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

Project 101192661 - FLEETfor55

Executive Summary of Deliverable D2.4 - Preliminary technical evaluation of EETs

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Acronyms and Abbreviations	Meaning
2-S ICE	Two-Stroke Internal Combustion Engine
4-S ICE	Four-Stroke Internal Combustion Engine
ALS	Air Lubrication System
BOG	Boil-Off Gas
CCS	Carbon Capture and Storage
CoG	Center of Gravity
CRP	Contra-Rotating Propeller
DC	Direct Current
EET	Energy Efficiency Technology
ESD	Energy Saving Device
ESS	Energy Storage System

Acronyms and Abbreviations	Meaning
HPDI	High-Pressure Direct Injection
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
IAS	Integrated Automation System
ICE	Internal Combustion Engine
JIT	Just-in-Time (arrival strategy)
LH_2	Liquid Hydrogen
LNG	Liquefied Natural Gas
M/E	Main Engine
MGO	Marine Gas Oil
MSB	Main Switch Board
NO_x	Nitrogen Oxides
OPS	Onshore Power Supply
PEM	Proton Exchange Membrane (fuel cell)
PLC	Programmable Logic Controller
PtL	Power-to-Liquid
PV	Photovoltaic
PTO	Power Take-Off
PTI	Power Take-In
RFB	Redox Flow Battery
SCR	Selective Catalytic Reduction
SFOC	Specific Fuel Oil Consumption
VFD	Variable Frequency Drive
WED	Wake Equalizing Duct
WtW	Well-to-Wake
WHRS	Waste Heat Recovery System
WAPS	Wind-Assisted Propulsion System
IAS	Integrated Automation System

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Executive Summary

This deliverable provides the preliminary technical evaluation of Energy Efficiency Technologies (EETs) for waterborne transport within the FLEETfor55 project. The activities of WP2 follow a progressive logic, moving from the identification of a wide range of EETs (D2.1), to the assessment of their maturity and market context (D2.2), and finally to their preliminary technical evaluation. Deliverable 2.4 represents the third step in this sequence, building directly on the outputs of Deliverables 2.1 and 2.2. The focus is strictly on technical feasibility, integration complexity and operational/environmental performance, independent of economic or deployment-specific business constraints. Main scope is to perform a systematic, engineering-driven screening and ranking of EETs, using a structured multi-criteria assessment framework.

The multi-criteria assessment framework is exclusively based on individually examination of each EET and does not consider the desktop cases developed within FLEETfor55.

For this technical pre-feasibility study, five key technical attributes were identified that influence the applicability and feasibility of EETs and, consequently, their suitability across different vessel types:

- Maturity of Technology.
- Space and Weight requirements.
- Integration complexity.
- Operational compatibility.
- Operational and Environmental Performance.

These criteria provide an initial basis for the new categorization of EETs, based on the major technical characteristics that may affect their engineering analysis. Accordingly, EETs were classified into “globally applied EETs” and “ship-related EETs.” The former includes solutions that can be theoretically implemented across all vessel types without significant integration or implementation challenges and with minimal engineering modifications. Most globally applied EETs are operationally oriented and/or digitally optimized. However, methods based on electrification systems, hydrodynamic improvements, and optimized engineering approaches were also included in this category, as the required modifications can be applied across various vessel types.

In contrast, “ship-related EETs” are considered the most technically demanding, facing significant engineering and technical barriers that strongly affect the five previously identified technical attributes. In this category, EETs from all categories are included expect from operationally oriented.

Following further literature analysis and research, several categories referenced in previous deliverables were either removed or consolidated, while others were expanded. The extensions concern technologies that exhibit distinct operational or design characteristics, which necessitated their differentiation into more specific type of EETs. Specifically, several adjustments were made within the "Globally applied EETs" category. Energy Management Systems were excluded, as the majority of vessels are already equipped with such systems supporting onboard electrical demand and energy distribution. CPP pitch optimization was also excluded, as it is classified under propeller ESDs within the "ship-related EETs" category. Additionally, several EETs were merged: speed optimization, port turnaround time reduction, and autopilot upgrade and adjustment were consolidated under the Just-in-Time (JIT) Arrival Strategies category within Operations & Digital Optimization; HVO was incorporated into the Biodiesel category; and hull cleaning and ultrasound-based hull protection were included under Hull Surface Coatings & Low-Drag Paints. Finally, Reduced Auxiliary Power Demand was divided into Variable Frequency Drives (VFDs), as identified in Deliverable 2.1, and LED lighting applications, both contributing to overall reductions in auxiliary power demand. Table 1 shows the consolidated catalogue of "globally applied EETs".

Table 1: Globally Applied EETs

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

Within the "Ship-related EETs" category, water-emulsified fuel technology was excluded, as its primary benefits relate to improved combustion efficiency and NO_x reduction. Only PEM and SOFC fuel cells were retained for analysis, while other fuel cell types were excluded. Turbosails were also excluded due to high mechanical complexity, limited operational data, integration challenges on commercial hulls, and the absence of commercial adoption. In addition, certain EETs were merged: Power-to-Liquid (PtL) e-fuels and synthetic e-fuels were grouped into a single category (Synthetic e-fuels); electric propulsion systems and thrusters were analysed as part of full electric propulsion concepts; and the DynaRig system was included under soft sail solutions. Finally, alternative 4-stroke and 2-stroke ICEs were divided into six distinct EETs based on the type of fuel used for combustion. A consolidated catalogue of "ship-related" is presented on Table 2.

Table 2: Ship related EETs

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

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

Based on an extensive technical literature review and the collective expertise of the involved technical partners, key findings were identified to support the technical assessment framework developed in Deliverable 2.4 for the “Ship related EETs”. he five core technical attributes assigned specific weightings, while each EET was scored on a 1–9 scale against each attribute, reflecting the degree to which the attribute affects its technical suitability. The scoring was informed by a detailed evaluation of installation and integration constraints, operational boundaries, expected energy and emission performance, retrofit feasibility, and implications for newbuild design, resulting in a consolidated technical ranking of EETs across the assessed attributes.

Maturity of Technology

Regarding the Maturity of Technology, the EETs were evaluated by the respective experts within the consortium, and their resulting ranking (sorted from highest to lowest score) is presented in Table 3. By applying the relevant **weight factor (0.19/1)**, the resulting scores **range from 1.68 to 0.63**,

highlighting the significant differences among the examined technologies, with some already fully mature and deployed, and others still at the prototype validation and market investigation stage.

More specifically, at the top of the ranking one typically finds technologies and alternative fuels that have been widely applied in recent years (e.g., shaft generators and methanol), internal combustion engines (ICEs) that require only minor modifications to the current conventional ones, and energy-saving devices (ESDs), such as ducts and fins, which the maritime industry has increasingly adopted in recent years. On the contrary, technologies related to future carbon-neutral fuels such as ammonia and hydrogen (e.g., ICEs, reformers/crackers), although being intensively investigated by the relevant stakeholders, and ranking among the hottest topics in maritime R&D, still require further examination and development in order to reach a sufficient level of maturity for widespread onboard deployment. The status is almost the same for various technologies related to vessels' electrification or wind assisted propulsion.

It is important to note, however, that a low score in technological maturity may be due to two different factors: either the aforementioned genuine need for further developments (technical, safety, regulatory), or the fact that although the technology has already reached the necessary level of development, it has not been widely applied for other reasons (e.g., complexity, uncertainty, etc.), and, therefore, cannot be considered mature.

Table 3: Final Scoring of EETs for Maturity level

Number	Name of EET	Maturity of Technology
1	Shaft Generator PTI, PTO, PTI/PTO	**1.68**
2	Alternative Fuelled 4-S ICEs/ Gensets (Biofuels)	**1.67**
3	Pre-swirl ESD Wake Equalizing Ducts (WEDs)	**1.67**
4	Post-swirl ESD PBCF (Propeller Boss Cap Fins)	**1.67**
5	Propeller-Retrofitting Advanced Propeller Blade Sections (e.g. Winglets/kappel)	**1.66**
6	Pre-swirl ESD ESD Fins	**1.64**
7	Methanol	**1.64**
8	Alternative Fuelled 2-S ICEs (Methanol)	**1.61**
9	Alternative Fuelled 4-S ICEs/Gensets (Methanol)	**1.61**
10	SOLAR - Photovoltaic (PV) Panels for Ships	**1.57**

Number	Name of EET	Maturity of Technology
11	Onshore Power Supply [OPS]	**1.52**
12	Energy storage systems (ESS) – lithium-ion batteries	**1.51**
13	Waste heat recovery systems (WHRS)	**1.51**
14	WAPSs - Flettner Rotors (Magnus Effect Rotors)	**1.48**
15	Biomethane	**1.48**
16	Advanced HVAC & cooling systems	**1.47**
17	Propeller Nozzle (e.g. Kort)	**1.47**
18	Bulbous Bow Optimization	**1.42**
19	Ammonia	**1.40**
20	Steam/heat plant improvements/optimization	**1.39**
21	WAPSs - Suction Wings (Ventifoils)	**1.39**
22	Alternative Fuelled 4-S ICEs/Gensets (Hydrogen)	**1.35**
23	Post-swirl ESD Contra-rotating propellers (CRP)	**1.35**
24	Synthetic e-fuels	**1.35**
25	PEM fuel cells	**1.33**
26	Alternative Fuelled 2-S ICEs (Ammonia)	**1.32**
27	Variation of block coefficient/lengthening (Inland)	**1.30**
28	WAPSs - Rigid Wing Sails	**1.29**
29	Hull Openings and Skeg Shape Optimization	**1.26**
30	Hull Form Optimization (Streamlined Design for Efficiency)	**1.24**

Number	Name of EET	Maturity of Technology
31	Onboard Carbon Capture and Storage (CCS) Systems	**1.22**
32	Air lubrication systems (ALS)	**1.19**
33	Alternative Fuelled 4-S ICEs/Gensets (Ammonia)	**1.16**
34	Post-swirl ESD Grim Vane Wheel	**1.16**
35	SOFC fuel cells	**1.11**
36	WAPSs - Kite Propulsion Systems	**1.10**
37	Hydrogen	**1.09**
38	Full Electric Propulsion Concepts (e.g. dynafin, Superconducting electric motors)	**1.06**
39	Fuel Reforming/Cracking	**1.06**
40	DC Grid technologies	**1.01**
41	Energy storage systems (ESS) – redox flow batteries (RFB)	**0.97**
42	Manoeuvring devices (e.g. Gate rudder)	**0.97**
43	WAPSs - Soft Sails	**0.93**
44	Alternative Fuelled 2-S ICEs (Hydrogen)	**0.77**
45	Hydrofoil-Based Wave Energy Converters	**0.68**
46	Heaving Oscillating Systems	**0.63**

Space and Weight:

For the space and weight attribute, the weight factor assigned to this attribute is **0.18/1**, while the partners' scores for each EET **range from 0.43 to 1.55**. As shown in the final results of Table 4, technologies requiring large and heavy components, or major structural modifications, consistently appear at the lower end of the ranking. Among them are:

1. Carbon Capture Systems, which involve very large equipment and substantial additional weight, including a pre-treatment system for exhaust gases; a carbon capture plant that serves as the core unit responsible for CO_2 separation from exhaust gases; an after-treatment system that prepares the captured CO_2 for safe handling and storage; and a temporary storage system that retains the processed CO_2 on board until discharge or utilization.
2. Alternative-fuel ICEs/gensets which create significant space limitations, particularly in retrofit applications. A six-cylinder four-stroke hydrogen-fuelled marine engine can be accommodated within dimensions of approximately 4 m × 1.5 m × 2.5 m and weighs about 11 tonnes. In comparison, a six-cylinder four-stroke ammonia-fuelled engine set has main dimensions of around 5.0 m × 2.3 m × 3.5 m and a weight of approximately 23 tonnes. Two-stroke hydrogen-fuelled engines show a wide range of sizes, with estimated lengths varying from 4 m to 23 m and weights ranging from 80 to 2,300 tonnes. Similarly, a two-stroke ammonia-fuelled engine has approximate dimensions of 8 m × 4 m × 11 m and weighs about 400 tonnes.
3. Compressed hydrogen which can achieve a volumetric energy density of 5 MJ/L, which is significantly lower than Marine Gas Oil (MGO), with a volumetric density of 35 MJ/L. As a result, compressed hydrogen requires larger storage space on ships compared to MGO (4.5 times bigger tanks).
4. Redox Flow Batteries, which have relatively low volumetric energy density, typically 15–25 Wh/L for vanadium systems and 20–40 Wh/L for other chemical compounds such as bromine/polysulfide. This corresponds to approximately 16–33 kWh/m³ at the system level, making RFBs particularly bulky and requiring large tank volumes as well as heavy supporting systems.

In contrast, hydrodynamic EETs are ranked on the top positions, as these retrofits are simple, lightweight, and can be installed during a typical dry-dock without any notable impact on available space or vessel weight.

In the middle of the table, many electricity-based EETs appear, as their space and weight impacts depend strongly on ship type, energy demand, and the number of units needed. Examples include lithium-ion batteries, with a specific energy of around 150–250 Wh/kg and a relatively high volumetric energy density of approximately 350–700 Wh/L, and photovoltaic panels, whose main

limitation is deck space. These systems primarily cover the vessel's hotel loads, which also determines the number of units required.

This distribution highlights that the ranking is driven by the physical components required to implement each solution and the space and/or weight requirements needed to implement those

Among Wind-Assisted Propulsion Systems, kite propulsion ranks significantly higher than other WAPS technologies because it imposes minimal onboard space and weight constraints. In comparison, Flettner Rotors and rigid wing sails require substantial deck space and add considerable weight, affecting vessel stability. Flettner Rotors typically measure 18-30m in height and weigh 34-90 tonnes, while rigid wing sails range from 10-50m in height and 3-20m in width, with a mass of 45-100 tons. Both systems demand significant deck space and careful stability considerations due to their impact on the vessel's center of gravity.

Alternative fuels appear at different ranking levels depending on the size and type of storage tanks required. Based on volumetric energy density, biomethane, with 20 MJ/L, requires tanks approximately twice as large as MGO, similar to LNG. Methanol, with a volumetric energy density of 15.8 MJ/L, requires tanks about 2.5 times larger than MGO. Ammonia, at 12.8 MJ/L, needs tanks roughly 3.1 times larger, while, as previously mentioned, compressed hydrogen has the lowest energy density and requires tanks approximately 4.5 times larger than MGO.

Table 4: Final Scoring of EETs for Space and Weight

Number	Name of EET	Space and weight
1	Pre-swirl ESD Fins	**1.55**
2	Post-swirl ESD PBCF (Propeller Boss Cap Fins)	**1.55**
3	Propeller-Retrofitting Advanced propeller Blade Sections (e.g. Winglets/kappel)	**1.53**
4	Alternative Fuelled 4-S ICEs/ Gensets (Biofuels)	**1.44**
5	Pre-swirl ESD Wake Equalizing Ducts (WEDs)	**1.37**
6	Onshore Power Supply [OPS]	**1.36**
7	Advanced HVAC & cooling systems	**1.35**
8	WAPSs - Kite Propulsion Systems	**1.35**
9	Hull Openings and Skeg Shape Optimization	**1.32**

Number	Name of EET	Space and weight
10	DC Grid technologies	**1.32**
11	Synthetic e-fuels	**1.30**
12	Bulbous Bow Optimization	**1.23**
13	Biomethane	**1.23**
14	Steam/heat plant improvements/optimization	**1.13**
15	Hull Form Optimization (Streamlined Design for Efficiency)	**1.13**
16	Waste heat recovery systems (WHRS)	**1.08**
17	Alternative Fuelled 4-S ICEs/Gensets (Methanol)	**1.08**
18	Shaft Generator PTI, PTO, PTI/PTO	**1.05**
19	WAPSs - Suction Wings (Ventifoils)	**1.05**
20	Propeller Nozzle (e.g. Kort)	**1.04**
21	Air lubrication systems (ALS)	**1.02**
22	Methanol	**1.00**
23	Manoeuvring devices (e.g. Gate rudder)	**0.99**
24	Alternative Fuelled 2-S ICEs (Methanol)	**0.96**
25	Hydrofoil-Based Wave Energy Converters	**0.95**
26	Full Electric Propulsion Concepts (e.g. dynafin, Superconducting electric motors)	**0.95**
27	Post-swirl ESD Grim Vane Wheel	**0.95**
28	Post-swirl ESD Contra-rotating propellers (CRP)	**0.90**
29	SOLAR - Photovoltaic (PV) Panels for Ships	**0.88**

Number	Name of EET	Space and weight
30	Energy storage systems (ESS) – lithium-ion batteries	**0.87**
31	PEM fuel cells	**0.85**
32	WAPSs - Flettner Rotors (Magnus Effect Rotors)	**0.81**
33	Ammonia	**0.80**
34	WAPSs - Rigid Wing Sails	**0.78**
35	Heaving Oscillating Systems	**0.77**
36	WAPSs - Soft Sails	**0.76**
37	Variation of block coefficient/lengthening (Inland)	**0.72**
38	Alternative Fuelled 4-S ICEs/Gensets (Ammonia)	**0.72**
39	Fuel Reforming/Cracking	**0.72**
40	SOFC fuel cells	**0.70**
41	Alternative Fuelled 4-S ICEs/Gensets (Hydrogen)	**0.67**
42	Alternative Fuelled 2-S ICEs (Ammonia)	**0.66**
43	Alternative Fuelled 2-S ICEs (Hydrogen)	**0.60**
44	Hydrogen	**0.59**
45	Energy storage systems (ESS) – redox flow batteries (RFB)	**0.54**
46	Onboard Carbon Capture and Storage (CCS) Systems	**0.43**

Integration:

Integration is another evaluated attribute (with a weighted value: **0.20 / 1**) that is considered to evaluate the technical aspects of the EETs. In terms of subject task, assessment values of respective experts within consortium multiplied with regard factor resulted in scores that range from **1.67** to **0.54** with most of them clustered close to 1.0 – 1.2, reflecting a moderate complexity rate. The relevant ranking (from highest to lowest) of the EETs is presented in below Table 5.

In particular, half of the propeller ESDs (4 of 8), among them:

1. Propeller Boss Cap Fins
2. Pre-Swirl ESD Fins
3. Pre- Swirl Wake Equalizing Ducts (WEDs)
4. Propeller-Retrofitting Advanced propeller Blade Sections

All of them are widely applied to vessel aft part could be seen at the top of the ranking. Their implementation on them can be succeeded during a typical drydocking. For pre-swirl ESD fins and WEDs is required analysis of stern structure to ensure sufficient strength and limit potential cracking in the areas where the fins and WED are welded to the hull.

Synthetic e-fuels (excluding e-ammonia, e-methanol, and e-hydrogen), the tanks and integration systems closely resemble those used for conventional fuels, for which shipboard experience and integration expertise are already well established. For biomethane, Type C tanks similar to LNG are used, and a reliquefication plant may be required to manage boil-off gas, along with a gas combustion unit to control tank pressure. ICEs fuelled with biofuels can utilize existing equipment with minimal modifications, which is why they are ranked highly.

Advanced energy systems that can be implemented as replacements for existing equipment are ranked at the top of the list. Specifically, auxiliary boiler fuel conversion to liquefied natural gas (LNG) is suitable for newbuild vessels, requiring installation of walled piping, a complex gas valve train, gas detection units, and extraction fans. Another option is the installation of exhaust gas economizers (EGEs) on auxiliary engines, which involves fitting economizers downstream of the engine exhaust. The determination of the optimal system design relies on accurately predicting the ship's electrical load profile and the corresponding number of operating generator sets. Furthermore, this measure presents a challenging conflict with electrification solutions, such as shaft generators or shore power capability, since these reduce generator operation and thereby limit the potential benefits of the economizers. Finally, improvements to the operation of the steam plant may include installing an oxygen analyser to control the air–fuel ratio, upgrading insulation of the steam piping, optimizing sensor placement, enhancing soot blower operation, recovering waste heat from exhaust gases to preheat feedwater, and installing variable speed drives (VSDs) on

feedwater pumps. The integration of HVAC with the ship's auxiliary machinery presents minor technical difficulty, mainly attributed to the electrical installations, the design of the fresh and sea water heat transfer streams and the location of the chiller unit.

For Heaving Oscillating Systems Installation often requires under-hull recesses or stern-mounted structures, adding complexity to dry-docking and occupying large spaces onboard. Retraction or locking mechanisms are necessary to protect the system in shallow waters, during port operations, or in extreme sea states. If configured as an energy generator, electrical integration involves PTO systems and cabling that must comply with machinery space and hazardous area requirements.

Hydrogen is one of the most challenging alternative fuels. Liquid hydrogen is stored in cryogenic tanks, which are cylindrical or spherical double-walled vessels with multiple vacuum-insulated layers between the inner and outer walls to provide thermal insulation. These tanks require specialized materials capable of withstanding the extremely low temperatures of liquid hydrogen and preventing hydrogen permeation. Liquefaction (at –253°C) requires approximately three times the energy needed for compression (about 35% of the stored energy), and suitable bunkering and safety systems are necessary to manage its flammability. Additionally, a boil-off gas (BOG) management system is required to safely handle evaporated hydrogen from storage.

Within the same framework, two-stroke internal combustion engines (2-S ICEs) face several integration challenges. To meet IMO Tier II emission regulations, a selective catalytic reduction (SCR) system is required for NO_x reduction. Hydrogen injection is most effective via high-pressure direct injection (HPDI), which delivers hydrogen directly into the combustion chamber at very high pressure (around 30 MPa). Finally, a dedicated cooling system is necessary to manage engine heat and ensure safe and efficient operation.

Ammonia’s toxicity is the primary concern; therefore, leak detection, venting, and prevention systems are required. In addition, a reliquefication system is needed to control boil-off. During bunkering, the designation of hazardous and toxic areas, along with forced ventilation and continuous monitoring of the bunkering station, is also required.

Regarding renewables technologies, rigid wing sails demand major structural reinforcement at the mast step to handle high cyclic loads and overturning moments. Soft sails require robust masts, foundations, and local structural reinforcement to withstand heeling loads, overturning moments, and fatigue stresses. Multiple control systems must interface with the ship’s IAS such as wind sensors, actuators, PLCs, and emergency release hardware. Installation must respect bridge visibility regulations, cargo-handling envelopes, and crane sweep paths, often necessitating specific mast placement or retractable designs. Routing of power, control cabling, and (if relevant) inflation compressors add mechanical and electrical integration burdens, especially on retrofits where deck penetrations and CoG changes must be carefully assessed.

Table 5: Final Scoring of EETs for Integration

Number	Name of EET	Integration
1	Post-swirl ESD PBCF (Propeller Boss Cap Fins)	**1.67**
2	Alternative Fuelled 4-S ICEs/ Gensets (Biofuels)	**1.56**
3	Pre-swirl ESD Fins	**1.55**
4	Biomethane	**1.51**
5	Synthetic e-fuels	**1.51**
6	Steam/heat plant improvements/optimization	**1.48**
7	Pre-swirl ESD Wake Equalizing Ducts (WEDs)	**1.47**
8	Variation of block coefficient/lengthening (Inland)	**1.43**
9	Advanced HVAC & cooling systems	**1.38**
10	Propeller-Retrofitting Advanced propeller Blade Sections (e.g. Winglets/kappel)	**1.38**
11	SOLAR - Photovoltaic (PV) Panels for Ships	**1.31**
12	WAPSs - Suction Wings (Ventifoils)	**1.30**
13	Energy storage systems (ESS) – lithium-ion batteries	**1.29**
14	WAPSs - Kite Propulsion Systems	**1.29**
15	Onshore Power Supply [OPS]	**1.28**
16	Methanol	**1.25**
17	Air lubrication systems (ALS)	**1.22**
18	Alternative Fuelled 4-S ICEs/Gensets (Methanol)	**1.22**

Number	Name of EET	Integration
19	Full Electric Propulsion Concepts (e.g. dynafin, Superconducting electric motors)	**1.22**
20	Bulbous Bow Optimization	**1.18**
21	Propeller Nozzle (e.g. Kort)	**1.17**
22	Hull Openings and Skeg Shape Optimization	**1.15**
23	Alternative Fuelled 2-S ICEs (Methanol)	**1.15**
24	Shaft Generator PTI, PTO, PTI/PTO	**1.15**
25	DC Grid technologies	**1.15**
26	Hull Form Optimization (Streamlined Design for Efficiency)	**1.07**
27	WAPSs - Flettner Rotors (Magnus Effect Rotors)	**1.05**
28	Alternative Fuelled 2-S ICEs (Ammonia)	**1.02**
29	Alternative Fuelled 4-S ICEs/Gensets (Hydrogen)	**1.02**
30	Manoeuvring devices (e.g. Gate rudder)	**1.02**
31	Post-swirl ESD Grim Vane Wheel	**1.02**
32	Fuel Reforming/Cracking	**1.02**
33	Waste heat recovery systems (WHRS)	**0.98**
34	PEM fuel cells	**0.96**
35	Onboard Carbon Capture and Storage (CCS) Systems	**0.94**
36	WAPSs - Rigid Wing Sails	**0.88**
37	Post-swirl ESD Contra-rotating propellers (CRP)	**0.87**
38	WAPSs - Soft Sails	**0.86**

Number	Name of EET	Integration
39	Ammonia	**0.84**
40	Alternative Fuelled 4-S ICEs/Gensets (Ammonia)	**0.82**
41	Energy storage systems (ESS) – redox flow batteries (RFB)	**0.76**
42	SOFC fuel cells	**0.71**
43	Heaving Oscillating Systems	**0.71**
44	Hydrogen	**0.70**
45	Hydrofoil-Based Wave Energy Converters	**0.66**
46	Alternative Fuelled 2-S ICEs (Hydrogen)	**0.54**

Operational Compatibility:

In terms of Operational Compatibility, the respective evaluation/scoring of the EETs by the consortium experts is reflected in Table 6. For subject evaluated attribute the considered **weight factor is 0.18/1** whereas the scores **range from 1.46 to 0.64,** from which it is evident again (in a similar manner with the previously evaluated attributes) that there is a strong deviation of the way that the assessed EETs perform under subject prism. Of course, this is very reasonable considering that in the total of 46, exist technologies that are very easy to match with the infrastructure and the operational pattern of any potential vessel under consideration, whereas others require specific conditions or considerable modifications in order to suit and perform efficiently.

Given the above, it is no surprise that shaft generators (in any possible combination of PTI, PTO or PTI/PTO) is the top performing EET in terms of operational compatibility, since it can adapt with minor modifications to vessel's propulsion system and in parallel without any negative effect in terms of operational profile (i.e. vessel's speed, routes, idle days etc.). Specifically, In PTI mode electrical power is 'fed' to the shaft enhancing its rotational motion with lower power contribution of Main Engine (M/E). During PTO mode, this EET acts as an electrical generator, producing electricity from mechanical shaft rotation that is supplied to vessel's Main Switch Board (MSB) / Power Management System (PMS) with the elimination of power contribution from auxiliary generator engines. The same also applies in principle for the technologies focusing on propeller and propulsion optimization as well as energy and heat optimization, since both EET categories focus on the improvement of existing vessel components for an adopted/considered operational behaviour.

Finally, for OPS operational constraints include voltage/frequency compatibility and the coordination of OPS with simultaneous cargo operations

At the lower end of the ranking scale are found technologies which require significant alterations in terms of systems and very specific operational patterns, like ICEs running on Hydrogen or Ammonia and alternative electrification (i.e. Hydrofoil-Based Wave Energy Converters and Heaving Oscillating Systems) respectively.

Hydrogen and ammonia face significant safety barriers due to their challenging characteristics. Hydrogen is a non-toxic, colourless fuel; however, it has a wide flammability range (4–75%), making it highly flammable, and its flames are nearly invisible, which complicates fire detection. Material-related challenges are also critical, as hydrogen storage tanks must be lightweight yet strong enough to meet stringent stress, strain, and safety requirements. In addition, hydrogen embrittlement can degrade certain metals, particularly high-strength steels. One of the main hazards associated with hydrogen is the risk of asphyxiation, as it can displace oxygen in enclosed spaces, while liquid hydrogen (LH_2) can cause frostbite or cold burns upon contact. All these factors emphasize the need for strict compliance with operational and safety regulations, as well as thorough crew familiarization and training. Furthermore, the use of pilot fuel is typically required to enable stable hydrogen combustion.

For ammonia, toxicity is the primary concern; therefore, comprehensive leak detection, venting, and prevention systems are required. Ammonia is corrosive to copper alloys containing more than 6% copper and reacts with acids, halogens, and oxidizing agents, imposing strict material compatibility requirements. Although it has a high auto-ignition temperature and a narrow flammability range, ammonia can still explode if released in an enclosed space in the presence of an ignition source or if a vessel containing anhydrous ammonia is exposed to fire. Due to these characteristics, the handling and operational use of ammonia demand enhanced safety measures, strict regulatory compliance, and specialized crew training to ensure safe storage, bunkering, and onboard operation.

Hydrofoil- Based Wave Energy Converter’s viability is subject to significant constraints, as performance is highly dependent on specific near-shore wave climates and susceptible to variability. Furthermore, complex hydrodynamic interference with the vessel's hull necessitates sophisticated mounting solutions, and designs must account for extreme sea states and real-fluid effects like turbulence and cavitation to ensure endurance and accurate power prediction. Performance advantages for heaving oscillation systems are strongly dependent on the operational environment. They deliver the greatest benefit on routes with consistent wave energy and moderate sea states, where controlled oscillation can reduce propulsion power demand or generate supplemental electricity. These systems act as hydrodynamic energy harvesters rather than conventional appendages, with performance linked to local sea-state energetics.

In conclusion, from an operational perspective, RFBs are attractive where high cycle life and long-duration energy storage are required. Vanadium RFBs commonly achieve more than 10,000 cycles with minimal degradation and maintain round-trip efficiencies in the range of 70–85%. However,

due to their low energy density, they are not suitable for high-power marine applications where weight and space constraints are critical. The operational performance of soft sails is highly dependent on route-specific wind conditions, true and apparent wind angles, vessel speed, and the system's ability to maintain its aerodynamic shape under dynamic conditions. Performance benefits are strongest in beam and broad-reach wind sectors and significantly reduced or negligible in headwinds or low-wind regions. Poor trimming, heavy seas, or excessive heel can erode expected gains or even increase resistance. Safety considerations include air-draft limitations, icing, visibility obstruction, interference with simultaneous operations involving cargo gear, and the requirement for emergency stowage in high-wind conditions.

Table 6: Final Scoring of EETs for Operational Compatibility

Number	Name of EET	Operational Compatibility
1	Shaft Generator PTI, PTO, PTI/PTO	**1.46**
2	Propeller-Retrofitting Advanced propeller Blade Sections (e.g. Winglets/kappel)	**1.41**
3	Steam/heat plant improvements/optimization	**1.37**
4	Onshore Power Supply [OPS]	**1.33**
5	Advanced HVAC & cooling systems	**1.32**
6	Bulbous Bow Optimization	**1.31**
7	Post-swirl ESD PBCF (Propeller Boss Cap Fins)	**1.31**
8	Alternative Fuelled 4-S ICEs/ Gensets (Biofuels)	**1.28**
9	Pre-swirl ESD Wake Equalizing Ducts (WEDs)	**1.28**
10	Pre-swirl ESD Fins	**1.28**
11	Biomethane	**1.28**
12	SOLAR - Photovoltaic (PV) Panels for Ships	**1.25**
13	Manoeuvring devices (e.g. Gate rudder)	**1.23**
14	Propeller Nozzle (e.g. Kort)	**1.23**

Number	Name of EET	Operational Compatibility
15	Variation of block coefficient/lengthening (Inland)	**1.22**
16	Alternative Fuelled 2-S ICEs (Methanol)	**1.22**
17	Alternative Fuelled 4-S ICEs/Gensets (Methanol)	**1.22**
18	Onboard Carbon Capture and Storage (CCS) Systems	**1.20**
19	WAPSs - Suction Wings (Ventifoils)	**1.17**
20	Hull Openings and Skeg Shape Optimization	**1.16**
21	DC Grid technologies	**1.16**
22	Alternative Fuelled 4-S ICEs/Gensets (Hydrogen)	**1.15**
23	Synthetic e-fuels	**1.13**
24	Methanol	**1.07**
25	WAPSs - Flettner Rotors (Magnus Effect Rotors)	**1.06**
26	Energy storage systems (ESS) – lithium-ion batteries	**1.03**
27	Waste heat recovery systems (WHRS)	**1.02**
28	Air lubrication systems (ALS)	**1.00**
29	Alternative Fuelled 2-S ICEs (Ammonia)	**0.97**
30	Hull Form Optimization (Streamlined Design for Efficiency)	**0.96**
31	Full Electric Propulsion Concepts (e.g. dynafin, Superconducting electric motors)	**0.96**
32	Fuel Reforming/Cracking	**0.95**
33	PEM fuel cells	**0.94**
34	WAPSs - Kite Propulsion Systems	**0.91**

Number	Name of EET	Operational Compatibility
35	Post-swirl ESD Contra-rotating propellers (CRP)	**0.87**
36	Post-swirl ESD Grim Vane Wheel	**0.87**
37	WAPSs - Rigid Wing Sails	**0.82**
38	Alternative Fuelled 2-S ICEs (Hydrogen)	**0.79**
39	Alternative Fuelled 4-S ICEs/Gensets (Ammonia)	**0.79**
40	Hydrogen	**0.76**
41	Ammonia	**0.73**
42	SOFC fuel cells	**0.71**
43	WAPSs - Soft Sails	**0.69**
44	Energy storage systems (ESS) – redox flow batteries (RFB)	**0.68**
45	Hydrofoil-Based Wave Energy Converters	**0.64**
46	Heaving Oscillating Systems	**0.64**

Operational and Environmental Performance:

After the assessment of the performance and environmental impact of these technologies by the consortium experts, resulted scores, regarding the relevant technical attribute and the respective **weight factor 0.24/1**, fell between **values 0.0/2.08.** The resulting scores illustrated notable variations in the expected operational benefits among the examined solutions. These differences reflect the degree to which each technology can contribute to improving vessel efficiency and reducing emissions under real-world conditions.

For this factor, several key parameters were considered, including emission savings, energy and/or fuel savings, to develop a complete and representative overview of the performance of each technology. Specifically, while many technologies demonstrate strong potential for emission reductions, in several cases these benefits are accompanied by increased energy demand, which may result in direct higher fuel consumption or greater electrical power requirements. This occurs because certain emission-saving technologies rely on significant energy supply. Therefore, although

the emission savings may be notable, the associated rise in energy or fuel consumption must also be considered when evaluating the net environmental and operational performance of each EET.

In particular, at the top of the ranking one, typically finds technologies that deliver substantial energy savings or propulsion efficiency improvements, such as sustainable and low emission fuels (Hydrogen, Ammonia). Green Hydrogen present a Well to Wake (WtW) performance from 0 to 0.5gCO_{2eq}/gH_2, while ammonia from 0.1 to 0.3 gCO_{2eq}/gNH_3. E-fuels respectively offer near-zero WtW CO2 emissions compared to their fossil equivalents.

Considering the performance of hydrogen-fuelled 4-stroke ICEs compared to other alternative fuelled 4-stroke engines, and assuming the same heat rate, the specific fuel consumption (SFOC) is expected to be significantly lower than that of other alternative fuels, given hydrogen's high heating value of approximately 120 MJ/kg.

The core advantage of ESS -Lithium-ion batteries lies in the combination of high specific energy (around 150 to 250 Wh/kg) and elevated volumetric energy density (≈350–700 Wh/L), significantly surpassing legacy technologies such as lead-acid or nickel-cadmium105. Modern maritime and grid-scale ESS platforms typically employ NMC-based chemistries, valued for their balance of energy density, cycle life, and charge/discharge efficiency. The working principle relies on reversible lithium-ion intercalation between the anode and cathode, enabling high round-trip efficiencies of 90% and fast response times suitable for peak shaving. Furthermore, Li-ion ESS deliver stable and predictable performance, yielding high efficiency across most load profiles and enabling effective smoothing of renewable generation and meaningful reductions in auxiliary engine usage. Their lifetime typically reaches 3000 cycles (approximately 10 years) before major capacity reduction, though degradation and is accelerated at high temperatures, deep cycles, or if operated at elevated C-rates.

OPS delivers substantial environmental and fuel benefits, typically reducing 25–50% of auxiliary fuel consumption for a standard berth call and avoiding 5–15 tons of CO_2 per 8–10 hours, depending on vessel type, hotel load, and shore-side grid mix.

Conversely, technologies positioned at the lower end of the ranking often include solutions that, while promising in theory or under controlled conditions, currently exhibit limited impact on overall vessel performance, are cost and space ineffective or depend heavily on complementary systems to achieve their full potential. Such technologies, (Hydrofoil Energy Based Converters, Wind Assisted Propulsion, Waste Heat Recovery Systems), require further optimization and integration flexibility before their performance benefits can be fully realized. Furthermore, many of the EETs included in Propeller Energy Devices which redirect the flow toward the propeller achieving the necessary wake redirection (i.e. WEDs) or after reducing the rational losses (i.e. Propeller Boss Cap Fins) provide fuel savings from 2 -7% according to literature analysis, however the combination of these EETs with

other type of EETs can provide significant reductions and benefits to fuel consumption and respectively to exhaust gas emissions.

Table 7: Final Scoring of EETs for Operational and Environmental Performance

Number	Name of EET	Operational and Environmental Performance
1	Hydrogen	**2.08**
2	Synthetic e-fuels	**1.98**
3	Alternative Fuelled 4-S ICEs/Gensets (Hydrogen)	**1.96**
4	Ammonia	**1.96**
5	Alternative Fuelled 2-S ICEs (Hydrogen)	**1.92**
6	Alternative Fuelled 2-S ICEs (Ammonia)	**1.80**
7	Onshore Power Supply [OPS]	**1.78**
8	Shaft Generator PTI, PTO, PTI/PTO	**1.78**
9	Energy storage systems (ESS) – lithium-ion batteries	**1.76**
10	PEM fuel cells	**1.72**
11	Methanol	**1.72**
12	Hull Form Optimization (Streamlined Design for Efficiency)	**1.68**
13	Variation of block coefficient/lengthening (Inland)	**1.68**
14	Alternative Fuelled 4-S ICEs/Gensets (Ammonia)	**1.68**
15	Post-swirl ESD Contra-rotating propellers (CRP)	**1.68**
16	Biomethane	**1.68**
17	SOFC fuel cells	**1.65**

Number	Name of EET	Operational and Environmental Performance
18	Onboard Carbon Capture and Storage (CCS) Systems	**1.63**
19	Bulbous Bow Optimization	**1.63**
20	Propeller-Retrofitting Advanced propeller Blade Sections (e.g. Winglets/kappel)	**1.62**
21	WAPSs - Flettner Rotors (Magnus Effect Rotors)	**1.60**
22	WAPSs - Suction Wings (Ventifoils)	**1.59**
23	Hull Openings and Skeg Shape Optimization	**1.52**
24	Alternative Fuelled 2-S ICEs (Methanol)	**1.52**
25	Alternative Fuelled 4-S ICEs/Gensets (Methanol)	**1.52**
26	Alternative Fuelled 4-S ICEs/ Gensets (Biofuels)	**1.52**
27	Propeller Nozzle (e.g. Kort)	**1.50**
28	WAPSs - Rigid Wing Sails	**1.48**
29	Air lubrication systems (ALS)	**1.44**
30	DC Grid technologies	**1.44**
31	Fuel Reforming/Cracking	**1.44**
32	Waste heat recovery systems (WHRS)	**1.39**
33	Energy storage systems (ESS) – redox flow batteries (RFB)	**1.38**
34	Full Electric Propulsion Concepts (e.g. dynafin, Superconducting electric motors)	**1.32**
35	Manoeuvring devices (e.g. Gate rudder)	**1.32**
36	Pre-swirl ESD Wake Equalizing Ducts (WEDs)	**1.30**

Number	Name of EET	Operational and Environmental Performance
37	Post-swirl ESD Grim Vane Wheel	**1.26**
38	WAPSs - Soft Sails	**1.20**
39	WAPSs - Kite Propulsion Systems	**1.20**
40	Pre-swirl ESD Fins	**1.15**
41	Advanced HVAC & cooling systems	**1.08**
42	SOLAR - Photovoltaic (PV) Panels for Ships	**1.06**
43	Steam/heat plant improvements/optimization	**1.02**
44	Hydrofoil-Based Wave Energy Converters	**0.96**
45	Post-swirl ESD PBCF (Propeller Boss Cap Fins)	**0.91**
46	Heaving Oscillating Systems	**0.90**