International Clean Mobility Study

Prepared for:
econext

Prepared by:
Angler Solutions Inc.
100 New Gower St., Suite 803
St. John's, A1C 6K3

Date

April 06, 2026

econext
Advancing Newfoundland & Labrador's
Green Economy

Partially Funded by Natural Resources Canada

Financé partiellement par Ressources naturelles Canada

Canada

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List of Acronyms

AFC	Alkaline Fuel Cell
AIS	Automatic Identification System
CCG	Canadian Coast Guard
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
ECCC	Environment and Climate Change Canada
EEZ	Exclusive Economic Zone
EF	Emission Factor
EU	European Union
FPSO	Floating Production Storage and Offloading
GBS	Gravity Based Structure
GFI	Greenhouse Gas Fuel Intensity
GHG	Greenhouse Gas
GT	Gross Tonnage
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LF	Load Factor
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MCA	Maritime and Coastguard Agency
MCR	Maximum Continuous Rating
MCTS	Marine Communications and Traffic Services
MDO	Marine Diesel Oil
MEIT	Marine Emissions Inventory Tool
MGO	Marine Gas Oil
m-MSR	Marine Molten Salt Reactor
NL	Newfoundland and Labrador
NO_x	Nitrogen Oxides
NS	Nova Scotia
O&G	Oil & Gas
QC	Quebec
RNG	Renewable Natural Gas
RO/RO	Roll On/Roll Off
SO_2	Sulphur Dioxide
tCO_2e	Tonnes Carbon Dioxide Equivalent
VLSFO	Very Low Sulphur Fuel Oil
VOC	Volatile Organic Compound
WAPS	Wind Assisted Propulsion System
WHR	Waste Heat Recovery

1.0. Executive Summary

The International Clean Mobility Study Program assessed practical pathways to reduce greenhouse gas emissions across Newfoundland and Labrador’s marine sector. It combines international research, policy analysis, technical evaluation, and stakeholder engagement to assess technologies, alternative fuels, and operational strategies for marine decarbonization.

The global maritime industry is transitioning in response to increasingly stringent emissions regulations, evolving fuel standards, and growing expectations to reduce environmental impacts. This study program reviews Canadian and international policy frameworks alongside current technology developments to inform future marine operations.

Throughout this study, a wide range of energy diversification options were assessed, including efficiency improvements, hybrid propulsion systems, battery-electric technologies, alternative fuels, and carbon capture solutions. Each option presents distinct advantages and limitations, with applicability varying by vessel type, operating profile, and infrastructure. Newfoundland and Labrador’s marine sector is highly diverse, spanning ferry services, fishing vessels, offshore oil and gas support vessels, cargo shipping, and government fleets. As a result, no single solution can address all decarbonization needs. A combination of near-term incremental improvements and longer-term technology adoption will be required, supported by infrastructure and coordinated planning.

An emissions analysis, completed as part of this study, indicates that marine emissions in the province are highly influenced by offshore oil and gas activity, particularly tanker operations. While emissions remained relatively stable between 2015 and 2023, a significant increase in 2024 demonstrates the extent to which offshore production cycles can drive variability. This suggests that achieving meaningful emissions reductions will require addressing high-emitting and variable sectors alongside broader sector-wide improvements.

The findings of this study indicate that the transition to low-emission marine transportation will be gradual, region-specific, and dependent on coordinated action across multiple stakeholders. In the near-term, emissions reductions are most likely to be achieved through efficiency improvements, hybridization, and the use of lower-carbon or drop-in fuels, while longer-term solutions such as hydrogen, methanol, and ammonia will require further development, infrastructure investment, pilot demonstration projects, and regulatory alignment.

Building on these findings, a second phase of work will focus on practical demonstration projects that reflect the operational realities of Newfoundland and Labrador’s marine sector. Given the high capital costs associated with major propulsion system changes and uncertainty around long-term fuel pathways, early efforts should prioritize smaller-scale, lower-risk initiatives that can deliver measurable results and inform future investment decisions.

Key potential Phase 2 demonstration activities include:

- Efficiency upgrades for smaller vessels
- Hybrid and battery demonstration projects
- Renewable and lower-carbon fuel trials
- Port and shoreside demonstration initiatives
- Technology demonstration through partnerships and local facilities

These demonstration activities will support data collection, reduce implementation risk, and build local capacity, while positioning the province to adopt more advanced technologies as they mature. The province is positioned to contribute to this transition through targeted pilot projects, infrastructure development, and continued collaboration with domestic and international partners.

2.0. Project Introduction and Background

International shipping is under increasing pressure to reduce greenhouse gas (GHG) emissions while maintaining safe, reliable, and cost-effective operations. Shipping remains critical to global trade but contributes significantly to global carbon emissions. In response, international frameworks, such as the IMO's Net-Zero Framework, and national policies are increasingly focused on decarbonizing marine operations through the adoption of alternative fuels, electrification, hybrid systems, and energy-efficient vessel technologies. Canada's Green Shipping Corridors Framework and the 2030 Emissions Reduction Plan reflect this commitment and provide strategic direction for modernizing the marine sector. Within this context, Newfoundland and Labrador (NL), with its strong marine heritage and strategic Atlantic position, is well positioned to become a leader in clean maritime innovation.

The primary objective of this study is to evaluate realistic and practical energy diversification options for marine vessels operating in NL. This includes assessing the feasibility and integration of alternative fuels such as hydrogen, ammonia, and biofuels, along with hybrid propulsion systems, batteries, powertrains, vessel coatings, and electrification technologies. The study focuses on reducing emissions, improving energy efficiency, and identifying pathways for modernization of the provincial marine fleet. Given the scale of change required to meet climate targets, it is important to understand which technologies are practical in the near- and mid-term. These include improving the use of existing resources, implementing quick wins, and strengthening stakeholder alignment.

Interim solutions can also be adopted. These include optimizing passage to reduce fuel consumption and deploying onboard guidance systems that account for real-time conditions such as wind, tide, waves, and using hybrid approaches – such as mixed fuel alternatives for existing internal combustion engine propulsion systems. These near-term actions help build momentum while longer-term strategies are developed.

Engagement with industry, academia, and government stakeholders supported collaboration across operators, regulators, researchers, and technology providers. This process facilitate knowledge exchange, identification of challenges, and potential paths forward relevant to NL's maritime context.

3.0. International Document Review

3.1. Canadian Policy and Regulatory Landscape

Canada's marine sector is increasingly influenced by national climate policy, clean fuel regulation, and targeted programs that accelerate the deployment of low- and zero-emission technologies. Together, these frameworks establish regulatory drivers, market incentives, and funding mechanisms that support clean fuel production, infrastructure development, and vessel adoption.

At the highest level, Canada's climate commitments are governed under the **Canadian Net Zero Emissions Accountability Act**, which requires the federal government to set national emissions reduction targets and prepare emissions reduction plans toward achieving net-zero GHG emissions by 2050[1]. Canada's current national target is to reduce economy-wide emissions by 40-45% below 2005 levels by 2030[1]. This puts increasing pressure on transportation sectors, including marine, to reduce both emissions intensity and fuel consumption.

Complementing this framework, **Natural Resources Canada's Hydrogen Strategy for Canada** identifies hydrogen as a major component of Canada's energy transition. The strategy identifies heavy transportation and marine applications as priority areas where hydrogen and hydrogen-derived fuels can contribute to decarbonization. The strategy emphasizes development across the full value chain, including production, storage, distribution, standards, and end-use deployment. For coastal and offshore jurisdictions such as NL, the strategy identifies opportunities for regional hydrogen hubs, export development, and domestic marine use cases linked to port infrastructure and vessel operations[2].

Canada has also implemented **Clean Fuel Regulations (CFR)**, which require liquid fossil fuel suppliers to progressively reduce the lifecycle carbon intensity of fuels used in Canada. The CFR establishes a credit-based compliance system that incentivizes blending, alternative fuels, and clean energy inputs across transportation sectors. For marine operations, this creates an economic incentive for renewable diesel, biodiesel, hydrogen-derived fuels, and other lower-carbon alternatives, while encouraging investment in fuel supply chains and bunkering infrastructure[3].

At the implementation and demonstration level, Transport Canada has launched the **Green Shipping Corridor Program** as a mechanism to accelerate marine decarbonization[4] by providing funding for projects that contribute to:

- Removing barriers to the adoption of emission reducing equipment and infrastructure.
- Incentivizing industry-led partnerships and investments to accelerate the adoption of GHG emission-reduction technologies and infrastructure.
- De-risking investments to increase the technology-readiness level of low carbon and zero-emission ship technology and marine fuels for the domestic vessel fleet.

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[1] Canadian Net-Zero Emissions Accountability Act – Government of Canada
[2] The Hydrogen Strategy – Government of Canada
[3] Compliance With the Clean Fuel Regulations – Government of Canada
[4] Green Shipping Corridor Program – Government of Canada

- Building capacity among Canadian vessel owner/operators with respect to their ability to identify, plan, and implement next generation low carbon and zero-emission ship technology and marine fuels into their vessel operations.

The program supports the establishment of low- and zero-emission shipping corridors and is delivered through two complementary funding streams:

- the Clean Ports Stream, which funds shore power systems, port electrification, alternative fuel storage and bunkering, and emissions-reduction infrastructure at Canadian ports.
- the Clean Vessel Demonstration Stream, which supports pilot projects and demonstrations of low- and zero-emission vessel technologies, including alternative fuels, propulsion systems, hybridization, and onboard energy systems.

The Green Shipping Corridor Program aligns Canada's marine sector with international green corridor initiatives by signing the Clydebank Declaration in 2021[5]. This requires ports, vessel operators, fuel producers, and governments to coordinate fuel supply, infrastructure, and vessel certification.

The **Hydrogen Development Action Plan** by the Government of NL outlines short-term actions to enhance the understanding of the domestic market for green hydrogen and highlights the need to identify Research and Development (R&D) requirements to support the sector and pursue long-term opportunities for hydrogen projects, demonstrations, and start-ups. When aligned with federal funding, interest areas, and international regulatory trends, provincial initiatives improve the investment opportunity to accelerate the commercialization of clean fuels for marine applications[6].

3.2. International Emissions Targets and Regulatory Drivers

At the global level, the International Maritime Organization (IMO) regulates emissions from international shipping. The **2023 IMO Strategy on Reduction of GHG Emissions from Ships** establishes an ambition for international shipping to reach net-zero GHG emissions by or around 2050[7]. It also sets indicative checkpoints, including a reduction in carbon intensity of at least 40% by 2030 compared to 2008 levels and an increase in the uptake of zero- and near-zero-emission technologies and fuels to 5-10% of total energy use by 2030[7].

In parallel with long-term targets, the IMO has implemented near-term technical and operational measures under **MARPOL Annex VI**, including the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII). These measures apply to most oceangoing vessels and are already influencing operational practices, retrofits, and technology adoption.

To operationalize these goals, the IMO is considering a **Net-Zero Framework**, which if implemented will introduce globally consistent emission limits and a pricing mechanism applicable to large vessels, intended to incentivize emissions reductions and generate funding for low-carbon infrastructure and capacity building. The framework would apply to all oceangoing vessels with

[5] Canadian Green Shipping Corridors Framework – Government of Canada
[6] Hydrogen Development Action Plan – Newfoundland and Labrador
[7] 2023 IMO Strategy on Reduction of GHG Emissions from Ships – IMO

over 5,000 gross tonnage (GT), which are responsible for over 85% of global shipping emissions and are already covered by reporting requirements for fuel data collection. The framework would establish a global system in which ships, regardless of flag state, are required to use cleaner fuels or technologies. If their calculated GHG fuel intensity is too high, they would be required to pay a price corresponding to the GHG emissions they emit over the threshold. Vessels would be required to report their GHG Fuel Intensity (GFI) to the IMO each year and be responsible for keeping their emissions below set GFI limits, forecasted to get stricter each year[8]. It is important to note that the IMO's Marine Environment Protection Committee met in October 2025 to consider the adoption of the framework but could not reach a consensus and pushed their decision to October 2026. Therefore, the future of this framework is uncertain, and its earliest possible implementation is March 2028[9].

Beyond the IMO, regional frameworks are also shaping the regulatory environment for shipping. The European Union's (EU) **FuelEU Maritime Regulation**, adopted under the "**Fit for 55**" package, requires ships calling at EU ports to progressively reduce the lifecycle GHG intensity of their energy use. The regulation establishes staged reductions beginning in 2025 and increasing toward long-term decarbonization targets by 2050. This framework also encourages the use of shore power and other zero-emission technologies at berth, reinforcing the case for port-side electrification and infrastructure investment[10].

The UK Maritime and Coastguard Agency (MCA) actively drives the implementation of green marine regulations, aiming to advance sustainability across the UK maritime sector. Key initiatives and regulatory measures include:

- **Marine Decarbonization Strategy:** The MCA's Marine Decarbonization Strategy sets legally binding targets for reducing GHG emissions from UK domestic shipping. These targets align with the UK's Climate Change Act 2008 and the Net Zero by 2050 commitment. The UK government requires that domestic shipping emissions be cut by 30% by 2030, 80% by 2040, and net-zero achieved by 2050. The strategy includes regulatory interventions such as mandatory reporting of emissions, implementation of the UK Emissions Trading Scheme for maritime, and incentives for the adoption of alternative fuels and energy saving technologies.
- **Marine Equipment Regulations:** The MCA oversees the Marine Equipment Regulations 2016, which implement the EU Marine Equipment Directive into UK law. Following Brexit, these regulations now include the UK Conformity Assessment mark, replacing the CE mark for marine equipment placed on the UK market. The ongoing consultation aims to update these regulations, providing flexibility for the approval and use of innovative, greener technologies such as advanced emission control systems, hybrid propulsion, and energy storage solutions. The regulatory framework ensures that only approved, environmentally compliant equipment is installed on UK ships, supporting the transition to low-carbon maritime operations.

[8] The IMO Net-Zero Framework FAQs – IMO
[9] Decision on the IMO Net-Zero Framework delayed for one year – DNV
[10] Decarbonising maritime transport – FuelEU Maritime

- **Clean Maritime Demonstration Competition:** The MCA participates in the Clean Demonstration Competition, funded by the Department for Transport, which supports UK-based projects trialling zero-emission vessels and infrastructure. Regulatory support includes fast-track approval for experimental green technologies, collaboration with the UK Ship Register to facilitate retrofitting on existing vessels, and guidance on compliance with Merchant Shipping (Prevention of Air Pollution from Ships) Regulations 2008. The Demonstration encourages adoption of hydrogen, battery-electric, and wind-assisted propulsion in line with UK regulatory standards.

4.0. Energy Diversification Options for Marine Vessels

A wide range of technologies are currently being explored to reduce emissions in the marine sector. Strategies may relate to general efficiency improvements, machinery advancements, alternative fuels, or carbon capture, and each of these categories is discussed in detail throughout the following section.

Each option presents different trade-offs in terms of cost, performance, and feasibility. No single technology or fuel pathway can address all operational requirements, and trade-offs between cost, performance, and feasibility must be considered.

4.1. Efficiency Enhancements

Given the vast amounts of fuel used in marine transportation, small improvements in efficiency can greatly reduce total fuel consumption and emissions. The following techniques for efficiency enhancement are broken down into weather routing, hydrodynamic considerations and dynamic onboard vessel management.

4.1.1. Weather Routing

Ocean weather is dramatic and fluctuating, and factors such as wind, wave conditions, water depth, and currents all influence a ship's overall fuel efficiency[11]. As a result, a wide selection of weather routing algorithms have been developed or are currently in development, which plot routes based on real-time weather predictions and specific ship considerations. These algorithms use advanced computing, machine learning, or artificial intelligence to consider a wide range of variables and weigh complex uncertainties, beyond what manual route planning can achieve[12]. In practice, weather routing is divided into three components: onboard analytics used by the captain, shore-side routing services that provide safety and performance guidance, and web-based platforms used by commercial operators to align operational and commercial objectives.

In addition to the potential fuel savings, weather routing can improve safety and the reliability of arrival times, reduce travel time and emissions, and increase profits. Key benefits are summarized in Table 1.

[11] The Orcelle project: Towards Wind-Powered Ships for Deep Sea Cargo Transport – S. Werner et al.
[12] State-of-the-art optimization algorithms in weather routing – ship decision support systems: challenge, taxonomy, and review – Y. Chen et al.

Table 1: Summary of weather routing benefits[12].

Fuel Savings	Up to **10%**
Time Savings	Up to **5%**
Emission Savings	Up to **12.5%**
Profit Increase	Up to **7.9%**

When weather routing is combined with wind assisted propulsion systems, which are discussed further in Section 4.2, the fuel savings can be doubled when compared to direct route shipping[13].

Weather routing can be applied to any ship, with potential savings increasing with ship size and route duration. Reasons for weather routing not being more widely used include concerns about model accuracy and a greater degree of trust in on-board expertise[14].

4.1.2. Hydrodynamics

Additional efficiency improvements can be achieved through reducing drag. There are various strategies available which focus on reducing the frictional forces between the vessel and the water, including hull coatings, cleaning, air lubrication, hull form optimization, and propeller efficiency.

Hull coatings are crucial in reducing drag due to their ability to reduce biofouling. Biofouling refers to the accumulation of barnacles, algae, or other organisms on the hull, which significantly affect a ship's ability to move smoothly through the water. Not only can hull coatings minimize biofouling, but they can also minimize erosion. Effective hull coatings must be durable, hydrophobic, and compatible with environmental regulations to minimize biofouling without harming marine ecosystems[15].

Figure 1: Example of biofouling on a ship's hull[16].

An additional strategy to prevent biofouling is regular **hull cleaning**. Typically, hull cleaning is completed by divers or remotely operated vehicles to remove the accumulation of debris and organisms. This is a crucial step in improving efficiency, as even a light layer of slime on the hull

[13] Wind-Assisted Propulsion Systems (WAPS): How WAPS can help to comply with GHG regulations – DNV
[14] Weather & Route Planning – Sail Magazine
[15] Exploring The Impact Of Hull Coatings On Ship Efficiency – Seacoat
[16] The Impact of Salinity on Boat Hull Fouling – Underwater Marine Solutions Florida

at 50% coverage can increase fuel usage and emissions by 20-25%[17]. Fuel savings can be further increased by implementing an enroute cleaning system such as a hydroblasting system, which uses high pressure nozzles to clean the hull while in transit[18].

To further reduce friction and drag, an air lubrication system may be implemented. A typical **air lubrication system** produces a constant flow of air bubbles against the hull, creating a layer between the water and hull, and reducing resistance by up to 6%. This method is more applicable to existing vessels and is more effective at lower speeds, while **air cavity systems** are more effective for high-speed vessels and are easier to implement on new builds. In this case, the bottom of the hull is designed in a way to contain a large air cavity below the ship and against the water, creating a more robust air barrier and reducing drag by up to 26%[19].

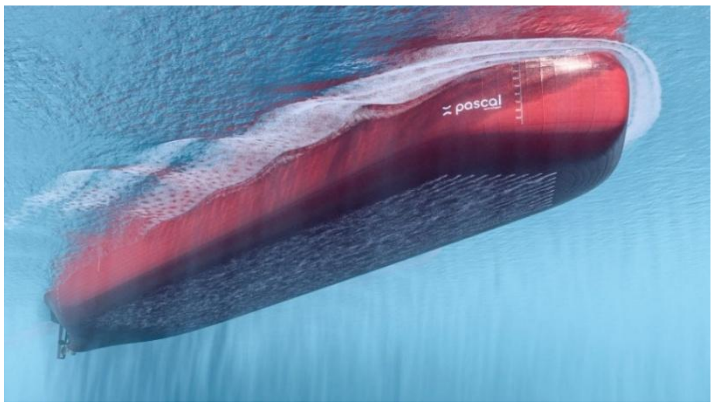

Figure 2: Example of an air lubrication system[20].

For new builds, specific care should be put into the **hull form design**. During the design phase, the hull form may be optimized based on a variety of technical parameters, including speed, maneuverability, low speed performance, or overall efficiency. Computational fluid dynamics is commonly used to simulate flow and optimize hull form for efficiency under expected operating conditions[21].

Many of these strategies can be modified and applied to the propeller as well as the hull. Fouling and surface damage to the propeller can decrease efficiency by 3-7%, requiring proper coating and cleaning, and propeller design should prioritize hydrodynamic efficiency and resistance to fouling and surface damage[22].

4.1.3. Dynamic Onboard Vessel Management

Modern onboard vessel management systems use real-time data, including weather conditions, vessel performance, and operational parameters, to support decision-making related to speed

17 How biofouling impacts vessel efficiency and how to fix it – E. Heaslip, Sofar Ocean
18 En-route operated hydroblasting system for counteracting biofouling on ship hull – J. Hua et al.
19 Review of current regulations, available technologies, and future trends in the green shipping industry – M. Tadros et al.
20 Pascal Technologies' advanced control systems for ALS slash shipping emissions – Business Norway
21 Hull form optimization – IMO GreenVoyage 2050
22 Improving Ship Efficiency – Copenhagen Centre on Energy Efficiency

and routing. These systems provide guidance aimed at improving fuel efficiency, reducing emissions, and maintaining safe operating conditions.

By continuously adjusting to changing conditions, they can help reduce fuel consumption and improve consistency in voyage planning. Post-trip analytics can also be improved to assess performance and identify opportunities for further efficiency improvements.

4.2. Machinery Advancements

4.2.1. Engine Modifications

Given the importance of the engine to a ship's operation, there are many related considerations in terms of its efficiency and compatibility with other emission reduction strategies.

The efficiency of marine engines is relatively high compared to typical internal combustion engines, but there are a few operational considerations that can further increase their efficiency. Engine efficiency can be improved by optimizing combustion conditions, including compression ratios and temperature control[23]. Maintaining a lower temperature reduces the heat that is lost to surroundings, allowing more of the fuel energy to be harnessed for propulsion and reduces NO_x emissions.

Traditional marine engines are designed to run on diesel, and while some alternative fuels may be burned with or in place of diesel without engine modifications, others require retrofits. Typically, that means modifying the engine to become a **dual fuel engine**, which can burn both diesel and an alternative fuel. These engines may be configured in a variety of ways, with the most common in the marine sector being the micro-pilot system. This configuration uses less than 5% diesel during regular operation, primarily running on an alternative fuel and using diesel to initiate ignition. To retrofit a diesel engine to the micro-pilot system, certain engine components may remain the same, others must be modified, and a few key components must be added. Most importantly, the micro-pilot and gas supply system must be added, with important modifications done to components including but not limited to the control system, cylinder head, and intake port[24].

According to DNV, the cost of retrofitting ranges from 5-15 million USD depending on fuel type. It is generally recommended for the cost of retrofit to not exceed 25% of the newbuild, therefore making retrofitting more viable for larger vessels, which incur greater newbuild costs. In addition to cost, a current barrier to retrofitting is the IMO requirement for testing on the same engine type. This is difficult for old vessels, as many of the engines are no longer commercially available and cannot be acquired for testing[25].

In addition to established dual-fuel configurations, emerging retrofit technologies are enabling the integration of hydrogen into conventional marine fuel systems. In blended or dual-fuel applications, **hydrogen** can be combined with traditional fuels to improve combustion efficiency and reduce emissions of SO_x and NO_x, and particulate matter. These systems can enhance

[23] A review of low and zero carbon fuel technologies: Achieving ship carbon reduction targets – Y. Wang et al.
[24] Challenges and opportunities of natural gas dual-fuel engines for marine applications – Y. Tang et al.
[25] Challenging road ahead for retrofitting to dual-fuel engines – DNV

engine performance, including improved fuel efficiency and optimized power output, while maintaining compatibility with existing engines. A key advantage is their ability to be retrofitted without requiring significant vessel redesign or major changes to fuel supply infrastructure.

With the small amount of diesel used in these systems, the related emissions are low and can be further reduced by blending or replacing diesel with biodiesel or renewable diesel. The alternative fuels available to dual fuel engines will be discussed in Section 4.3, including hydrogen, ammonia, liquefied natural gas (LNG), liquefied petroleum gas, and methanol.

4.2.2. Waste Heat Recovery

As previously discussed, marine engines are relatively efficient, but they still lose roughly 50% of the input fuel energy to waste heat[26]. Utilizing this waste heat for heating, electricity production, freshwater production, or refrigeration can greatly improve the overall efficiency of the system. The main carriers of waste heat are the exhaust and cooling water, which typically exit the system at 200-500 °C and 70-125 °C respectively[27].

To extract heat from exhaust, the gases are typically fed through a heat exchanger before being released to the atmosphere (or before undergoing a carbon capture process). There are certain concerns regarding corrosion and soot buildup which should be mitigated by avoiding cooling the exhaust gas below its acid dew point. In practice, this means releasing the exhaust to the atmosphere at a temperature above 165 °C. The heat extracted by the heat exchanger may then be used for direct heating or to power either a thermoelectrical generator or a bottoming power cycle such as a Rankine Cycle or Kalina Cycle to generate electricity for onboard use.

The heat carried by the cooling water can be utilized as part of an organic Rankine cycle, which is able to generate electricity from low temperature fluids, or as part of the desalination process to provide freshwater from the sea.

These waste heat recovery methods are suitable for both retrofits and newbuilds and can reduce fuel consumption by 5-15% while supplementing electricity and freshwater generation[28].

4.2.3. Fuel Cells

Fuel cells have received increasing attention as an alternative to traditional engines for both land-based and marine applications. Fuel cells eliminate the need for combustion by directly converting chemical energy into electricity, typically using hydrogen. This is a highly efficient and quiet process, and produces no emissions, with the only byproducts being water and heat.

When applied to the marine industry, fuel cells provide long range operation with stable and reliable power. Additionally, refuelling can be fast and fuel cells are modular by design, therefore highly scalable for varying needs[29]. Most marine fuel cells operate on hydrogen, although some systems can also use LNG or diesel. The fuel cells currently suited to the marine industry are summarized in Table 2.

[26] A review of waste heat recovery from the marine engine with highly efficient bottoming power cycles – S. Zhu et al.
[27] A review of waste heat recovery technologies for maritime application – D. Singh & E. Pedersen
[28] Marine Exhaust Gas Heat Recovery Systems – Sustainable Ships
[29] Fuel cells for marine vessels: Why the time to transition is now – M. Kammerer, Ballard

Table 2: Summary of fuel cell types for maritime applications[30].

Type of Fuel Cell	Benefits	Suitable Application
Proton Exchange Membrane Fuel Cell (PEMFC)	• High power density • Fast startup times • Low operating temperatures	• Small to medium sized vessels, ferries, and onboard power for large ships
Solid Oxide Fuel Cell (SOFC)	• Can use LNG or diesel • Highly efficient • High power density	• Large vessels including cruise ships, naval vessels, and cargo ships
Alkaline Fuel Cell (AFC)	• Highly efficient • Durable	• Research vessels, not yet widely used for maritime applications
Molten Carbonate Fuel Cell (MCFC)	• Can use LNG	• Applications where combined heat and power is necessary such as cruise ships and offshore platforms
Direct Methanol Fuel Cell (DMFC)	• Simple operation	• Small vessels such as recreational boats and yachts

The primary challenge regarding fuel cells in the marine sector is the storage of hydrogen. Hydrogen storage requires very high pressures and low temperatures, as well as significant storage space. This barrier will be discussed further in Section 4.3. Fuel cells can potentially be retrofitted onto existing vessels but are more suited to newbuilds due to the extensive modification requirements[31].

4.2.4. Nuclear Reactors

While not yet widely used in commercial shipping, nuclear power is currently being used on icebreakers, submarines, and naval vessels. A paper published in *Nuclear Engineering and Design* presented a strengths, weaknesses, opportunities, and threats (SWOT) analysis assessing the viability of nuclear power for commercial marine vessels[32]. The primary strengths were identified as the high-power output, lack of emissions, and substantial cargo capacity, and the weaknesses were identified as the lack of maturity, social perception, and high investment cost. Opportunities include decarbonization targets, the reduction of fossil fuel dependence, and the elimination of fuel price fluctuations, and threats include safety and security challenges, prohibition of port and canal access, and the six degrees of freedom of ship vibration. The analysis concluded that the strengths and opportunities outweigh the weaknesses and threats, demonstrating the viability of nuclear as a marine fuel, but highlighting that significant attention must be paid to the concerns surrounding safety and security.

One potential technology for nuclear propulsion in the maritime sector is the marine **Molten Salt Reactor (m-MSR)**, which uses liquid salts to prevent overheating and pressure buildup, and can drain the fuel to a heat sink in an emergency. These reactors are compact, designed with passive safety features and can provide power for up to 30 years without the need to refuel. When

[30] Fuel Cell Technology for Marine Propulsion – Spectra Fuels
[31] Energy-efficiency measures and technologies – DNV
[32] Analysis of the nuclear energy systems as an alternative propulsion system option on commercial marine vessels by utilizing the SWOT-AHP method – M. Bayraktar & O. Yüksel

compared to vessels designed for and powered by very low sulphur fuel oil (VLSFO), HFO, LNG, and ammonia, the m-MSR reactor had the overall lowest life cycle costs and emissions[33].

Although the life cycle costs are relatively low, the capital costs are significant. It is technically possible to retrofit existing ships to be powered by nuclear reactors, but it is not considered economically feasible and instead these ships are typically built new, requiring significant upfront capital[34].

4.2.5. Battery Energy Storage Systems

Ship propulsion may be electrified and powered by onboard battery energy storage systems (BESS), which are low in emissions and able to efficiently manage onboard power loads. Using energy from batteries is emissions-free, but there may be emissions associated with the source electricity and the overall lifecycle of the battery, including manufacturing and disposal. The batteries used in the marine industry are typically either lithium-ion or lead acid, both of which offer significantly lower operating costs compared to traditional ship propulsion.

The primary challenges regarding battery energy storage for marine vessels are the range, battery charging capabilities, and exposure to marine elements. Currently, batteries have only been implemented for propulsion on small, short-distance vessels, as the limited range doesn't currently allow for long-voyage applications. There are various methods of port recharging, including wired charging, wireless charging, and battery swapping. Wired charging is the current standard but requires significant charging times in port. There are concerns regarding the prolonged marine exposure of both the battery shell and internal components, which requires diligent monitoring and maintenance.

Battery weight and reliance on rare earth minerals are significant factors affecting the design, efficiency, and sustainability of battery-electric vessels. Batteries for marine applications are typically large and heavy, which can affect vessel weight, stability, and cargo capacity. This may also require structural modifications to maintain seaworthiness. Additionally, the production of batteries often relies on rare earth minerals such as lithium, cobalt, and nickel. These minerals are sourced through mining processes that can have environmental and geopolitical implications. Limited global supply, ethical sourcing concerns, and fluctuating market prices for rare earth elements pose challenges to scaling electric vessel adoption. As the demand for battery-powered ships grows, manufacturers and operators must address these issues by exploring alternative battery chemistries, improving recycling technologies, and developing supply chain strategies to mitigate risks associated with weight and rare earth mineral dependency.

Battery-powered ships may use a hybrid configuration or batteries alone. Hybrid ships typically rely on diesel-powered propulsion for the bulk of their power, with batteries being used to supplement propulsion during port departure, barred speed ranges, peak operation, or adverse weather conditions. The use of battery-powered propulsion during port departure reduces emissions within ports, mitigating air quality concerns near human activity. Battery propulsion may

[33] Sustainable decarbonization of ocean transportation from marine Molten Salt Reactors (m-MSR) for zero-emissions electric propulsion – G. Gennaro & M. Bøe
[34] Nuclear retrofits technically feasible, economically impractical – G. Howard, Seatrade Maritime

also be used during barred speed ranges, the ranges at which a vessel experiences issues with excess engine vibration. During peak operation, batteries can aid in peak shaving, typically providing cost savings and operational stability. Similarly, batteries can provide extra torque in adverse weather, enhancing reliability.

Both hybrid configurations and completely battery-reliant vessels may be retrofitted from existing vessels or be built new, with there being ten times more retrofits than new builds as of 2024.

4.2.6. Wind Assisted Propulsion Systems

Wind Assisted Propulsion Systems (WAPS) are increasingly adopted to supplement engine propulsion using wind energy. WAPS use principles from traditional sailing to harness energy from the wind to supplement engine propulsion. As of January 2025, there were 52 seagoing ships with WAPS installed with a further 97 newbuilds with WAPS in the orderbook[13]. This section will review the various types of WAPS, including rotor sails, suction sails, wing sails, soft sails, and kites, and discuss the benefits and challenges associated with these systems.

Rotor sails, Flettner sails, or Flettner rotors consist of several large vertical cylinders installed on the ship deck, each with an electric motor. As wind passes across the rotor sails, the motors rotate the cylinders to induce the Magnus effect, where a pressure differential is generated across the cylinder, generating a lift force perpendicular to the wind direction. This form of WAPS uses a very small energy input compared to the propulsion energy output[13] and generates a large ratio of lift force to sail area[31]. While a large lift force is desirable, this system also generates a significant drag force, decreasing the usable propulsion force[31].

Figure 3: Example of a bulk carrier utilizing rotor sails[35].

Suction sails, also known as suction wings, operate on a similar principle to rotor sails where wind passes over vertical sails, inciting a lift force and propulsion perpendicular to the wind direction. The difference lies in how the lift force is generated. A suction sail uses a sail shape like that of an airplane wing to generate a lift force without the need for rotation and uses fans to generate a suction force within the wing. A vertical gap exposes the external air flow to the internal suction, preventing separation of the air flow from the sail to increase the generated lift

[35] Lloyd's Register Finds 'Significant' Efficiency Benefits for Newcastlemax Bulk Carrier Design Featuring Rotor Sails – M. Schuler, gCaptain

force and reduce drag. This system also requires the ability to rotate so that the sail may be rotated to the optimal angle of attack with the wind. The energy required to generate the suction force and control the angle of attack is overall small compared to the resulting propulsion energy[13].

Figure 4: Example of an oil and chemical tanker utilizing suction sails[36].

Wing sails are a simplified version of suction sails, where the lift force is generated only by the sail shape and does not use suction forces. The vertical sails operate nearly identically to airplane wings, where the shape of the sail itself generates the lift force, and the angle of attack may be controlled to optimize lift and reduce drag. Just like rotor and suction sails, this system incites propulsion perpendicularly to the wind direction but unlike the previous systems, it does not require a constant energy input and instead generates propulsion passively.

Figure 5: Example of a bulk cargo carrier utilizing wing sails[37].

Soft sails refer to traditional sailing technology where a flexible fabric is supported by mast and boom. Modern features may be installed to optimize the performance of soft sails, primarily in the form of control systems and automation to reduce the need for physical human interaction[13].

36 Spanish owner opts for suction sails to save fuel, cut emissions – riviera
37 Wing Sails for Cargo Ships Pass First Test – M. Abrams, The American Society of Mechanical Engineers

Figure 6: Example of a cargo vessel utilizing soft sails[38].

Kites may also be used, and they differ significantly from other forms of WAPS. For this system, a kite is flown at high altitudes, tethered to and pulling a vessel and creating a propulsion force parallel to the wind direction. The aerodynamic performance is often enhanced by the dynamic motion of the kite itself[31].

Figure 7: Example of a cargo vessel utilizing a kite[39].

Unlike other methods of reducing marine emissions, the energy source for WAPS is completely free as the wind itself is readily available, and implementing WAPS typically reduces emissions by up to 20% but can in some cases reduce emissions by over 30%. Similarly, because of the reduced engine usage, WAPS can help reduce underwater radiated noise, minimizing the impact on aquatic life[13].

In contrast to the proven benefits of these systems, there are some challenges related to the implementation and use of WAPS. The structures themselves may increase deck noise and vibration, potentially impacting on-board life, and the systems are large and require significant modifications to a vessel's structure, requiring in-depth safety and structural analysis to ensure the vessel remains seaworthy. As for navigation and control, the physical presence of the

[38] Neoliner Origin, the 'world's first' sailing RoRo vessel, is finally here – S. Kosmajac, Offshore Energy
[39] Beluga Shipping: Pioneering Wind-Driven Cargo Vessels with SkySails – Energy, Oil & Gas Magazine

structures may reduce visibility from the control deck, and additional control systems must be implemented[31].

These factors all contribute to why WAPS have not been more widely implemented, in addition to considerations of cost and data availability. The capital costs of these systems are significant, ranging from an estimated EUR 230,000 to EUR 2,931,000, including asset and installation costs, with an additional EUR 10,000 for crew training[40]. These values are highly dependent on the chosen system and whether it is a retrofit or new build. Like any emerging technology, there is a limited amount of data available regarding performance, operability, safety, durability, and economics, which can reduce stakeholder willingness to invest in technologies with limited operating history[11].

4.3. Alternative Fuels

Fuel choice is the primary factor influencing marine vessel emissions. Ships today typically use HFO, MGO, or MDO, which cause emissions at varying levels. Of these three fuels, HFO, the residual mixture leftover from the processing of crude oil, causes the most significant emissions[41]. Its high emissions have led to it being banned in many areas, but it is still widely used in large commercial vessels due to it being roughly 30% cheaper than MGO and MDO[42]. MGO and MDO are both distillates and lower in emissions than HFO, and MGO is higher in quality and cost than MDO, owing in part to MDO being a distillate blend that typically includes small amounts of HFO[43]. MGO is used in a wide variety of vessels and is slowly becoming more common in large vessels as a result of emissions restrictions impacting the use of HFO[44]. MDO is typically used in small to medium scale vessels, in addition to being used as an auxiliary fuel in large vessels[45].

Even though the emissions resulting from MGO and MDO are lower than from HFO, they are still significant. In pushing for global emissions reductions, the availability of alternative fuels is steadily growing. This section will discuss hydrogen, ammonia, LNG, liquefied petroleum gas (LPG), methanol, biodiesel, and renewable diesel as potential alternative fuels for the marine sector.

Table 3: Summary of alternative fuels.

Fuel	Benefits	Challenges
Hydrogen	• High heating value • High combustion efficiency • Completely free of emissions	• Very difficult to store
Ammonia	• Twice as energy dense as hydrogen • Free of CO_2 emissions	• Emits NO_x • Poorer combustion characteristics than hydrogen • Highly toxic
LNG	• Readily available	• Not emissions-free

40 Potential of wind-assisted propulsion for shipping – European Maritime Safety Agency
41 Types of Marine Fuels – James Hallam Insurance Brokers
42 The 5 most relevant marine fuels right now – Senmatic
43 What is the difference between MDO and MGO? – Livebunkers
44 Everything you need to know about marine gas oil – Oilfast
45 Marine Diesel Oil (MDO) & Intermediate Fuel Oil (IFO) – Oiltanking

LPG	• Easier to store and handle than LNG • Readily available • Very efficient	• Emits some CO_2 • Corrosive and toxic
Methanol	• Easy to store and handle	• Emits some CO_2 • Toxic and flammable
Biodiesel	• Carbon neutral	• Poor cold weather performance
Renewable Diesel	• Chemically identical to conventional diesel but with significantly lower emissions	• Not completely free of emissions

4.3.1. Hydrogen

Hydrogen is increasingly considered for marine applications due to its high energy content by mass and the potential for zero-emission combustion. As discussed in Section 4.2, traditional diesel engines may be retrofitted to burn a combination of diesel and hydrogen, or fuel cells may be used to burn hydrogen alone. These characteristics make hydrogen an attractive marine fuel, but there are many additional considerations influencing its feasibility, including the fuel source, energy content, storage requirements, and safety measures.

Hydrogen is generally regarded as a clean fuel, but of the various available methods of hydrogen production, not all are emissions-free. Two of the common methods used to produce hydrogen are steam methane reforming and coal gasification, both of which result in impure hydrogen and produce emissions. For hydrogen to truly be a clean fuel it must be produced via electrolysis powered by renewable electricity. Electrolysis uses input electricity to break water into its constituent parts, resulting in hydrogen gas, referred to as green hydrogen, and oxygen gas.

There is significant research currently being done on other potential methods of clean hydrogen production, such as steam hydrolysis of chemical hydrides, which is carbon-free and produces only hydrogen gas, but requires specific chemical hydrides and may require elevated temperatures[46].

Hydrogen's energy profile presents both advantages and challenges, as its energy content by mass is incredibly high, but its energy content by volume is incredibly low. Hydrogen gas is very light, but has low density, so while its energy content by mass is roughly three times that of gasoline, its volumetric energy content is only one quarter of gasoline's energy content when in liquid phase, and one fifth of gasoline's energy content when in its gaseous phase[47].

The low volumetric energy content of hydrogen makes it unrealistic to store in its gaseous phase, so must be compressed to its liquid phase, requiring high pressures and/or low temperatures. This makes containment quite challenging. To maintain high pressures, tanks must be physically small, requiring a greater number of tanks to compensate for their small size, and to maintain low temperatures, tanks must be double wall vacuum insulated[48]. Additional care must be taken in

[46] Process integration of hydrolysis and hydrogen generation processes in the six-step Cu-Cl cycle for green hydrogen production – R. Kadam & G. Yadav
[47] Hydrogen Factsheet – University of Michigan Center for Sustainable Systems
[48] Fuel Choices for Carbon Reduction and Impact on Vessel Design – C. Baker et al.

tank design to mitigate the effects of hydrogen embrittlement, where the small hydrogen atoms diffuse into the metal containment, reducing its strength.

Figure 8: Example of hydrogen storage tanks[49].

There are various surface treatments available to prevent hydrogen embrittlement including coatings, thermochemical modification, high-energy surface treatment, mechanical treatment, and laser treatment. In general, these treatments either create a barrier between the hydrogen and the container or prevent the formation and propagation of cracks[50].

Figure 9: Example of hydrogen embrittlement[51].

If hydrogen gas were to escape its containment, there are potential fire risks and moderate risks to humans breathing the gas. Hydrogen gas is flammable, and the flames are not visible in daylight, making fires difficult to identify and extinguish. While hydrogen gas is non-toxic, it can displace oxygen, thereby causing serious health risks, including asphyxiation[48].

4.3.2. Ammonia

As an alternative to hydrogen fuel, ammonia may be used. Ammonia's energy density is nearly double that of hydrogen, making it far easier to store in large quantities. It is also less volatile and

[49] Hydrogen Fireball in a storage area using EFFECTS – Gexcon
[50] Hydrogen embrittlement mitigation by surface modification: A review on current advances and future perspectives – H. Maurya & F. Akhar
[51] Hydrogen Embrittlement – Wikipedia

easier to handle, but results in NO_x emissions and has poorer combustion characteristics[52]. Like hydrogen, ammonia is commonly combusted in dual-fuel engines, where diesel is used as the pilot fuel. While it is theoretically possible to combust pure ammonia in a compression ignition engine, it requires incredibly high compression ratios and temperatures, making it unrealistic at this point in development.

Historically, ammonia has been produced from natural gas and nitrogen, and while this is still a common method of production, ammonia produced this way cannot be considered an emissions-free fuel due to the CO_2 emissions associated with its production. As an alternative, ammonia may be produced from green hydrogen, resulting in green ammonia.

Both the traditional method of ammonia production using natural gas and the carbon-free option using green hydrogen typically use the Haber-Bosch process to combine the source fuel (natural gas or hydrogen) with nitrogen from the air to create ammonia under high pressures and temperatures of 200-400 bar and 400-600°C. This process is energy-intensive, so electrochemical synthesis may be used instead, which combines the production of green hydrogen and ammonia into the one process powered by renewable energy[53].

The potential for ammonia fuel to be completely free of CO_2 emissions is its primary benefit as a marine fuel, along with its production being energy-efficient and highly scalable. While it is widely considered one of the most promising alternative fuels for marine applications, there are three primary drawbacks that must be considered: the associated safety concerns, the space required for storage, and the cost.

Significant attention must be given to safety measures surrounding ammonia fuel, as ammonia is highly toxic. Recommended safety measures from the 2025 DNV white paper on ammonia[54] include:

- implementing systems to prevent operational releases of ammonia,
- providing safe havens for people onboard where they can seek refuge,
- having plans in place for safe evacuation in case of accidental ammonia release, and
- ensuring suitable protective equipment is available.

Compared to traditional fuels, ammonia has a relatively low volumetric energy density, meaning that to store the same amount of energy as would typically be needed for a vessel, a much greater storage capacity is required. Ammonia's energy density is roughly one third that of MGO[55], therefore requiring three times the storage space for the same amount of energy.

In terms of economics, both ammonia-powered vessels and the fuel itself are associated with higher capital and fuel costs. As of September 2025, ammonia powered vessels were 15-16% more expensive than their traditional counterparts, but this is likely to reduce as technology

52 Hydrogen and ammonia as a primary fuel – A critical review of production technologies, diesel engine applications, and challenges – S. Manigandan et al.
53 Green ammonia production: Process technologies and challenges – N. Bora et al.
54 Ammonia in shipping: Tracing the emergence of a new fuel – DNV
55 Volumetric energy density of alternative marine fuels – Marine Service Noord

advances and becomes more widely available[54]. The fuel itself is also expensive but similarly will likely level out with technological advancements and GHG pricing.

Figure 10: Example of an ammonia-powered vessel[56].

4.3.3. Liquefied Natural Gas

LNG is seen as a promising step towards emissions-free shipping due to its potential to significantly reduce both CO_2 and SO_2 emissions. While the majority of vessels powered by LNG use dual-fuel technology, vessels that use pure LNG exist, but only in the form of new builds, as diesel engines cannot be retrofitted to burn LNG alone.

Traditional LNG is becoming widely used, but another form of LNG that should be noted is liquified renewable natural gas (RNG). RNG is a processed form of biogas, made from biological sources. Biogas can be produced from landfills, livestock operations, wastewater treatment, and other sources, and may then be conditioned to remove water, CO_2, and other non-methane elements. This produces RNG, which may also be called biomethane, and can be handled and liquified just as traditional natural gas would be. Since liquified RNG can be easily blended into LNG, it may be used to reduce the life cycle emissions of LNG as it continues to be used in vast quantities.

While emissions due to the combustion of LNG are low in comparison to diesel, this may be negated if issues of methane slip are not properly mitigated. Methane slip refers to the emission of methane from the combustion chamber, which is cause for significant concern as the global warming potential of methane is roughly 23 times that of CO_2. Therefore, even small amounts of methane slip can reverse the intended emissions reduction or even intensify emissions. Significant research has been done into the methods of reducing methane slip, which include optimizing gas supply and valve timing, reducing crevice volumes, and increasing turbulence and temperature[24].

A further concern that requires proper mitigation is the issue of transient operation. During rapid acceleration, the dual fuel engine is more prone to knocking, and during deceleration is more prone to misfiring. It is important to implement general knocking reduction strategies and ensure sufficient airflow to avoid issues[24].

[56] Japan to launch first ammonia-fueled ammonia gas carrier in 2026 – Offshore Energy

4.3.4. Liquefied Petroleum Gas

An alternative fuel that is frequently compared to LNG is LPG. LPG refers to a mix of hydrocarbon gases, primarily propane, butane, or a combination, that can be produced from natural gas, oil refining, waste, or renewable sources. When produced from renewable sources, the fuel is referred to as renewable LPG, and when produced from biological waste, is referred to as bioLPG. Compared to LNG, LPG is easier to store and handle due to its less extreme temperature requirements and is easier to implement, both in terms of engine compatibility and bunkering[57].

Globally, there is a surplus of LPG production, with bioLPG readily available on the European market. With many ports around the world having LPG bunkering infrastructure in place, it is a realistic option as an alternative fuel for long voyages, especially due to its high thermal efficiency. The octane number of LPG is quite high, making it highly efficient and giving it the longest running range of any alternative fuel. Just as with LNG, existing diesel engines may be retrofitted to run as a dual-fuel engines with LPG, or new engines must be built to run LPG alone[57].

While LPG is a promising alternative fuel, it is not completely emissions-free and can be expensive to implement. Compared to traditional fuels, LPG can nearly eliminate particulate emissions but can only reduce CO_2 emissions by roughly 15%[58]. LPG is generally more cost effective than LNG, but while retrofitting diesel engines to burn LPG is possible, it is typically more economically beneficial in the long term to implement LPG on new builds, requiring significant capital expenditures[57].

Two of the primary disadvantages to LPG fuel are its corrosivity and ease of leakage. LPG corrosion can damage storage tanks, piping, and engine components, and can increase the risk of leakage. In the case of LPG leakage, there may be significant safety concerns as although LPG is nontoxic, it can displace oxygen, potentially causing asphyxiation and other serious health concerns[59]. This risk necessitates thorough safety measures and proper crew training.

In the long term, LPG can be used to bridge the gap between traditional fuels and ammonia, as many of the requirements for ammonia-powered vessels also apply to LPG-powered vessels, including the storage tank and engine design[57]. Particularly if LPG-powered vessels are designed with a future transition to ammonia in mind, modifications needed for transition could be minimal.

4.3.5. Methanol

With a comparable volumetric energy density to ammonia, but easier handling and storage due to it being liquid under atmospheric conditions, methanol is a promising alternative fuel for maritime applications. Methanol fuel can be produced from a variety of sources, including coal, natural gas, and coke oven gas, and its renewable alternatives, bio-methanol and e-methanol, can be produced from biomass and a combination of green hydrogen and renewable CO_2 respectively[23].

Because it is liquid under atmospheric conditions, methanol is easier to handle, transport, and store compared to other alternative fuels. While the ease of handling is a significant benefit of

[57] LPG for Marine Engines: The Marine Alternative Fuel – The World Liquid Gas Association
[58] Benefits of LPG Propulsion – BW LPG
[59] Liquefied Petroleum Gas: Occupational Hazards – Chemscape

methanol fuel, there are safety concerns and emission considerations to be aware of. Methanol is toxic and flammable, therefore requiring thorough safety measures and crew training to avoid issues and be prepared for emergency situations. Additionally, if methanol is sourced from fossil fuels rather than renewable sources, the life cycle emissions may be higher than that of a conventionally fuelled vessel. If e-methanol is used, emissions are roughly 7% lower than for a conventional vessel[60].

Similarly to hydrogen, methanol can be used in a dual fuel engine with diesel, or it may be used in a fuel cell, but methanol may also be combusted on its own. Of these configurations, only methanol-diesel dual fuel configurations are widely researched and used, but methanol is considered one of the most promising alternative liquid fuels for use in internal combustion engines, and of the total ships that are on order, methanol powered vessels are the second most ordered, just after LNG. This is supported by the wide availability of methanol, as storage capabilities have been identified at 115 ports worldwide. Engines that can run on methanol are also compatible with ethanol, providing flexibility for future fuel use, depending on the trajectory of alternative fuels[23,60].

4.3.6. Low-Carbon Diesel

Since 2023, roughly 0.3% of the total energy consumption in the marine shipping sector was comprised of biofuels[61]. Biofuels are defined as fuel derived from living matter, and may be produced from sugars, starches, or oils in food crops, grasses, woody materials, algae, or cyanobacteria[62]. Depending on the feedstock and production method, biofuels may be chemically identical to conventional fuels, allowing for direct drop-in replacement without engine modification. Since 2015, DNV has identified more than 60 ports globally where biofuel bunkering has taken place, primarily concentrated in Europe, with scattered ports in North and South America, the Middle East, and Asia[61].

Two of the most common biofuels are fatty acid methyl ester, also known as biodiesel, and hydrotreated vegetable oil, also known as renewable diesel. Biodiesel is produced through a process called transesterification and is considered a carbon-neutral fuel, as although burning biodiesel does emit CO_2, this is offset by the CO_2 absorbed by the feedstock[63]. The primary concern regarding biodiesel is its cold weather performance, as it may begin to solidify in cold weather, causing concerns regarding separation, filtration, and pumping. Depending on the feedstock, the cloud point, the temperature at which solidification begins, ranges from 0 °C to 17 °C[64]. It is generally recommended to keep the fuel at least 10 °C above its cloud point, therefore sometimes requiring heating to maintain adequate biodiesel performance[65]. Biodiesel is operationally suitable to blending with traditional fuels and may even improve the lubricity of the blend, thereby improving engine efficiency, even when a low percent of biodiesel is used[63]. Due

60 Methanol fuel in shipping – DNV
61 Biofuels in shipping: Current market and guidance on use and reporting – DNV
62 Bioenergy – A. Dahiya
63 Biodiesel – Alternative Fuels Data Center
64 Biodiesel Cloud Point and Cold Weather Issues – Farm Energy
65 Biodiesel Science and Technology – J. Bart et al.

to its cold weather issues, biodiesel is more suited to fuel blending, rather than being used as a full diesel replacement.

Renewable diesel is similar to biodiesel in its level of emissions and that it may easily be blended with traditional fuels but differs in its method of production and certain performance characteristics. Renewable diesel is produced from fats and oils using hydrotreating, biological sugar upgrading, catalytic sugar conversion, gasification, pyrolysis, or hydrothermal processing, and is chemically identical to conventional diesel[66]. It therefore behaves just like conventional diesel and can be blended or used as a direct replacement in diesel engines.

4.3.7. The Future of Alternative Fuels

Different alternative fuels are expected to be adopted across vessel classes based on operational requirements, infrastructure availability, and cost considerations. The adoption of alternative fuels is happening quickly, with close to two thousand ships on the order book with alternative fuel capabilities as of 2025. While this represents 26% of ships on order, the types of ships are primarily large, fuel intensive vessels, resulting in the fuel by tonnage of ships on order reaching 51% alternative fuel. The type of ship on order with the greatest number of alternatively powered vessels is containerships, followed by tankers and bulkers. Roughly half of these ships will run on LNG, with 23% battery/hybrid, and 17% methanol. The remaining vessels will run on LPG, ammonia, or hydrogen[67].

An important consideration that is not included in these statistics is the use of fuel replacements such as renewable diesel and biodiesel. In 2024, roughly 0.3% of energy used in the maritime sector came from biofuels, primarily biodiesel and renewable diesel. The sale of these fuels continually increased from 2021 to 2024 and is likely to continue to increase as GHG regulations become more stringent[61]. Alternative fuels that do not require engine modifications are a promising interim solution while ships continue to be retrofitted and built with various alternative fuel capabilities.

4.4. Carbon Capture and Sequestration

In cases where it is not feasible to power a vessel without emitting CO_2, carbon capture and sequestration (CCS) can be applied to avoid releasing the CO_2 to the atmosphere. The process of CCS for maritime applications can be broken into three parts: capture, onboard storage, and sequestration, and is able to capture up to 90% of CO_2 that would otherwise be emitted[68].

4.4.1. Capture Methods

Carbon capture can occur before, during, or after combustion through pre-combustion capture, oxy-fuel combustion, and post-combustion capture.

[66] Renewable Diesel – Alternative Fuels Data Center
[67] Maritime Forecast to 2050 – DNV
[68] How efficient is carbon capture and storage? – MIT Climate Portal

To separate and capture the carbon before combustion, the fuel must be converted to syngas, enabling separation of carbon dioxide and the combustion of pure hydrogen[69]. Syngas can be created through gasification, wherein fuel is introduced to an oxygen-depleted, high pressure and temperature environment, or through steam methane reforming[70]. Pre-combustion capture is scalable for various ship sizes and power requirements, and can be retrofitted to existing infrastructure, but may incur high capital and operating costs.

Carbon may be separated during the combustion process using a process called oxy-fuel combustion. In this case, fuel is combusted with pure oxygen rather than air, resulting in pure CO_2 exhaust which can be collected directly. Not only does this effectively capture the carbon dioxide that would otherwise be released to the atmosphere, but it also avoids the emission of NO_x and increases the system's overall energy efficiency. A primary challenge associated with this system is the added difficulty in avoiding high combustion temperatures due to the absence of non-reactive elements in the combustion process[69].

To avoid modifying the engine, carbon capture may happen after the combustion process. In post-combustion capture, the exhaust gases are separated using chemical absorption, membrane separation, or cryogenic separation.

Chemical absorption passes the exhaust over a liquid solvent into which the CO_2 is dissolved and later evaporated out of. This is a common method of CO_2 separation due to its high efficiency and adaptability, but it consumes more energy than other processes and the liquid solvent may be toxic and/or corrosive. Alternatively, membrane separation employs selective membranes to separate the CO_2, requiring little energy consumption. The membranes may be susceptible to degradation and fouling, so must be properly maintained and/or replaced to remain usable. Cryogenic separation utilizes the different solidification points of the exhaust components, using an energy intensive process to cool the exhaust to the point of CO_2 solidification so it may be easily separated and collected[71].

4.4.2. On-Board Storage

After the CO_2 has been effectively separated, it must be stored on board until it can be offloaded. Typically, it is liquefied and stored at high pressures and/or low temperatures to maintain its liquid phase, but it may also be mineralized for solid storage[69].

In the case of liquid storage, vessels that have greater storage capacity typically store the CO_2 at lower pressures and temperatures. For example, vessels with more than 10,000 m^3 of storage generally use pressures between 7-10 bar and temperatures around –50°C, using a smaller number of large tanks. For vessels with less than 10,000 m^3 of storage capacity, pressures between roughly 15-20 bar are often used with temperatures of around –30°C. These vessels typically use a greater number of small tanks for storage, requiring more steel and therefore weighing more. If low temperatures are unrealistic, it is possible to store liquid CO_2

[69] Beyond the Horizon: Carbon Neutral Fuel Pathways and Transformational Technologies – American Bureau of Shipping
[70] Syngas: What is it, how is it made & where is it used? – Gas Data
[71] Assessing absorption-based CO2 capture: Research progress and techno-economic assessment overview – U. Khan et al.

at ambient temperatures, but it requires pressures of over 40 bar and even smaller storage tanks[72].

A concern during storage is the potential existence of impurities in the CO_2. Impurities can create a corrosive environment and/or modify the compression requirements, both of which may have serious consequences. Common impurities include water, inorganic compounds, and volatile organic compounds (VOCs). The primary concern of water entering the system is its ability to create a corrosive environment and damage the storage tanks. This is similar to inorganic compounds, which can create sulfuric and nitric acid, leading to corrosion. VOCs may also lead to a corrosive environment, in addition to potentially influencing the phase behavior of the CO_2, leading to the specified storage temperature and pressure potentially not being sufficient to maintain a liquid phase of the CO_2[73].

4.4.3. Sequestration

During sequestration operations, the vessel may either offload the CO_2 to a land-based transportation and sequestration service or deliver the CO_2 to an offshore sequestration facility. These facilities utilize subsea depleted hydrocarbon reservoirs or saline aquifers to sequester CO_2. These locations can store vast amounts of CO_2 long-term, and the oil and gas industry already has extensive knowledge of these sites due to previous exploration[72].

Injection at an offshore sequestration facility may take a few different forms. Depending on the design of the site, CO_2 may be directly injected into the reservoirs from the vessel, injected via a bottom-fixed installation, or injected via a floating installation with or without storage[73]. At installations without storage, the vessels are required to wait at the site as the CO_2 is injected, which may be a long process. The injection rate is dependent on the initial reservoir pressure, fracture pressure, size of the reservoir, sand thickness, and permeability. The injection process may require large amounts of energy, likely to be sourced from gas turbines, diesel engines, or grid electricity through transmission cables from shore[72].

5.0. Applicability and Suitability in NL

5.1. Marine Transportation Segments within NL

Marine transportation plays an essential role in the economy of NL. The province has over 29,000 km of coastline, a dispersed population, remote northern communities, and significant offshore natural resource activity, which together creates a strong dependence on marine transportation. Vessel operations in NL span a wide range of segments that differ substantially in scale, purpose, vessel design, ownership structure, operating profile, and fuel consumption. Understanding these differences is critical for assessing the applicability of alternative fuels and technologies, identifying realistic demonstration opportunities, and interpreting the relevance of emerging domestic and international regulatory requirements within the NL context.

[72] The Design Characterization of Offshore Carbon Sequestration Marine Units – E. Almquist et al.
[73] CO2 Shipping: Design, safety, and regulatory considerations for an emerging fleet – DNV

The main marine transportation segments in NL include the ferry system, commercial fishing fleet, offshore O&G support vessels, tanker traffic associated with offshore production and fuel distribution, cargo and container services, cruise tourism, and government marine services such as the Canadian Coast Guard (CCG) and Fisheries and Oceans Canada.

5.1.1. Ferry Services

Ferries are a core component of NL's transportation system, linking remote communities, supporting interprovincial mobility, and providing essential year-round access. The provincial ferry network is operated primarily by Marine Atlantic, Labrador Marine, and the Government of NL and serves both long-distance interprovincial routes and short-distance connections between coastal and island communities.

Gulf of St. Lawrence Ferry Services

This service is operated between Port aux Basques, NL and North Sydney, NS, and seasonally from Argentia, NL to North Sydney. These routes represent NL's primary gateway to mainland Canada and are served by Marine Atlantic, a federal corporation, utilizing large roll-on/roll-off (RO/RO) passenger vessels. Marine Atlantic's fleet includes the MV Highlanders, MV Blue Puttees, Leif Ericson, and recently acquired Ala'suinu.

These vessels are powered with conventional marine diesel engines, with the exception of the Ala'suinu. The newest vessel was designed with GHG emissions in mind and is outfitted with dual-fuel engines (marine diesel and LNG) and equipped with a battery-hybrid technology. Figure 11 below depicts Marine Atlantic's ferry routes.

Figure 11: Marine Atlantic's ferry routes[74].

[74] Ferries to Nova Scotia & Newfoundland – Marine Atlantic

Interprovincial Ferry Routes

NL operates an extensive domestic ferry system linking island and coastal communities. Major routes include the Strait of Belle Isle linking St. Barbe, NL and Blanc Sablon, QC (Qajaq W. – Labrador Marine), and the Bell Island service connecting Portugal Cove and Bell Island (MV Flanders and MV Legionnaire). Additional routes serve communities such as Fogo Island, Change Islands, Burgeo, and Francois. These domestic ferries are generally smaller displacement vessels operating short routes with high frequency and repeated port calls. Because of their predictable operating profiles and centralized terminals, many of these vessels present good opportunities for electrification, hybrid-propulsion, shore power infrastructure, and alternative fuel demonstrations at a limited number of ports. Table 4 below details all interprovincial passenger ferry routes in the province (except Labrador Marine routes in Labrador).

Table 4: Passenger ferry routes in Newfoundland.

Route	Automobile	Freight
Bell Island – Portugal Cove	X	
St. Brendan's – Burnside	X	
Fogo Island – Change Islands – Farewell	X	
Long Island – Pilley's Island	X	
Charlottetown – Norman's Bay		X
Blanc Sablon – St. Barbe	X	
La Poile – Rose Blanche		X
Ramea – Grey River - Burgeo	X	
Francois – Grey River – Burgeo		X
Gaultois – McCallum – Hermitage		X
Rencontre East – Bay L'Argent – Pool's Cove		X
South East Bight – Petite Forte		X

Figure 12: Northern Peninsula / East Coast Labrador ferry routes

Figure 13: Newfoundland ferry routes.

Labrador Marine Services

Northern communities in Labrador rely on seasonal ferry services provided by Labrador Marine (Kamutik W.) from Happy Valley – Goose Bay to ports such as Rigolet, Makkovik, Postville, Hopedale, and Nain, and on selected dates to Cartwright and Black Tickle as presented in Figure 14 below. These routes provide essential resupply and passenger services to remote, road inaccessible regions.

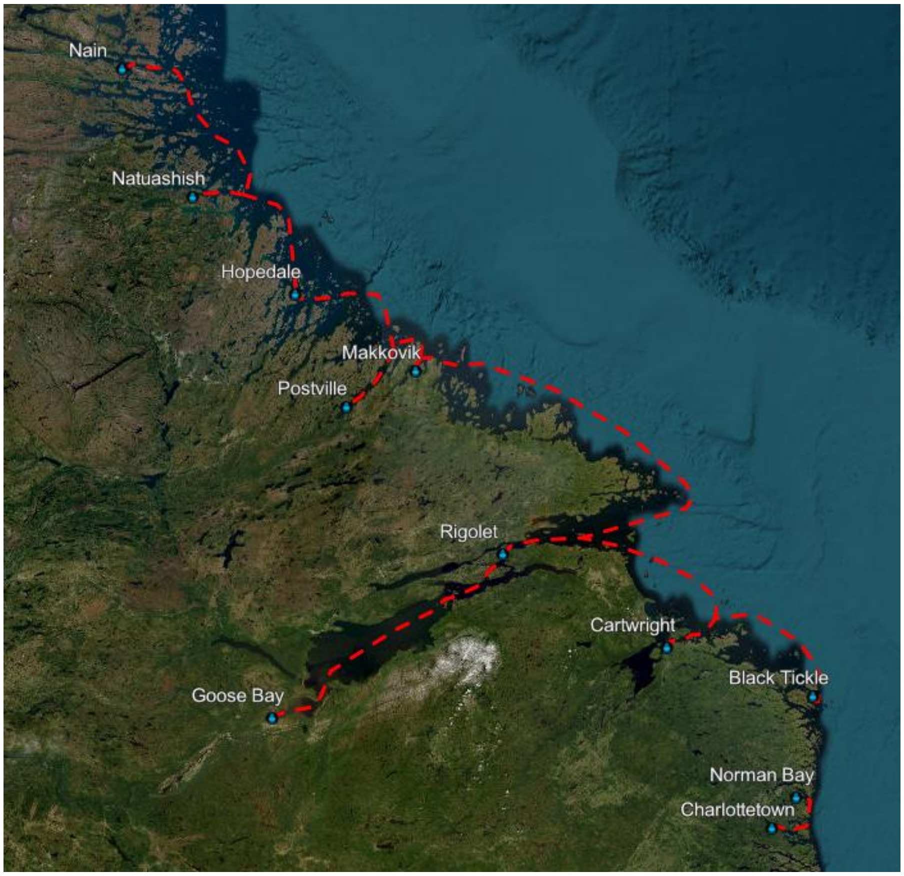

Figure 14: Labrador Marine ferry routes.

Labrador ferries operate in challenging environmental conditions and over relatively long distances. Their operating profiles make them potential candidates for hybrid propulsion, efficiency retrofits, and future alternative fuel use where infrastructure constraints can be managed at key hubs such as Goose Bay.

5.1.2. Commercial Fishing Fleet

Fishing has long been central to NL's economy and identity for centuries and remains one of the province's most active maritime sectors. While the sector has evolved significantly since the cod moratorium, the fishing fleet continues to generate a high volume of vessel movements across provincial waters.

The fishing fleet in NL includes:

- **Small inshore fishing vessels** operating seasonally with low-to-moderate horsepower engines
- **Mid-shore and offshore trawlers** operating over longer distances with higher fuel consumption
- **Factory freezer trawlers** capable of year-round operation

Inshore vessels are often independently owned and returned to the same port each day, making them suitable candidates for renewable diesel, hybrid auxiliary systems, and potentially battery-assisted propulsion for short-range operations.

Mid-shore and offshore trawlers, including vessels operated by companies such as Ocean Choice International (Newfoundland Lynx, Katsheshuk II and Calvert) and Labrador Fishermen's Union Shrimp Co. (Nain Banker, Belle Isle Banker, and Northern Osprey III), combine propulsion demand with continuous hotel, refrigeration, and processing energy requirements. Factory freezer trawlers have high installed power and long operational durations, which make full electrification and alternative fuels challenging due to space constraints, but create opportunities for alternative fuels, fuel blending or dual-fuel technology, waste heat recovery, and energy-efficiency retrofits.

Although individual fishing vessels are small compared to tankers or offshore supply ships, the size and activity level of the fleet make it a meaningful contributor to provincial marine emissions. Adoption pathways are influenced by ownership structure, capital availability, and harbour infrastructure, which must be considered when designing R&D and demonstration programs.

5.1.3. Offshore Oil and Gas Support Vessels

Offshore petroleum production is a major driver of marine traffic off NL's coast. Offshore supply vessels operate between shore bases, primarily St. John's and Bay Bulls, and offshore installations such as the Hibernia Gravity Based Structure (GBS), Hebron GBS, Terra Nova floating, production, storage and offloading vessel (FPSO), Sea Rose FPSO, and the West White Rose Extension.

These vessels are utilized for the following purposes:

- Transporting personnel, equipment, supplies, and consumables
- Supporting drilling and construction campaigns
- Providing standby, emergency, and towing services
- Operating year-round and in challenging weather situations

Offshore supply vessels servicing NL are owned and operated by specialized marine service providers such as Atlantic Towing (Paul A. Sacuta, and the Atlantic Shrike, Heron, Griffon, and Merlin) and DOF (Skandi Vinland, Mariner, Cutter, Mobiliser, Cutter). DOF has a new-build vessel expected to service the region and is being constructed with a battery-hybrid propulsion system and capable of burning biofuels or a biofuel blend. Additionally, the Atlantic Shrike has successfully completed a series of sea trials using BESS[75]. These vessels typically use high-powered propulsion configurations, with multiple engines commonly in the 1,500-4,500-kW range,

[75] Atlantic Towing completes sea trials operating on a renewable energy source – Irving

and supplemented with azimuth thrusters and dynamic positioning systems. They operate on fixed schedules, undertake long offshore transits, and spend extended periods in dynamic positioning mode resulting in high fuel consumption and continuous loads.

Because of their centralized shore bases, predictable routing, and corporate ownership structures, offshore supply vessels represent strong candidates for decarbonization pilot projects involving hybridization, battery systems for dynamic positioning operations, alternative fuels, and waste heat recovery technologies.

5.1.4. Tanker Traffic

Tanker activity in NL falls into two main categories: crude oil export tankers and refined petroleum product tankers.

Crude oil export tankers load offshore production either directly from FPSO units such as Terra Nova and SeaRose, or via transshipment operations, and transport crude to refineries and export terminals. These vessels are typically large, ocean-going vessels. Their size, installed power, and long voyage profiles make them less suitable for near-term electrification, but they are potential candidates for alternative fuels, onboard carbon reduction technologies, and efficiency retrofits. For example, in NL the Beothuk Spirit, Norse Spirit, and Dorset Spirit transports oil from the Grand Banks offshore fields to the Newfoundland Transshipment Limited terminal at Whiffen Head.

Refined petroleum product tankers deliver gasoline, diesel, aviation fuel, heating oil, and other products to ports across NL, including St. John’s, Come By Chance, and regional distribution points. Given the province’s reliance on marine delivery for fuel supply in many regions, product tankers represent a consistent portion of vessel activity and present opportunities for low-carbon bunkering, shore power, and fuel switching where supply chains can be developed. In 2025, the Algoma East Coast began operating in NL, and Woodwards Coastal Shipping Limited operates a fleet of four vessels (Kitikmeot W., Tuvaq W., Kivalliq W., Qikiqtaaluk W.) providing supply to Labrador’s coastal communities and the Canadian Arctic.

5.1.5. Cargo Shipping and Container Services

Beyond tankers, NL is served by a range of cargo shipments that support both import and export activity. These include:

- **Container vessels** operating at St. John’s and Corner Brook
- **Bulk carriers** transporting minerals such as iron ore and nickel
- **General cargo and RO/RO vessels** delivering consumer goods and vehicles

Container services are operated by shipping lines such as Oceanex, which provide regular service using vessels Oceanex Connaigra and Sanderling (RO/RO vessels carrying containers, trailers, and motor vehicles) and the Avalon (LO/LO vessel carrying only containers). These medium-sized feeder vessels operate on fixed routes between NL and mainland ports (St. John’s, Halifax, and Montreal). Their predictable schedules and repeated port calls make them suitable for shore power, hybrid auxiliary systems, and alternative fuel demonstrations where port infrastructure is available.

Bulk carriers and general cargo vessels operate less frequently but at higher individual fuel consumption per voyage, making them stronger candidates for efficiency technologies and alternative fuel adoption rather than full electrification. For example, the Umiak 1 transports ore from Voisey's Bay Mine in Labrador.

5.1.6. Cruise Tourism

Cruise vessels call at ports such as St. John's, Corner Brook, and St. Anthony during the seasonal tourism period. These vessels are owned and operated by international cruise companies and are characterized by very high hotel loads for accommodation, catering, and entertainment systems.

Although cruise ships typically operate internationally, their time spent at berth in NL ports results in localized emissions. Due to their international ownership and operating configurations, the province does not have much control over their powering mechanisms. However, port electrification and terminal-side emissions management rather than propulsion-based retrofits within provincial waters are possible.

5.1.7. Government and Public Service Vessels

Government-operated vessels in NL waters typically include fleets from the Canadian Coast Guard (CCG), Fisheries and Oceans Canada (DFO), and other federal agencies. These vessels perform icebreaking, search and rescue, scientific research, surveillance, patrol and environmental monitoring operations.

Examples include CCG icebreakers and offshore patrol vessels operating in Atlantic Canada, as well as smaller research vessels stationed in St. John's and regional ports. Government fleets are centrally managed and should be aligned with federal and international decarbonization objects, making them well suited for early adoption of alternative fuels, hybrid propulsion, and electrification pilot projects where operational risk can be managed through public programs. CCG vessels with NL home ports are shown in Table 5 below.

Table 5: CCG vessels with NL home ports.

Vessel (CCGS)	Home Port	Function
Ann Harvey	St. John's	High Endurance Multi-Tasked Vessel (Icebreaking)
Barrington Bay	Burin	Search and Rescue Lifeboat / Bay
Cape Fox	Lark Harbour	Search and Rescue Lifeboat / Cape
Cape Norman	Port Aux Choix	Search and Rescue Lifeboat / Cape
Cape Roger	St. John's	Offshore Patrol Vessel
Captain Molly Kool	St. John's	Medium Icebreaker
Conception Bay	Twillingate	Search and Rescue Lifeboat / Bay
Cygnus	St. John's	Offshore Patrol Vessel
Gabarus Bay	Burgeo	Search and Rescue Lifeboat / Bay

Georges R. Pearkes	St. John's	High Endurance Multi-Tasked Vessel (Icebreaking)
Groswater Bay	Lark Harbour	Search and Rescue Lifeboat / Bay
Henry Larsen	St. John's	Medium Icebreaker
Leonard J. Cowley	St. John's	Offshore Patrol Vessel
Louis S. St-Laurent	St. John's	Heavy Icebreaker
Pennant Bay	St. Anthony	Search and Rescue Lifeboat / Bay
Sacred Bay	Old Perlican	Search and Rescue Lifeboat / Bay
Sir John Cabot	St. John's	Offshore Fishery Science Vessel
Teleost	St. John's	Offshore Fishery Science Vessel
Terry Fox	St. John's	Heavy Icebreaker
Vladykov	St. John's	Near-Shore Fishery Research Vessel

5.2. Vessel Types within each Sector in NL

Marine transportation in NL is diverse, reflecting the province's geography, dispersed population, and resource-based economy. Vessels operating in NL waters include fishing boats, ferries, offshore supply vessels, tankers, tugs, scientific ships, and cruise vessels. Understanding these vessel types is important for interpreting GHG emissions, as different classes vary significantly in engine size, operating profiles, and fuel consumption.

The Marine Emissions Inventory Tool (MEIT) classifies vessels using a system of "classes" and "types". These categories originate from Marine Communications and Traffic Services (MCTS) data and are informed by international frameworks such as IMO guidelines and classification society standards (e.g., DNV, Lloyd's Register).

However, vessel classification is not consistently applied or globally standardized across jurisdictions or datasets. The same vessel may carry different labels depending on the database, year, or operating role. Because vessels typically have long service lines and may shift functions or uses over time, some MEIT categories overlap, and classification requires interpretation within a regional context.

For NL's GHG emissions analysis, MEIT vessels therefore need to be grouped into practical, regionally appropriate categories that reflect how vessels are actually used in NL waters.

Using MEIT, the vessel classes and types shown in Table 6 are most relevant in the NL context.

Table 6: Vessel classes and types.

Vessel Classes	Vessel Types
Merchant Container	-
Merchant Bulk	-
Tanker	Merchant Crude Merchant Chemical / Oil Products Tanker Merchant Chemical Merchant (Tanker) Merchant VLCC Merchant Ore / Bulk / Oil Merchant Liquefied Gas
Merchant Passenger	Merchant Ferry Merchant Passenger
Merchant Other	Merchant General Merchant RO/RO Merchant Auto Merchant Reefer Merchant Coastal Merchant Cement
Tug	Tug Supply Tug Tug Ocean Tug Harbour Tug Fire
Fishing	Fishing Vessel Trawler Factory Ship Fishery Patrol
Cruise	Cruise Merchant Passenger
Special Purpose	Special Purpose VSL Special Purpose Special Purpose Crane Ship Special Purpose Pilot Boat Special Purpose Pipe-Layer Special Purpose Survey Ship
Coast Guard	Coast Guard Icebreaker Coast Guard Scientific Coast Guard Rescue Coast Guard Lifeboat Coast Guard Tender
Excursion Passenger	-
War	Warship Surface Warship – General
DFO Fishing Surveillance	DFO Fishing Surveillance Vessel Coast Guard Patrol Marine Security Patrol CCG-RCMP

Descriptions of each vessel type, as understood by the project team have been described below.

Merchant Container

Merchant Container	A large cargo vessel designed to transport goods in standardized intermodal containers, which are stacked both above and below deck. In NL, this would indicate container ships that operate at ports in St. John's and Corner Brook.

Merchant Bulk

Merchant Bulk	A specialized merchant vessel designed to transport large quantities of unpackaged, dry cargo in its large holds. In NL, this would include the transportation of iron ore, nickel, etc.

Tanker

Tanker	A tanker ship is a vessel designed to transport liquid or gaseous cargo in bulk, such as crude oil, chemicals, and LNG.
Merchant Crude	A tanker ship that moves unrefined crude oil from extraction sites to refineries or intermediary destinations. Includes the transportation of crude from offshore oil production facilities in NL.
Merchant Chemical / Oil Products	A tanker ship that moves chemical or oil products. Includes the distribution of refined products to and throughout NL.
Merchant Chemical	A tanker ship that moves chemical products. Includes the distribution of refined products to and throughout NL.
Merchant	A tanker ship that moves unrefined crude oil or refined petroleum products like gasoline and diesel.
Other	A catch-all for tankers moving non-oil or non-chemical products.

Merchant Passenger and Cargo

Merchant Passenger	A commercial vessel designed primarily to transport more than 12 passengers. This includes all ferries operating in NL.
Merchant Other	A commercial vessel transporting cargo not as containers as not as defined in 'bulk'. This includes ships carrying automobiles.

Tug / Offshore Support

Supply / Ocean	Supply vessels carrying people, equipment, and other goods to NL's offshore oil and gas facilities.
Tug / Harbour	A marine vessel that manoeuvres other vessels by pushing or pulling them, with direct contact or a tow line such as those found within harbours or docking wharves.

Fishing

Fishing	All vessels involved in catching, harvesting, transporting, or processing fish and other aquatic life.
Fishing Vessel	A boat or ship used for catching, harvesting, transporting, or processing fish and other aquatic life.
Trawler	A commercial vessel designed to drag a large, funnel-shaped net called a trawl through the water to catch fish.
Factory Ship	A commercial vessel with extensive on-board facilities for processing and freezing caught fish.
Cruise and Excursion	
Cruise	A large ship that carries people on voyages for pleasure, typically calling at several ports. In NL, cruise ships port in St. John's, Corner Brook, and St. Anthony.
Excursion Passenger	A vessel used for short trips for pleasure or recreation, such as sightseeing, whale watching, or tours and carries passengers for hire. In NL, these vessels would be used within the tourism industry.
Specialized and Government Vessels	
Special Purpose	A vessel with a unique design and function, such as a research or icebreaker ship, built for specific tasks rather than general cargo. In NL this includes survey ships, pilot boats, crane ships, etc.
Coast Guard	All Coast Guard vessels active in NL which could include science vessels, recue vessels, icebreakers, lifeboats, etc.
War	Vessels owned and operated by the Department of National Defence or militaries from other jurisdictions.
DFO Fishing Surveillance	Vessels operated by both DFO and the RCMP for the purposes of surveillance, patrol, and security.

5.3. Preliminary Assessment on GHG Emissions

5.3.1. Data Acquisition and Source Systems

GHG emissions estimates for marine vessels operating in NL are derived from data and modelling approaches used in Environment and Climate Change Canada's (ECCC) Marine Emissions Inventory Tool (MEIT). The MEIT integrates vessel movement information collected by Marine Communications and Traffic Services (MCTS).

These systems provide real-time and historical information on vessel identity, position, speed, route, origin and destination, arrival estimates, and detailed movement tracks. They also contain vessel characteristics such as engine ratings, dimensions, draught, deadweight, build year, flag, and in some cases equipment like scrubbers or shore-power capability.

As previously discussed, MEIT categorizes vessels according to class and type, but these classifications do not always align perfectly across datasets. When interpreting emissions, this needs to be considered, and additional consideration of:

- Vessel traffic patterns
- Origin-destination behaviours
- Operational context
- Regional marine economic activity

was necessary to ensure the categories reflect real-world vessel use. For example, MEIT's "tug – supply" category primarily represents vessels servicing offshore oil platforms and is interpreted in this study as offshore supply activity.

These methods and explanations are better detailed in the forthcoming marine emissions inventory publication by Environment and Climate Change Canada.

5.3.2. Simplified Calculation Approach

MEIT calculates emissions from main engines, auxiliary engines, and boilers using emission factors from the Fourth IMO GHG Study. Emissions depend on:

- Engine type and stroke
- Engine load factor
- Fuel type and sulphur content
- Activity mode
- Specific fuel consumption
- Low-load adjustment factors

The general formula used in the activity-based model is:

$$E = \sum (MCR \times LF \times \Delta T \times EF)$$

Where E represents emissions for each pollutant (e.g., CO_2, CH_4, N_2O), MCR represents the engine maximum continuous rating (kW), LF represents the calculated load factor, ΔT is the time in each operating mode, and EF is the emission factor based on engine and fuel characteristics.

Under special operating conditions, such as vessels equipped with exhaust-gas scrubbers or tugboats performing towing, additional adjustments are applied.

5.3.3. Findings from the MEIT Tool

Note: *The MEIT framework is under ongoing development and subject to refinement. The results presented herein are based on the version available at the time of analysis and may vary with future updates. All tables, figures, and conclusions are derived from model outputs generated for this study and are intended for informational purposes within the defined scope and assumptions.*

Under internationally recognized GHG accounting frameworks, emissions from international marine transportation are not attributed to individual countries and therefore are not classified as

"Canadian". Instead, these emissions are expected to be addressed through ongoing future regulatory measures led by the IMO.

Despite this distinction, emissions from international vessels have been included in this analysis. This included ships that are arriving in NL from international ports, as well as those departing NL for destinations abroad. Their inclusion reflects the material impact of international shipping on emissions within NL's jurisdiction and recognizes the sector's relevance to regional decarbonization effort. As a result, the marine transportation emissions presented in this report will differ from those presented by Canada and its provinces.

Including these emissions provides a more complete understanding of the marine sector's overall impact and helps identify where regional, national, and international partnerships may be required to support decarbonization efforts. It also reflects the reality that future demonstration projects and operational changes may involve vessels operating across other jurisdictions, rather than being limited to NL-specific fleets. Capturing these emissions supports a more comprehensive assessment of potential emission reductions with any future initiatives.

Table 7 below summarizes calculated vessel emissions in NL for the past ten years.

Table 7: Vessel emissions in NL from 2015-2024.

Year	Emissions CO_2e [t]
2015	511,317
2016	527,528
2017	563,448
2018	596,814
2019	604,569
2020	533,196
2021	496,583
2022	546,428
2023	565,052
2024	743,073

To better analyze the provincial emissions, they can be further broken down based on the vessel classes described in Section 5.2. Table 8 below describes the same 10-year period presented in Table 7 but broken down by individual vessel categories.

Table 8: Vessel emissions in NL 2015 - 2024 by vessel class.

Category	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Merchant Container	56,637	51,614	56,427	54,520	49,400	40,219	36,194	57,434	86,291	85,006
Merchant Bulk	21,050	21,339	25,790	25,310	26,153	25,433	31,830	38,522	36,768	65,132
Tanker	130,535	152,516	151,918	173,723	167,061	191,475	146,131	144,748	143,212	214,203
Merchant Other	28,832	30,938	34,381	33,546	38,141	33,559	37,971	32,999	38,197	71,374
Offshore Supply Ship	69,874	51,935	56,991	54,309	71,128	39,626	31,876	42,583	40,898	44,936
Tug – Ocean	28,000	23,078	33,290	34,760	29,079	12,720	7,383	5,326	4,676	11,590
Tug – Harbour	7,504	8,740	8,167	9,165	9,269	9,275	7,366	8,348	8,539	6,254
Fishing	31,488	39,001	38,563	48,284	40,646	35,973	57,406	47,129	40,863	85,796
Ferry	88,316	107,854	104,549	102,716	110,708	103,076	106,968	116,400	115,848	102,243
Cruise Ship	7,904	8,283	9,518	12,667	13,852	-	-	13,416	17,293	21,819
Excursion Passenger	867	2,875	1,889	1,940	1,921	-	1,485	1,958	1,901	1,292
Special Purpose	12,092	15,096	26,721	30,439	34,377	29,366	20,480	24,567	21,419	22,090
Barge	568	1	2,347	631	356	1,187	259	-	-	4,276
Other	188	196	138	185	143	240	283	246	184	47
Provincial Total:	**483,855**	**513,466**	**550,689**	**582,195**	**592,234**	**522,149**	**485,632**	**533,676**	**556,089**	**736,058**
Coast Guard	17,591	9,388	8,983	11,490	9,591	9,659	8,498	10,613	7,580	6,711
War	5,107	2,103	1,783	1,173	954	207	1,220	751	413	304
DFO Fishing Surveillance	4,762	2,573	1,991	1,956	1,791	1,141	1,233	1,387	969	-
Federal Total:	27,460	14,064	12,757	14,619	12,336	11,007	10,951	12,751	8,962	7,015
Combined NL Emissions:	**511,317**	**527,528**	**563,448**	**596,814**	**604,569**	**533,196**	**496,583**	**546,428**	**565,052**	**743,073**

Using the data presented in Table 8, Figure 15 and Figure 16 below better visualize the emissions by class year over year.

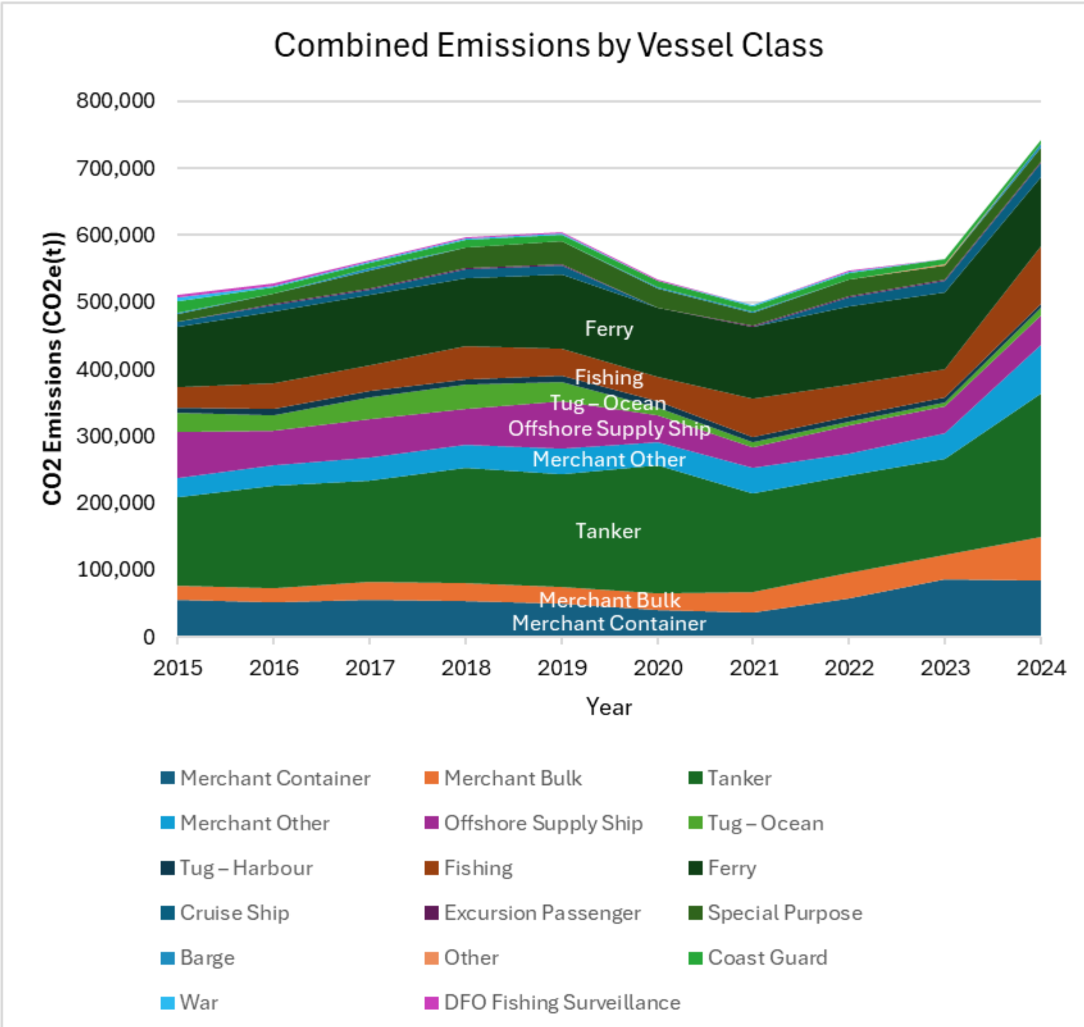

Figure 15: Combined emissions by vessel class.

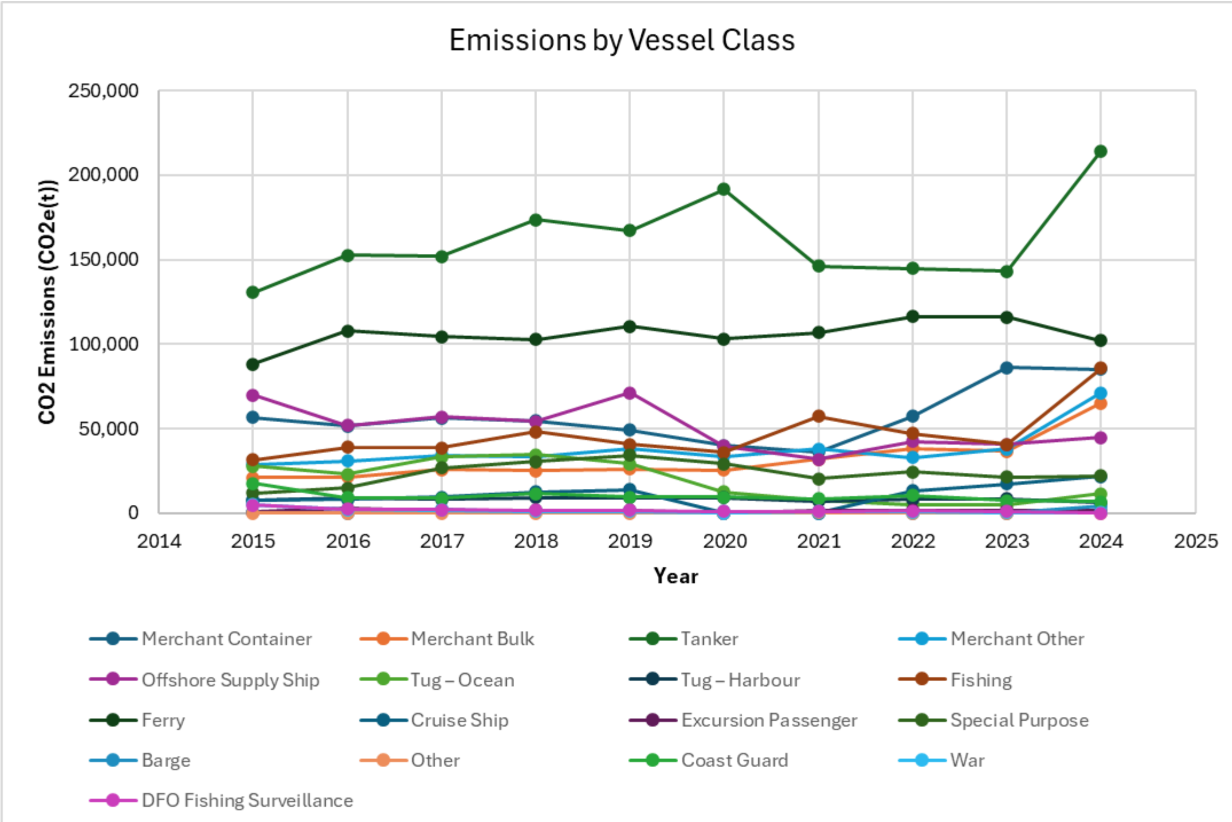

Figure 16: Emissions by vessel class.

5.3.4. Emission Analysis

Total marine vessel emissions in NL increased from 511,317 tCO_2e in 2015 to 743,073 tCO_2e in 2024, representing a net increase of approximately 45% over the ten-year period. Over the 2015-2023 period, annual marine emissions in NL remained relatively stable, generally ranging between 500,000-600,000 tCO_2e, with an average of approximately 568,500 tCO_2e. This stability reflects consistent baseline activity across core marine sectors, including ferries, fishing, and offshore support services.

The primary exception to this pattern occurred in 2021, when emissions declined to a ten-year low of 496,583 tCO_2e, likely reflecting reduced activity due to the COVID-19 pandemic.

A gradual year-over-year increase occurred between 2015 and 2019, with total emissions rising to a pre-pandemic peak of 604,569 tCO_2e in 2019. This growth was driven primarily by increases in tanker activity (from 130,535 to 167,061 tCO_2e) and ferry operations (from 88,316 to 110,708 tCO_2e), alongside rising emissions from special purpose vessels and merchant bulk shipping. These increases were partially offset by variability in offshore supply vessel activity, resulting in a moderate net growth rather than a sharp upward trend.

Emissions declined sharply in 2020 and reached a decade low in 2021 at 496,583 tCO_2e. Between 2019 and 2021, total emissions fell by approximately 18%, presumably coinciding with COVID-19 related disruptions. The decline was broad-based across most vessel categories, including offshore supply ships (which fell by more than 55% from 2019 to 2021), ocean-going tugs, and merchant container vessels. Tanker emissions also declined during this period, falling from 191,475 tCO_2e in 2020 to 146,131 in 2021, indicating reduced offshore production and export activity rather than changes in fleet composition.

From 2022 onward, emissions rebounded as offshore and marine operations resumed. Total emissions increased to 546,428 tCO_2e in 2022 and 565,052 tCO_2e in 2023, returning to levels consistent with the pre-pandemic range. Growth during this phase was distributed across multiple categories, suggesting normalization of marine activity rather than a concentration in any single sector.

A significant deviation from this pattern occurs in 2024, when total emissions increased to 743,073 tCO_2e, representing an increase of approximately 31% above the ten-year average and roughly 50% above the 2021 low. While this initially appears to be an outlier, the increase aligns with major shifts in offshore O&G activity. Following the completion of the SeaRose FPSO turnaround and the restart and ramp-up of the Terra Nova field, tanker and supply vessel activity increased substantially. Vessel-level data confirms that tanker operations account for the majority of the 2024 emissions growth, indicating that the increase is operationally driven.

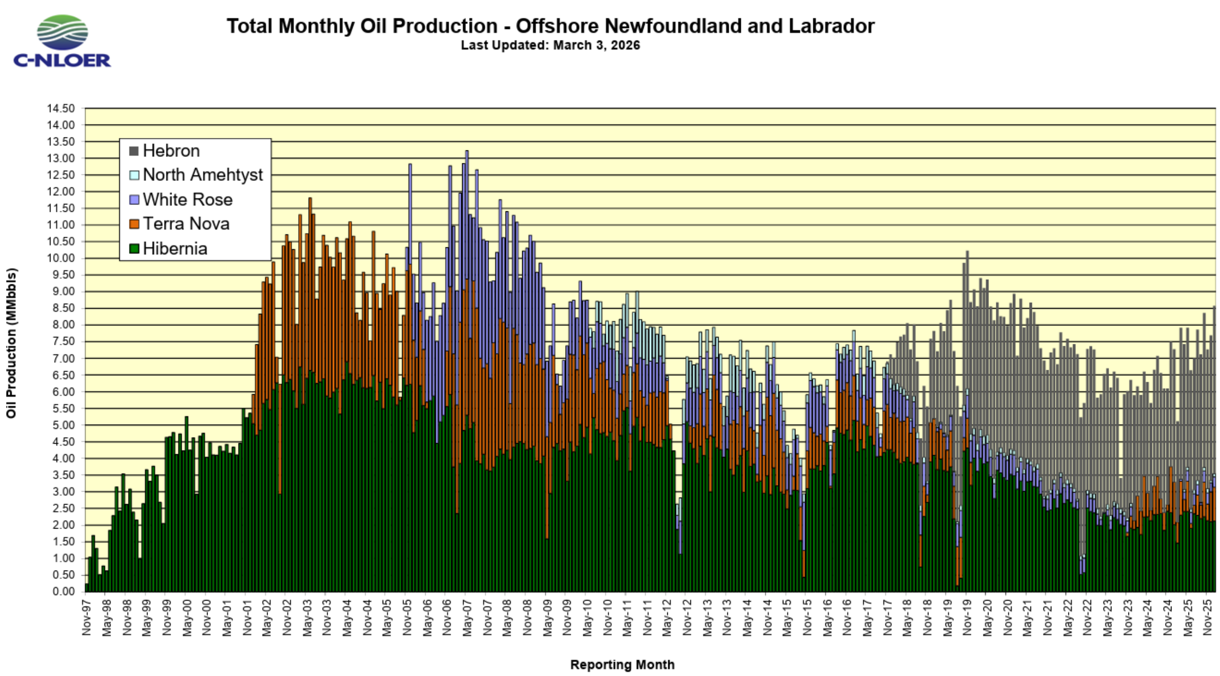

Figure 17: Monthly oil production offshore NL[76].

The year-over-year increase in 2024 is approximately 178,000 tCO_2e (+31%) relative to 2023. This change is overwhelmingly driven by tanker emissions, which increased by approximately 71,000 tCO_2e, accounting for roughly 40% of the total increase. Additional contributors include merchant bulk vessels, merchant container vessels, and fishing vessels. In contrast, ferry

[76] Statistical Information – C-NLOER

emissions declined slightly in 2024, indicating that the increase was not driven by passenger demand.

In proportional terms, tanker vessels accounted for approximately 29% of total marine emissions in 2024, making them the single largest contributing category. Ferries (14%), fishing vessels (12%), and merchant container vessels (11%) were the next largest contributors. Collectively, these four categories represented approximately two-thirds of total emissions.

A key observation from this dataset is the dominant influence of offshore O&G activity on total emissions. Variations in tanker emissions alone account for a substantial portion of overall year-to-year changes, indicating that provincial emissions are highly sensitive to offshore production cycles.

Rather than representing a single anomaly, the increase observed in 2024 highlights the extent to which emissions can escalate rapidly in response to changes to offshore production. This reinforces the importance of considering high-variability sectors when developing emissions forecasts and mitigation strategies.

This pattern has implications for decarbonizing planning. Efforts focused solely on smaller or more stable vessel categories may offer practical early opportunities for emissions reductions but are unlikely to significantly impact total emissions unless accompanied by strategies that also address high-emitting and highly variable sectors such as tanker operations.

However, more stable categories (such as ferries and harbour vessels) may be better suited for controlled pilot projects and incremental efficiency improvements, given their predictable operating profiles.

Overall, the analysis demonstrates that vessel emissions in NL are strongly correlated with offshore O&G production cycles. While emissions remained relatively stable for much of the past decade, recent changes, such as those observed in 2024, reflect a regional shift in offshore activity rather than structural changes in the broader marine transportation system.

5.4. Emerging Technology Options for Decarbonization

Technological options for reducing marine transportation emissions can be broken down into efficiency enhancements, machinery customization, alternative fuels, and carbon capture and sequestration.

5.4.1. Efficiency Enhancements

Marine transportation consumes over 330 Mt of fuel annually, therefore even small improvements in efficiency can greatly reduce fuel consumption and related emissions[77]. Two efficiency considerations that can have noticeable effects on emissions are weather routing and hydrodynamics.

Weather routing, when implemented correctly, can reduce emissions by up to 12.5% by avoiding adverse weather such as intense waves and strong headwinds[12]. Using real-time weather routing

[77] Biofuels for the marine shipping sector – IEA Bioenergy

systems based on advanced computing, machine learning, or artificial intelligence can save on both travel time and fuel and is suitable for implementation on any ship.

Hydrodynamic improvements involve reducing drag by minimizing friction between hull and water. Growth of organisms such as barnacles and algae on the hull significantly increase drag, and even a light layer of slime at only 50% coverage can increase fuel use by 20-25%[17]. This can be prevented using hull coatings while buildup can be removed with proper cleaning. Hull coatings are typically hydrophobic, making it difficult for organisms to attach to the hull, but can be toxic to other marine life. Cleaning may happen while docked or in transit using high pressure nozzles. To further reduce drag, air lubrication may be used to create a barrier between hull and water of either air bubbles or a layer of air trapped in a cavity. Using bubbles can reduce friction by 6%, and using an air cavity can reduce friction by 26%[19]. Additionally, during the ship design phase, the hull form should be designed to optimize efficiency and therefore reduce emissions.

5.4.2. Machinery Advancements

There are a significant number of machinery adjustments that can be made for the purpose of reducing emissions. These include implementing dual fuel engines, waste heat recovery, fuel cells, nuclear reactors, and WAPS.

Many of the alternative fuels available for marine transportation cannot be combusted alone and must instead use a secondary fuel for ignition. **Dual fuel engines** are designed to burn alternative fuels and diesel, with the diesel providing pilot ignition for the alternative fuel. Diesel engines can be retrofitted into dual fuel engines with certain additions and modifications, or they can be built new. The cost of retrofitting ranges from 5-15 million USD, and is generally only considered economical if that value is under 25% of the cost of an equivalent new build[25].

Waste heat recovery systems are designed to capture and utilize the excess heat that is lost from the engine to the environment during combustion. Roughly half of the input fuel energy is converted to mechanical energy, with the remaining half primarily being carried by the exhaust and cooling water[27]. The exhaust and cooling water may both be fed through a system to extract heat for direct heating or to power electricity generation. This can greatly increase the overall thermal efficiency of the system and subsequently reduce fuel consumption and emissions by 5-15% while supplementing onboard heat and power[28].

It is also possible to replace marine engines with **fuel cells**. Fuels cells are highly efficient, converting the chemical energy of hydrogen fuel to electricity. Due to their high efficiency, fuel cell powered vessels require infrequent fuelling but must overcome issues with onboard hydrogen storage. Hydrogen requires large amounts of storage space, high pressures, and low temperatures, and its storage is one of the primary barriers to fuel cell adoption, along with the high cost of installation.

As a further alternative to traditional engines and fuel cells, small **nuclear reactors** may be used in their place. Currently, they are only used on icebreakers and submarines due to their high cost and public safety concerns, but their high-power output and lack of emissions have led to compact and safe reactor development, including the marine molten salt reactor, which uses liquid salts to prevent overheating[33].

BESS may also be used for ship propulsion, storing energy in the form of chemical energy. Using battery energy is free of emissions, but there may be emissions associated with the source electricity and source of the battery materials. Challenges regarding BESS applications in the marine sector include the limited range and weight of the batteries themselves. BESS systems can be applied as the sole form of propulsion or as a hybrid configuration with other fuels.

To reduce the load on the engine, fuel cell, or nuclear reactor, **WAPS** may be installed. Based on sailing principles, WAPS may take the form of a variety of technologically advanced sails, including rotor sails, suction sails, wing sails, soft sail, and kites. A control system is usually required to adjust the sails based on the wind and propulsion requirements and a thorough structural analysis is required to ensure WAPS may be installed without compromising the integrity of the ship. Typically, WAPS reduce emissions by 20%, but in some cases can reduce emissions by over 30%[13].

5.4.3. Alternative Fuels

Replacing typical marine fuels with low to zero emission alternative fuels is one of the most important decarbonising strategies. Each alternative fuel has its respective benefits and challenges, and each can contribute to lowering the emissions of marine transportation.

As a completely emissions-free fuel, **hydrogen** is an attractive alternative, especially when its high combustion efficiency and light weight are considered. It is important to note that only green hydrogen, which has been produced from renewable energy, is completely free of emissions, as it may instead be produced from fossil fuels, causing emissions during its production. The primary drawback to hydrogen fuel is its storage challenges. Hydrogen storage requires a lot of space, incredibly high pressures, and low temperatures.

A potential alternative to hydrogen is **ammonia**, which is a hydrogen carrier with a much higher volumetric energy density. Ammonia may be produced from green hydrogen, which in that case is free of CO_2 emissions. Ammonia produced from fossil fuels emits CO_2, and regardless of its production method, burning ammonia emits NO_x. Ammonia is easier to store and handle than hydrogen, but has poorer combustion characteristics and is highly toxic, requiring extensive safety measures.

LNG is one of the most readily available alternative fuels and is relatively easy to store and handle. The emissions related to LNG are lower than traditional marine fuels, but LNG does emit CO_2 and NO_x and can cause significant methane emissions if not properly mitigated. Liquified RNG may be used as a drop-in replacement for LNG that is derived from biological sources.

A similar alternative fuel to LNG in terms of emissions and availability is **LPG**. While more efficient than LNG, LPG has additional issues related to corrosivity and toxicity that must be properly mitigated. As with LNG, LPG may be blended or replaced with bioLPG, a cleaner, renewable fuel that is chemically identical to conventional LPG.

Methanol is one of the easiest alternative fuels to handle due to it being liquid at atmospheric conditions. While methanol can be produced renewably, its combustion still releases CO_2, and its toxicity introduces handling and storage requirements.

Traditional diesel can be swapped out or blended with lower-emission versions to reduce emissions without requiring engine modifications. **Biodiesel**, made from biological feedstock, is carbon neutral but struggles with cold weather performance, making it more suitable for blending with traditional diesel. **Renewable diesel** is made from fats and oils and is chemically identical to traditional diesel, allowing it to be used as a direct replacement but resulting in some emissions.

5.4.4. Carbon Capture and Sequestration

When it is not feasible to eliminate CO_2 emissions from a vessel's operation, CCS may be applied to avoid releasing the CO_2 to the atmosphere. CCS involves capturing the carbon, storing it onboard, and sequestering it.

Carbon capture can happen before, during, or after combustion, with post-combustion capture being easiest to implement on existing vessels as it requires no engine modifications. Typically, carbon is captured using specially designed membranes, but cryogenic separation or chemical absorption may be used instead.

To **store** the carbon onboard, it is typically liquefied under high pressures and low temperatures but can be mineralized for solid storage. Care must be taken to avoid the introduction of impurities, which can cause corrosion in tanks.

To **sequester** the carbon, it is either offloaded to a land-based sequestration service or sequestered offshore in subsea depleted hydrocarbon reservoirs or saline aquifers. It may be injected directly from the vessel or delivered to an offshore sequestration facility for injection. This process can capture up to 90% of a vessel's CO_2 emissions and sequesters it away from land and marine life[68].

5.4.5. Digitalization and Autonomous Systems

Digitalization and autonomous vessel technologies are emerging as complementary tools for reducing emissions through operational optimization. Advanced onboard systems can optimize routing, speed, and fuel consumption in real time by incorporating weather data, vessel performance metrics, and operational constraints.

These technologies may also enable reduced crew requirements and improved energy efficiency of onboard systems, lowering overall vessel energy demand. In addition, the use of sensors, artificial intelligence, and machine learning supports predictive maintenance and improved asset management, helping vessels operate at peak performance.

5.4.6. Summary of Emerging Technologies

The opportunities for reducing emissions using technologies and alternative fuels are wide-ranging and cover various aspects of vessel operation. One of the primary benefits of these opportunities being so varied is that in most cases multiple strategies can be applied in tandem, reducing emissions more than if one single strategy were to be applied. No single technology or fuel is an ideal solution to decarbonization, as each has its respective strengths and weakness, the most notable of which are summarized in table 9.

Table 9. Strengths and weaknesses of emerging technologies and fuels.

Technology or Fuel	Strengths	Weaknesses
Weather Routing	• Fuel savings of up to 12.5% • Applicable to any ship	• Potential for model inaccuracy
Hydrodynamic Improvements	• Fuel savings of up to 25% • Versatile	• Coatings may be toxic • Hull form optimization is
Dual Fuel Engines	• Allows for combustion of alternative fuels with a pilot fuel	• Costly
Waste Heat Recovery	• Fuel savings of up to 15%	• Systems may be complex
Fuel Cells	• Highly efficient	• Difficulties with fuel storage
Nuclear Reactors	• Highly efficiency • No emissions	• Costly • Potential safety concerns
BESS	• Emissions-free sailing • Quiet	• Limited range • Potential source emissions
WAPS	• Fuels savings of up to 30%	• Complex implementation
Hydrogen	• Efficient • No emissions	• Very difficult to store
Ammonia	• More energy dense than hydrogen	• Highly toxic
LNG	• Readily available	• Some emissions
LPG	• More efficient than LNG	• Corrosive and toxic
Methanol	• Easy to handle	• Some emissions
Biodiesel and Renewable Diesel	• Lower emissions than traditional diesel	• Costly
CCS	• Captures 70-90% of emitted carbon	• Complex system
Digitalization and Autonomous Systems	• Versatile • Can be applied to most ships	• May require additional crew training

Some of the strategies that would be easy to apply to vessels not already doing so include weather routing, hydrodynamic improvements, and digitalization. To further optimize the vessels fuel use, waste heat recovery and WAPS may be implemented. These strategies can only reduce emissions to a limited extent if the fuel being consumed still emits CO_2, so alternative fuels must continue to be adopted for further decarbonization, using dual fuel engines or fuel cells. If it is not feasible to remove CO_2 emissions through fuel replacements, CCS should be used to reduce emissions to the atmosphere as much as possible.

6.0. Phase 2 Planning

6.1. Findings and How They Impact NL

The findings from this study confirm that decarbonization in NL will require a mix of approaches. A combination of efficiency improvements, hybridization, alternative fuels, and enabling infrastructure will be required, with solutions varying by vessel type and operating profile.

Across NL's marine sectors, the **strongest near-term opportunities** are associated with vessels that operate on fixed routes, have predictable schedules, and return regularly to the same ports. This includes much of the provincial ferry system, harbour craft, and certain nearshore fishing operations, which are better suited to electrification, hybrid propulsion, and shore power integration due to their operational consistency and the feasibility of centralized infrastructure.

In contrast, vessels operating offshore or over long distances, including offshore supply vessels, tankers, and large fishing vessels, face more significant barriers to full electrification. These vessels require higher energy densities and longer operating ranges, making them more reliant on **transitional solutions** such as improved efficiency, hybrid systems, and lower-carbon fuels such as LNG, methanol, and biofuels in the near to medium term. Hydrogen and ammonia remain longer-term options but are currently constrained by storage challenges, safety considerations, and a lack of supporting infrastructure.

A consistent finding across all areas of the study is that **infrastructure availability** will be a key determinant of technology adoption. Without access to shore power, alternative fuel bunkering, and sufficient electrical capacity (a concern with UK ports), vessel operators are unlikely to transition away from conventional fuels at scale, which is particularly relevant in NL where port infrastructure is distributed and largely designed around traditional marine operations.

The study also reinforces that **capital cost and technology risk remain significant barriers**. Many operators, particularly those with large or specialized vessels, are unlikely to commit major retrofits or new builds until there is greater certainty around fuel pathways, regulatory requirements, and long-term operating costs. This is especially true given the current global uncertainty surrounding alternative fuels and will limit near-term investment decisions, particularly for larger vessels where long asset lifecycles increase risk. At the same time, there are clearer opportunities for incremental progress. Efficiency improvements, hybridization, and the use of drop-in or low-carbon fuels can provide measurable emissions reductions without requiring significant changes to vessel design or operations, making these solutions more accessible to a broader range of operators.

The findings from this study suggest that Phase 2 should **focus** on practical, scalable initiatives that reduce risk, build local experience, and position NL to adopt more advanced technologies as they mature.

6.2. Priorities for R&D Activities to be Based in NL

Based on the findings from this study, R&D activities in NL should focus on applied, and locally relevant initiatives that support near-term implementation while positioning the province for longer-term opportunities. Rather than duplicating global research efforts, priority should be placed on applied work that aligns with local operating conditions, existing capabilities, and emerging areas of strategic advantage.

Consistent with the pathways and technologies discussed throughout this report, the following R&D priorities are recommended:

1. **Hydrogen and Related Fuel Pathways**

Hydrogen has been identified as a longer-term marine fuel option but can also be used to produce other fuels (such as methanol), which may see earlier adoption. As such, R&D efforts should consider hydrogen not only as a direct fuel, but as part of a broader fuel pathway.

Work in this area could include assessing how NL's renewable energy potential may support hydrogen production over time, as well as how that hydrogen could contribute to future methanol (or other) supply chains. Early consideration of production, storage, and distribution requirements would help position the province to participate in these emerging markets.

2. **Hybrid and Battery Systems for Targeted Use Cases**

While full electrification is not feasible for most vessels operating in NL, hybrid systems and partial battery integration may be suitable for certain applications. R&D efforts should therefore focus on identifying and evaluating these targeted use cases.

This could include assessing opportunities for battery use in auxiliary systems, short-duration operations, or vessels operating on fixed or predictable routes. Evaluating system configurations, operational impacts, and infrastructure requirements would help determine where these technologies can be most effectively applied.

3. **Focus on Key Vessel Segments in NL**

Given the diversity of the marine sector in NL, R&D efforts should prioritize vessel segments where there is both strong local relevance and a greater degree of influence over operations. These segments include ferries, fishing fleets, offshore support vessels, and government-operated fleets. Focusing on these areas allows for more targeted research that reflects real operating conditions, enabling solutions that are practical, scalable, and directly applicable within the province.

4. **International Collaboration and Technology Adaptation**

The study highlighted the value of international engagement in identifying emerging technologies and best practices. Continued collaboration with international partners provides an opportunity to test and adapt these technologies within the NL context.

R&D efforts in this area should focus on piloting technologies under local operating conditions, supporting knowledge transfer, and evaluating their applicability within the Canadian market. This approach helps ensure that global advancements can be translated into locally viable solutions.

5. **Biofuels and Fuel Blending Opportunities**

Biofuels have been identified throughout this report as a near-term pathway to reduce emissions from existing vessels without requiring significant modifications. As such, further R&D could focus on how these fuels may be incorporated into marine fuel supply chains across NL.

This may include evaluating the potential role of locally available biomass, and how biofuels can be blended with conventional fuels such as diesel. This type of work would support incremental emissions reductions while maintaining compatibility with existing engines and infrastructure.

6. **Vessel Efficiency Improvements**

Efficiency improvements represent one of the most practical and widely applicable opportunities identified in this study. R&D in this area should focus on technologies and operational strategies that can be deployed across a broad range of vessel types operating in NL.

Areas of focus may include hull coatings and drag reduction technologies, propeller optimization, and the use of digital energy management systems. These solutions offer relatively low-risk, cost-effective pathways to reduce fuel consumption and emissions, and often be implemented without major vessel modifications.

6.3. Potential Phase 2 Demonstration Plans

Phase 2 will focus on achievable demonstration projects that reflect the operational realities of NL's marine sector. Given the uncertainty surrounding long-term fuel pathways and the high capital costs associated with major vessel retrofits, it is unlikely that major vessel owners and operators will commit to significant propulsion system overhauls in the near-term. As a result, early efforts should focus on smaller-scale, lower-risk projects that can still deliver meaningful and measurable results.

Consistent with the opportunities identified throughout this report, potential demonstration plans have been recommended below:

1. **Efficiency Upgrades for Smaller Vessels**

Smaller vessels, including inshore fishing fleets, harbour-based vessels, and small commercial operators, present an opportunity for early demonstration due to their lower capital requirements and operational flexibility.

Demonstration projects in this area could focus on the implementation of proven efficiency measures such as advanced hull coatings, propeller upgrades and/or optimization, and onboard energy management systems. Where possible, projects should be structured to include before and after performance comparisons to clearly quantify fuel savings and emissions reductions.

These initiatives offer a practical entry point for Phase 2 as they can be deployed relatively quickly, require limited infrastructure changes, and provide measurable results that can be replicated across similar vessel classes.

2. **Hybrid and Battery Demonstration Projects**

Hybrid propulsion systems and battery integration should be tested in applications where full electrification is not feasible but partial electrification may provide operational and environmental benefits. Pilot projects could include battery integration to support auxiliary loads, peak shaving, or short-duration operations such as harbour maneuvering. In addition, hybrid retrofits could be explored for vessels operating on predictable routes or duty cycles.

These demonstrations should evaluate not only emissions reductions, but also impacts on fuel consumption, maintenance requirements, and operational performance. Findings will help identify where hybridization represents a viable pathway within the provincial fleet.

3. **Renewable and Lower-Carbon Fuel Trials**

Given the continued reliance on diesel across much of the fleet, demonstration projects should include the trialing of lower-carbon fuel options that can be used within existing propulsion systems. This could include the use of renewable diesel blends, with trials conducted on one, or numerous vessel types and operating profiles. Projects would assess fuel performance, emissions reductions, fuel handling considerations, and any operational impacts such as engine performance or maintenance requirements.

These trials represent a near-term decarbonization pathway that can be implemented without significant vessel modifications, making them well suited for early-stage demonstration.

4. **Port and Shoreside Demonstration Initiatives**

Shoreside and port-based projects provide an opportunity to reduce emissions independently of vessel retrofits while also preparing for future fuel transitions. Demonstration initiatives may include the installation of shore power systems at select terminals, allowing vessels to reduce or eliminate engine use while at berth. Additional opportunities include pilot-scale testing of fuel handling and storage systems for alternative fuels, as well as the implementation of energy management technologies within port operations.

These projects can deliver localized emissions reductions, particularly in port areas, while also supporting the development of infrastructure needed for longer-term transition pathways.

5. **Technology Demonstration Through Partnerships and Local Facilities**

Emerging technologies identified through international collaboration can be tested and validated within NL using both operational vessels and local testing infrastructure. Pilot installations on suitable vessels would allow technologies to be evaluated under real operating conditions, while controlled testing environments can be used to validate performance prior to deployment. Institutions such as the Fisheries and Marine Institute of Memorial University of Newfoundland provides facilities and expertise that can support testing, validation, workforce training, and data collection. This combined approach would aid in reducing implementation risk, supports knowledge transfer, and strengthens the province's capacity to adopt and scale new technologies.

All demonstration projects would need to incorporate structured data collection and performance monitoring to ensure that the outcomes are measurable and comparable. This includes tracking fuel consumption, emissions reductions, maintenance requirements, and overall operational performance. Phase 2 demonstration projects should also be designed with flexibility to adapt to funding availability, regulatory developments, and evolving technologies. Engaging with stakeholders will be critical to identifying pilot partners, refining the project/demonstration scope, and ensuring that the demonstrations align with industry needs and operational realities.

7.0. Conclusions

The International Clean Mobility Study Program provided a comprehensive assessment of opportunities to reduce GHG emissions across NL's marine sector. Drawing on international research, technical analysis, emissions data, and stakeholder input, the study highlights both the challenges of the transition and the practical opportunities available to the province.

A key takeaway is that there is no single pathway or "right answer" to marine decarbonization. Progress will depend on a combination of approaches, including efficiency improvements, hybrid systems, alternative fuels, and supporting infrastructure. The suitability of these options varies by vessel type, operating profile, and geography. These factors that are particularly diverse in NL, where marine activity ranges from short ferry routes to support vessels for offshore oil operations.

In the near-term, emissions reductions are most likely to come from incremental and readily deployable measures. Efficiency gains, hybridization, and lower-carbon fuels represent practical and scalable options. Longer-term solutions, such as hydrogen, methanol, and ammonia, offer greater potential, but remain limited by technology readiness, infrastructure needs, and cost considerations.

Recent emissions trends in the province reinforce the need for a targeted approach. Changes in emissions appear closely tied to offshore activity, including tanker movements, suggesting that the broader reductions will depend not only on technology adaptation but also on underlying industry dynamics. This points to the importance of flexible, data-informed strategies that can respond to shifting considerations.

Looking ahead, the focus should be on practical initiatives that reduce risk, build local expertise, and support informed investment. By prioritizing solutions that align with local conditions and existing strengths, NL can make steady progress while remaining positioned to adopt emerging technologies as they mature.

In summary, the transition to a low-emission marine economy in NL will be gradual and context-specific, requiring coordination across industry, government, and academia. With its established marine sector, access to renewable energy, and growing international connections, the province is well placed to contribute toward sustainable marine operations, while positioning itself as a practical testbed for clean mobility solutions in northern, coastal environments.

Appendix A - Project Collaborators

Oceans Advance

Oceans Advance is NL's Ocean Technology Innovation Cluster. It brings together members from industry, education and training, research and technology organizations, and government (federal, provincial, and municipal). Its core purpose is to:

- Foster collaboration across the ocean technology ecosystem
- Connect members with each other and with government partners
- Promote and identify opportunities within the sector
- Support member companies through learning sessions, training, networking events, and strategic advocacy

Members of the cluster deliver world-class technologies and services globally and help position NL as a leader in ocean innovation.

The current board members of Oceans Advance are:

- Chair – Dr. Paul Brett (Fisheries and Marine Institute of Memorial University of Newfoundland)
- Co-Chair – Ashley Noseworthy (Edgewise Environmental Ltd.)
- Board Member – Justin So (Jasco)
- Board Member – Natasha Hudson (Canadian Manufacturers & Exporters)
- Board Member – Dr. Freeman Ralph (C-CORE)
- Board Member – Marcel Montrose (Lir Maritime Consulting Ltd.)
- Director – Paul Dwyer (Rutter)
- Director – Capt. Kristopher Drodge (Fisheries and Marine Institute of Memorial University of Newfoundland)

Oceans Advance board currently has nine voting members, and the executive director is a non-voting member of the board. The organization is run by two staff members. Shelly Petten, CEO, and Mary Tucker, Program Manager. The board provides oversight and strategic guidance to ensure the organization meets its goals and objectives.

econext

econext is a not-for-profit association with a mission to accelerate clean growth in NL. econext has been working for over 30 years on behalf of its members across many sectors to support environmentally sustainable economic development. econext is focused in the following areas:

- Innovation – econext works with partners in the public, private, and academic sectors to stimulate and support R&D and innovation that advances clean growth in NL.
- Workforce – econext coordinates with private, public, and academic partners to ensure NL's workforce is prepared for the emerging green economy.
- Net-zero – econext is a catalyst for climate change action within NL, helping industry, businesses, and communities find a better balance between economy and environment.

econext is a driver for clean growth innovation in the province, a coordinator of green workforce development, and a catalyst for net zero by 2050 planning within NL's communities and industries.

Angler Solutions Inc.

Angler Solutions Inc. ("Angler") is a NL based consulting and technology firm delivering professional services in the energy and ocean technology sectors.

While formally incorporated in 2020, Angler's core team builds on years of industry experience in the offshore oil & gas and electricity sectors, providing a strong foundation of transferable skills that now underpin the company's contributions to the global energy transition.

Angler specializes in early-phase project development (FEL 1-2) with a focus on renewable energy, energy diversification, and ocean technology initiatives.

The firm provides an integrated suite of services including:

- Energy systems modelling using MESO (Model for Energy Systems Optimization)
- Techno-economic analysis (TEA) and feasibility studies for new energy concepts
- Renewable integration and grid interconnection assessments
- Supply chain and infrastructure readiness studies for wind, storage, and hydrogen projects
- Power systems design and site electrification studies for industrial clients
- Strategic planning, stakeholder engagement, and funding advisory support

Through these services, Angler supports clients in understanding technical potential, infrastructure alignment, and system-level development pathways across renewable energy systems. Angler's approach combines local knowledge and global partnerships, maintaining collaborations with energy, technology, and academic organizations across Canada, the UK, and Europe. This network allows Angler to deliver high-impact projects across the energy diversification, renewable energy, ocean technology, and upstream resources domains.

On The Layline Limited

One The Layline Limited is a specialist marine innovation consultancy based in the South West of the UK. Covering all aspects of marine innovation support, the business supports UK SMEs and international consortia to develop the next generation of marine technology.

On The Layline provides highly collaborative innovation services to support the next generation of marine technologies in advanced autonomy, clean propulsion, ocean health and monitoring, and digital and data. On The Layline covers all facets of innovation support, from high level advice through to bid preparation, collaborative partnership building, promotion both nationally and internationally, and overall business strategy.

Riga Technical University

Riga Technical University (RTU) is the largest university in Latvia and a state higher education institution focused on engineering and technology. Founded in 1862, RTU is the oldest technical university in the Baltic states and provides higher education across a range of disciplines, including engineering, natural sciences, maritime engineering, information technology, architecture, and economics.

The university offers study programs at the bachelor's, master's and doctoral levels and serves a large student population, including international students. Its academic and research activities are supported by modern infrastructure, including the Kipsala campus. RTU is engaged in scientific research and innovation through its faculties and research institutes, with activities aligned to engineering, technology development, and applied sciences.