kunz cavitation models	https://doi.org/10.1515/eng-2022-0034
21	2020	Computational Analysis of Air Lubrication System for Commercial Shipping and Impacts on Fuel Consumption	Skin friction resistance, high fuel consumption	MDO (Marine Diesel Oil)	Fuel efficiency, CO2 emission reduction	CFD (ANSYS FLUENT)	https://doi.org/10.3390/computation8020038

4 Overview of risk assessment to investigate the safety of EETs

4.1 Hazard identification – hazard models for HAZID, HAZOP and FMEA

The review work conducted in the previous sections has identified the characteristics, potential hazards, relevant rules, regulations, and risk assessment practices across various industries, focusing on EETs. Based on the technical properties of these technologies, the main potential hazards are related to system reliability and operational safety, including considerations for alternative fuels like hydrogen or ammonia where they are integrated or utilised. These hazards may involve factors such as low ignition energy, wide flammability limits, and high flame velocity, as well as the toxic or corrosive nature of certain fuel types. Furthermore, the application of these technologies may encounter risks such as the formation of oxygen-enriched atmospheres due to cryogenic processes, high permeability, and hydrogen embrittlement within the structural components or weld metals of the EET installations. To support the risk assessment proposed in this project, both qualitative and quantitative methods have been identified and selected to evaluate the safety of these systems. Accordingly, Hazard Identification (HAZID), Hazard and Operability study (HAZOP), and Failure Modes and Effects Analysis (FMEA) will be applied to qualitatively evaluate the risk levels of EETs and their associated handling systems. For quantitative assessment, the CFD (Computational Fluid Dynamics) method will be utilised to evaluate the impact of key hazards on the ship, such as the dispersion of leaked gases or toxic vapours, combustion effects, and the pressure exerted on the ship's structure as a result of fire and explosion. In this chapter, the selected risk assessment methodology will be presented with developed models and modified approaches specifically designed to fit the goal and scope of this project.

4.1.1 HAZID

It is imperative to identify hazards arising from the implementation and operation of Energy Efficient Technologies (EETs) affecting the persons on board, the structural integrity of the ship, and the environment. For this purpose, the HAZID methodology will be employed, which is a combination of identification, analysis, and brainstorming driven by a structured list of potential hazards, taking advantage of the collective experience of HAZID team members. Diverse groups of industry stakeholders, such as ship operators, class representatives, designers, and material experts, will support the brainstorming process. The aim is to investigate the safety of the systems and achieve an initial gauge of the potential design hazards that can be expected in large-scale EET installations. This study will be performed at an early stage of the design to identify potential major hazards,

review the effectiveness of the proposed safety measures, and, where required, propose further safeguards. The HAZID methodology followed in the project is consistent with the IACS Recommendation No. 146, "Risk assessment as required by IGF Code." The objective of the HAZID is to ensure that any risks arising from the EET implementation and associated fuel handling are under control—either eliminated or, in cases where this is not possible, managed through adequate safety barriers and requirements to ensure that these risks are mitigated to the ALARP (As Low As Reasonably Practicable) region.

Special consideration will be given but not limited to the following hazards related to the implementation and operation of EETs:

- Leakages of operating fluids, lubricants, or working mediums.
- Material fatigue and failure related to high operational stresses, pressures, or temperature variations.
- Fire risks arising from electrical components, static electricity, or mechanical friction in moving parts.
- Risks associated with high-speed mechanical components and structural instabilities.
- Accumulation of hazardous vapours or gases within EET-related enclosed spaces.
- Asphyxiation hazards in confined areas due to the displacement of oxygen by working gases or inerting mediums.
- System overpressure resulting from thermal insulation deterioration or control system malfunctions.
- Obstruction of ventilation or intake systems due to ice formation or environmental debris in specialised operational conditions.

The following nodes will be among the ones investigated in the HAZID study for the proposed EETs:

- EET structural and mechanical assemblies (e.g., wind-assist units, air lubrication components, or specialised propulsion aids).
- Fluid and power piping systems, including filters, valves, and monitoring sensors.
- Pressure relief and overpressure protection systems.
- Emergency Shutdown (ESD) and integrated safety control systems.

- Structural integration points and containment components, including primary and secondary supports.
- Specialised machinery spaces and EET control rooms.
- Venting and exhaust management systems.
- Fire protection, detection, and suppression systems specifically for EET zones.
- Emergency response protocols and backup power integration.

Finally, for the HAZID purposes, the following documentation is required:

- General Arrangement (GA) plans and specific EET installation layouts.
- Conceptual Process Flow Diagrams (PFD) and descriptions of system operational logic.
- Detailed piping and instrumentation diagrams (P&ID) for all auxiliary and safety-related systems.
- Ventilation and air management arrangements for EET-related spaces.
- Safety system arrangements, including detection and firefighting layouts.
- Specifications for materials and structural insulation properties.
- Hazardous area classification plans for integration zones and surrounding deck areas.
- New concept design documentation for the integrated EET system.

4.1.2 HAZOP

A fundamental component for the prevention of major accidents is the execution of a Hazard and Operability study (HAZOP) during the detailed design stage of EETs. HAZOP ensures that safety measures, including control mechanisms and integrated systems, are implemented and operated with high reliability to prevent serious incidents. As a form of qualitative risk assessment, HAZOP is a standard part of the safety management protocols used for advanced maritime and industrial systems.

Originally developed by Imperial Chemical Industries (ICI), the application of HAZOP during the design phase allows operators to optimise resources by identifying necessary safeguards early, rather than adding costly controls during the commissioning and operational stages of the EET

installations. If a HAZOP study is not performed, the need for these safety systems may only become apparent during actual operation, potentially leading to unforeseen risks.

HAZOP study is a highly disciplined technique that systematically examines every aspect of an EET system, section by section, using Piping and Instrumentation Diagrams (P&IDs) to determine how a process might vary from its intended design. The methodology involves the following:

- Guidewords: Used to identify deviations from typical operating conditions that could lead to dangerous situations.
- Nodes: The division of P&IDs into functional blocks to facilitate a methodical examination.
- Deviation Analysis: The assumption that a process becomes hazardous only when it departs from its design intent.
- Qualitative Evaluation: An assessment of the consequences and probability of these deviations to determine risk levels.
- Mitigation Identification: Recording or including potential safeguards as they become apparent during the investigation.

During the HAZOP study, a systematic brainstorming of the EET operational flow is carried out through a series of workshops and meetings. This multidisciplinary collaboration involves a range of specialists—including system designers, ship operators, and class representatives—whose diverse perspectives foster creative thinking and comprehensive risk identification. The analysis is completed by methodically applying process parameters and guide words to the various lines, components, and vessels within the EET system.

The analysis is completed by methodically applying process parameters and guide words to the various lines, components, and vessels within the EET system, based on technical documentations such as Piping and Instrumentation Diagrams (P&IDs)

4.1.3 FMEA

The Failure Mode and Effects Analysis (FMEA) was formalised by the US Armed Forces in 1949 through the introduction of the Mil-P 1629 procedure. FMEA is extensively used across a wide range of industries—including aerospace, automotive, and maritime—to identify and eliminate potential system issues, thereby reducing lifecycle costs and enhancing operational reliability. Within the context of EETs, FMEA is designed to fully identify and comprehend potential failure modes, their causes, and their effects. This allows for the prioritisation of effective corrective actions to address the most critical risks, ensuring that the design of the EET system, subsystem, or component reaches a manageable risk level.

As a structured, desk-based engineering analysis, FMEA is conducted by a cross-functional team of subject matter experts, including designers and operators, before the final implementation of the EET system. The process follows a systematic approach:

- Scope Definition: The boundaries of the FMEA are determined prior to the study to maintain focus and prevent the analysis from expanding unnecessarily into unrelated areas.
- System Breakdown: The EET system is decomposed into logical components based on function, hardware, or a combination of both. Each item is assigned a unique identification to facilitate a methodical investigation of its potential failure modes.
- Functional and Hardware Approaches: The functional approach evaluates whether each item performs its intended outputs, while the hardware approach focuses on individual equipment pieces. For complex EET systems, a hybrid of both approaches is often employed.
- Failure Analysis: Once the cause of a potential failure is determined, the team identifies the specific failure modes for each component and establishes the resulting consequences for the overall system.
- Risk Priority Number (RPN): A numerical score is assigned to the cause and effect of each failure to calculate the RPN. This value is used to prioritise mitigation measures, and the FMEA records are updated to reflect any implemented safety enhancements.

By applying this disciplined methodology, supported by a detailed review of process flow diagrams and operation modes, the reliability of EETs is significantly improved, ensuring that these innovative systems perform safely and effectively within the maritime environment.

4.2 Quantitative risk analysis – risk scenarios for CFD simulations

4.2.1 QRA approaches

In the field of Quantitative Risk Assessment (QRA) for EETs, there are two primary approaches that provide essential safety insights. Deterministic analysis aims to establish that an EET installation can safely manage identified hazards within its specific design basis, effectively setting the boundaries for safe maritime operation. In contrast, probabilistic analysis seeks to provide a realistic estimation of risk by quantifying both the likelihood and the consequences of potential failure events. Both approaches are utilised in modern safety assessments of EETs because they offer complementary perspectives; the deterministic method focuses on the system's tolerance to specific faults, while probabilistic analysis provides a broader view of risk by considering the variability and uncertainty inherent in these complex technological systems.

The deterministic approach for evaluating EETs is structured around worst-case scenario planning. This method evaluates the safety of a system against the most severe potential hazards to ensure that operations remain within a secure threshold relative to identified risks. The process begins with hazard identification and the determination of risk criteria through thorough consequence analysis, which eventually leads to the proposal of a satisfactory and robust design. This approach is commonly implemented to maintain regulatory compliance and to ensure that EET structures and processes are capable of managing the maximum expected risks during their lifecycle.

The probabilistic approach provides a methodical framework used to assess and manage risk by evaluating the safety criteria for various EET designs and systems. This methodology involves a comprehensive determination of all potential factors that could pose a risk, followed by a probabilistic evaluation to verify if a particular design meets established safety standards. Central to this methodology is the realistic anticipation of potential hazards through frequency and consequence analysis, which are conducted to measure risk against predefined safety criteria. Depending on these measurements, specific risk control options or design improvements are suggested. By incorporating a broad spectrum of risk factors and relying on robust simulations, the probabilistic approach provides a thorough and evidence-based verification of an EET system's safety and reliability, making it an invaluable tool for modern risk management and safety engineering.

4.2.2 QRA scope

The objective of this project is the development and integration of large-scale onboard EETs. The QRA for this project is specifically focused on the installation, operational management, and handling systems associated with these EETs. Due to the technical complexity and high-performance requirements of such systems, it is imperative to devise a comprehensive plan that encompasses a thorough examination of potential risks associated with their implementation onboard. Given the project's primary emphasis on EET infrastructure, the principal focus of the QRA will encompass the core EET units, their associated fluid and power distribution systems, and any related operational or bunkering interfaces. The safety measures for these technologies will be designed to mitigate the potential consequences of loss of function, structural or component damage, as well as the risks of fire and explosion within the integrated maritime environment.

4.2.3 QRA procedure

In the preliminary stage, a wide range of hazards and safety challenges associated with the implementation of EETs are identified through various analytical methodologies. Once these potential risks are recognised, they are prioritised for further investigation through detailed simulations that incorporate both frequency and consequence assessments of the selected scenarios. The findings from each specific scenario analysis are then integrated into the broader risk assessment framework, leading to a comprehensive evaluation of the overall risk level based on established safety and performance criteria.

Hazard identification

The initial phase of the Quantitative Risk Assessment (QRA) for EETs commences with hazard identification, which involves utilising brainstorming techniques to determine a comprehensive range of potential hazard scenarios that could occur throughout the vessel's operational lifespan. A significant portion of this effort is allocated to Task 5.2. Furthermore, should any risks remain unidentified during the qualitative risk assessments conducted in Task 5.2, subsequent stages will focus on the formulation of quantitative risk scenarios. These scenarios will be developed based on the conceptual design of the EETs, the layout of the associated storage or integration systems, and the auxiliary system designs provided by other WPs.

Frequency analysis

In the second phase, relevant failure frequencies are computed for each credible scenario involving EETs using rigorous analytical methods such as Bayesian analysis, Event Tree Analysis (ETA), and Fault Tree Analysis (FTA). To accomplish this, the instances in which an EET system or its associated working mediums—which may occasionally include alternative fuels like hydrogen or ammonia for specific efficiency-boosting applications—might fail or leak from the ship are systematically categorised, and the frequency of occurrence for each category is meticulously determined.

These scenarios are meticulously constructed by taking into consideration predefined parameter sets encompassing variables such as the dimensions of a component breach or pipe leak, the trajectory of the release, prevailing weather conditions, and the precise location of the EET installations and their supporting storage units, among other factors.

Consequence analysis

During the third phase of the process, each accident scenario undergoes a detailed geometric modelling procedure utilising advanced desktop modelling software. Subsequently, Computational Fluid Dynamics (CFD) simulations are executed to ascertain the precise direction and extent to which working fluids or associated alternative fuels—such as hydrogen or ammonia used within these systems—disperse in the event of a leakage, fire, or explosion, as dictated by each respective EET-related scenario. In essence, this phase involves the comprehensive simulation of the various accident scenarios previously identified, with the primary objective being the assessment of the repercussions of these events on factors including structural property damage, asset depreciation, financial ramifications, and potential human casualties.

Risk measure

This step represents the pivotal risk integration phase, where the frequencies and consequences of individual accident scenarios related to EETs are consolidated. This process enables the assessment of risk levels for each scenario, culminating in the determination of the system's aggregate risk profile.

As an illustrative example, the results are presented through a Frequency-Number of fatalities (F-N) curve. This graphical representation allows for a clear visualization of the technology's safety profile against established societal and regulatory risk acceptance criteria.

Regarding the risk acceptance criteria, this study primarily adheres to the IMO Guidelines for Formal Safety Assessment (FSA) (MSC-MEPC.2/Circ.12/Rev.2). For both individual and societal risks, the ALARP (As Low As Reasonably Practicable) principle is employed to evaluate risk tolerability. Furthermore, for emerging EETs with evolving international regulations—such as ammonia or hydrogen systems—these criteria are supplemented by classification society thresholds and relevant international standards to ensure a robust and conservative safety evaluation.

Risk criteria

Once the F-N (Frequency-Severity) diagram for the EETs has been established, the final step entails defining the risk acceptance criteria, which are typically derived from expert judgment and established maritime safety standards. This step involves evaluating whether the assessed risk associated with the EET installation falls within the "As Low As Reasonably Practicable" (ALARP) or tolerable region. For instance, the delineation of various risk regions by boundary lines serves to

verify that all calculated risks remain within an acceptable range; in such cases, no supplementary safety measures are deemed necessary.

Nevertheless, in cases where the assessed risk of the EET system extends beyond the tolerable region, it is necessary to identify and implement additional risk control measures and safeguards. These measures are designed to achieve the following:

- **Prevention:** Reducing the frequency of potential accidents by addressing the root causes of failure within the EET system.
- **Mitigation:** Minimising the consequences in the event that an accident cannot be completely averted, thereby protecting the ship's crew and structural integrity.

The overarching objective is to systematically reduce the operational risk of these technologies to a level that aligns with the ALARP region, ensuring the highest attainable level of safety for the integrated system.

5 Prioritisation of Technologies for Risk Assessment and AiP

The integration of EETs as part of the FLEETfor55 initiative involves a wide spectrum of solutions, ranging from mature mechanical optimisations to radical shifts in propulsion and energy storage.

To streamline the path toward commercialisation and regulatory compliance, this project prioritises Safety and Risk Assessment for the nine defined Use Cases (UCs) covering oceangoing and Short Sea Shipping (SSS) vessels, which require Approval in Principle (AiP). The rationale for this prioritisation is two-fold:

- **Integrated Regulatory Gap Analysis:** AiP is granted not just to individual components but to the specific combination of EETs within a UC. Standard classification rules often do not cover the interactions between multiple novel technologies. The UC-based assessment serves as the essential bridge to prove "equivalent safety" for the entire system configuration.
- **Tiered Risk Scrutiny:** The complexity of the risk assessment is determined by the specific characteristics of the EET combination within each UC. While UCs consisting of mature mechanical optimisations require a standard review, those incorporating "High-Priority Technologies" carry inherent uncertainties that necessitate intensive formal assessments (HAZID/HAZOP).

Not all Use Cases require the same level of scrutiny. We categorise the 9 UCs into two distinct tiers based on their EET complexity to determine the scope of the risk assessment:

Tier 1: High-Priority Use Cases (AiP Required)

These UCs are the primary focus of this chapter's safety assessment. They are defined by the presence of one or more "Novel Concepts" or "High-Priority Technologies" (as shown in Table 25) that significantly alter the vessel's safety profile:

- **UCs with Sustainable & Low-Emission Fuels:** Use Cases involving hydrogen, ammonia, or methanol, requiring rigorous assessment of toxicity, flammability, and cryogenic storage.
- **UCs with Renewable Energy Systems:** Use Cases integrating Flettner Rotors, Rigid wing sails, or Kite propulsion systems, which impact the vessel's intact stability and structural integrity.
- **UCs with Advanced Power Solutions:** Use Cases utilizing fuel cells or large-scale Energy Storage Systems (ESS), involving complex chemical and thermal risk management.

Table 25. EET lists (AiP required)

Category	Specific Technologies	Ground / Reason for AiP
Sustainable Fuels	Hydrogen, methanol, ammonia, LOHC, synthetic methane/ethanol	Safety & regulatory gap: These fuels are toxic, highly flammable, or require cryogenic storage. Existing SOLAS/IGF codes do not fully cover them yet, so AiP is required to prove the design meets safety equivalency.
Power Conversion	Fuel cells, large-scale battery systems (energy storage)	Risk management: Fuel cells involve chemical reactions and hydrogen management. Large batteries pose thermal runaway/fire risks. Class societies require AiP to validate the safety systems and integration.
Renewables	Flettner rotors, Kite propulsion systems, suction wings, rigid wing sails	Structural & stability impact: These add massive wind loads and change the ship's stability profile. As "Wind-Assisted Propulsion Systems" (WAPS), they require AiP to ensure the vessel remains seaworthy under extreme wind conditions.
Hydrodynamics	Air Lubrication Systems	System Complexity: This involves pumping air under the hull, which affects buoyancy and machinery integration. Because it interacts deeply with the hull structure, an AiP is often sought for new designs.

Tier 2: Standard Optimisation Use Cases (Plan Approval Only)

UCs that primarily consist of the technologies listed in Table 26 such as Propeller Boss Cap Fins (PBCF), LED lighting, and weather routing are excluded from the primary AiP-focused risk assessment. These are considered "proven technologies" with well-established safety records. Consequently, these UCs will follow standard Plan Approval processes during the vessel's design or retrofit phase, bypassing the preliminary "Principle" validation stage.

Table 26. EET lists (Plan Approval only)

Category	Specific Technologies	Ground / Reason
Propeller Designs	Pre-swirl fin, gate rudder, Propeller Boss Cap Fin (PBCF), wake equalizing duct	Established hydrodynamics: These are passive mechanical components. They are well-understood by Classification Societies and only require standard structural and vibration analysis.
Operations	Weather routing, Just In Time (JIT), slow steaming, hull/propeller monitoring	Operational/software based: These are management strategies or digital tools. They do not change the physical safety architecture of the ship's machinery or hull.
Engineering Approach	LED lighting, VFD (Variable Frequency Drives), HVAC optimization, M/E tuning	Standard efficiency upgrades: These use mature industrial technologies. They fall under standard electrical and machinery rules (e.g., SOLAS Chapter II-1).
Power Conversion	Shaft generators (PTI/PTO), waste heat recovery, OPS	Standardised systems: Shaft generators and economisers have been used for decades.
Renewables	Solar panels	Low power impact: On commercial ships, solar is usually a secondary "micro-grid" addition. Unless it is the primary power source, it follows standard electrical plan approval.

For the Tier 1 technologies identified above, a systematic risk assessment will be conducted to satisfy the requirements of the issuing Classification Society.

6 Conclusion

This D5.1 has conducted an in-depth safety analysis regarding the adoption of novel Energy Efficiency Technologies (EETs) for both new ship designs and retrofits. Through a comprehensive review of typical technical characteristics and inherent hazards—ranging from the toxicity, flammability, and cryogenic requirements of alternative fuels to the structural and operational challenges of wind-assisted propulsion and battery energy storage—this task has systematically mapped the current regulatory landscape. By obtaining a clear comprehension of existing guidelines provided by major classification societies and scrutinising the shortcomings in current safety evaluation protocols, this task successfully identifies critical regulatory gaps.

To streamline the path toward commercialisation and regulatory compliance, the investigated technologies were classified based on their maturity. This prioritisation separates them into Tier 1 technologies, which represent novel concepts requiring an Approval in Principle (AiP) to prove equivalent safety, and Tier 2 technologies, which are proven and require only standard Plan Approval.

By identifying these regulatory gaps and potential safety shortcomings, this task proposes an enhanced risk assessment framework tailored to the specific needs of these emerging technologies. A blend of qualitative and quantitative risk evaluation models has been developed in response to the needs of safety evaluation on various EETs in accordance with different design stages and specific hazard types.

Ultimately, the key findings, hazard data, and specific mitigation strategies established in this deliverable will serve as the foundational reference material for the upcoming safety and risk assessments. Specifically, the collected data will be directly utilised for qualitative evaluations including HAZID (T5.2), HAZOP (T5.3), and FMEA (T5.3), as well as Quantitative Risk Analysis (QRA) studies (T5.4). Furthermore, these outcomes will be actively utilised as a critical reference for the basic and concept designs of EETs in WP4, providing a vital foundation for detailed, safe, and compliant engineering development.

7 References

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