D5.4 Handbook for Implementation of Greening Retrofit Solutions

Synergetics | Synergies for Green Transformation of Inland and Coastal Shipping

GRANT AGREEMENT NO.	101096809
DURATION OF THE PROJECT	42 months
DELIVERABLE NUMBER	D5.4
DISSEMINATION LEVEL	Public
DELIVERABLE LEADER	SPB
STATUS	FINAL
SUBMISSION DATE	28-05-2026
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DOI	10.5281/zenodo.20431571

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List of abbreviations

ADA	Alternative Design Approval
ADN	European Agreement concerning the International Carriage of Dangerous goods by Inland Waterways
AFIR	Alternative Fuels Infrastructure Regulation
CCC	IMO Sub-Committee on Carriage of Cargoes and Containers
CCNR	Central Commission for Navigation on the Rhine
CCS	Carbon Capture and Storage
CII	Carbon Intensity Indicator
DOC	Diesel Oxidation Catalyst
DP	Dynamic Positioning
DPF	Diesel Particulates Filter
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EMSA	European Maritime Safety Agency
ENI	European Number of Identification
ES-TRIN	European Standard laying down Technical Requirements for Inland Navigation Vessels
EU	European Union
EU-ETS	European Union Emission Trading System
FAME	Fatty Acid Methyl Ester
FC	Fuel Cell
GEME	Group of Experts on Marinised Engines
GT	Gross Tonnage
HAZID	Hazard Identification (dangers and risks study in design phase of vessel)
HAZOP	Hazard and Operability (study in relation to safety risks in operational processes)
HVAC	Heating, Ventilation and Air Conditioning
HVO	Hydrotreated Vegetable Oil
IBC Code	International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk
ICE	Internal Combustion Engine
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquified Gases

IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
IMO	International Maritime Organisation
IPCC	United Nations Intergovernmental Panel on Climate Change
IWT	Inland Waterway Transport
LNG	Liquified Natural Gas
MARPOL	International Convention for preventing pollution from ships
MDO	Marine Diesel Oil
MEPC	IMO Marine Environment Protection Committee
MGO	Marine Gas Oil
MRV	Monitoring, Regulation and Verification
NECA	Nitrogen Emission Control Areas
NRMM	Non-Road Mobile Machinery
OEM	Original Equipment Manufacturer
OPS	On-shore Power Supply
OSV	Offshore Supply Vessel
PM	Particulate Matter
PV	Photovoltaics
RFNBO	Renewable Fuels of Non-Biological Origin
RVIR	Rhine Vessel Inspection Regulations
SECA	Sulphur Emission Control Area
SEEMP	Ship Energy Efficiency Management Plan
SOLAS	International Convention for the Safety of Life at Sea
SCR	Selective Catalytic Reduction
TRL	Technology Readiness Level
TTW	Tank-To-Wake
ULEV	Ultra Low Emission Vessel
ULSFO	Ultra Low Sulphur Fuel Oil (maximum sulphur content <0.10 %) for ECA
UN	United Nations
VLSFO	Very Low Sulphur Fuel Oil (maximum sulphur content <0.5 %) outside ECA
WASP	Wind-Assisted Propulsion System
WTT	Well-To-Tank
WTW	Well-To-Wake

Release Approval

1 | Release Approval

Name	Role	REMARKS
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Executive Summary

This Handbook (SYNERGETICS Deliverable D5.4, Work Package 5 – Acceleration) helps owners and operators of inland waterway and coastal vessels choose practical, retrofit-ready ways to reduce emissions. It translates the technical, regulatory and economic findings of SYNERGETICS into guidance that can be applied to existing vessels today.

Its aim is to bridge research and day-to-day decision-making. For each shortlisted retrofit option – alternative fuels, battery-electric propulsion, hybrid concepts and energy-efficiency measures – the Handbook sets out applicability, the regulatory pathway, operational constraints and economic feasibility. Together these allow retrofit choices to be matched to the rules that apply and to the way the vessel is actually operated.

Inland and coastal vessels are treated separately throughout. They sit under different legal frameworks (CCNR/CESNI and the EU NRMM Regulation for IWT; IMO/MARPOL/SOLAS and EU instruments for coastal), face different safety and certification regimes, and differ in autonomy, fuel availability and onboard space. Each chapter is therefore structured around this IWT/coastal split.

The scope matches the SYNERGETICS technology catalogue (WP4) and the Decision Support Tool developed in Task 5.1. The Tool produces a vessel-specific shortlist of economically attractive greening solutions from a few user inputs; the Handbook provides the technical, regulatory and operational depth behind that shortlist. It can be read stand-alone but is primarily designed as the follow-up reference after using the Tool.

The Handbook covers retrofits of existing vessels only and limits itself to technologies whose technology readiness level (TRL) is high enough for near-term deployment or full-scale demonstration. Most of these measures are still voluntary today, but will become increasingly difficult to avoid as EU, IMO and national emission rules tighten.

A wide range of greening retrofit solutions is addressed, including:

- Engine renewal to modern emission standards (NRMM Stage V for IWT, IMO Tier III and ULEV concepts for coastal vessels);
- Exhaust after-treatment solutions such as SCR and DPF systems;
- Renewable and low-carbon drop-in fuels, notably HVO, with discussion of future e-diesel pathways;
- Full and hybrid battery-electric propulsion concepts, including fixed and swappable battery systems;
- Methanol solutions (single-fuel ICE, dual-fuel ICE, and methanol fuel cells);
- Hydrogen solutions (combustion engines and fuel cells, with fixed or swappable storage);
- Methane solutions, including LNG and Bio-LNG;
- Energy-efficiency measures, such as solar panels and hydrodynamic improvements.

To reflect the strong diversity of the European fleet, the Handbook applies the concept of “fleet families”. This approach groups vessels with similar characteristics and operational constraints, enabling more targeted guidance. For IWT vessels, fleet families follow established classifications developed by CCNR-related studies, while for coastal shipping SYNERGETICS provides one of the first structured classification approaches.

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Each technology chapter contains a dedicated regulatory assessment. For inland navigation, this means the interaction of ES-TRIN, the ADN, and the NRMM Regulation, including the derogation routes used for innovative fuels such as methanol and hydrogen. For coastal vessels, this means the layered framework of IMO instruments (MARPOL, SOLAS, IGF Code), EU instruments (MRV, EU-ETS, FuelEU Maritime), and flag-state requirements. Approval pathways, safety-assessment processes and the consequences for certification are described where relevant.

No single solution fits every vessel. In short: HVO is the easiest drop-in for much of the existing fleet; battery-electric is best where routes are short, fixed and have predictable port calls (ferries, certain inland container ships); methanol and hydrogen offer long-term decarbonisation but at higher CAPEX, with extra safety measures and more complex approvals; LNG is a short-term transitional fuel, while Bio-LNG remains relevant in the medium and long term, especially for high-energy-demand vessels with room for cryogenic tanks.

Energy efficiency is considered as an enabler for every other pathway. Hydrodynamic optimisation, propulsor upgrades and aftship replacement reduce energy demand, which in turn cuts operating cost and downsizes the alternative-fuel or energy-storage system needed. Efficiency is therefore presented as a synergetic measure for cost-effective decarbonisation.

The main aim of SYNERGETICS is to achieve emission reductions. The technologies and solution presented in the Handbook have different impacts on emissions. The Handbook shows that emission savings vary strongly by technology and by vessel type, and that the biggest gains are achieved when the technology matches the vessel’s route, power demand and available infrastructure.

- HVO is the most accessible short-term option for the existing fleet, because it can be used as a drop-in fuel and can deliver substantial GHG savings, especially when based on waste or renewable feedstocks.
- Stage V engine renewal and SCR/DPF retrofits deliver the strongest reductions in air pollutants, especially NOx and PM, but bring only small CO2 savings unless combined with renewable fuels.
- Battery-electric propulsion can provide the highest operational emission savings, including zero tailpipe emissions, particularly for ferries and vessels on short, fixed routes with reliable charging.
- Methanol offers a promising pathway for decarbonisation, especially in dual-fuel applications for tankers, cargo vessels and ferries; its emission benefit depends strongly on the type of methanol used, with green methanol offering major GHG reduction potential while grey methanol provides only limited improvement over diesel.
- Hydrogen, especially in fuel-cell systems, has the potential for near-zero or zero tailpipe emissions and very strong long-term decarbonisation, but today it is constrained by very high CAPEX, fuel cost, storage volume, safety requirements and limited bunkering infrastructure.
- LNG reduces NOx, SOx and PM and can lower CO2 somewhat, but methane slip limits its long-term climate benefit, while Bio-LNG performs better in lifecycle GHG terms.
- Finally, energy-efficiency measures such as hydrodynamic optimisation, propulsor upgrades and solar panels reduce overall energy demand and therefore strengthen the emission savings of every propulsion pathway.

Decision matrix

The table on the next page summarises which retrofit options fit which vessel category, with indicative TRL (Technology Readiness Level), CAPEX and OPEX positioning. It is intended as a quick scan for vessel owners; the detailed reasoning per technology is given in the relevant chapter.

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2 | Decision matrix

Technology	IWT fit	Coastal fit	TRL	CAPEX	OPEX
HVO (drop-in fuel)	All vessel types	All vessel types	9	Very low	High (fuel cost)
Stage V engine renewal / SCR+DPF	Most types (not unregulated)	Most types (Tier III)	9	Medium	Low
Battery-electric, fixed	Ferries, day-trip, short-route cargo	Short-route ferries	8-9	Very high	Low (shore power)
Battery-electric, swappable	Container vessels with terminal access	Limited	8	Low (rental)	Medium (lease fees)
Diesel-electric / hybrid	Variable-load vessels	OSV, ferries	9	High	Medium
Methanol ICE dual-fuel	Tankers, container	Cargo, ferries	7-8	High	Medium-high
Methanol fuel cell	Niche	Niche	6-7	Very high	High
Hydrogen ICE	Niche, short routes	Niche	6-7	Very high	Very high (fuel)
Hydrogen fuel cell	Fixed routes, short autonomy	Short ferries	7-8	Very high	Very high
LNG (fossil)	Large fuel consumers	Ferries, OSV, dry cargo	9	Medium-high	Volatile gas price
Bio-LNG	Same as LNG	Same as LNG	8-9	Medium-high	Higher than fossil LNG
Solar panels (mainly aux. power)	Limited (hatch covers)	Coastal vessels with deck space	9	Low	Negligible
Hydrodynamic / aftship repl.	All types (esp. cargo)	Limited	9	Medium-high	Lower (saves fuel)

CAPEX / OPEX scale (indicative order of magnitude per retrofit): Very low = <€50k; Low = €50k-€250k; Medium = €250k-€1M; High = €1M-€3M; Very high = >€3M. Actual figures depend strongly on vessel size, retrofit scope and local market conditions.

Approval pathway summary: HVO, Stage V renewal, SCR/DPF, LNG, solar and hydrodynamic measures follow standard certification (NRMM type-approval, ES-TRIN, IGF Code). Methanol and hydrogen require a derogation procedure under NRMM Articles 34/35 (IWT, see section 5.1.1) or an Alternative Design Approval process under SOLAS (coastal, see sections 5.1.2 / 6.1.2).

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Indicative cost and approval comparison

A pooled view of the CAPEX/OPEX indications and approval-route complexity across the technology chapters. Figures are indicative and intended for scoping; vessel-specific cost calculations should rely on the DST output and supplier quotes.

3 | Indicative cost and approval comparison

Technology	CAPEX indication	OPEX impact	Approval complexity
HVO drop-in	Negligible additional	Higher fuel cost (~50 - 100 %)	None additional
Stage V engine + SCR/DPF	Medium	Lower fuel cost vs older engine	NRMM type approval
Battery-electric, fixed	Very high (battery + shore infra)	Lower with shore power	Standard ES-TRIN
Battery-electric, swappable	Low (rental)	Includes lease fees	Standard ES-TRIN
Diesel-electric / hybrid	High (powertrain change)	Medium (depends on duty cycle)	Stage V cert. for gensets
Methanol ICE single-fuel	High	Methanol price dependent	Derogation (IWT, Art. 34/35)
Methanol ICE dual-fuel	High	Mixed fuel cost	Derogation (IWT)
Methanol fuel cell	Very high (FC + battery)	Needs high-purity methanol	Derogation (IWT)
Hydrogen ICE	Very high	High fuel cost	Derogation (IWT)
Hydrogen fuel cell	Very high (FC + battery + storage)	Very high fuel cost	Derogation (IWT)
LNG	Medium-high (cryogenic tank)	Volatile gas price	In ES-TRIN / IGF Code
Bio-LNG	Same as LNG	Higher than fossil LNG	Same as LNG
Solar panels (mainly aux. power)	Low	Saves fuel	Standard
Hydrodynamic / aftship repl.	Medium-high (aftship replacement)	Reduces fuel cost	ES-TRIN re-inspection

Approval complexity: "None additional" = no new approval needed beyond existing certificate; "Type approval" = standard NRMM procedure; "Standard ES-TRIN" / "Standard / IGF" = covered by existing technical framework; "Derogation" = NRMM Article 34/35 (IWT) or Alternative Design Approval (coastal) – significantly longer and more involved.

1. Introduction

1.1 Background

SYNERGETICS Work Package 5 ("Acceleration") brings the project results together in tools, scenarios, guidance reports and this Handbook. Task 5.4 specifically delivers the *Handbook for Implementation of Greening Retrofit Solutions*. Its purpose is to help individual vessel owners and operators take concrete measures to reduce emissions on their vessels. Because IWT and coastal vessels operate under different legal frameworks and operational requirements (e.g. required autonomy), the Handbook treats them separately and translates the project outcomes into guidance that is usable in real operational settings.

The retrofit landscape has become genuinely hard to navigate. The Handbook's aim is to give vessel owners structured, neutral support: SYNERGETICS solutions are presented alongside other available propulsion and emission-reduction technologies so that owners can compare options on equal footing. The Handbook is a companion to the web-based Decision Support Tool (see https://www.synergetics-project.eu/dstool/), developed in Task 5.1. The tool asks for a few vessel-specific inputs and the owner's emission-reduction target, then returns a shortlist of the most economically attractive technical options for that vessel. The Handbook can be read on its own, but its primary role is to provide the technical and regulatory depth behind that shortlist.

In short, the Handbook is intended to help owners and operators choose the retrofit strategy that best matches their vessel type, operational pattern, technical constraints, regulatory environment and budget – and then to follow that strategy through to a workable, compliant outcome.

1.2 Scope and structure of Handbook

Task 5.4 inherits its scope from the WP4 catalogue and the Decision Support Tool (Task 5.1): a curated set of retrofit options for greening the existing fleet. The reference engines and the resulting solution space are summarised below before being detailed in the following chapters.

For the IWT application the reference diesel internal combustion engines are the following, while using only low sulphur gasoil (max 10 ppm / 0.001 %) according to the EN590 specification:

- Unregulated diesel engine (build before year 2003)
- CCNR1 diesel engine (2003-2007)
- NRMM Stage 3A / CCNR2 diesel engine (2008-2019 and partly transition period)
- NRMM Stage V diesel engine (>2021)

For coastal vessels the reference internal combustion engines and fuel types are the following:

- IMO Tier II engine using Ultra Low Sulphur Fuel Oil (ULSFO) (max 0.1 % sulphur contents)
- IMO Tier II engine using Very Low Sulphur Fuel Oil (VLSFO) (max. 0.5 % sulphur contents)
- IMO Tier III engine using ULSFO
- IMO Tier III engine using VLSFO

For coastal vessels IMO Tier I engines also exist, which were the first maritime engine group with NOx emission limits. In the current regulations existing engines installed before 2000 are still allowed to perform at IMO Tier I NOx emission levels. However, based on experts from SYNERGETICS it was found that these old engines are hardly used anymore. As a result, they are not included in the scope of SYNERGETICS. The reason that only low sulphur containing fuels are included in the scope of SYNERGETICS is because the assumption was made that the vessel that fall in the scope generally do not contain scrubbers, meaning they are obligated to use low sulphur containing fuels. The two low sulphur fuel types that where found the most relevant for this application are ULSFO and VLSFO.

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The selection of greening solutions used in the Decision Support Tool are technologies that either already exist on the market or have sufficiently high TRL to be used for full-scale demonstration projects on the short term. Many of them are not imposed by authorities but shall be seen as voluntary options, especially in the context of retrofitting existing vessels and engines.

The distinguished solutions and energy types to reduce emissions of existing vessels are the following:

- Engine renewal (retrofit) to Stage V engine (for IWT)
- Engine renewal (retrofit) to Tier III engines (for coastal)
- Engine renewal (retrofit) to Stage V/ ULEV (Ultra-low emission vessels) (for coastal)
- SCR (Selective Catalytic Reduction) after-treatment system for engines (for coastal)
- DPF (Diesel Particulates Filter) and SCR after-treatment for engines
- HVO as drop-in fuel: renewable diesel which can be replaced by e-diesel on longer term
- Methanol Dual-Fuel combustion engines, fixed tanks, both grey and green methanol
- Methanol Single-Fuel combustion engines, fixed tanks, both grey and green methanol
- Hydrogen combustion engines, Dual-Fuel and Single-Fuel, swappable or fixed containers, both grey and green hydrogen
- Hydrogen fuel cell, swappable or fixed containers, both grey and green hydrogen
- Full battery electric propulsion with a choice between swappable pay-per-use batteries or fixed battery packs with charging from shore
- Liquid Natural Gas (LNG), both grey and Bio-Methane (Bio-LNG)
- Solar panels
- Methanol Fuel Cell, fixed tanks, both grey and green methanol

In both the coastal and IWT sector many different vessel types exist, and hardly any ship is the same as another ship. Therefore, the concept of ‘fleet families’ was introduced to be able to classify vessels into a category and to provide remarks, assessments and guidance on next steps for application of solutions for particular fleet family. For example, taking into account the applicable legislation and amount of space on board which differs between vessel types.

Examples for IWT are the ADN regulation in case of transporting dangerous goods which is relevant for tanker vessels but not for vessels carrying dry bulk cargo. Also, for passenger vessels there are specific legislations and limitations to be taken into account because of safety requirements. Moreover, on push boats for example, the available room on board to accommodate engines and energy storage is generally quite limited which reduces the options to be considered to achieve emission reduction.

For coastal vessels there are legislative differences for vessels in different weight categories. For example, the MRV regulation is relevant for vessels above 400 GT but the FuelEU Maritime and the EU-ETS regulations only apply for cargo and passenger vessels above 5000 GT. Fishing vessels on the other hand have different flag state legislation. Fishing vessels are not allowed to fish anywhere and a maximum amount of fish is limited, which on its turn depends on the type and size of fishing vessel. Finally, passenger transport vessels (ferries) also have specific legislative requirements.

The distinguished fleet families for the IWT sector in SYNGERGETICS follow those outlined in the CCNR study[1] which was slightly modified based on the EU-funded project PROMINENT[2]. They are the following:

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[1] the Central Commission for the Navigation of the Rhine (CCNR), 2021. STUDY ON FINANCING THE ENERGY TRANSITION TOWARDS A ZERO-EMISSION EUROPEAN IWT SECTOR, Strasbourg: the Central Commission for the Navigation of the Rhine (CCNR).

[2] EU Horizon2020 project executed May 2015 – April 2018 dedicated to greening the IWT fleet with 6.25 mln euro budget, see the website of PROMINENT for more information: https://www.prominent-iwt.eu/

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- Large cabin vessels: a passenger vessel longer than 86 m and with overnight passenger cabins.
- Push boats (P < 500 kW): a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of less than 500 kW.
- Push boats (500 ≤ P < 2000 kW): a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of more than 500 kW but less than 2000 kW.
- Push boats (P > 2000 kW): a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of more than 2000 kW.
- Motor vessels dry cargo (L ≥ 110 m): a vessel equal to or longer than 110 m, intended for the carriage of dry goods and containers and built to navigate independently under its own motive power.
- Motor vessels liquid cargo (L ≥ 110 m): a vessel equal to or longer than 110 m, intended for the carriage of goods in fixed tanks and built to navigate independently under its own motive power.
- Motor vessels dry cargo (80 m ≤ L < 110 m): a vessel with length between 80 and 109 m, intended for the carriage of dry goods and built to navigate independently under its own motive power.
- Motor vessels liquid cargo (80 m ≤ L < 110 m): a vessel with length between 80 and 109 m, intended for the carriage of goods in fixed tanks and built to navigate independently under its own motive power.
- Motor vessels (L < 80 m): a vessel shorter than 80 m and longer than 19 metres, intended for the carriage of all type of goods and built to navigate independently under its own motive power.
- Coupled convoys: a motor vessel (generally longer than 95 m) intended to be operated with one or several lighters.
- Ferries: a vessel providing a service crossing the waterway.
- Day trip and small cabin vessels: a passenger vessel for day-trip operation as well as a passenger vessel with overnight passenger cabins but shorter than 86 m.

For the coastal vessel sector there was, however, no such knowledge base from previous studies or projects. Another complexity is that there is no exact global or European definition of a ‘coastal vessel’. In some cases, flag state administrations even have their own definitions of coastal vessels. Therefore, no fleet families were mapped and identified yet for the coastal shipping sector before the SYNERGETICS project started. Significant groundwork was done in SYNERGETICS to try to fill this knowledge gap.

In the exploration work package of SYNERGETICS (WP1) research has been done to define the coastal vessel sector, which now led to a definition of fleet families for the coastal vessel sector in the published Sustainability (Journal) paper by SYNERGETICS[3].

The defined fleet families currently in SYNERGETICS are:

- Dry cargo vessels up to 79.99 m
- Dry cargo vessels between 80 to 89.99 m
- Dry cargo vessels between 90 to 99.99 m
- Dry cargo vessels over 100 m and <5000 GT
- Ferries with an installed power between 0-999 kW
- Ferries with an installed power between 1000-1999 kW
- Ferries with an installed power between 2000-2999 kW
- Ferries with an installed power between 3000-3999 kW

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[3] See: Greening of Inland and Coastal Ships in Europe by Means of Retrofitting: State of the Art and Scenarios and Replacing Fossil Diesel for All European Inland Waterway Transport: A Prospective Pathway Analysis on Remaining Emissions and Costs | Springer Nature Link

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- Ferries with an installed power between 4000-8000 kW
- Ferries with an installed power above 8000 kW
- Ferries High Speed Ferries
- OSVs weighing <2000 GT
- OSVs weighing between 2000-3000 GT
- OSVs weighing between 3000-4000 GT
- OSVs weighing over 4000+ GT
- Fishing vessels of the type VL0012
- Fishing vessels of the type VL1224
- Fishing vessels of the type VL2440
- Fishing vessels of the type VL40XX

1.3 Decision Support Tool integration

Although the Handbook can be read on its own, its main intended use is as the follow-up reference after using the Decision Support Tool (see https://www.synergetics-project.eu/dstool/).

To make this link tangible, condensed per-technology factsheets are prepared and attached to the tool results in Part 1: a vessel owner who receives a shortlist also receives the relevant pages of the Handbook for the top three solutions. The full deliverable is integrated in the tool's document section.

An additional lightweight HTML widget is planned for the tool: a vessel owner selects vessel type, technology, exploitation method and daily sailing time, and the relevant Handbook scenarios appear directly — without forcing the reader to navigate the full PDF.

1.4 About this deliverable

This deliverable D5.4 contains the guidance itself. Chapter 2 sets the regulatory frame for green propulsion (greenhouse-gas and air-pollutant emission reduction), with separate IWT and coastal subsections because the legal regimes diverge. Chapters 3 to 8 then cover the individual technology pathways — diesel-engine renewal and after-treatment (Ch. 3), battery-electric (Ch. 4), methanol (Ch. 5), hydrogen (Ch. 6), methane/LNG (Ch. 7) and energy-efficiency measures (Ch. 8). Every technology chapter contains its own regulatory subsection followed by vessel-type-specific guidance for IWT and coastal vessels, plus implemented or near-market example cases.

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2. Regulatory framework for green propulsion solutions[4]

2.1 Inland waterway transport

Three EU instruments together form the binding framework for the use of (alternative) fuels and propulsion technologies on inland waterways, and for the carriage of these fuels as cargo:

1) Directive laying down technical requirements for inland navigation vessels, Directive [5] (EU) 2016/1629, complemented by the Central Commission for the Navigation of the Rhine (CCNR) Rhine Vessel Inspection Regulations (RVIR)[6].

2) Directive on the inland transport of dangerous goods, 2008/68/EC[7] and European Agreement concerning the International Carriage of Dangerous goods by Inland Waterways (ADN).

3) Regulation on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery", Regulation (EU) 2016/1628 (NRMM Regulation)[8].

2.1.1 ES-TRIN

Regarding the technical requirements of vessels, vessels operating on European Union (EU) waterways or on the Rhine must carry either a Union Inland Navigation Certificate or Rhine Vessel Inspection Certificate or a national certificate. The required certificate depends on the area of sailing. According to Article 7 (b) of Directive (EU) 2016/1629 the Rhine certificate is valid on the Rhine (Zone R) waterways, but it is also recognised on the Zone 3 and 4 EU waterways. The Union certificate is valid in every EU inland waterway, except for the case where there is no Zone R approval included in the certificate. In this case the Union certificate is not valid for sailing on the Rhine and its descendants. Accordingly, vessel owners that want to sail everywhere in the EU need to have an approval on their certificate from both the Rhine and Union authorities. For local (domestic) transport also national certification can be sufficient.

Both certificates confirm the full compliance of the vessel with their corresponding technical requirements, so when complying with the European Standard laying down Technical Requirements for Inland Navigation Vessels (ES-TRIN)[9] the vessel will comply to all the relevant requirements on every EU river. In case a certain technology is not yet included in the ES-TRIN, a derogation process needs to be initiated. If it is expected that similar technology derogations are requested more frequently, it could lead to a provision of the technical requirements to include the technology or energy carrier in the general technical regulations. This avoids having to go through a derogation procedure. The most recent version, ES-TRIN 2025/1, entered into force on the 1st of January 2026. ES-TRIN 2025 explicitly expands and consolidates rules for fuels with a low flashpoint such as methanol. ES-TRIN 2025 and is

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[4] SYNERGETICS - D4.6

[5] Directive (EU) 2016/1629, http://data.europa.eu/eli/dir/2016/1629/2024-01-01

[6] Rhine Vessel Inspection Regulation (Rheinschiffsuntersuchungsordnung, 01.12.2024), https://www.ccr-zkr.org/13020500-en.html

[7] Directive 2008/68/EC on the inland transport of dangerous goods, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0068-20250213

[8] Regulation (EU) 2016/1628 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02016R1628-20220717

[9] ES-TRIN, various editions, https://www.cesni.eu/en/standards-and-explanatory-notices/#01

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planned to be followed by the updated version ES-TRIN 2027/1, which will enter into force on the 1st of January 2028. For example, the use of hydrogen fuel-cell propulsion systems is expected to be covered by ES-TRIN 2027/1.

2.1.2 ADN

The ADN regulation strengthens the technical requirements, since it includes all the necessary safety precautions for the transportation of dangerous goods. For alternative fuels this effects the safety compliance level of the vessel in two different ways. On the first hand some alternative fuels are denoted as ADN grated substances, like methanol, hydrogen, and ammonia for example, due to which safety regulations are increased compared to using diesel. This leads to specific fire and ventilation measures, stricter electrical system safety requirements, specialised materials for the containment and on-board transport of the substance, and if applicable extra explosion safety measures. On the other hand, if a vessel is already ADN compliant, it needs to be taken into account during the derogation process that not every alternative fuel is suitable. Propulsion systems like battery electric, for example, form a hazard when transporting ADN freight. This can lead to complications in the derogation process due to safety concerns or lead to very high investment costs.

The ADN regulation only applies when any type of ADN freight is on board during transport. This means that it will not be relevant in all scenarios and it does not have the same effect on every vessel that had to comply with the ADN. Therefore, the ADN regulation can be a limiting factor for the use of certain alternative fuels, but it will be case-by-case specific in which way, depending whether or not the vessel is planned to transport ADN freight. This concerns mostly tanker vessels and vessels that transport containers with dangerous goods in scope of ADN regulations.

2.1.3 NRMM regulation

As of yet, most vessels in inland navigation rely on diesel propulsion. In an effort to reduce the exhaust emissions the EU developed the NRMM regulation, which regulates exhaust emissions for newly installed engines after 2016. Internal combustion engines (ICE) with a power above 19 kW intended for use in inland navigation may only be placed on the EU market and installed on inland navigation vessels if they are type-approved. Requirements for type-approval includes, amongst other elements, compliance with emission limits for several gaseous and particulate exhaust gas components and long-term emission performance characteristics using precisely defined reference fuels. Other than the NRMM, the EU currently lacks specific, enforceable standards for emissions reductions pathways in inland navigation and mainly relies on voluntarily incentives and directives. Future policy that is currently under development, however, is shifting towards the focus on mandatory emission reduction regulations.

In the NRMM regulation it is denoted in Article 25(2) which fuels are approved by the EU to be used in an ICE. Currently the following six types of reference fuels are listed in this article:

- Diesel
- Petrol
- Petrol/oil mixture (for two stroke spark-ignition engines)
- Natural gas/Bio methane
- Liquid petroleum gas (LPG)
- Ethanol

Alternative fuels such as methanol, hydrogen, or ammonia are not yet contained in the list of permitted reference fuels. Hence, type-approval cannot be granted for engines using these fuels. Due to this a derogation process is required for these types of fuels.

Article 34(4) of the NRMM regulation (in combination with Annex XI of the Delegated Regulation (EU) 2017/654 [6]) allows engines without type approval to be placed on the market temporarily for up to 24 months with the possibility to extent this with another 24 months for field testing purposes. The conditions for this field-testing exemption are quite stringent, with one of the requirements being that the engine in question will be under the ownership of the original engine manufacturer (OEM) over the

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entire field-testing period. This may collide with national requirements of the Member States regarding ownership of an inland navigation vessel and its equipment (cf. e.g. IVR Paper on Emission Legislation4, May 2025, p. 36 ff; Commission Delegated Regulation (EU) 2017/654 (Annex XI (1))).

Article 35 of the NRMM regulation provides the derogation framework for exemptions for new technologies or new concepts, addressing in particular technologies or concepts that do not meet all the requirements of the Regulation, like for example engines using fuels that are not included in the list of reference fuels in accordance with Article 25(2). Article 35, therefore, opens a pathway to apply for a type-approval certificate for engines falling into its scope. The EU type-approval certificate for new technologies or new concepts will be granted by the European Commission. During the decision-making process of the European Commission on the EU type-approval, Member States are allowed to provide a provisional EU type-approval. This provisional type-approval will only be valid in the territory of that Member State. This type of approval is valid for at least 36 months (cf. Article 35(4)).

Approval authorities of other EU Member States may decide to accept a provisional EU type-approval certificate within their territories (Article 35(5)). These provisions of the NRMM regulation could therefore in principle be applied to tests as well as pilot installations using engines that run on alternative fuels such as methanol or hydrogen on board inland navigation vessels.

2.2 Coastal vessels

For coastal vessels the legal landscape is significantly more layered than for IWT. Because coastal vessels can sail in international waters, they also fall under the International Maritime Organisation (IMO, part of the UN). The binding framework for propulsion fuels, propulsion technologies and fuel-as-cargo on coastal/maritime navigation therefore combines IMO instruments, EU legislation and flag-state administrative requirements:

1. International Maritime Organisation (IMO), where the following regulations are of relevance:
    - International Convention for the Safety of Life at Sea (SOLAS)[10]
    - International Convention for preventing pollution from ships (MARPOL)[11]
    - International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code)[12]
    - International Code for the Construction and Equipment of Ships Carrying Liquified Gases (IGC Code)[13]
    - International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC Code)[14]
2. European Union (EU) legislative instruments
3. Flag state administrative requirements

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[10] International Maritime Organisation (IMO), International Convention for the Safety of Life at Sea (SOLAS), Consolidated edition 2020. London: IMO

[11] International Maritime Organization. (1973/1978). International Convention for the Prevention of Pollution from Ships (MARPOL). London: IMO

[12] International Maritime Organization. (2014). International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code). London: IMO

[13] International Maritime Organization. (1983). International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). London: IMO

[14] International Maritime Organization. (1983). International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC Code). London: IMO

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2.2.1 IMO / MARPOL

Regarding emissions, the IMO MARPOL Annex VI - Prevention of Air Pollution from Ships lays down the global standards to which all the coastal vessels have to comply. MARPOL includes, amongst others elements, the emission reduction target timeline and it defines the Emission Control Areas (ECAs) for GHG, Sulphur Oxides (SOx) and Nitrogen Oxides (NOx) emissions, where the latter two are referred to as the SECAs and the NECAs. Within these areas emissions are restricted and access will be denied if the vessel does not comply with these requirements.

In order to reduce shipping's impact on climate change, IMO has started in the early 2000s to consider technical and operational measures to improve the energy efficiency of ships. In 2011, IMO adopted amendments to MARPOL Annex VI to mandate technical and operational energy efficiency measures to reduce the amount of CO2 emissions from international shipping. The Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) entered into force on 1 January 2013. The EEDI is an important technical measure aiming at promoting the use of more energy efficient designs, equipment and engines for new ships in order to make them less polluting. The EEDI provides a specific figure for an individual ship design, expressed in grams of carbon dioxide (CO2) per ship's capacity-mile (the smaller the EEDI, the more energy efficient the ship design) and is calculated by a formula based on the technical design parameters for a given ship. In 2014, MEPC adopted amendments to the EEDI regulations to extend the scope of EEDI to: LNG carriers, ro-ro (roll-on roll-off) cargo ships; ferries and cruise passenger ships. These amendments mean that ship types responsible for approximately 85 % of the CO2 emissions from international shipping are incorporated under the international regulatory regime. EEDI applies for ships of 400 GT and above engaged in international voyages.

The Ship Energy Efficiency Management Plan (SEEMP) is an operational mechanism to improve the energy efficiency of a ship in a cost-efficient manner. The SEEMP urges the ship owner and operator at each stage of the plan to consider new technologies and practices when seeking to optimise the operational performance of a ship. The SEEMP also provides an approach for shipping companies to manage ship and fleet efficiency performance over time using recognised monitoring tools. The 2022 guidelines for the development of the SEEMP incorporates best practices for fuel efficient ship operation as well as templates for the development of SEEMPs, which should comprise three parts: Part I: Ship management plan to improve energy efficiency, Part II: Ship fuel oil consumption data collection plan and Part III: Ship operational carbon intensity plan.

From 1 January 2023 it became mandatory for all ships to calculate their attained Energy Efficiency Existing Ship Index (EEXI) to measure their energy efficiency and to initiate the collection of data for the reporting of their annual operational carbon intensity indicator (CII) and CII rating. As a stimulus to reduce carbon intensity of all ships by 40 % by 2030 compared to 2008 baseline, ships are required to calculate two ratings. Carbon intensity links the GHG emissions to the amount of cargo carried over distance travelled. A ship's attained EEXI indicates its energy efficiency compared to a baseline. The attained EEXI will then be compared to a required Energy Efficiency Existing Ship Index based on an applicable reduction factor expressed as a percentage relative to the Energy Efficiency Design Index (EEDI) baseline. It must be calculated for ships of 400 GT and above, in accordance with the different values set for ship types and size categories. The calculated attained EEXI value for each individual ship must be below the required EEXI, to ensure the ship meets a minimum energy efficiency standard.

The CII applies to ships above 5000 GT and determines the annual reduction factor needed to ensure continuous improvement of a ship's operational carbon intensity within a specific rating level. The actual annual operational CII achieved must be documented and verified against the required annual operational CII. This enables the operational carbon intensity rating to be determined.

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2.2.2 IMO/SOLAS

Each coastal vessel has to comply with the global IMO standards. In addition to this, it also has to comply with the local legislations of their flag states, who are responsible for the conversion of the standards set by IMO into their local law. Coastal vessels that sail under an EU flag also have to comply with EU legislation as well. If a vessel exclusively sails within the waters of a single Member State, the EU also allows that Member State to enforce specific rules on the vessel. Combined this creates a diversified legislative landscape for the coastal sector.

Within this diverse landscape the SOLAS is mandatory for each coastal vessel as it denotes the safety requirements to which a vessel has to comply with. The SOLAS defines the type of fuels that can be used for propulsion which includes fuel types like diesel, HVO and FAME or certain fuels with a low flashpoint (a flashpoint below 60 °C) like liquified methane gas. The safety requirements of the allowed low flashpoint fuel types are included through the mandatory IGF safety standards for low flash point fuels and liquified methane gas which is also referred to as Liquified Natural Gas (LNG). Other low flashpoint fuel types like Hydrogen and Methanol are currently not included in the IGF code, but the intention is to include them as well in a later stage. Although an interim guideline for methanol was approved in 2021 and recently the IMO Sub-Committee on Carriage of Cargoes and Containers (CCC) finished interim guidelines for the use of hydrogen as fuel, for using fuel-cell power, and to carry liquid hydrogen in bulk, these alternative solutions still require a special case-by-case approval process.

Where the SOLAS is the legal basis for approval of deviating technical solutions and arrangements from binding requirements, the main guideline for the flag administrations in the approval process is the IMO general methodology for the approval of new fuels and technologies, as set out in the Guidelines for the Approval of Alternatives and Equivalents (MSC.1/Circ.1455). This approval process is based on a risk assessment approach, requiring that the safety level of the alternative design needs to achieve at least the equivalent to the safety level of a conventional oil-fuelled ship. This methodology is commonly referred to as the Alternative Design Approval (ADA) process.

2.2.3 Flag state requirements

In addition to complying with IMO standards, vessels must obtain a certificate of approval from the flag state administration. This certification is typically granted through a classification society recognised by the flag state, which may act on its behalf. These classification societies establish their own rules for vessel design, safety, and maintenance, aligned with relevant IMO instruments.

Several classification societies, including Lloyd’s Register, Det Norske Veritas, Bureau Veritas, and the Croatian Register of Shipping, have developed specific rules for the use of alternative fuels such as hydrogen and methanol. When a vessel design complies with both the technical requirements of the classification society and applicable domestic regulations, the society can issue a certificate of approval on behalf of the flag state.

The flag state administration determines the geographical validity of this certificate and grants either national or international approval to the vessel owner. The certificate is only recognised in those flag states that have officially authorised the respective classification society.

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2.2.4 Requirements by the EU

The base for EU emission regulation is the Monitoring, Reporting, and Verification (MRV) regulation. The MRV requires all cargo, passenger and offshore vessels above 400 GT to monitor, report and verify their emissions. This regulation ensures emission data availability and acts as an emission verification tool for the maritime sector. It also provides the basis for the introduction of the FuelEU Maritime and ETS regulation for seagoing vessels.

The EU Emission Trading System (EU-ETS), will only apply for passenger and cargo vessel above 5000 GT. The EU-ETS regulation requires the vessels that have to comply with this to buy emission credit when emitting carbon. This means that for every kg CO2e they emit, a certain amount has to be paid. Within the EU-ETS only a limited number of credits is available where the availability will gradually decrease over time, with the cap reaching zero in 2039. This has to enforce vessel owners to switch to alternative fuels to prevent being fined in case not enough credits are available.

Another emission related EU regulation is the FuelEU Maritime regulation. This regulation requires cargo and passenger vessels above 5000 GT to gradually reduce the GHG intensity of the fuel used. FuelEU Maritime sets maximum limits for the yearly average greenhouse gas (GHG) intensity of the energy used by ships above 5000 gross tonnage calling at European ports, regardless of their flag. Targets will ensure that the greenhouse gas intensity of fuels used in the sector will gradually decrease over time, starting with a 2 % decrease by 2025 and reaching up to 80 % reduction by 2050. The targets cover not only CO2 as greenhouse gas but also methane and N_2O on Well-to-Wake (WTW) basis. Furthermore, to reduce air pollution in ports, passenger and container ships at berth or moored at the quayside must use on-shore power supply (OPS) or alternative zero-emission technologies from 1 January 2030 onwards in ports covered under article 9 of the alternative fuels infrastructure regulation (AFIR), and from 1 January 2035 in all EU ports that develop OPS capacity. Member States may choose to apply the obligation to ports not covered by article 9 of AFIR, from 1 January 2030. By taking a goal-based and technology-neutral approach, FuelEU Maritime allows for innovation and the development of new sustainable fuels and energy conversion technologies, offering operators the freedom to decide which fuels and technologies to use based on ship-specific or operation-specific profiles. The regulation also provides for different flexibility mechanisms, supporting existing fleets to find suitable compliance strategies and rewarding first-movers for early investment in energy transition.

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3. Diesel engine solutions

Summary on diesel engine solutions:

Most suitable for: Engine renewal to Stage V (IWT) or Tier III with SCR/DPF (coastal) on all vessel types with engines <25 years old; HVO drop-in (HVO30 to HVO100) for the whole existing fleet; DPF/SCR retrofit on CCNR1, CCNR2 and Tier II engines.

Not suitable: DPF/SCR retrofit on unregulated engines (engine-out PM too high); blends >7 % FAME on IWT Stage V engines without engine-supplier certification.

Open points: GEME group decision on HVO certificate-of-approval administrative requirements; national tax/customs treatment of cross-border HVO blends; E-diesel cost trajectory; longer-term position of FAME-blends above 7 %.

3.1 Reference diesel engines

Which retrofit options are available depends first of all on the reference diesel engine already installed on the vessel. Some older engines can still be retrofitted with after-treatment systems, others cannot meet modern limits and need replacement, and modern engines already include SCR and DPF. The reference engine classes used in SYNERGETICS are introduced below.

This section provides an overview of the different diesel engines and their technically feasible retrofit solutions for both the IWT and coastal vessels. More information can also be found in the catalogue of greening technologies, factsheet Drop-in Fuels[15].

3.1.1 IWT

For the IWT vessels there are three types of diesel engine types which can be classified as older diesel engines and one type which is referred to as a new diesel engine. The old diesel engine types which are distinguished are:

- the unregulated diesel engines build before the year 2003
- the CCNR1 engine, usually installed between 2003 and 2007
- the Stage IIIA / CCNR2 diesel engine, usually installed between 2008 and 2021/2022.

The new diesel engine needs to comply with the NRMM regulations and the Stage V emission limits which are prescribed. All engines have to comply with the latest NRMM emission standards, which are much stricter compared to the old diesel engine categories with respect to air pollutant emissions such as NOx and PM. One has to comply with Stage V emission limits in case (P= maximum power of the engine):

- The production date of the vessel – is not later than the 30th June 2021 for P < 300 kW and not later than 31st December 2021 for P ≥ 300 kW.
- The engine complies with the latest applicable emission limits defined in the relevant legislation applicable on 5 October 2016 (meaning RVIR CCNR II or Directive 97/68/EC).
- The engine is placed on the market not later than 31st December 2021 for P < 300 kW and not later than 30th September 2022 for P ≥ 300 kW.
- The inland navigation vessel is placed on the market not later than 31st December 2021 for P < 300 kW and not later than 30th September 2022 for P ≥ 300 kW
- The engine was produced before the beginning of the transition period (meaning 1st January 2019 for P < 300 kW and 1st January 2020 for P ≥ 300 kW).

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[15] Drop-In Fuels - Fact Sheet No.3

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For IWT vessels the IWP and IWA engine categories define engine types in the NRMM that are specifically designed for IWT use. It is also allowed to marinise a NRE type engine, which are generally designed for land-based applications, to be used in the IWT sector. Furthermore, it is possible to use a marinised EURO VI truck engine. For these engine types the same timeframes as described above apply for newly installed engines.

The reason why the unregulated, the CCNR1, and the Stage IIIA /CCNR2 diesel engines are referred to as older diesel engines is because they do not use after-treatment systems. The emission limits of air pollutants such as NOx and PM for these older engines are quite lenient when compared to the Stage V engines. In case of engine renewal of the vessel in an existing vessel, it is mandatory to install a NRMM Stage V compliant engine. However, older engines can still be repaired or overhauled to continue their use. It needs to be stressed that there is no legislation in place that forces a vessel owner to install a new engine. In fact, vessels can basically endlessly continue to operate the existing older engines.

Unregulated Diesel Engines

Diesel engines built and installed in inland vessels before 2003 do not have any formal emission limits. They typically run at high PM and NOx emissions, which are estimated around 10 g/kWh for NOx. Most pre-2003 engines still use mechanical injection with no electronic engine management, which complicates retrofitting modern after-treatment systems. However, these older engines are often more fuel-efficient than CCNR1/CCNR2: lowering NOx emissions without SCR required to lower the efficiency to reduce the temperature. Where the unregulated engines are optimized on fuel efficiency, the CCNR1 and CCNR2 are more optimised for reaching NOx emission limits without the need for installing more expensive SCR systems.

CCNR1 Diesel Engines

CCNR1 was the first generation of regulated inland-navigation engines. While emissions were reduced compared to unregulated models, PM and NOx levels remained high compared to current limits. For these engine types the emission limits for NOx are depending on the RPM and range between 13 g NOx/kWh (low speed) and 9.2 g/kWh (high speed) while for PM a fixed limit of 0.12 g/kWh applies. In contrast to the unregulated diesel engine models some CCNR1 engines include partial electronic engine management.

Stage 3A / CCNR2 Diesel Engines

CCNR2 engines meet stricter NOx emission standards than their CCNR1 predecessors. Some of these engines are already equipped with factory-installed Diesel oxidation catalysts (DOCs), yet there is a big difference with the Stage V requirements for both the NOx and PM limits[16]. For the CCNR2 engines the emission factors for NOx are a bit more complex. The reason for this is because the emission limit depends on the cylinder displacement and the power output[17] for the Stage 3A engine and it depends on the engine speed for the CCNR2 engine. For Stage 3A, the larger the cylinder displacement and power output the higher the NOx emission limits become, starting from 7.2 g/kWh to a maximum of 11 g/kWh. For PM the emission factor is roughly 0.14 g/kWh. Since these engines are even further optimised to reduce NOx emission, they typically have the lowest efficiency of the three old diesel engine types. For the CCNR2 diesel engine, the NOx emission limits vary between 11 and 6 grams NOx per kWh, depending on the engine speed. Beyond 3000 RPM, the limit is 6 grams NOx per kWh. Just like the CCNR1 engine type some engines contain electronic engine management components.

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[16] CE_Delft_190325_STREAM_Freight_Transport_2020_FINAL.pdf

[17] Emission Standards: Europe: Nonroad Engines

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Stage V Diesel Engines[18]

Stage V is the current NRMM regulatory benchmark for inland navigation (Regulation (EU) 2016/1628). The Stage V engine in SYNERGETICS scope is the IWA/IWP-graded engine above 300 kW. IWA covers auxiliary use (e.g. generators); IWP is for direct propulsion. Both are restricted to inland waterway applications. These engines are typically factory-equipped with DOC, DPF and SCR and therefore deliver much lower PM and NOx.

Besides this type of new diesel engines, there are a number of different other types of engines that are represented by the Stage V engine group of which three are of relevance here. The first one is the IWA/IWP Stage V engine with a power below 300 kW. These engines typically have higher emission limits and they do not necessarily include a DPF system. Below 300 kW the emission limits are 2.1 g/kWh for NOx and 0.10 g/kWh for PM.

The second engine type is a NRE diesel engine. NRE type engines are developed for industrial applications. In addition to the IWP/IWA engines, the NRE engines with a power below 560 kW can also be used for inland waterway applications if they meet the required safety requirements. NRE engines below 560 kW have a stricter NOx emission limit compared to IWP/IWA graded engines, where the NOx emission limit is 0.40 g/kWh instead of 1.8 or 2.1 g/kWh. The PM limits are the same compared to the larger IWA/IWP engines.

Another engine type that falls under the Stage V diesel engine group for inland waterway applications is the marinised EURO VI engine. EURO VI engines are used in heavy duty road vehicles, such as trucks and busses. The limits are measured in a different type of test cycle (transient) but generally the engine types have a better emission performance compared to IWA/IWP Stage V diesel. As result of lower emission limits for EURO VI engines[19], it is expected to be similar to the NRE <560 kW regarding NOx emissions (=0.4 grams/kWh) and also PM emissions, which are very low (0.01 g/kWh). The option of using marinised truck engines is suited for vessels which can use one or more smaller engines. This is due to the fact that the engine power range of trucks is much more limited (e.g. up to 400 kW per engine) compared to the engine power ranges of inland waterway engines which can go beyond 1000 kW per engine. However, using several EURO VI engines in a parallel configuration is also an option to reach in total the same power compared to one or two traditional larger main engines.

Since for all the Stage V engines the emissions are reduced by exhaust after-treatment systems, the engine can still be optimised for low fuel consumption. As a result, the Stage V engine is the most efficient engine of all reference engines resulting in low fuel consumption and related CO2 emissions per kWh while also having the best air pollutant emission performance (NOx and PM emissions).

3.1.2 Coastal vessels

Besides different emission limits coastal vessels also use different fuel types compared to the IWT sector. For IWT vessels diesel is the standard fuel type, while coastal vessels use Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), Ultra Low Sulphur Fuel Oil (ULSFO), or Very Low Sulphur Fuel Oil (VLSFO) depending on the vessel type and sailing area. Since SYNERGETICS focusses on coastal vessel types that sail in Sulphur Emission Controlled Areas (SECA) or more general in Emission Controlled Areas (ECA). In these areas HFO and MGO are not allowed due to their sulphur limits exceeding the allowed limits in these areas. For this reason, the Decision Support Tool includes only ULSFO and VLSFO. In total this gives four types of reference engines, which are IMO Tier II using VLSFO or ULSFO and IMO Tier III using VLSFO or ULSFO.

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[18] Regulation - 2016/1628 - EN - EUR-Lex

[19] Regulation - 459/2012 - EN - EUR-Lex

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Retrofit strategies for coastal vessels generally not only include emission reduction solutions for NOx, PM, but also Sulphur Oxides (SOx). However, due to the fact that only low Sulphur containing fuels are included, the Decision Support Tool only focusses on NOx, PM and overall greenhouse gas emissions, that comply with MARPOL Annex VI. Even though the IMO does not regulate engines on PM emissions it is still included in the tool since some specific areas like harbours, still require a PM limit. A New Diesel Engine is in this case also a greening solution and not a reference diesel engine, since the emission factors for a Stage V engine go beyond the IMO limits and it is, therefore, on a voluntary basis to reduce PM emissions. In official terms the equivalent of a Stage V graded engine in the coastal sector is referred to as an Ultra-Low Emission Vessel (ULEV), for which the voluntary emission standards are developed by Bureau Veritas in collaboration with the inland waterway NRMM regulation[20].

IMO Tier II Engines

IMO Tier II engines are designed to meet emission limits for NOx in the Tier II category established under MARPOL Annex VI, but they were certified prior to the implementation of the stricter Tier III limits. As mentioned above, when operating on ULSFO or VLSFO, these engines already comply with Sulphur content limits and, therefore, mainly focus on the NOx limits when designing the engine. The exact NOx limit to which the engine has to comply with per Tier category depends on the engine speed of and only apply to vessels with a power output above 130 kW. For a Tier II engine the limits are determined using the values in table 2. In table 2 n is the engine's rated speed in RPMs. The left column is for low-speed engines, the middle column for medium speed engines and the right column for high-speed engines.

4 | NOx limits in kg/kg$_{fuel}$ for a category Tier II engine for different rated speeds of the engine

NOx limit in kg/kg$_{fuel}$	$n < 130$	$130 \leq n < 2000$	$n \geq 2000$
IMO Tier II	0.080	$0.244\ n^{-0.23}$	0.043

Engines running on VLSFO or ULSFO present similar challenges, but they may exhibit slightly different combustion characteristics due to variations in fuel viscosity and sulphur content. This is the case for both IMO Tier II and III engines.

IMO Tier III Engines

IMO Tier III engines are designed to meet stricter NOx limits, applicable in designated Nitrogen Emission Control Areas (NECAs). In these areas a Tier III engine is mandatory and, therefore, a Tier II would not be sufficient. An IMO Tier III engine uses a Selective Catalytic Reduction (SCR) after-treatment system to further reduce NOx emissions. Since PM is not regulated, IMO Tier III engines do not usually include a DPF system in contrast to a Stage V engine. However, if needed a DPF system can also be installed to comply with Stage V PM emission limits. For a category Tier III engine, the NOx limits are shown in table 3.

5 | NOx limits in kg/kg$_{fuel}$ for a category Tier III engine for different maximum operational engine speeds.

NOx limit in kg/kg$_{fuel}$	$n < 130$	$130 \leq n < 2000$	$n \geq 2000$
IMO Tier III	0.019	$0.050\ n^{-0.23}$	0.011

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[20] Ultra-Low Emission Vessels | Marine & Offshore

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3.2 Bio-Diesel and E-Diesel

The easiest emission-reduction step for both IWT and coastal vessels is switching to renewable diesel – either Bio-Diesel or E-Diesel. Both require minimal engine and fuel-system changes. Bio-Diesel is produced from organic feedstock; E-Diesel is synthesised from green hydrogen and carbon dioxide (CO2) which comes from a non-fossil primary origin.

Bio-Diesel is cheaper to produce than E-Diesel, but bio-feedstock is itself limited. Aviation, road transport and deep-sea shipping are competing for the same feedstock, which keeps green-diesel priced above fossil diesel – though it remains a low-effort emission-reduction path. E-Diesel is not yet commercially available in the waterborne sector.

HVO (Hydrotreated Vegetable Oil) is the most established Bio-Diesel. It is currently mostly produced from Used Cooking Oil (UCO); animal fats, industrial residues or tall oil are alternative feedstocks. Chemically HVO is close to fossil diesel and in some cases performs slightly better. Testing on modern Stage V engines has shown that no engine modifications are required to run on HVO100 without affecting emission performance or durability. The remaining question is administrative: must engine suppliers add HVO explicitly to their certificate of approval? This is still under discussion within the GEME group, an expert group organised by the European Commission[21]. In practice, this means no regulatory steps are required before sailing on HVO. If HVO100 is too expensive, an HVO30 blend (30 % HVO, 70 % diesel) limits the OPEX increase while still delivering meaningful CO2 emissions (WTW) into some extent. Practically, all these blends are allowed by regulation without the need for an updated certificate of approval. However, in the IWT sector blends could in some cases face obstacles due to national tax/customs regulations. The practical advice for vessel owners remains: check with your fuel supplier and national tax/customs authority before blending diesel and HVO, especially when sailing cross-border.

Another drop-in fuel that has been brought out on the market is the Bio-Diesel called Fatty Acid Methyl Ester (FAME). This Bio-Diesel, however, comes with some complexities especially for the IWT vessel due to its difference in chemical properties, the used feedstock and the production process. The shelf life of FAME is limited which makes it only applicable when the fuel is consumed within a short time frame. Coastal vessels are used to using lower quality fuels like HFO and MGO that already require fuel pre-heating. However, the diesel that the IWT sector uses has to be EN590 graded, the paraffinic diesel equivalent for this is EN15940. Due to the different chemical properties, like for example its high cloud point, alterations in the fuel storage system may be required. Also rest diesel can affect the FAME so intensive cleaning is required in order to use FAME. Moreover, the filters in the fuel intake system get clogged easily, especially at lower temperatures, so they will need more frequent checks and cleaning or replacement. Besides this, FAME is produced using the process transesterification, which includes using heavy metal catalysts. These heavy metals remain in the fuel if not filtered out with an extra chemical step in the production process. Also, the organic feedstock can contain heavy metals and phosphor and nitrogen holding elements. Due to this the purity of FAME is not as good as that of HVO and regular diesel and also the quality of the FAME differs greatly depending on where the feedstock comes from and which feedstock is used. Therefore, with FAME additional investments may be needed to prepare the fuel system and SCR systems can have a reduced technical lifetime (experts indicate a 75 % reduction), leading to higher maintenance costs.

As mentioned before, these problems mostly occur in IWT vessel engine systems. Currently for IWT vessels using Stage V engines only up to 7 % FAME can be mixed with diesel, because below this mixing percentage the diesel still falls within the EN590 diesel quality standard. Higher blends can also be used if the FAME meets the requirements set in the EN14214 EU standard, and if the Stage V engine is

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[21] The details on the GEME expert group meeting can be found here: https://circabc.europa.eu/ui/group/57232555-1ae6-4eb4-bad2-35a236725afc/library/c01ca53c-33ec-4e64-9d8a-aca2a6dfcc6e/details

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certified to use higher blends, but these higher blends currently still come with engine performance uncertainties and are, therefore, currently only used in pilot projects. Due to the uncertainty that FAME brings and the current regulatory restrictions the Decision Support Tool does not yet include FAME. For coastal vessels the regulations on FAME are different. In this sector FAME can be blended up to 100 % if it meets the requirements set in the ISO 8217:2024[22].

3.3 DPF and SCR

After-treatment is the quickest path to lower air-pollutant emissions on an existing engine. A DPF (Diesel Particulate Filter) captures roughly 99 % of PM. An SCR (Selective Catalytic Reduction) system converts engine-out NOx emission into harmless other gasses. This is done by injecting AdBlue, which is Urea, into the exhaust system which will then react with the exhaust gasses to break down the NOx into carbon dioxide (CO2), nitrogen (N_2) and water (H_2O). These systems are two separate systems that can be installed separately into the exhaust system. As can be seen, the SCR therefore produces some CO2 emissions depending on the amount of urea required to reduce the NOx emissions in the exhaust gasses.

As noted in section 3.1, all modern (Stage V) diesel engines already include SCR, and most include DPF as well (especially above 300 kW). IMO Tier III also includes SCR to meet its NOx emissions limits. Since IMO regulation does not regulate PM emissions, a DPF system is mainly relevant for IWT vessels. However, it is still a possibility for a coastal vessel to also include a DPF system as well.

For IWT, after-treatment is not a practical option on unregulated engines because their PM is too high for a DPF system to handle. It is suitable for CCNR1, CCNR2 and IMO Tier II engines, where it can bring emissions down to Stage V levels or better. Before committing, check the engine-out emissions with the SCR/DPF supplier to confirm the system can operate without excessive regeneration or maintenance.

Space is the other constraint: SCR and DPF units take room, which is scarce on high-power push boats in particular. Verify space availability before committing.

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[22] CIMAC WG 7 Fuels | ISO 8217:2024 - Marine-fuels containing FAME: A guideline for shipowners & operators

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4. Battery electric solutions

Summary on battery electric solutions:

Most suitable for: Day-trip and small cabin vessels, ferries on short fixed routes, container vessels with terminal-side battery-swap (e.g. ZES). Coastal short-route ferries and OSVs with battery in hybrid set-up for peak shaving.

Not suitable for: Push boats with high power/energy demand and limited space (especially P ≥ 2000 kW), long-haul motor cargo vessels (L ≥ 110 m) requiring high autonomy on open international corridors, ADN-compliant tankers using swappable systems.

Open points: Charging-infrastructure scaling along international corridors; the fast-charging standard maturity (Megawatt Charging System); EMSA/IMO 2028 safety framework for batteries on ships; long-term cost trajectory of lithium-ion battery packs.

This chapter covers battery-electric retrofit options – both full-electric and hybrid concepts – for IWT and coastal vessels. Additional technical details are available in the SYNERGETICS catalogue factsheet on battery-electric sailing. Battery-electric propulsion is also discussed in the hybrid context in section 4.2. (overall positioning of this technology: see the Decision Matrix in the Executive Summary)[23].

4.1 Full electric battery sailing

Using battery-electric propulsion is promising because of the overall energy efficiency, the expected developments in energy density, charging capacity and the price drops which are expected. The total cost of ownership is expected to reduce significantly over time.

A full battery-electric retrofit involves the complete replacement of the diesel powertrain with electric propulsion systems, including motors, battery packs, and power management components. The process begins with an energy and operational assessment to determine required power, operational range, charging frequency, and peak load demands. Following this assessment, existing diesel engines, gearboxes, and fuel systems are removed or decommissioned and replaced with electric propulsion motors, inverters, controllers, and high-capacity lithium-ion batteries.

Structural modifications are typically required to support the new system configuration. These include redistributing weight to maintain vessel stability and creating dedicated battery compartments that are fire-protected, ventilated, and equipped with cooling systems. In addition, the retrofit integrates shore power charging systems and an energy management system to control both propulsion and onboard (hotel) loads. Compliance with classification society rules and safety regulations—particularly concerning fire protection and mitigation of thermal runaway risks—is essential. Commissioning includes system testing, harbour and sea trials, and crew training.

Fully electric vessels offer zero-emission operation at the point of use, low noise levels, and high energy efficiency. However, due to battery weight, cost, and range limitations, they are currently most suitable for short-sea shipping, ferries, inland navigation, and harbour operations. Large-scale deployment is still constrained by the availability of charging infrastructure and limitations in grid capacity.

In fully electric inland vessels, all onboard energy demand—both propulsion and auxiliary loads—is supplied by batteries that are recharged from shore-based electricity. Energy replenishment concepts can be divided into two main categories: fixed (installed) battery systems and swappable (containerised) battery systems. The key differences between these concepts relate to time efficiency, financial structure, and onboard space requirements.

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[23] Batteries - Fact Sheet No.4

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Swappable battery systems minimise energy replenishment time, as battery containers can be exchanged rapidly. This is particularly advantageous for vessels with tight schedules or high utilisation rates. Container vessels may benefit from this concept since they already call at terminals where such battery containers can be transhipped. Current systems, such as those provided by Zero Emission Services (ZES), can replace a 3 MWh battery container in approximately 30 minutes, equivalent to an effective energy transfer rate of around 6 MWh per hour. Future increases in container capacity, for example to 5 MWh, could further reduce replenishment time. In contrast, fixed battery systems rely on onboard charging, which requires more time but can be optimised when vessels have idle periods, when detours are undesirable, or where operational flexibility allows longer port stays.

From a financial perspective, **fixed battery systems** involve higher upfront investment, as the vessel owner must purchase the batteries, but they provide full asset ownership and control. Swappable battery systems, typically accessed through leasing or rental models, reduce initial capital expenditure and shift maintenance, performance, and technology risks to the service provider. This can be advantageous given the rapid development of battery technology, including expected cost reductions and improvements in energy density, allowing vessel owners to avoid long-term investment in potentially outdated systems.

Onboard space requirements further differentiate the two concepts. Swappable batteries must be accessible for crane operations, typically requiring vertical handling. As a result, they cannot be placed in cargo holds and instead require dedicated deck space or the allocation of part of the cargo area, potentially reducing payload capacity. Fixed batteries, by contrast, remain permanently installed and can be integrated more flexibly within the vessel, for example in the former engine room below deck, often without sacrificing cargo space. The choice between the two systems therefore depends on whether space or turnaround time is the primary constraint.

For fixed battery systems, charging is provided via shore connections with varying power levels depending on operational requirements. Standard charging solutions, using AC or lower-power DC connections (around 180 kW), require relatively low grid capacity and infrastructure investment, reduce battery degradation, and are suitable for vessels with predictable schedules and long port stays or for supplying hotel loads while berthed. For higher power demand, fast charging stations delivering up to 1 MW can be used. A standard for even higher capacity charging, the Megawatt Charging System (MCS), is under development and is expected to support charging rates of up to 3.75 MW. While high-power charging significantly reduces turnaround times, it requires substantial grid capacity, increases infrastructure costs, and may accelerate battery wear due to higher charge rates and associated heat generation. This makes it particularly suitable for vessels with short, frequent port calls, such as ferries, or for operations with sufficient idle time to recharge without significant productivity loss.

Swappable battery systems differ fundamentally in that energy replenishment is achieved through physical exchange rather than onboard charging. This allows large amounts of electrical energy to be supplied quickly, minimising downtime. However, these systems require standardised container formats, specialised onboard connection interfaces, suitable terminal handling equipment, and a well-developed logistics and charging network ashore. The Megawatt Charging System (MCS) may also evolve into a standard interface for such systems. Due to the need for coordinated infrastructure and logistics, the development of a dense swapping network is more complex compared to the relatively straightforward deployment of multiple shore charging points along inland waterways.

In summary, the choice between fixed and swappable battery systems depends on a balance between time efficiency, space availability, regulations (ADN), infrastructure requirements, and financial considerations.

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4.2 Diesel-electric and hybrid solutions

Hybrid options between full-electric and full-diesel are usually tailor-made – which is also why they are not modelled in the Decision Support Tool – but they remain worth considering, especially when longer autonomy is needed and renewable energy is not always available.

Two driveline configurations matter. In a diesel-electric driveline, diesel generators produce electricity that powers electric propulsion motors. Adding a battery enables peak-shaving and short zero-emission stretches in ports or urban areas. The big advantage is flexibility: power management is easier, vessel layout is more flexible, and the vessel is well-positioned to swap to other electric energy carriers and energy converters (e.g. hydrogen fuel cells) later.

A hybrid driveline keeps the mechanical powertrain in place and adds a battery that supplies energy via the mechanical drive. CAPEX is lower because the powertrain is not rebuilt, but flexibility is also lower: power management is less sophisticated, and switching to fully electric energy carriers later is harder.

For bunkering, both configurations use the existing diesel infrastructure – no logistics changes needed – and on-board generators can charge the battery when shore power is unavailable. This removes the dependence on shore charging that constrains full-electric vessels. The trade-off is emissions: when diesel remains the main energy source, GHG and air-pollutant performance can be worse than direct-drive diesel due to additional energy conversion losses, so the main benefit is local: cutting noise and air-pollutant emissions in urban areas and Natura 2000 zones.

In space terms, hybrids need a much smaller battery than a full-electric vessel does for the same range, so the energy-storage footprint shrinks and payload loss is reduced. Hybrid and diesel-electric set-ups are often framed as a transitional technology for inland shipping – partial electrification with operational continuity. But when combined with HVO, they can also deliver high lifetime emission reductions, which makes them a credible long-term greening solution – particularly for vessels with variable load profiles, limited on-board space, long operating hours, or limited access to charging infrastructure. (when combined with HVO – see section 3.2 – lifetime emissions can be reduced substantially)

4.3 Battery electric specific regulatory framework

4.3.1 IWT

As mentioned before regarding the propulsion system, there are three main regulatory frameworks to which every type of IWT vessels has to comply with. The first regulatory framework is the "Non-Road Mobile Machinery (NRMM) Regulation" in which emission limits for newly installed engines are denoted. As no combustion engines are used, this regulation is not applicable when retrofitting to a fully electric propulsion system. For a retrofit to diesel-electric and hybrid sailing the newly installed generators or diesel engines, if applicable, need to be Stage V certified. For full-electric sailing this means that as a result of the NRMM regulation no further regulatory steps need to be taken for the engine and the process of obtaining a certificate of approval will be equal to that of sailing on diesel.

The second regulatory framework is the ES-TRIN with the latest version being the "ES-TRIN edition 2025/1" implemented in January 2026. This one is much more relevant for electric propulsion systems. ES-TRIN regulation contains all technical requirements to which the vessel has to comply with and the requirements for electric sailing are mainly covered in chapter 10 and 11 of the regulation[24]. Examples of regulations that are in the ES-TRIN are where batteries may or may not be placed, what type of ventilation is required, which alarm systems need to be in place and how to arrange redundancy in the system in case of failure of system components (e.g. with back-up systems). For the shipowner the ES-TRIN generally does not pose any exemptions or extra regulatory steps to be taken. ES-TRIN is mainly

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[24] ES-TRIN 2025/1 - European Standard laying down Technical Requirements for Inland Navigation vessels

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used by the vessel designer to ensure that the vessel complies with the regulation. However, when using new types of batteries, not yet described in ES-TRIN, it may require additional regulations or permits from EU or CCNR. For the vessel owner ES-TRIN regulation mostly affects the initial investment cost of the electric propulsion system due to its requirements, e.g. the required system redundancy.

The third regulation is the ADN, which outlines the safety regulations for transporting dangerous goods. The transportation of Lithium or Natrium batteries are part of the class 9 substances of the ADN. This means that extra safety measures are required when using Lithium or Natrium batteries as alternative energy, especially for vessels which are subject to ADN classification, such as tanker vessels for transportation of dangerous goods. Section 2.2.9.1.7 includes all ADN regulations related to these two types of batteries. Just as the ES-TRIN regulation, ADN regulation does not require extra regulatory steps that have to be taken, it only increases the required safety measures that need to be included in the vessel design.

4.3.2 Coastal vessels

Coastal vessels in SYNERGETICS scope are subject to IMO regulations, EU legislation and flag-state law. SOLAS is the common ground: every IMO-subject coastal vessel must comply with it. SOLAS Chapter II-1 Part D sets general electrical-installation requirements, but it was written around conventional power generation and does not treat batteries as a main electrical power source. The IMO has now finalised a workplan to close this gap, with safety rules for lithium-ion batteries and swappable battery containers in development. A key milestone is the adoption of amendments to SOLAS regulation[25] II-1/41, allowing batteries to be used as the main source of electrical power, is 2028.

In practice, this means there is currently no binding international instrument on battery safety for coastal/international navigation. Battery-electric safety has so far been governed by classification rules and industry standards, with limited flag-state experience to draw on. EMSA, supported by the European Commission, Member States and industry, has issued non-mandatory Guidance to push toward uniform implementation of essential safety requirements for battery energy-storage systems on board ships in the interim.

EU-flagged coastal vessels also face emission rules: MARPOL Annex VI applies to all, EU-ETS and FuelEU Maritime apply to cargo and passenger vessels above 5000 GT, and MRV applies to cargo, passenger and offshore vessels above 400 GT. A full-battery-electric vessel counts as zero-emission in all four, so compliance is automatic. Partial-electric (hybrid) operation carries more regulatory overhead than full-electric. EU-ETS allowances are still required, propulsion emissions must be monitored/reported/verified, and FuelEU Maritime transport-activity targets are only met if enough of the energy comes from electricity rather than diesel.

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[25] Draft workplan agreed on safety rules for battery, wind and nuclear-powered ships

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4.4 Vessel type specific scenarios

4.4.1 IWT

On paper, the regulatory framework, technology maturity and zero-emission profile make battery-electric sailing relevant for every vessel type. In practice however, it is much more selective: certain sailing profiles and vessel-design constraints rule it out. The most important constraint are the required space and the weight which need to be accommodated. Batteries have much lower energy density than diesel but high material density. A battery system equivalent in energy contents to a diesel tank is therefore much larger in volume and also heavier. In some cases, this additional weight or volume can not be accommodated due to physical limitations. In other cases, depending on whether the vessel is weight-critical or volume-critical, this energy storage can be accommodated but may lead to reduced payload. As battery capacity is expected to increase, the problem will get smaller, but still there will be a challenge to accommodate the (swappable) batteries in the vessel.

For weight-critical vessels (e.g. motor cargo vessels carrying iron or heavy containers), the extra system weight directly reduces usable payload. For volume-critical vessels, cargo space must be given up to fit the larger battery system. This effectively rules out full-electric operation for push boats, apart from pushers operating in port areas only, with 500 kW $\leq P <$ 2000 kW and $\geq$ 2000 kW – the combination of high power demand and limited deck space makes it impractical. For the other IWT vessel types, the limitation is reduced autonomy in terms of the time it can operate without the need to recharge or swap the battery containers. Especially on long routes the autonomy is a critical parameter. This also depends very much on the available infrastructure along waterways and in ports for recharging or swapping facilities for batteries in ports. The operational profile of the vessel is decisive. For vessels operating on long term contracts on fixed routes, the infrastructure can be arranged as the demand for recharging or swapping can be predicted and ensured into some extent. To overcome the risk of lacking infrastructure, hybrid concepts using diesel generators (e.g. using HVO) combined with batteries for the energy provision, can be applied to serve as range extenders, when there are no options to recharge or swap the batteries.

A second important limitation is the combination of swappable battery packs with ADN-compliant operation. The propulsion system is formally exempted from the ADN-regulation, but in practice the vessel design must still ensure the propulsion system poses no risk to ADN cargo. Lithium-ion battery fires can be self-igniting and cannot be extinguished effectively. As a result, the battery must be fully separated from the cargo holds. For ADN-compliant motor tankers this points to fixed battery systems in a well-protected below-deck space, rather than swappable batteries. The same logic applies to passenger vessels.

As mentioned, a strong limitation is the infrastructure and charging speed. Fast-charging up to 1 MW is technically available but still very scarce at the moment. The more widely available shore connections are sized for hotel loads during mooring and deliver much less power. Larger IWT vessels therefore need long charging windows: for using fixed batteries, even at 1 MW, charging can take 6 hours per day to have sufficient energy to operate during the next day. This will erode productivity and competitiveness if the charging can not be done during idle hours. Swapping batteries can be a better option as the time-loss is reduced, this will be most suitable for container transporting vessels where the same crane can be used to handle the swappable battery containers as well at the container terminal.

However, when looking at motor tankers, the full battery electric propulsion seems rather impractical. Furthermore, also for many dry bulk vessels it will be a challenge as most of them are operating on the spot market with varying routes and cargo types.

There is much more potential for full battery electric sailing for the passenger vessels. In particular the day-trip, small cabin vessels, and ferries can be mentioned. They usually operate on fixed routes for a stable period and have modest power demand and frequent mooring and also idle times (e.g. during the night). This means that there could be a business case to take the risk to invest in the required infrastructure. Furthermore, the required battery capacity seems acceptable to be accommodated and

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the charging windows fit the schedule. For these vessels full-electric is often actively encouraged. In particular in sensitive areas such as Natura 2000 areas, where zero-emission sailing is required and within large cities the batter-electric propulsion is a suitable and cost-effective technology for the future. Furthermore, the noise reduction also improves passenger comfort.

4.4.2 Coastal vessels

Depending on the operational profile, battery-electric propulsion can be an attractive option for full emission reduction compliance or as part of a hybrid setup with other options to improve efficiency. The choice between using batteries for full electric or in combination with another energy carrier mainly depends on the operational profile (such as the use of dynamic positioning and required power), required autonomy, ship size, cargo type (either being weight or volume critical) and the availability of charging or battery swap infrastructure. The autonomy, the time the coastal vessel needs to be able to sail on batteries without the need to recharge or swap the batteries, is the most critical factor. Compared to inland vessels, which can use facilities along inland waterways, the options to recharge or swap batteries for seagoing vessels are expected to be much smaller as they cross or visit ports less often.

Additionally, when a coastal vessel is being retrofitted to either fully battery-electric or fully fuel-cell electric propulsion it is important to note that this implies that the complete energy-to-power system must be changed unless the vessel is already a diesel-electric vessel. This requires new switchboards, electric propulsion motors and new cabling between the batteries/fuel cells and the switchboards. This is a significant cost factor aside from the investment required for the batteries and fuel cells.

Basically, full-electric operation is typically only feasible for short routes with frequent port calls, where charging can be performed during idle time or during loading or unloading of passengers or goods. Consequently, for most coastal vessels, batteries are more interesting in hybrid configurations. When using full-electric, battery swapping can significantly reduce downtime but requires dedicated port infrastructure and standardisation, limiting the applicability to specific routes or regions. Fixed batteries on the other hand simplify integration but increase reliance on shore-side charging capacity which may constrain the operational flexibility.

Similar to IWT, full-electric propulsion has the strongest potential for ferries operating on short, fixed routes or on coastal vessels where predictable schedules and frequent port calls allow for well-planned charging. When the route is well-defined with low variability and at relatively short distance, the required safety measures due to the presence of passengers can be managed. However, for longer routes, the energy density of batteries and charging requirements are the limiting factor. On the other hand, the charging capacities can be improved and battery energy densities are expected to increase significantly over the next years and decades. Nevertheless, if full electric is feasible for around 50 % of seagoing ferries, a main barrier for broad adaptation is expected to be the impact on autonomy next to the increase in total cost of ownership and the required charging infrastructure[26]. Seen the space and weight of battery systems, it may be required to charge or swap batteries with off-shore facilities to make it possible to operate with relatively small autonomy.

Contrastingly, for Offshore Supply Vessels (OSVs) with variable operational profiles including Dynamic Positioning (DP) operations, systems combining batteries with other energy carriers are primarily relevant. In this case, batteries can be used for peak shaving or as spinning reserve, significantly reducing

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[26] T&E. "Full Charge Ahead : Investigating the Potential to Electrify Europe's…." May 1, 2026. https://www.transportenvironment.org/articles/full-charge-ahead-investigating-the-potential-to-electrify-europes-ferries.

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fuel consumption. The use of larger battery installations depends strongly on whether batteries are used for DP and the availability of below-deck volume.

For fishing vessels, full or partly electric operation could be interesting to reduce noise and emissions, but applicability depends on vessel type (trawlers with high demand operations versus longliners) and time at sea. The higher total cost of ownership is however expected to be a big barrier. Furthermore, battery safety, weight and volume requirements can have impact on vessel stability, operational capability and payload.

Full battery-electric propulsion can be attractive for vessel owners operating relatively short, fixed routes with predictable schedules. Vessels with larger or more variable operational loads can still benefit from combining batteries with other energy carriers. Key barriers remain, including high capital costs of battery systems[27], dependence on reliable charging or swapping infrastructure and the reduction of payload capacity or usable volume due to battery weight and space requirements. However, when compared to e-fuels, full-electric propulsion is expected to be more cost efficient, as e-fuel pathways involve additional conversion that introduce energy losses. Overall, battery-electric systems are a highly efficient solution for specific coastal applications, particularly when operational profiles are predictable and infrastructure is available, but they are less suitable as a universal solution across the coastal fleet.

4.5 Example cases

4.5.1 IWT

Den Bosch Max Groen

Operator: NEDCARGO
Operation area: The Netherlands, a fixed route between Den Bosch, the Maasvlakte, and Moerdijk
Year of construction: 2021
Source: [28]

Vessel type: Motor vessels dry cargo (80 m ≤ L < 110 m) (containers)
Vessel size: length 86 m, width 11.4 m, draught 3 m
Propulsion system: 2 main engines with each a power of 510 kW and a 2.9 MWh battery capacity through two 20ft swappable ZES battery containers.
Benefits: Due to the daily fixed route between container terminals where also one terminal provides battery swapping services, limited bunker time losses occur. By fully sailing on electricity, no emissions arise and therefore, potentially 800 to 900 tons of CO2 per year could be saved compared to diesel sailing.

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[27] Koričan, Marija, Ailong Fan, and Nikola Vladimir. "Analysis of Environmental-Economic Sustainability of Fishing Vessels and Its Improvement by Alternative Powering Options in Projected Decarbonization Scenarios." *Fisheries Research* 285 (May 2025): 107385. https://doi.org/10.1016/j.fishres.2025.107385.

[28] Persbericht ITG Nedcargo ZES, Revolutie in de binnenvaart: dit elektrische schip vaart op verwisselbare batterijen - Rijnmond, DEN BOSCH MAX GROEN (MMSI 244001927), Inland, Motor Freighter | Position & specs (picture)

Alphenaar

Operator: NEDCARGO
Operation area: The Netherlands, a fixed route between Alphen aan den Rijn and Moerdijk
Year of construction: 2021
Source: [29]

Vessel type: Motor vessels dry cargo (80 m ≤ L < 110 m) (containers)
Vessel size: length 90 m, width 10.5 m, draught 3.8 m
Propulsion system: 2 electrical engines with each a power of 406 kW and a diesel generator set as redundancy. The electrical engines are installed on top of the two Veth L-Drives with which the vessel steers. It uses 2 swappable containers with a combined capacity of 2.9 MWh. With this it sails a 2 times 6 hour round trip emission free.
Benefits: The fixed route between container terminals, where the terminal in Alphen aan den Rijn provides battery swapping services, over a small distance of 60 km enables zero emission sailing using swappable battery systems without having large bunker times.

Letitia

Operator: HTS Group
Operation area: Rotterdam, Antwerp-Bruges, and Duisburg
Year of construction: 2024
Source: [30]

Vessel type: Motor vessels dry cargo (L ≥ 110 m) (containers)
Vessel size: length 135 m, width 17.2 m, draught 3 m
Propulsion system: The Letitia has a diesel-electric propulsion system combined with a full-scale hydrogen FC engine system. It has 2 main electrical engines of each 1600 kW with a fixed battery system that has a total capacity of 1030 kWh and a 1.2 MW fuel-cell system. The diesel part consists out of 4 diesel generators. Due to this combination the Letitia can sail fully electric, fully on hydrogen, diesel-electric, or fully on diesel.
Benefits: It can sail zero emission and has a great fuel flexibility since it can use electricity, hydrogen, and diesel. It is also equipped to sail autonomic.

E-Pusher (Type M)

Operator: KOTUG
Operation area: between Amsterdam and Zaandam
Year of construction: 2023
Source: [31]

Vessel type: Push boats (500 ≤ P < 2000 kW)
Vessel size: length 15 m, width 7.5 m, draught 1.35 m
Propulsion system: 2 electrical engines with 300 kW each and a 2 MWh swappable battery on board. Charging is done during idle time in Zaandam with the electricity being supplied from wind energy.

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[29] Zero Emission Services start met operatie - Zero Emission Services (picture), Alphenaar: elektrisch en emissieloos over Gouwe en IJssel - Binnenvaartkrant, PowerPoint-presentatie, ⚓'ALPHENAAR' vrachtschip met E motoren 02338177, met containers uit Moerdijk, gespot 15 10 2019

[30] Letitia - Schepen, Letitia is paradepaardje voor de hele binnenvaart - Binnenvaartkrant (picture), 100-jarig Olthof viert oplevering 'modernste schip op de Rijn' - maritiemmedia.nl

[31] D4.1 Stocktaking and good practices (picture)

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Benefits: The E-pusher is built in a modular way, due to which it is also possible with limited effort to switch to other technologies like Hydrogen, LNG, or Stage V diesel for maximum fuel flexibility, while due to its fixed route with the required infrastructure it can also sail zero emission its entire round trip. This makes it a future proof vessel setup.

Amsterdam GVB ferries

Operator: GVB
Operation area: Amsterdam
Year of construction: 2019
Source: [32]

Vessel type: Ferries
Vessel size: length 41 m, width 13.9 m
Propulsion system: It has 2 electric engines with each a power of 300 kW and 2 battery systems with a combined capacity of 680 kWh. It does include a small diesel generator but this is only used in conditions above wind force 8. The vessel is charged by a 1600 kW charger each time it reaches shore. It is charged 3 minutes every time which is during the day just enough to last the power supply the whole day.
Benefits: Its fixed route over a small distance and well-established infrastructure makes is suitable for fully battery electric sailing. It also reduces the emission by 2400 tonnes of CO2e per year within the city area, which is beneficial for health of the residents in the area.

Sendo Liner

Operator: SENDO Shipping
Operation area: Amsterdam
Year of construction: 2019
Source: [33]

Vessel type: Motor vessels dry cargo (L ≥ 110 m) (containers)
Vessel size: length 110 m, width 11.45 m, draught 3.2 m
Propulsion system: It is diesel-electric, where it has 2 electric engines with each a power of 350 kW located in the back and 2 generator sets of each 425 kW located at the front of the vessel. It also includes a battery system with a capacity of 564 kWh. On top of this, heat is reused and frequency regulators are used saving up to 35 % in on-board power system energy use.
Benefits: The propulsion system and the operational profile allow to sail up to 95 % of the time with one genset. In combination with its optimised vessel design and hull shape the vessel saves up to 32 % in fuel used.

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[32] ABB technology ensures fast charging for Amsterdam's new electric ferries | News center, GVB Amsterdam will provide zero-emission public transport - Ship & Offshore, Amsterdam GVB Ferry editorial stock photo. Image of netherlands - 260822408 (picture)

[33] Microsoft Word - Beschrijving Sendo Liner Accupakket 2019.docx, Sendo Shipping | – Innovation is our course (picture)

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4.5.2 Coastal vessels

M/F Tycho Brahe

Operator: Øresundslinjen
Operation area: between Helsingør (Denmark)- Helsingborg (Sweden)
Year of construction: 1991
Source: [34]

Vessel type: Ferries (4000 kW ≤ P < 8000 kW)
Vessel size: length 111.2 m, width 28.2 m, draught 5.3 m
Propulsion system: It has 4 electrical thrusters with each a power of 1.5 MW supplied by 640 water-cooled Lithium-ion batteries with a combined capacity of 4160 kWh. The battery pack is charged by a 10 MW automatic charging system, where at each stop 1175 kWh is charged in roughly 7 minutes. It also has diesel generators a back-up.
Benefits: It transports 7.1M passengers, 1.3M cars, 452,000 trucks and 16,500 buses a year from Denmark to Sweden which can be done zero-emission. Also, its high-capacity charging system on a fixed route ensures that there is no operational time loss when charging the batteries.

Havila Capella Cruise

Operator: Havila Voyages
Operation area: Norway
Year of construction: 2021
Source: [35]

Vessel type: Ferries (4000 kW ≤ P < 8000 kW)
Vessel size: length 124m, width 22m, draught 5.3m
Propulsion system: It is a gas-hybrid vessel that has 4 LNG dual fuel engines onboard, where two have a power of 1620 kW and two 2430 kW, and a battery pack with a total capacity of 6.1 MWh.
Benefits: It can sail for 4 hours zero emission and when sailing on LNG it can save up to 25 % CO2e and 90 % NOx emissions. It is also modular build to accommodate hydrogen and ammonia as fuel in the future.

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[34] The ferry site, Riviera - News Content Hub - ForSea Ferries battery conversion: a 'big little journey' (picture)

[35] Havila Capella, Ship That Can Run on Batteries, Hydrogen or Ammonia Received the Next Generation Ship Award (picture), KM supplies engine and thruster package for cruise vessel on new Havila Kystruten route along the Norwegian coast | Shippax, Bergen Engines to power Norway's famed coastal shipping route | News, C26:33L | Marine Engine | Bergen Engines

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Rem Commander

Operator: Rem Offshore AS
Operation area: Norway
Year of construction: 2011
Source: [36]

Vessel type: OSVs (3000 GT ≤ m < 4000 GT)
Vessel size: length 94.9 m, width 20 m, draught 6.7 m
Propulsion system: It is a diesel-electric vessel with four gensets, where two have a power of 188 kW and two a power of 100 kW, a battery pack with a capacity of 870 kWh, and a back-up generator of 195 kW. The engine system propels two main 200 kW thrusters, 1 azimuth thruster of 880 kW and two tunnel thrusters with each a power of 880 kW.
Benefits: Its hybrid configuration can save up to 20 % fuel consumption which reduces emissions and operational cost.

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[36] Rem-commande_Rem_Vessel-spec_-template-300925.pdf (picture), REM signs contract with Vard Electro for a vessel retrofit project - VesselFinder

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5. Methanol solutions

Summary on methanol solutions:

Most suitable for: IWT tankers (operators already familiar with methanol cargo), inland motor cargo vessels in dual-fuel set-up, coastal cargo and Ro-Pax ferries in dual-fuel mode, harbour craft.

Not suitable for: Smaller fishing vessels and other space/volume-critical vessels where the 2x tank-volume penalty cannot be absorbed. Vessels in regions without methanol bunkering infrastructure.

Open points: Stage V methanol engine certification; availability of low-carbon (bio-/e-) methanol at scale; methanol fuel-cell purity standardisation and supply chain; formaldehyde emissions in low-load operation.

5.1 Properties of methanol, general considerations, solutions and requirements

Considering a methanol retrofit is always a case-by-case engineering exercise. Methanol's practical advantage over methane, hydrogen and ammonia is that it is liquid at ambient conditions, with a density (0.792 kg/l) close to diesel (0.832 kg/l) – so existing liquid-fuel logistics can be partly used. Its drawback is energy content: roughly 20 MJ/kg against 42.8 MJ/kg for diesel. Methanol needs about twice the tank volume and fuel mass to maintain the same autonomy, or proportionally more frequent bunkering. The regulatory framework is described in section 5.1; the IWT derogation process is in section 5.1.1. Overall positioning of this technology: see the Decision Matrix in the Executive Summary.

Regulatory and classification requirements of the vessel and the engine must also be reviewed at an early stage in the process, since methanol is toxic and highly flammable. For the application in inland navigation approvals from the relevant inland shipping authorities and a classification society are still mandatory until the regulations are adopted in ES-TRIN and also to get the exempt for the Stage V engine. It may take a few years before methanol is acknowledged as a reference fuel in the NRMM regulation for the Stage V engine certification. For coastal vessels the time needed to get permissions can be shorter as result of a different legal framework.

One result of the stricter regulation for storing methanol is that electrical systems near fuel tanks must adhere to higher safety standards, including being explosion-proof, engine and fuel compartments should have proper ventilation, and gas detection systems and emergency own protocols must be in place. Comprehensive risk assessments, such as HAZID and HAZOP studies, are typically required for classification approval.

Crew training is also an essential component of the process. Operators must be trained in handling methanol safely, emergency procedures, bunkering operations, and routine maintenance of the new fuel and engine systems. Operational manuals should be revised to provide clear guidance on methanol use as fuel for the vessel. Classification society and flag state inspections confirm compliance and allow the vessel to operate legally. The efforts required for crew training and operation of methanol as fuel will be less burdensome if it concerns tanker vessels which are able to carry dangerous goods such as methanol. In these cases, the crew already has skills and knowledge on how to operate methanol as fuel for the transhipment of the cargo. In the inland tanker vessels for example, we also see the largest interest to use methanol as fuel for the propulsion of the vessel, as this is also in the interest of the clients of IWT (methanol producing and trading companies).

So, for any retrofit using methanol as fuel, converting an inland vessel to accommodate methanol on board will involve a combination of technical modifications, safety system upgrades, regulatory approvals, and crew training. Key considerations include the lower energy density of methanol, potential dual-fuel operation to maintain flexibility, and early engagement with authorities and classification societies. Since methanol can be used in three different configurations, depending on the engine that will be used the retrofit process can become even more complex.

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More information on methanol used as fuel for combustion engines can also be found in the SYNERGETICS catalogue factsheet about methanol[37]. For combustion, two options are considered: single fuel and dual fuel. And there is also the option to use methanol as hydrogen carrier and to use a fuel cell to generate electricity.

Methanol ICE Single-fuel

Methanol can run as a single fuel in two ways: spark-ignited (Otto cycle), or compression-ignited (Diesel cycle) using an ignition improver. In either case only the engine and fuel tank need replacement – the conventional mechanical powertrain stays. The advantage over dual-fuel is that the engine does not need to be certified for diesel operation or for different fuel-replacement rates. Methanol's lower air-pollutant signature also reduces the after-treatment scope compared with diesel engines of the same Stage V category.

The difficulty with the single-fuel configuration is however that methanol is less lubricant than diesel and also more corrosive which can lead to higher wear and higher maintenance cost. Furthermore, the NRMM regulation provides a clear barrier, as there are no certified marinised single fuel methanol engines on the market yet. This option can therefore only be considered on the short term in case an engine manufacturer/supplier is willing to provide an experimental engine, using article 34 or 35 of the NRMM regulation for the exemption process.

Methanol ICE Dual-fuel

Depending on the combustion concept, the dual-fuel configuration uses a small share of diesel (or HVO) as pilot fuel to ignite methanol in a compression-ignition set-up. The advantages over single-fuel methanol are practical: diesel/HVO acts as lubricant and reduces corrosion (lower wear, lower maintenance) and, for some combustion concepts, the engine retains the ability to run on 100 % diesel/HVO when methanol is unavailable or too expensive – a safety net requested by many end-users.[38] The share of methanol to diesel/HVO depends on the required engine characteristics (torque demand, constant or variable speed) and the configuration of the engine. For the smaller engines, that fall within the scope of the Decision Support Tool realistic fuel replacement rates[39] are at around 70 %. However, engine suppliers are developing dual fuel engines for the IWT and coastal sector which would be able to run with higher rates like 80 % in the near future. However, it needs to be remarked that when (Stage V) engine runs on 100 % diesel the emission limits shall be reached, which requires extensive after treatment systems.

When retrofitting to a Dual-fuel configuration parameters such as engine type, age, operational profile, and power requirements must be evaluated to determine whether the existing diesel engine can be converted to methanol or whether installing a new engine is more appropriate. For conversion, the existing diesel engine must be adapted with methanol-compatible fuel injectors and fuel supply systems, using a port-injection approach (no direct high-pressure injection). In this case adjustments to the existing engines are typically necessary to optimise the combustion of methanol. It is, in the case of application in inland navigation, however questionable if retrofitted engines would reach also the Stage V limits. Therefore, it seems more likely that new Stage V engines are being installed to ensure that the NRMM emission limits are reached resulting in a structural solution for inland vessels and compliance to the regulations such as EU Taxonomy (relevant for financing and obtaining grants). Therefore, seen also the other investments and efforts required to use methanol as fuel, it seems more

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[37] Methanol ICE - Fact Sheet No.1

[38] See for more information MAN engine: https://www.man-es.com/applications/projectguides/2stroke/content/199196250.pdf

[39] We power your future | Anglo Belgian Corporation

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recommendable to install a new Stage V methanol Dual-fuel engine once certification challenges are solved. This approach may simplify regulatory approval and ensure compliance with safety standards, although it generally requires higher capital expenditures.

Methanol fuel cell

The third configuration uses methanol as an energy carrier for conversion to electricity in a fuel-cell system, described in a separate SYNERGETICS catalogue factsheet[40]. Methanol fuel-cell systems do exist that use methanol directly, but the SYNERGETICS-modelled concept is a low-temperature PEM fuel cell (PEM = Proton Exchange Membrane) fed with hydrogen extracted from methanol. The case for this route is hydrogen density: a methanol molecule contains four hydrogen atoms, giving significantly higher hydrogen density than liquefied hydrogen and far more than compressed hydrogen. Together with the simplicity of liquid methanol logistics, the extra step of separating hydrogen on board – in a methanol reformer – is considered an acceptable trade-off.

Retrofitting a conventional diesel-powered vessel to a fuel-cell system involves replacing or supplementing the propulsion system with an electric powertrain. The process begins with a feasibility study to assess power requirements, operational profile, available space, and methanol supply. Since fuel cells are expensive assets and perform best in near-steady state operation, usually battery packs are included for peak-shaving and transient power demand including safety-relevant crash-stop manoeuvres. However, in ideal sailing situations fuel-cell systems can achieve higher energy efficiencies compared to combustion engines and may thus reduce the operational costs. This depends on the comparison of the lifetime of methanol and fuel-cell system with combustion engines. In case the lifetime of fuel cells and required battery storage systems is much lower, additional maintenance (overhauling) cost for the fuel cell and batteries are to be considered in the overall cost assessment. The retrofit to a fuel-cell system also has the benefit of being quieter, though fuel-cell systems combined with batteries and energy management systems require a higher capital expenditure compared to combustion engines.

A second complication is fuel quality. Methanol fuel cells require a much higher purity grade[41] of methanol up to 99.85 %. Industrial methanol is, therefore, not suitable for FC applications. This complicates obtaining the required fuel supply needed for a Methanol FC propulsion system compared to Methanol ICE systems. Marine methanol has a dedicated international product standard. ISO 6583:2024 defines general requirements and specifications for methanol from all production pathways at the custody-transfer point for use in marine diesel engines, fuel cells, and other marine applications and defines three different quality categories: MMA, MMB and MMC. This gives shipowners and fuel buyers a more robust basis for marine procurement than relying solely on general chemical-market specifications. In commercial market practice, the non-marine specific IMPCA reference specification for Methanol remains relevant, because price reporting and methanol commodity trading still align strongly with IMPCA-conforming product. In project terms, that means methanol procurement should specify not only the fuel name, but also the applicable fuel grade, purity expectations, traceability basis, and any sustainability certification required for compliance or reporting. This element creates additional burden and attention for the vessel owner/operator to ensure with the fuel suppliers that the right quality level of methanol is used and that no contamination takes place during the bunkering process and in the fuel system on board of the vessel.

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[40] Fuel Cells - Fact Sheet No.8

[41] SYNERGETICS T6.5 Teaching module 2

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5.2 Methanol specific regulatory framework

5.2.1 IWT

EN 18071:2025 provides a harmonized methanol bunkering standard for inland navigation. However, in the IWT sector the engine systems are subjected to the "Non-Road Mobile Machinery (NRMM) regulation (EU 2016/1628)" which has impact on engines supplied to the market from the year 2021. As mentioned earlier, in the EU NRMM regulation methanol is not included as a reference fuel. The consequence of this is that bringing engines on the market is not straightforward. Instead, the NRMM regulation does allow pathways to accommodate pilot projects via articles 34 and 35 in this regulation. Therefore, by following the regulatory derogation route for pilot projects it is possible to receive a certificate of approval for a limited time span and also the geographic application may be limited to the Member State that provided the approval for usage of the methanol fuelled engine.

To accommodate this route, the CESNI Committee included initial technical requirements for methanol in the ES-TRIN 2025/1 edition, which formally entered into force on 1 January 2026. The technical requirements for sailing on a fuel with a flashpoint lower than 55 °C like methanol is outlined in chapter 30 and specific regulations on methanol can be found in Appendix 8 section 2 chapter 2 and Appendix 8 section 3 chapter 1 and 3 of the ES-TRIN[42]. The ES-TRIN is the EU technical regulatory framework that includes all the technical requirements a vessel has to oblige to. While the safety regulations are still very strict due to lack of experience its presence in the ES-TRIN simplifies the derogation process due to the clear rules around the technical requirements.

There are two types of certificates of approval that can be obtained by following the derogation process, each corresponding to different sailing areas in which they are valid. The first certificate is the Rhine vessel inspection certificate. This certificate is valid on the EU defined Zone R, 3 and 4 waterways. The second certificate is the Union certificate for inland navigation vessels approved by the CESNI-PT group.

The CESNI-PT certificate has the advantage that it is valid in a larger area when the Zone R is also included in the certificate, however, the final publication process of the certificate tends to take much longer than the Rhine vessel certificate.

This delay in the final step for the Union Certificate usually leads to waiting times of over a year for the approval of the certificate, while the CCNR generally approves the Rhine vessel certificate within two weeks. Below, a timeline of the derogation process is shown. In here it is shown that up until step 3 the derogation for both certificates follows the same route and take the same amount of time. After this it depends on how fast the corresponding body approves the certificate.

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[42] ES-TRIN 2025/1 - European Standard laying down Technical Requirements for Inland Navigation vessels

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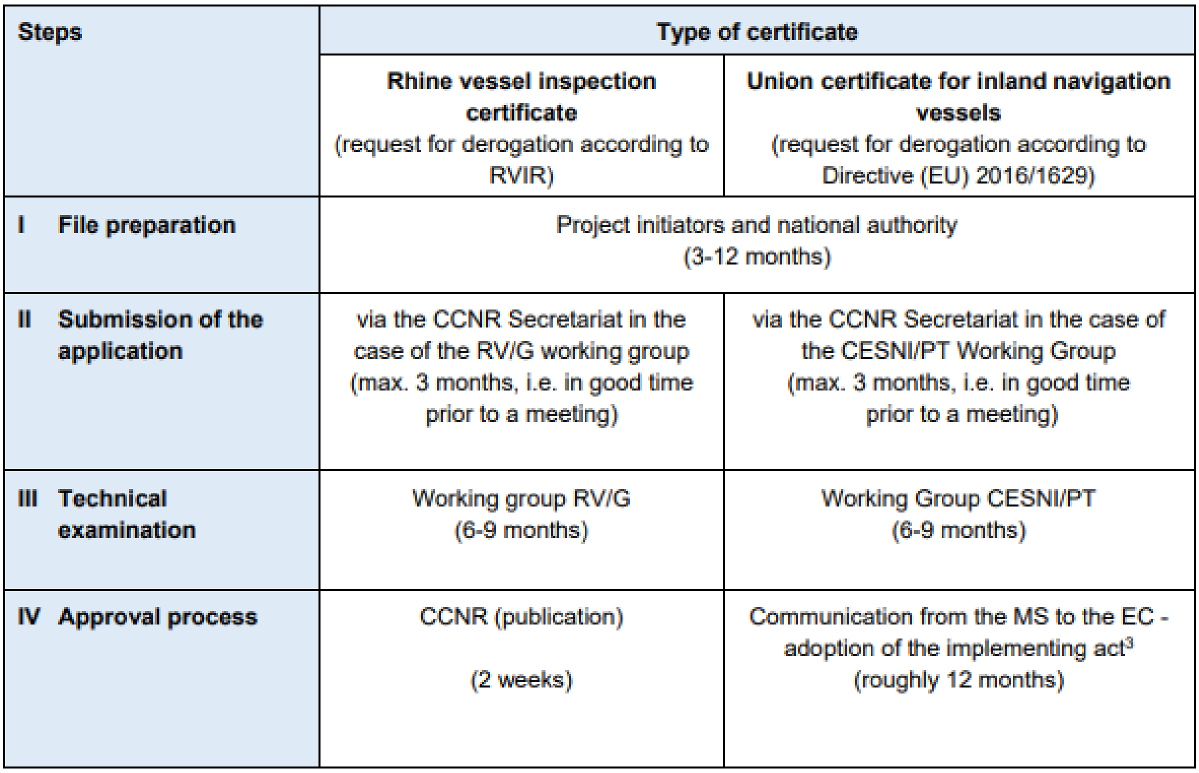
6 | Types of certificates for inland waterway vessels



Steps	**Type of certificate**	
	Rhine vessel inspection certificate (request for derogation according to RVIR)	**Union certificate for inland navigation vessels** (request for derogation according to Directive (EU) 2016/1629)
I File preparation	Project initiators and national authority (3-12 months)	
II Submission of the application	via the CCNR Secretariat in the case of the RV/G working group (max. 3 months, i.e. in good time prior to a meeting)	via the CCNR Secretariat in the case of the CESNI/PT Working Group (max. 3 months, i.e. in good time prior to a meeting)
III Technical examination	Working group RV/G (6-9 months)	Working Group CESNI/PT (6-9 months)
IV Approval process	CCNR (publication) (2 weeks)	Communication from the MS to the EC - adoption of the implementing act[3] (roughly 12 months)

1. File preparation

It is necessary to create a substantiated proposal together with the project initiator, suppliers, shipyard vessel designer, certification and inspection services, and national authority, taking into account all derogations which the project touches on. In SYNERGETICS D4.6 chapter 5 (D4.6 also lists the full file requirements per derogation step) a guideline has been developed where all the necessary documentation required for the derogation application can be found[43]. It is recommended to first seek contact with the national authority. A second point of contact could be the CCNR-secretariat for more information if the national authority cannot answer your question. Preparing extensive documentation with all the necessary information is crucial in this stage of the derogation process. The next steps will be very time consuming if information is missing or unclear. In that case the process step has to be redone.

2. Submission of the application

For both certificates the submission of the application needs to go via the CCNR-secretariat through the RV/G working group for the Rhine vessel certificate and through the CESNI-PT working group for the Union inland navigation certificate.

3. Technical Examination

The working group experts and member states together have to do the internal technical examination.

4. Approval Process

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[43] SYNERGETICS - D4.6

Rhine vessel certificate: Receiving the adopted Rhine Vessel Inspection Certificate together with the recommendation based on the derogation proposal. This also comes with conditions on which the derogation is allowed, for example, time intervals for inspections, duration of the derogation, which sailing areas are allowed, etc.

Union inland navigation certificate: Receiving the Ship Certificate and the implementing act with a communication of the European Commission to the Member States. This implementing act mentions the requested derogation and the conditions which need to be met, for example time intervals for inspections, duration of the derogation, which sailing areas are allowed etc.

In the derogation process the main element in convincing the CCNR and CESNI-PT to allocate a certificate of approval is to prove that the vessel is equally safe as a conventional diesel vessel with similar dimensions and sailing profiles.

Important to note here is that Methanol is not zero-emission at the tailpipe and it is also an ADN class 3 classified substance (UN-1987). This means that a new methanol engine that is approved through a derogation in accordance with Article 34 or 35 of the NRMM-Regulation has to comply with the Stage V emission limits. These elements need to be taken into account during the design phase of the derogation procedure.

5.2.2 Coastal vessels

For all coastal vessels the regulatory frameworks of the IMO and the respective flag state apply. Coastal vessels that sail under an EU flag also have to comply with EU legislation. Regarding the IMO, the International Convention for the Prevention of Pollution from Ships (MARPOL) and International Convention for the Safety of Life at Sea (SOLAS) regulations are relevant for the issuance of ship certificates. Where the MARPOL convention outlines the emission limits for the engine, the SOLAS regulation includes the safety regulations of the vessel. Also, the Interim Guidelines for the Safety of Ships using Methyl/Ethyl Alcohol as Fuel published by IMO’s Maritime Safety Committee (MSC.1/Circ.1621) remain relevant.

Same as for the IWT sector the current legal framework reflects the fact that there are no detailed and prescriptive IMO regulations to support flag administration approval for ships using methanol. Consequently, IGF Code requirements for these alternative fuels remain non-mandatory or are in the process of being developed because they only exist as interim guidelines until adopted into IGF Code.

In the IMO guideline SOLAS, which is described in more detail in section 2.2, it is described that exemptions can be made if one can prove equal safety standards compared to conventional diesel. This exemption can be approved only by the flag state administration under which the vessel owner will sail. In section 5.6 of SYNERGETICS Deliverable 4.6 a detailed flow diagram on the different steps within the exemption approval process is shown. Below a summary of this process is given.

1. **Initial consolidation meeting**

The first step in the approval process is to have an initial consolidation meeting between the flag state administration and every party involved in the vessel development. This includes the vessel owner, the shipyards vessel builder and designer, the recognised organisation/classification society, and any other stakeholder that will be involved. In this meeting the project is introduced, initial designs are discussed, a plan and timeline regarding the safety assessments is developed and acceptance criteria for the certification will be defined. The latter is crucial to be included in this meeting because the required risk assessments and certification criteria are determined case-by-case.

2. **Preliminary design**

Based on the outcomes of the initial consolidation meeting the design team will develop the required documentation, including the agreed upon plans, reports and design drawing.

3. **Preliminary approval**

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After the design team hands over the agreed upon documentation the Flag state administration will give a preliminary approval if the design seems feasible and if all the safety measures and critical hazards are adequately addressed. The preliminary approval generally includes detailed description of improvements that have to be made for the final approval. It should be noted that the preliminary approval does not guarantee a final approval. If the design team fails to implement the improvements outlined in the preliminary approval the final approval will not be given.

4. Final design

With the preliminary approval the design team can start with developing the final design. The final design includes besides the development of the detailed drawing and system integration plans also system testing and further detailed risk assessment.

5. Final approval

When the design team has finished the final designs and all the required system tests and risk assessments are complete the flag administration or a recognised certification body that works on their behalf will give the final approval if they deem the design to meet all the agreed upon criteria. After the final approval is obtained, the vessel is allowed to sail on methanol under the condition that the approved design is used.

There is no fixed timeline as to how long this process of approval will take since it will be a case-by-case determined process. However, do keep in mind that it will be a time and cost consuming process with the risk of not getting the final approval if not being thorough enough and in case of lack of preparation.

Besides the MARPOL emission reduction targets coastal vessels in the scope of SYNERGETICS also have to comply with emission related regulations that include the EU-ETS for cargo and passenger vessel above 5000 GT, the Fuel-EU Maritime for cargo and passenger vessels above 5000 GT, based on the MRV for cargo, passenger, and offshore vessels. Both configurations of methanol combustion engine systems emit NO_x emissions. Therefore, in order to comply with the MARPOL air pollutant emission limits any methanol ICE configuration needs to meet the Tier III emission limits. For a Methanol Dual-Fuel system it is mandatory to use either VLSFO or ULSFO to comply with the MARPOL SOx limits that are set within the EU sailing regions. A methanol fuel cell system does not emit any air pollutant emissions and, therefore, is assumed to comply with the Tier III air pollutant emission limits without further mitigation measures.

For the EU FuelEU Maritime and ETS the type of methanol is relevant. For the scope of ETS, renewable or green Methanol (so either Bio- or E-Methanol) is considered to be net zero in GHG emission[44]. This means that in the case all engines including generators or other auxiliary engines use 100 % pure green methanol, and no CO2 emission rights have to be purchased to comply with ETS legislation related to the methanol consumption. This is possible to achieve using methanol ICE single-fuel technology. For Dual-Fuel engines, also no ETS rights are required when using Bio-Diesel such as FAME or HVO. However, if fossil fuel is used, such as fossil methanol or fossil diesel the ETS rights are relevant.

Furthermore, for compliance with FuelEU Maritime, the scope of emissions concerns the overall WTW performance (grams of CO2e per MJ). Here, there can still be some emissions of CO2 for renewable/green methanol, depending on feedstock and production process.

When using Methanol ICE dual-fuel it depends of course on how much diesel is used in the blend whether the GHG emission limits in the FuelEU Maritime and ETS are met, but coastal vessels can, as mentioned above, reach a blend of up to 95 % which still results in low GHG emissions when using green Methanol. This makes a methanol ICE dual-fuel configuration still a viable transitional solution,

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[44] SYNERGETICS D4.5 The Catalogue of greening retrofit solutions

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while possibly renewable methanol with lower WTW emission levels may become available on the market.

It needs to be remarked that grey methanol (usually produced from fossil natural gas (methane)), has a significant emission profile, which in combination with its lower energy density results in a GHG emission profile that is just slightly below a Stage V diesel engine. This means that when using grey methanol only a very small emission reduction is reached compared to a new diesel engine running on fossil diesel. Seen the higher CAPEX, questions about fuel prices and availability and increased risks, grey methanol could, therefore, be only a temporary solution in case green methanol is not available or it is too expensive. It can be ignored as a greening solution on its own in the future.

5.3 Vessel type specific scenarios

5.3.1 IWT

For inland vessels, methanol is interesting for two reasons: as a direct ICE fuel and as a hydrogen carrier for fuel-cell systems. The practical advantages are that it is liquid at ambient conditions, leverages existing liquid-fuel logistics, is sulphur-free, and produces very low soot and PM in operation. Bio-methanol is also expected to draw from a broader feedstock pool than HVO and to be cheaper per litre.

The downsides are equally real: methanol is toxic, has a low flash point, has a much lower energy density than diesel, and the bunkering network is still thin. Ship integration, safety design, fuel-storage volume and access to bunkering are therefore central project constraints. For methanol fuel cells there is an extra hurdle: the fuel must be much higher purity compared to combustion engines, which complicates the supply chain.

The European regulatory frame for methanol in IWT has improved significantly: ES-TRIN 2025/1 contains dedicated methanol provisions, ISO 6583:2024 specifies methanol as a fuel, and EN 18071:2025 provides a harmonised methanol bunkering standard. The remaining difficulty is therefore less about missing rules than about project-specific approval, technical integration, crew training and fuel sourcing.

For inland vessels, methanol is most relevant where three conditions are met: the vessel can accommodate the additional volume required for energy storage on board, a viable bunkering concept is available, and the owner can manage a more complex approval and safety-engineering pathway than for diesel. Recent scientific work and demonstrator projects show that methanol ICE is technically feasible in retrofit-oriented dual-fuel concepts and in compression-ignited concepts using pilot fuel or ignition improvers. However, they also point towards to need for formaldehyde emission control measures, low-load combustion stability, material compatibility, corrosion mitigation and lubrication management. There are still key engineering challenges to be addressed in view of certification of engines which can have a solid durability and emission performance. Also, as result of the lack of certified Stage V engines for wide application in Europe, there are no showcases yet in Europe. However, there are projects ongoing such as the motor tanker Chicago active in bunkering/transportation of methanol.

5.3.2 Coastal vessels

For the coastal fleet, methanol is widely positioned as a transitional fuel. Its operational appeal is real: it is liquid at ambient conditions, leverages existing liquid-fuel logistics, and is compatible with internal-combustion engines in dual-fuel set-ups, making it familiar to operate compared with gaseous fuels. Applicability however differs sharply between single-fuel ICE, dual-fuel ICE and fuel-cell systems, and depends on vessel size, available volume and weight for storage. Long-term, IMO compliance hinges on the availability of low-carbon methanol feedstock for methanol production.

Compared to conventional diesel systems, methanol requires additions and modifications regarding fuel treatment, and safety measures such as cofferdams, and double walled piping. Methanol’s lower energy density compared to marine diesel results in larger fuel volumes being required for equivalent range, directly affecting vessel autonomy and tank arrangement. In dual-fuel ICE systems, diesel or HVO are always required as pilot fuel for ignition and load stability, while the maximum substitution rate depends

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on engine size and design. Furthermore, depending on the methanol-to-diesel ratio, additional after-treatment such as SCR systems are required to meet ECA NOx emission limits. Alternatively, methanol fuel-cell systems require more extensive retrofitting as they require a full-electric drive train. Moreover, additional safety requirements and hybrid control strategies are needed to manage load variations, possibly requiring also batteries. Furthermore, depending on the type, fuel-cell systems require reforming methanol to hydrogen, either internally or through additional reformers.

Especially for smaller fishing vessels, methanol fuel-cell system requirements can significantly reduce usable volume and may impact payload, stability, and autonomy, while also requiring additional training from crew, making adoption less straightforward. Contrastingly, in the dry cargo segment, where operational profiles are comparatively simple, methanol dual-fuel ICE systems can already be installed by retrofitting the existing engines, whilst offering fuel flexibility and compliance to regulations. The main trade-offs are the reduction of autonomy and cargo capacity due to lower volumetric energy density and the need for additional space for accommodating tanks and due to the required cofferdams [45]. For other coastal vessel types, such as OSVs or ferries, methanol can offer similar benefits, while the relative advantage of methanol increases where operational flexibility and fuel availability are prioritized over zero-emission capability in port.

Consequently, methanol is most attractive for vessel owners who desire fuel flexibility during transitional emissions-reduction phases, operate medium-range coastal vessels where full electrification is not feasible, or have the ability to newbuild or major retrofits where additional tank volumes and safety systems can be integrated.

When converting to methanol, one should consider the additional space requirement for tanks, cofferdams, and fuel treatment systems, but also the increased system and operational complexity related to ventilation, hazardous zones, and fire safety. At the same time, it should also be noted that medium to long-term IMO and EU regulation compliance relies on bio- or e-methanol availability.

Overall, methanol, particularly in dual-fuel ICE configurations (as single fuel methanol ICE and methanol fuel-cell systems are still immature), is a practical and relatively conventional option for coastal vessels seeking emission reductions without fundamentally changing operational patterns. However, its long-term use for IMO compliance depends heavily on the scalability and availability of low-carbon methanol feedstocks.

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[45] Laasma, Andres, Riina Otsason, Ulla Tapaninen, and Olli-Pekka Hilmola. "Evaluation of Alternative Fuels for Coastal Ferries." *Sustainability* 14, no. 24 (2022): 16841. https://doi.org/10.3390/su142416841.

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5.4 Example cases

Stena Germanica

Operator: Stena line
Operation area: Gothenburg, Sweden and Kiel, Germany
Year of construction: 2015 (retrofit)
Source: Stena Line [46]

Vessel type: Ro-Pax ferry
Vessel size: length 241 m, width 29 m
Propulsion system: 4×6000 kW Sultzer 8ZA40S main engine converted to methanol
Benefits: Lower emissions of pollutants (PM, SOx)

Tug 21 / Methatug

Operator: Port of Antwerp
Operation area: Port of Antwerp
Year of construction: 2002 (2024 retrofit)
Source: [47]

Vessel type: Harbor tug
Vessel size: length 29.5 m**,** width 11 m
Propulsion system: 2×1945 kW ABC 8DZC dual-fuel engine
Benefits: MGO/methanol dual fuel demonstrated with a permission to retrofit the vessel without after-treatment system.

Fastwater 120 SE pilot boat

Operator: Swedish Maritime Administration
Operation area: Oxelösund Sweden
Year of construction: 2021 (project start)
Source: [48]

Vessel type: pilot boat
Vessel size: length 14.4 m**,** width 4.6 m
Propulsion system: 1×415 kW ScandiNAOS MD97 engine
Benefits: CI methanol engine demonstrated reducing NOx by 75 % without aftertreatment.

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[46] https://www.stenaline.de

[47] fastwater.eu

[48] fastwater.eu

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6. Gaseous Hydrogen solutions

Summary on gaseous hydrogen solutions:

Most suitable for: IWT vessels on short fixed routes with reliable bunkering, smaller urban-delivery vessels, niche coastal applications with strong zero-local-emission requirement (e.g. fjord ferries), modular setups.

Not suitable for: Long-haul motor cargo and push convoys on Rhine/Danube (autonomy and CAPEX prohibitive), ADN-relevant tankers using swappable storage, large coastal cargo where competing with Bio-LNG on cost.

Open points: NRMM listing of hydrogen as reference fuel; ES-TRIN 2027/1 hydrogen technical requirements; IGF Code finalisation for hydrogen; cost trajectory of green hydrogen and bunkering infrastructure roll-out; on-board hydrogen safety training certification.

6.1 Properties of hydrogen; general considerations, solutions and requirements

A hydrogen retrofit is one of the most invasive options described in this handbook. The integration of a propulsion system using hydrogen as fuel changes the propulsion train, the fuel-supply and bunkering process, and the crew skill requirements. The next paragraphs explain why hydrogen behaves differently from diesel and what that means for storage, powertrain architecture, safety and approvals. (regulatory frame in section 6.2; the IWT derogation process structurally follows section 5.2.1).

Most of the properties of hydrogen differ largely from that of diesel, with the most important being that hydrogen is a gas at ambient temperature with a very low mass density but a high energy density. The size of a hydrogen molecule is very small, it can lead to significant material degradation known as hydrogen embrittlement, and it is highly flammable and explosive. While methane gas is usually liquified at around -162 °C for storage on inland and coastal vessels, hydrogen liquefies at even lower temperatures around -253 °C.

Hydrogen is generally being stored under high pressure of at least 350 bar and up to 700 bar as compressed gas on board of vessels in specific tanks. To achieve these high pressures significant amounts of energy are consumed. These pressure tanks are quite voluminous and take up most of the space of the storage system. Taking into account the storage, it results in a lower overall energy per volume storage capacity of a factor between 6-8, depending on the hydrogen pressure, compared to diesel[49].

The engine, the fuel storage system and the fuel supply system, therefore, require special materials to prevent leakage and corrosion, and it requires extra fire and explosion safety measures. Also, generally the complete hydrogen storage and propulsion system requires more space compared to diesel. The required space limits the maximum autonomy that can be reached with a hydrogen powered propulsion system. Consequently, bunkering of hydrogen needs to happen more often, or other backup systems such as diesel generators are being used as range extenders.

Safety is due to the physical properties of hydrogen a critical aspect of hydrogen application in vessels and also in retrofits. Regulatory and classification requirements must be reviewed early, and approvals from the relevant inland shipping authorities and classification society are mandatory. Comprehensive risk assessments, such as HAZID, HAZOP, and CFD explosion and fire risk simulation studies, are

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[49] The data on the storage factors container energy densities for different energy types can be found in the following database provide by MARIN: https://sustainablepower.application.marin.nl/energy-carriers/table

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typically required for classification approval. Also, specific trainings for the crew on using hydrogen on board are required, even though there is no official certificate for training personnel on hydrogen.[50]

As mentioned before, storing hydrogen requires tanks with special materials that can also withstand high pressure gas. Since these are specialised and high safety demanding tanks, the hydrogen fuel tank systems are generally certified separately from the fuel supply systems and the engine. Currently two primary approaches are considered for the storage of hydrogen on board:

1. Fixed hydrogen storage systems.
2. Swappable hydrogen container systems.

Fixed hydrogen storage systems consist of tanks that are permanently integrated into the vessel's structure. These tanks are typically custom-designed to fit the available space and operational requirements of the vessel. As a result, fixed systems generally allow for more efficient use of volume and higher total hydrogen capacity compared to standardised containers. In addition, fixed installations involve fewer mechanical interfaces, reducing the number of potential leak points and simplifying day-to-day operation. For vessels with fixed routes and longer range requirements, fixed storage systems are often better suited from a technical perspective.

However, these advantages of fixed tanks come with notable drawbacks. Fixed hydrogen storage systems require substantial upfront capital investment, as the vessel must be structurally modified and the tanks must be made, installed, and approved by the classification society. Furthermore, ownership of the tanks places the responsibility for inspection, maintenance, periodic pressure testing, and certification entirely with the vessel owner. The operational flexibility is also limited, as the fuel capacity cannot easily be adjusted and bunkering depends on the availability of dedicated hydrogen infrastructure at ports. Also, the speed of the bunkering of hydrogen is much lower than for example bunkering of diesel. Therefore, significant time will be required for bunkering hydrogen into a fixed tank on board. This can lead to a significant loss of productivity of the vessel and therefore to economic costs. For hydrogen stored under 700 bar this infrastructural challenge is further increased since specialised pressure machines are required to pump the hydrogen in at these high pressures.

Swappable hydrogen container systems therefore represent an alternative approach in which standardised hydrogen containers are installed on deck and connected to the vessel's fuel supply system. Instead of refuelling onboard, empty containers are swapped for filled ones saving significantly in bunker time. This reduces the productivity loss of the vessel, but it requires handling capacity of these swappable hydrogen MEGCs (Multiple-Element Gas Container) at ports. Another key advantage of this concept is the significantly lower capital expenditure, particularly when the containers are rented or leased from a third-party provider or the energy supplier. This reduces or eliminates the need for the vessel owner to invest in hydrogen storage assets and associated certification. Maintenance, inspection, and regulatory compliance of the containers are typically handled by the hydrogen fuel supplier, reducing both cost and operational effort for the operator. In this case only the fuel supply system and engines are the responsibility of the vessel owner in terms of investment, maintenance and certification. In addition, swappable container systems offer a higher degree of operational flexibility. The number of containers carried can be adjusted depending on route length, power demand, or operational profile, and as already mentioned the refuelling through container swapping can be performed relatively quickly under the assumption that cranes are available in the port.

Despite these benefits, swappable container systems also have limitations. It is yet not legally accepted to use swappable containers across different vessels and it therefore makes efficiency gains to pool swappable containers for a number of vessels complex. Standardized container dimensions result in lower volumetric efficiency and reduced total hydrogen capacity compared to vessel-specific fixed tanks.

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[50] H2 ICE - Fact Sheet No.2

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The repeated connection and disconnection of containers introduce additional mechanical interfaces, increasing the need for robust leak detection and safety management making the retrofit more complex. From a financial perspective, while upfront investment is reduced, ongoing rental or leasing fees could lead to higher operational expenditure over time.

In conclusion, fixed hydrogen storage systems are generally better suited as a long-term solution for vessels operating on predictable routes with established hydrogen bunkering infrastructure, an exploitation profile that allows for extra bunker time and sufficient capital resources. However, seen the high capital investment, such situations seem unlikely in reality as a high productivity of the vessel will be required to earn back the much higher investment compared to traditional vessels and other greening options.

Swappable hydrogen container systems, particularly when based on a rental system, provide a flexible and lower-risk entry point into hydrogen propulsion. They are especially well suited for early adoption, where minimising upfront investment and operational complexity is a priority, even if this comes at the expense of extra space requirements and higher long-term operating costs.

For gaseous hydrogen powered vessel three different configurations exist. The fuel storage method that is selected, the type of safety studies and training, and the certification steps that have to be taken do in most scenario’s not really depend on which configuration is used. It might happen that when other substances like ADN graded goods are being transported as well, certain storage configurations are not possible due to the required safety measures. The powertrain and related safety measures on board, however, always depend on the type of engine that is used.

Hydrogen ICE Single Fuel[51]

A hydrogen ICE Single-fuel uses spark-ignited combustion of hydrogen. These engines are not yet commercially available because hydrogen is not (yet) an NRMM reference fuel; the European Commission has confirmed that hydrogen will be added in an upcoming NRMM revision, which will significantly lower the certification barrier and opens commercial sales of hydrogen fuelled combustion engines. A typical diesel to hydrogen ICE retrofit requires the following steps:

1. Replace the existing engine to enable hydrogen combustion.
2. Install a hydrogen fuel storage and supply system.
3. Integrate safety systems such as gas detection, ventilation, and emergency shutdowns.
4. Update control and automation systems.
5. Early involvement of classification societies and flag states, and completion of risk assessments to ensure compliance with the emerging hydrogen regulations.

While less efficient than fuel cells, hydrogen ICE retrofits benefit from the fact that the engines have similar mechanical layouts, shorter development timelines due to the fact that the mechanical powertrain can remain unaltered, and the ability to leverage existing engine-room layouts and operational practices. The combustion engines are typically more reliable and cheaper compared to using fuel cells. The ICEs can use lower quality hydrogen fuel and are more easily maintained with the existing dealer/support network. Furthermore, the lifetime of ICE’s is expected to be much larger than the lifetime of fuel cells, which reduces the overhauling and maintenance costs.

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[51] See also SYNERGETICS Fact Sheet No 2 on H2 combustion engines: https://www.synergetics-project.eu/Fact_Sheet_2/

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Hydrogen ICE Dual-Fuel

The hydrogen internal combustion engine in dual fuel configuration typically uses diesel or HVO as pilot fuel for compression-ignition of hydrogen. The big practical advantage is fuel flexibility: such a dual-fuel engine can also run on 100 % diesel or HVO. The drawbacks are higher CAPEX (after-treatment must handle both pure diesel-mode NOx for NRMM Stage V / IMO Tier III compliance and dual-fuel mode) and more expensive certification (dual fuel type-approval). Furthermore, the tank-to-wake GHG emission reduction may be less than a single fuel hydrogen ICE as still some share of diesel is being used.

It is possible to retrofit an existing engine into a hydrogen dual-fuel engine. Parameters such as engine type, age, operational profile, and power requirements, however, must be evaluated to determine whether the existing diesel engine can be converted to hydrogen or whether a new Stage V replacement engine is more appropriate. Hydrogen ICE engines require specific fuel injection strategies that not all diesel engines can accommodate. When a diesel engine is retrofitted to a hydrogen ICE Dual-Fuel engine it is typically necessary to optimise the combustion of hydrogen.

It is, in the case if application in inland navigation, however questionable if retrofitted engines would reach also the Stage V limits. Therefore, it seems more likely that new Stage V engines are being installed to ensure that NRMM emission limits are reached resulting in a structural solution for inland vessels and compliance to the regulations such as EU Taxonomy (relevant for financing and obtaining grants). Therefore, seen also the other investments and efforts required to use hydrogen as fuel, it seems more recommendable to install a new Stage V hydrogen dual-fuel engine. This approach may simplify regulatory approval and ensure compliance with safety standards, although it generally requires higher capital expenditures. However, for coastal vessels, the situation can be different because of more lenient regulations on the emission performance of the engines used in seagoing vessels. The mixing rate that these engines use can vary, where the Decision Support Tool uses 75 % hydrogen as a mixing rate based on information gathered within the consortium. Some engines can work already with an 85 % mixing rate[52].

Hydrogen fuel cell[53]

The third configuration is the Hydrogen fuel-cell system. This is currently the most common hydrogen configuration in IWT, demonstrated by SYNERGETICS partner Future Proof Shipping with the retrofitted H2Barge1 and H2Barge2. A typical diesel-to-hydrogen-fuel-cell retrofit involves the following steps:

1. Define the vessels sailing profile and operational power demand
2. Decide on the propulsion architecture: fully fuel cell electric or hybrid fuel cell + battery
3. Remove or isolate the diesel engine and fuel system
4. Install the electric propulsion system
5. Integrate the hydrogen fuel cell system
6. Add the hydrogen storage and fuel supply system
7. Add the battery energy storage system
8. Add safety, ventilation and fire-protection upgrades
9. Add cooling, HVAC system (Heating, Ventilation and Air Conditioning) and thermal integration
10. Control, monitoring and automation
11. Reassessment of stability, weight and space
12. Apply for classification, flag state and certification
13. Test phase

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[52] More information available from engine supplier ABC: https://www.abc-engines.com/en/markets/marine-propulsion/applications/inland-waterway-vessels

[53] See also SYNERGETICS Fact Sheet No 8 on fuel cells: https://www.synergetics-project.eu/Fact_Sheet_8/

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The advantage of a hydrogen fuel cell over a combustion engine is the complete elimination of GHG and air-pollutant emissions, combined with higher energy efficiency under steady-state sailing – both of which can slightly lower OPEX given that hydrogen is currently expensive. A second benefit is architectural: the electric powertrain needed for a fuel cell makes it straightforward to switch later to other electricity-driven options such as swappable battery containers or fixed batteries on board.

The downsides are equally clear. CAPEX of H2 fuel cell systems are much higher than for combustion engines: the fuel cell, the electric powertrain and the typical peak-shaving battery pack add many cost, complexities and space. Fuel cells also degrade faster than ICEs, which drives up maintenance and overhaul cost. Finally, fuel cells need very high hydrogen purity (up to 99.97 %[54] due to which industrial hydrogen is not suited for fuel cell applications. This leads to a more complex fuel supply chain and higher risks of system failures in case there are problems with the purity. The standards for the Hydrogen quality can be found in the Alternative Fuel Infrastructure Regulation (EU) 2023/1804 which refers to ISO 14687-2 and the EN 17124.

6.2 Hydrogen specific regulatory framework

6.2.1 IWT

Combustion engine systems are subjected to the Non-Road Mobile Machinery (NRMM) regulation (EU 2016/1628) for engines which became operational in 2021 (smaller engines) or 2022 (larger engines). This NRMM regulation does not yet list hydrogen as a reference fuel. The consequence of this is that sailing on hydrogen with a hydrogen combustion engine is quite challenging. It is announced that the NRMM will be revised to enable hydrogen as reference fuel for the certification. Furthermore, for the short term, the NRMM regulation does allow pathways to accommodate pilot projects via the articles 34 and 35 of the regulation.

Furthermore, there are specific technical regulations for inland vessels, as defined in ES-TRIN. By following the regulatory derogation route for pilot projects, it is possible to receive a certificate of approval for a limited time span.

To accommodate this route for hydrogen, the CESNI Committee approved the draft requirements for gaseous hydrogen storage in October 2024 as interim guidelines for pilot projects. In September 2025, they were supplemented with requirements for the use in propulsion / auxiliary systems. In practical terms, this means that the working document could be freely circulated outside CESNI by member states and approved organisations, thereby facilitating the use of the draft requirements by developers of innovative vessel projects. These interim guidelines have been included in ES-TRIN. The technical requirements for sailing on a fuel with a flashpoint lower than 55 °C like hydrogen is outlined in chapter 30 and specific regulations on hydrogen can be found in Appendix 8 section 2 chapter 3 and Appendix 8 section 3 chapters 1 and 4 of ES-TRIN[55]. In 2027 an updated version of ES-TRIN is expected, ES-TRIN 2027/1, in which the official EU technical requirements for hydrogen will be included. The draft requirements do not prejudge the final content of ES-TRIN 2027/1, but it allows for experience to be gained with the draft requirements and where appropriate to adapt the requirements before the adoption of ES-TRIN 2027/1 in 2028.

There are two types of certificates of approval that can be obtained by following the derogation process, each corresponding to different sailing areas in which they are valid. The first certificate is the Rhine vessel inspection certificate. This certificate is valid on the EU defined Zone R, 3 and 4 waterways. The second certificate is the Union certificate for inland navigation vessels approved by the CESNI-PT group. The CESNI-PT certificate has the advantage that it is valid in a larger area when the Zone R is also

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[54] SYNERGETICS T6.5 Teaching module 3, see https://www.synergetics-project.eu/downloads/

[55] ES-TRIN 2025/1 - European Standard laying down Technical Requirements for Inland Navigation vessels

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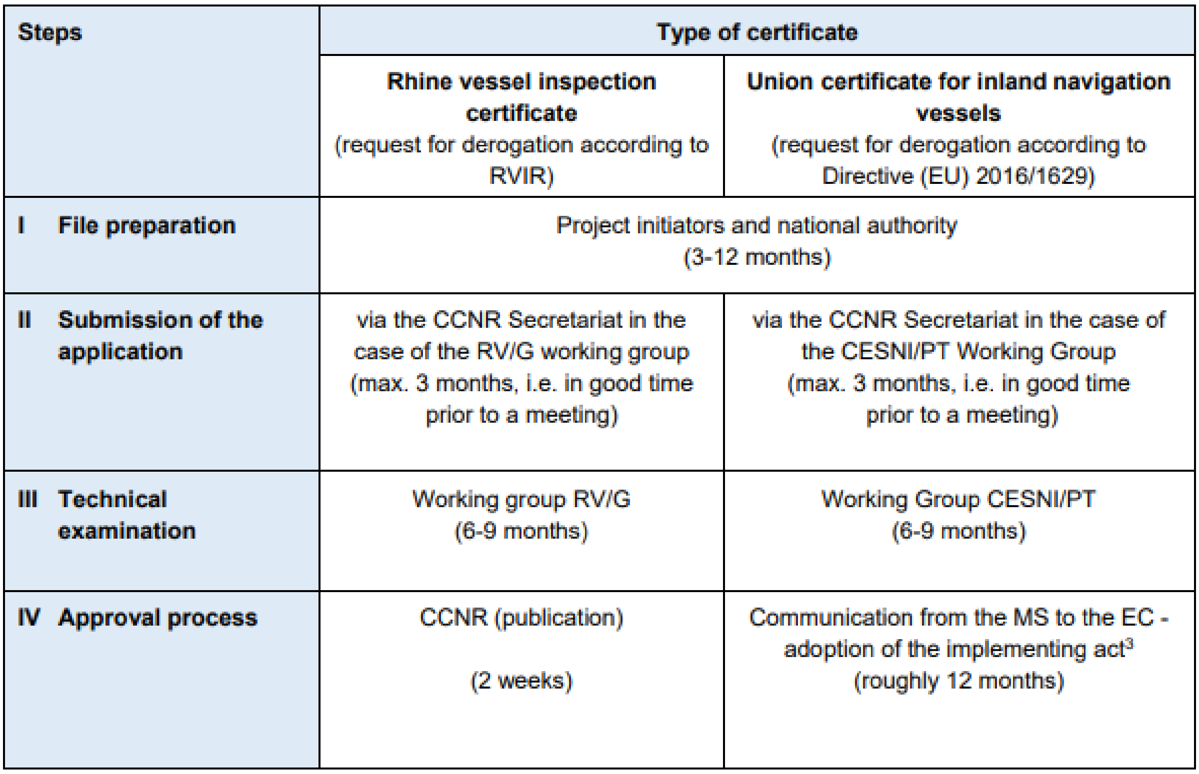
included in the certificate, however, the final publication process of the certificate tends to take longer than the Rhine vessel certificate. This delay in the final step for the Union Certificate usually leads to waiting times of over a year for the approval of the certificate, while the CCNR generally approves the Rhine vessel certificate within two weeks. Below, a timeline of the derogation process is shown. In here it is shown that up until step 3 the derogation for both certificates follows the same route and takes the same amount of time. After this it depends on how fast the corresponding body approves the certificate.

7 | Types of certificates for inland waterway vessels



Steps	**Type of certificate**	
	Rhine vessel inspection certificate (request for derogation according to RVIR)	**Union certificate for inland navigation vessels** (request for derogation according to Directive (EU) 2016/1629)
I File preparation	Project initiators and national authority (3-12 months)	
II Submission of the application	via the CCNR Secretariat in the case of the RV/G working group (max. 3 months, i.e. in good time prior to a meeting)	via the CCNR Secretariat in the case of the CESNI/PT Working Group (max. 3 months, i.e. in good time prior to a meeting)
III Technical examination	Working group RV/G (6-9 months)	Working Group CESNI/PT (6-9 months)
IV Approval process	CCNR (publication) (2 weeks)	Communication from the MS to the EC - adoption of the implementing act[3] (roughly 12 months)

To complete the regulatory pilot derogation process, the following steps need to be taken for both types of certificates of approval:

1. File preparation

It is necessary to create a substantiated proposal together with the project initiator, suppliers, shipyard vessel designer, certification and inspection services, and national authorities, taking into account all derogations which the project touches on. In SYNERGETICS D4.6 chapter 5 a guideline has been developed where all the necessary documentation required for the derogation application can be found[56]. If there still exist uncertainties, the certification bodies and relevant national representatives can be contacted or if they cannot answer the question the CCNR-secretariat can be contacted for more information. A thorough documentation with all the necessary information is crucial in this stage of the derogation process.

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[56] SYNERGETICS - D4.6

2. Submission of the application

For both certificates the submission of the application needs to go via the CCNR-secretariat through the RV/G working group for the Rhine Vessel Inspection Certificate and through the CESNI-PT working group for the Union inland navigation certificate.

3. Technical Examination

The working group experts and member states together have to do the internal technical examination.

4. Approval Process

Rhine vessel certificate: Receiving the adopted Rhine Vessel Inspection Certificate together with the recommendation based on the derogation proposal. This also comes with conditions on which the derogation is allowed, for example time intervals for inspections, duration of the derogation, which sailing areas are allowed, etc.

Union inland navigation certificate: Receiving the Ship Certificate and the implementing act with a communication of the European Commission to the Member States. This implementing act mentions the requested derogation and the conditions which need to be met, for example time intervals for inspections, duration of the derogation, which sailing areas are allowed etc.

In the derogation process the main element in convincing the CCNR and CESNI-PT to allocate a certificate of approval is to prove that the vessel is equally safe as a conventional diesel vessel with similar dimensions and sailing profiles.

Important to note here is that compressed hydrogen is an ADN class 2 classified substance (UN-1049) and in case of the of hydrogen ICE it is also not zero-emission at the tailpipe. For example, there can be NOx emissions which may need mitigation by application of an SCR. This means that a hydrogen ICE engine that is approved through a derogation process in accordance with Article 34 or 35 of the NRMM-Regulation has to comply with the Stage V emission limits. These elements need to be taken into account during the design phase of the derogation procedure.

6.2.2 Coastal vessels

For coastal vessels the regulatory framework of the IMO applies. Regarding the IMO the International Convention for the Prevention of Pollution from Ships (MARPOL) and International Convention for the Safety of Life at Sea (SOLAS) regulations are relevant for the issuance of ship certificates. Where the MARPOL convention outlines the emission limits to which an engine has to oblige to, the SOLAS convention includes the safety regulations of the vessel.

Same as for the IWT sector the current legal framework reflects the fact that there are no detailed and prescriptive IMO regulations to support Flag administration approval for ships using hydrogen. Consequently, IGF Code requirements for these alternative fuels remain non-mandatory or are in the process of being developed because they exist only as interim guidelines until adopted into IGF Code. CCC 11 finalized interim guidelines for the safety of ships using hydrogen as fuel. The interim guidelines are limited to liquefied hydrogen concepts, as well as portable compressed and fixed compressed hydrogen concepts, all of which should be fitted on open deck.

In the IMO guideline SOLAS, which is described in more detail in section 2.2, it is described that exemptions can be made if one can prove equal safety standards compared to conventional diesel. This exemption can be approved only by the flag state administration under which the vessel owner will sail. In section 5.6 of SYNERGETICS Deliverable 4.6 a detailed flow diagram on the different steps within the exemption approval process is shown. Below a summary of this process is given.

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1. Initial consolidation meeting

The first step in the approval process is to have an initial consolidation meeting between the flag state administration and every party involved in the vessel development. This includes the vessel owner, the shipyards vessel builder and designer, the recognised organisation/classification society, and any other stakeholder that will be involved. In this meeting the project is introduced, initial designs are discussed, a plan and timeline regarding the safety assessments is developed and acceptance criteria for the certification will be defined. The latter is crucial to be included in this meeting because the required risk assessments and certification criteria are determined case-by-case.

2. Preliminary design

Based on the outcomes of the initial consolidation meeting the design team will develop the required documentation, including the agreed upon plans, reports and design drawing.

3. Preliminary approval

After the design team hands over the agreed upon documentation the Flag state administration will give a preliminary approval if the design seems feasible and if all the safety measures and critical hazards are adequately addressed. The preliminary approval generally includes detailed descriptions of improvements that have to be made for the final approval. It should be noted that the preliminary approval does not guarantee a final approval. If the design team fails to implement the improvements outlined in the preliminary approval the final approval will not be given.

4. Final design

With the preliminary approval the design team can start developing the final design. The final design includes besides the development of the detailed drawing and system integration plans also system testing and further detailed risk assessments.

5. Final approval

When the design team has finished the final designs and all the required system tests and risk assessments are complete the flag administration or a recognised classification society that works on their behalf, will give the final approval if they deem the design to meet all the agreed upon criteria. After the final approval is obtained, the vessel is allowed to sail on Hydrogen under the condition that the approved design is used.

There is no fixed timeline how long this process of approval will take since it will be a case-by-case process. However, do keep in mind that it will be a time and cost consuming process with the risk of not getting the final approval if not being thorough enough and in case of lacking preparation. For the emission limits as mentioned before coastal vessels have to comply with the MARPOL emission reduction targets and coastal vessels that are in scope of SYNERGETICS also have to comply with emission related regulations. These regulations include the EU-ETS for cargo and passenger vessels above 5000 GT and the Fuel-EU Maritime for cargo and passenger vessels above 5000 GT based on MRV.

When choosing a hydrogen fuel cell solution, no emissions are emitted to air. Using hydrogen from fossil fuels (e.g. made from natural gas) does, however, lead to higher well-to-wake (WTW) emissions compared to fossil diesel. Therefore, it is strongly recommended to use green hydrogen as a renewable fuel, the so-called Renewable Fuel of Non-Biological origin (RFNBO). This is assigned by regulation at a zero WTW GHG intensity for FuelEU Maritime and for ETS and MRV no CO2e emissions are calculated. However, in reality there is still some WTW emissions as was also presented in WP1 of SYNERGETICS[57].

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[57] See for example the SYNERETICS Deliverable 1.2: https://www.synergetics-project.eu/wp-content/uploads/2026/04/SYNERGETICS_D1.2_Report-on-suitability-of-identified-technical-solutions_FINAL-V2.pdf

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Moreover, grey hydrogen still has a large Well-to-Tank (WTT) emission profile, which is an issue for FuelEU Maritime compliance as it applies the WTW scope (grams CO2e per MJ). But from tank-to-wake perspective there are no CO2 emissions, so for MRV and ETS there are no CO2 emissions to report when using fossil hydrogen.

Both hydrogen ICE solutions emit NOx emissions. Therefore, in order to comply with the MARPOL emission limits all the engines need to be Tier III graded. For a hydrogen dual-fuel system it is also mandatory to use either VLSFO or ULSFO to comply with the MARPOL SOx emission limits.

For the EU regulations regarding GHG emission it depends on which ICE configuration (which blend) is used and whether green or grey hydrogen is used to which degree the vessel would comply with all emission targets now and in the future. A hydrogen ICE single-fuel emits no GHG emission from tank-to-wake perspective which is favourable for ETS and MRV. In the case of hydrogen ICE dual-fuel it depends of course how much (fossil) diesel is used in the blend, but coastal vessels can, as mentioned before, reach a blend of up to 85 % which still results in a significant emission reduction compared to diesel engines. It does, however, require emission monitoring which is an administrative downside of using a hydrogen ICE dual-fuel solution instead of an ICE single-fuel solution. For the ICE solutions the same counts for the fuel cell solution, grey hydrogen has a large WTT emission factor. This can result in issues to comply with FuelEU Maritime and also in the future in case other regulations (such as MRV and ETS) will shift towards a full WTW approach instead of the limited TTW focus. Usage of fossil hydrogen (usually produced from fossil natural gas) is therefore only seen as a temporary solution in case green hydrogen is not available.

6.3 Vessel type specific scenarios

6.3.1 IWT

Using hydrogen as fuel is an effective solution to reduce the tank-to-wake (TTW) emissions, and when using the RFNBO type hydrogen it is also effective to reduce the GHG emissions on well-to-wake scope (WTW). In theory, the solution could be used on any vessel type. In practice however, two limitations do give resulted in a smaller scope of vessels which would be suitable to use hydrogen as fuel.

The first characteristic of hydrogen is the very low density of hydrogen at ambient conditions. This makes it required to stored it either at high pressure (350-700 bar) or cryogenically (around -253 °C). Both options induce voluminous and heavy fuel-storage systems which give challenges to accommodate it in the vessel. A second characteristic is that hydrogen is highly flammable and explosive, which results into strict fire- and explosion-safety requirements to mitigate the risks. The required systems result into significant investment costs (CAPEX).

Translating these limitations to specific vessel scenarios the storage system volumes and extra safety requirements result in a limited autonomy that a vessel can reach. Sailing 24 hours a day for multiple days in a row is economically not feasible since the fuel storage system takes up much space and would result in too high operational costs because of the investments would be extremely high. At the same time there would be a dramatic loss of payload resulting in high loss of revenues. Furthermore, for some vessel types the required space for energy storage of hydrogen on board is simply not available. For example, large pushers operating as push-convoy on international corridors such as the Rhine or Danube require a high autonomy and have large energy consumption while the available deck space is quite limited. This basically eliminates using hydrogen as fuel for larger push barges which are operated 24/7.

For other vessels there may be options to use hydrogen as fuel. It may however result in significant part of the load capacity or passenger capacity being reduced in order to facilitate the total hydrogen system on board. Here it shall be noted that also a redundancy battery pack is required which requires space and more investments. Furthermore, from the studies done in SYNERGETICS, it was found that hydrogen is a relatively expensive fuel in comparison with other renewable energy types. However, for vessels operating with less autonomy, having the opportunity to frequently bunker without losing too much operational activity, using hydrogen as fuel would be practically feasible.

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Hydrogen's fire and explosion safety requirements bite hardest on ADN-relevant vessels. The propulsion fuel is itself exempted from the ADN, but vessel design and storage layout still need to keep hydrogen fully separated from ADN cargo. For tankers this means no on-deck swappable tanks – fixed below-deck tanks are required, and these refuel much more slowly than tank swaps, reducing productivity. For ADN container vessels, swappable tanks are possible but require physical separation from cargo, which reduces payload and therefore revenue. The same separation logic applies to passenger vessels: hydrogen has to be fully isolated from passenger spaces, which again makes swappable containers difficult.

Besides technical limitations hydrogen also comes with economic limitations. Energy costs of green hydrogen are significantly higher compared to other renewable options. This means that the operational expenses (OPEX) of large fuel consumers will be very high. In combination with high investments (CAPEX) this results in a poor business case. Other alternatives like liquid bio-methane, usage of green methanol or HVO are expected to be much more cost-effective to reduce GHG emissions and can reduce air pollutant emissions at the same time. Moreover, on the medium- and longer-term usage of fixed or swappable batteries is expected to be a competitive solution to achieve zero tank-to-wake emissions, once there is an extensive network of recharging points and swapping terminals along international corridors.

All the challenges for using hydrogen on inland vessels lead to very limited uptake so far of this option. Logically the infrastructure for bunkering hydrogen is also quite limited. This reduces the areas in which sailing on hydrogen is currently practically possible. These limitations can be partially overcome by sailing on a fixed route with a long-term contract. Some companies also have hydrogen as a waste product or create hydrogen with a local electrolyser. By committing to a long-term contract with these types of entities the hydrogen can be obtained at a lower price. For a large-scale breakthrough however, a significant reduction needs to be seen in the price levels of green hydrogen.

6.3.2 Coastal vessels

Hydrogen fuel-cell systems offer a clear zero-emission pathway, but storage volume, safety, cost and energy density all narrow down the practical use case. For coastal shipping, hydrogen is therefore mainly relevant for specific vessel types and operating profiles. It is not expected to be a large-scale solution. The price of green hydrogen would need to be reduced massively to make hydrogen competitive compared to other options.

In general, hydrogen is less suited for longer routes, due to lower volumetric energy density in combination with safety requirements (cofferdams, hazardous-zone separation, and ventilation). For ferries, hydrogen is applicable on short, fixed routes with predictable schedules, where dedicated refuelling infrastructure can be developed in the ports. However, the safety regulations play a critical role in adaptation, also for the refuelling infrastructure on shore. Moreover, on such fixed routes over relatively shorter distances, the hydrogen fuel application competes with battery-electric systems. The battery systems have even less energy density but seem a lot more viable from an economic viewpoint. In offshore support vessels (OSV's), hydrogen systems are technically feasible but complex and costly. For OSV's fuel-cell systems can be used in combination with batteries to support quick variations in power demand. Hydrogen could be integrated below deck, but many concept designs prefer hydrogen tank placement on deck to manage safety and ventilation requirements, which impacts deck space. Furthermore, for smaller fishing vessels, the volume, weight and safety requirements often make hydrogen

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impractical[58]. In contrast, for larger fishing vessels with short routes and moderate power demand, hydrogen in combination with a fuel cell could technically be feasible, provided the vessel is large enough to accommodate pressurized tanks, safety systems, and auxiliary equipment[59]. For dry cargo coastal vessels, the application mainly depends on whether vessels are weight-critical or volume-critical, as hydrogen storage is primarily volume-intensive, which limits operational and economic feasibility for many coastal vessels.

Regarding technical requirements, pressurized hydrogen storage results in significant volume requirements, making autonomy a key limiting factor. Liquified hydrogen (cryogenic) could be considered as an alternative, but liquification costs energy and the fuel would also be more costly and heavier and more expensive tanks are needed. So far, there was only one pilot realised in Norway, the ferry MF Hydra[60]. Since there are no more upcoming projects known by today, the liquified option is therefore left out of scope of SYNERGETICS. Fixed tanks for compressed storage simplify integration but permanently occupy volume, while swappable tanks can reduce downtime but require specialised port infrastructure and international standardisation. Additionally, combustion engines could be retrofitted to dual-fuel hydrogen-diesel engines but need to make sure that the ECA NOx emission limits are respected. Furthermore, the commercial viability for marine applications is still lacking due to high costs for both the investment and operation (energy costs). In additional there is regulatory uncertainty as well.

Retrofitting typically involves removing the conventional propulsion system, adding fuel cells, batteries, and hydrogen storage, and converting the vessel to a fully electric architecture. Fuel-cell systems require hydrogen of very high-purity and are sensitive to fuel quality. From a climate mitigation perspective, fossil-based (grey) hydrogen offers no well-to-wake benefits, on the contrary, it gives more GHG emissions compared to usage of fossil diesel fuel. Therefore, the compliance depends on access to green or low-carbon hydrogen.

In general, it can be concluded that hydrogen may be considered by vessel owners which operate on short, fixed coastal routes with predictable energy demand. In addition, there shall be an opportunity to justify high upfront investments (e.g. through access to grant schemes or a client willing to pay the additional costs). Moreover, the advanced safety concepts and crew training need to be acceptable as well for the vessel owner. Key limitations to consider include the high CAPEX for storage, fuel-cell systems, and safety integration and high OPEX because of the high fuel costs and maintenance. Furthermore, increased design complexity related to explosion and fire safety and increased volume and weight requirements, which reduce cargo, passenger, or operational space are elements to take into account. Additionally, future compliance of this option is dependent on the availability and reduction of cost of truly low-carbon hydrogen.

Overall, hydrogen fuel cell systems are technically proven but remain costly and operationally restrictive for most coastal vessels. Near-term applications are likely to remain limited to demonstration projects

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[58] Jafarzadeh, Sepideh, Jarle Ladstein, Anders Ødegård, et al. "Electrification of the Coastal Fishing Fleet Using Hydrogen and Ammonia-Fed Fuel Cells." Paper presented at ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering. September 22, 2023. https://doi.org/10.1115/OMAE2023-101707.

[59] Giannini, Leonardo, Sepideh Jafarzadeh, Alessandro Campari, Federico Ustolin, and Nicola Paltrinieri. "Inspection Planning in the Marine Sector, A Case Study of a Hydrogen-Fuelled Fishing Vessel." Paper presented at ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering. September 22, 2023. https://doi.org/10.1115/OMAE2023-100914.

[60] https://www.norled.no/en/nyhet/mf-hydra-the-worlds-first/

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and highly specific operational niches until fuel availability, infrastructure, and regulatory frameworks mature further.

6.4 Example cases

6.4.1 IWT

H2Barge1

Operator: Future Proof Shipping
Operation area: Between the Port of Rotterdam (the Netherlands) and the BCTN port in Meerhout (Belgium)
Year of construction: 2023 (retrofit year)
Source: [61]

Vessel type: Motor vessels dry cargo (L ≥ 110 m) (containers)
Vessel size: length 110m, width 11.45m (23.5m in case of 2 barge setup is used), draught 2m.
Propulsion system: It has three PEM hydrogen fuel cell units with each a power of 275 kW which are connected to an 800 kW electro-motor. In total 2 containers with each 500 kg of hydrogen under 300 bar can be stored on board which is supported by a 504 kWh fixed battery on board.
Benefits: Its fixed route between the port of Rotterdam and Meerhout in Belgium, where the port of Meerhout provides the service of swapping the hydrogen fuel storage containers, makes it suitable for hydrogen sailing using swappable fuel storage tanks. It is also estimated to save about 2000 tons of CO2e each year.

ZULU 06

Operator: Sogestran
Operation area: France
Year of construction: 2024
Source: [62]

Vessel type: Motor vessels (L < 80 m)
Vessel size: Length 55m, Width 8m, Draught 1.5m
Propulsion system: It has 2 fuel cell systems with each a power output of 200 kW and a hydrogen storage capacity of 300 kg stored under 300 bar, which is good for maximum range of 500 km.
Benefits: It is a small vessel designed to supply different types of goods within urban areas. These vessel types usually require low power outputs and travel small distances with makes frequent bunkering possible. It is also zero emission in urban areas which improves air quality in these areas and, therefore, human health in these areas.

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[61] Fleet – Future Proof Shipping, H2 Barge 1 - Schepen (picture), VESSEL REFIT | H2 Barge 1 – Dutch operator adds hydrogen-powered boxship to inland fleet

[62] Sogestran news: [Logistics] Christening of the ZULU 06 (picture), France's first hydrogen-powered inland vessel, ZULU 06 (MMSI 226016710), Inland, Motor Freighter | Position & specs

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Antonie

Operator: NPRC
Operation area: Delfzijl to the Botlek (Rotterdam)
Year of construction: 2023
Source:[63]

Vessel type: Motor vessels dry cargo (L ≥ 110 m) (dry bulk)
Vessel size: Length 135m, Width 11m, Draught 3m.
Propulsion system: It is a hydrogen-electric vessel with two 500 kW electric propulsion engines, a 600 kW back-up generator and a supporting 420 kW Bow thruster supplied by a 320 kW fuel cell system, 1200 kg of hydrogen under 300 bar and a fixed 1100 kWh battery pack.
Benefits: The combination between using hydrogen and battery electric sailing with a back-up generator creates fuel use flexibility while also being able to sail zero-emission and save up to 880 tonnes of CO2e per year. Its fixed route and long-term contract with a salt manufacture that has hydrogen as waste product results in easy hydrogen access and a business case for this vessel.

Ms. Letitia

Operator: HTS Group
Operation area: Rotterdam, Antwerp-Bruges, and Duisburg
Year of construction: 2012
Source: [64]

Vessel type: Motor vessels dry cargo (L ≥ 110 m) (containers)
Vessel size: length 135m, width 17.5m, draught 3m
Propulsion system: The Letitia is diesel-electric combined with a full-scale hydrogen FC engine system. It has 2 main electrical engines of each 1600 kW with a fix battery system that has a total capacity of 1030 kWh and a 1,2 MW fuel cell system. The diesel part fungates as back-up and consists out of 4 diesel generators. Due to this combination the Letitia can sail fully electric, fully on hydrogen, diesel-electric, or fully on diesel resulting in fuel flexibility.
Benefits: It can sail zero emission and has a great fuel flexibility since it can use electricity, hydrogen, and diesel. It is also equipped to sail autonomic.

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[63] PowerPoint-presentatie, Startsein eerste nieuwbouw binnenvaartschip groene waterstof | NPRC (picture), ANTONIE (MMSI 244030668), Inland, Motor Freighter | Position & specs, WEVA Project | Zero-Emission Binnenvaart

[64] Letitia - Schepen, Letitia is paradepaardje voor de hele binnenvaart - Binnenvaartkrant (picture), 100-jarig Olthof viert oplevering 'modernste schip op de Rijn' - maritiemmedia.nl

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Mannheim I + II

Operator: RHENUS
Operation area: Between the ARA corridor and Duisburg (Germany)
Year of construction: 2024
Source: [65]

Vessel type: Coupled convoy (containers)
Vessel size: Length 193 m, Width 11.45 m, Draught 1.2 m to 2.9 m
Propulsion system: It is a diesel-electric vessel that also sails on hydrogen, where the vessel is powered by two electro engines of each 960 kW supplied by 5 × 390 kW Euro 6 engines, a 840 kWh fixed battery pack and up to 4 20ft hydrogen storage container that can store 500 kg of hydrogen under 500 bar each.
Benefits: Its modular design offers great fuel use flexibility and due to the installed flex-tunnel it can sail in waterways with a minimum depth of only 1.2m. Besides its future proof vessel design it can reduce CO2e and NOx emissions by 100 % when sailing on hydrogen and when using HVO100 for the diesel generators also high reduction values can be obtained.

6.4.2 Coastal vessels

HydroBingo

Operator: JPN H2YDRO (CMB Tech involvement)
Operation area: Japan
Year of construction: 2021
Source: [66]

Vessel type: Ferries (0 kW ≤ P < 1000 kW)
Vessel size: Length 19.4m, Width 5.4m, Draught 1.75m
Propulsion system: It has two hydrogen Dual-Fuel engines with each a power of 441 kW. The hydrogen is stored in a mobile trailer on board.
Benefits: Due to its Dual-Fuel configuration it can reduce CO2e emissions by up to 50 %. Dual-Fuel engines also have the benefit to be able to sail fully on diesel/HVO in case hydrogen is not available. The mobile hydrogen trailer allows for quick fuel changes reducing bunker time loss.

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[65] D4.1 Stocktaking and good practices, Nachhaltige Schifffahrt: Wasserstoff-Schiff ausgezeichnet (picture),

[66] VESSEL REVIEW | HydroBingo – World's first hydrogen ferry starts operating in Japan (picture), Hydro BINGO, the first hydrogen-powered ferry, has been presented | PRESS RELEASE | JPNH2YDRO CO., LTD.

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7. Methane engine solutions

Summary on methane solutions:

Most suitable for: Larger IWT fuel consumers with space for cryogenic tanks, coastal ferries and OSVs in regions with developed LNG bunkering, as a near-term step before Bio-LNG availability scales.

Not suitable for: Smaller IWT vessel types and push boats (cryogenic tank does not fit), coastal vessels in regions without LNG bunkering, applications where methane slip outweighs CO2 reduction.

Open points: Methane-slip A-factor evolution in NRMM; Bio-LNG supply growth versus competing renewable fuels; ETS/FuelEU compliance dynamics post-2035 when LNG-only is no longer sufficient; on-board carbon capture (CCS) potential.

7.1 (Bio-)LNG ICE

A (Bio-)LNG retrofit is increasingly seen as a pragmatic near-term route for vessel owners aiming to cut emissions. Its main strength is the strong reduction in NOx and PM air-pollutant emissions. When the methane is sourced from waste or biological feedstocks (e.g. wet manure), large CO2e reduction can be achieved. Switching to LNG can already significantly lower carbon dioxide emissions, up to 20 % (depending on the methane slip), while virtually eliminating SOx and PM.

When Bio-LNG is used, which is chemically identical to LNG but derived from renewable sources, the lifecycle carbon footprint is assumed to be reduced to 85 percent on average[67] and with some feedstocks achieving even higher reductions (e.g. using wet manure in closed process for the production of Bio-LNG). Compared to HVO, it is expected that Bio-LNG can be produced from a wider range of feedstocks and at lower prices. This could be favourable for the total costs of ownership, especially when using large amounts of fuel.

Additionally, methane gas engines typically produce less noise and vibration than diesel engines, which can improve onboard comfort and reduce engine wear. However, it has to be noted that in all cases methane is an issue to consider as this is also a gas causing global warming with a stronger impact, a factor 27, compared to CO2[68] according to the IPCC (United Nations Intergovernmental Panel on Climate Change). This means that when the methane slip is larger than 3.1 % it would worsen the GHG emission impact compared to sailing on diesel. Methane slip, the release of unburned methane during operation, can partly diminish the climate benefits of LNG if the ignition or exhaust gas after treatment are not properly managed. As a result, mitigation measures were taken in the NRMM Stage V to set limits to the maximum level of methane emissions in the exhaust gasses. The engine technology itself is mature and proven, with multiple engine manufacturers offering dual-fuel solutions as well as single fuel solutions for methane gas, addressing the methane slip issues as well. The retrofit of a vessel can be designed to comply with international safety standards such as the IGF Code.[69]

Despite these advantages, retrofitting to LNG or Bio-LNG is not without challenges. The capital expenditure is substantial, as it involves either converting existing engines to dual-fuel operation or replacing the engines entirely, as well as installing expensive cryogenic storage tanks, high-pressure fuel gas supply systems, and comprehensive safety systems. LNG tanks require considerably more space than conventional fuel tanks, which may reduce cargo capacity or affect vessel stability, particularly on smaller ships. Moreover, the availability of Bio-LNG is still limited in many regions, and it yet commands a premium price compared to fossil LNG since there is no internalisation of external costs of GHG

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[67] SYNERGETICS D4.5 The Catalogue of greening retrofit solutions

[68] IPCC AR6 Methane GWP Tables | GHG Management Institute

[69] International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code)

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emissions in the price of LNG. Bunkering infrastructure for LNG, while well-developed in Europe, is not yet omnipresent, which can complicate route planning for vessels in both the IWT and coastal sector. For the longer term, it creates a dependency on renewable drop-in alternatives such as bio-methane or methane as RFNBO (Renewable Fuels of Non-Biological Origin) using green hydrogen, also known as e-LNG.

7.2 Methane engine specific regulatory framework

7.2.1 IWT

As presented in chapter 2, three regulatory frameworks are relevant for IWT vessels with respect to the scope of SYNERGETICS. One is the "Non-Road Mobile Machinery (NRMM) regulation (EU 2016/1628)" which regulates the emission limits for newly installed engines from 2021/2022 onwards. Within the NRMM regulation, methane is a formal reference fuel. No derogation process is required for the engine. For the mitigation of methane slip emissions, a specific provision is included, the so-called A-factor which sets an absolute limit at 6 grams of C_xH_y emissions per kWh.

Another regulatory framework is ES-TRIN. As mentioned, this framework includes all technical requirements to which a vessel has to comply to and the latest version the "ES-TRIN edition 2025/1" has been implemented in January 2026. The technical requirements for sailing on a fuel with a flashpoint lower than 55 °C like LNG is outlined in chapter 30 and specific regulations on LNG can be found in Appendix 8 chapter 1 of the ES-TRIN[70]. These guidelines, for example, include where the cryogenic storage system has to be placed, to which standards the system needs to comply with and what type of safety measures are required. The guidelines do not require any additional regulatory steps or derogations for the vessel owner. However, they will affect the cost and space requirements of the system and will, therefore, be of importance for the vessel designers. Also, it needs to be noted that compressed storage of methane (known as 'Compressed Natural Gas' (CNG)) is not regulated in the ES-TRIN. This is seen as a gap by some stakeholders, in particular to apply (bio)methane as fuel for smaller vessels which may be able to use compressed storage. Using compressed storage for methane would therefore require a derogation process similar to the process for methanol or hydrogen to get the CCNR or CESNI approval.

Another relevant regulation is the ADN which covers the safety regulations for transporting dangerous goods. LNG is listed under the name methane as a class 2 dangerous good with the classification number UN-1972. Since LNG is a fuel with a flashpoint below 55 °C it was historically not allowed to be used. After the uptake of LNG in the ES-TRIN an exemption was made for fuels like LNG as long as they comply with chapter 30 of the ES-TRIN regulation. Just as for the ES-TRIN the ADN does not require additional regulatory steps that have to be taken, it only increases the required safety measures that need to be included in the vessel design and also for the engines (e.g. the fuel systems), which can create additional requirements set by certification bodies.

7.2.2 Coastal vessels

The applicable rules for coastal vessels are differentiated. It depends on the type of vessel, the registered flag state and its size (e.g. thresholds at 400 GT and 5000 GT) which legislation is relevant. legislation is relevant. Coastal vessels are subjected to IMO legislation and their flag state law, but coastal vessels sailing under an EU flag state are also subjected to EU legislation. EU legislation on its turn excludes certain types of vessels and vessels below a certain gross tonnage from its legislation. This results in the fact, that the legislative landscape can differ case-by-case for coastal vessels.

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[70] ES-TRIN 2025/1 - European Standard laying down Technical Requirements for Inland Navigation vessels

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The SOLAS convention includes all technical requirements to which a coastal vessel that is subjected to the IMO regulations has to comply with. The technical requirements are made applicable in the SOLAS convention through the IGF code, which includes all the technical requirements for sailing on low flash-point fuels (flashpoint below 60 °C) and gasses like LNG, and the IGC code, which includes all the technical requirements for the transport of liquified methane gas. This means that technical requirements of sailing on LNG exist and no derogation process is required to get relevant ship certificates for the vessel as long as these requirements are followed. A flag state administration can impose extra or deviating technical requirements especially in the case of coastal vessels that are not in the scope of SOLAS.

As second IMO regulation that is of importance for all coastal vessels is the International Convention for the Prevention of Pollution from Ships (MARPOL), which denoted the emission limits in the different Emission Control Areas (ECAs). In the ECAs emission limits GHG emissions, Sulphur Oxides (SOx) and Nitrogen Oxides (NOx) are imposed where the latter two are referred to as SECAs and NECAs respectively. The coastal vessels in scope of SYNERGETICS all sail in SECAs and NECAs, which leads to the obligation of having an IMO Tier III graded gas engine and the use of VLSFO, ULSFO (in case of dual fuel configuration) or SOx exhaust gas cleaning systems to meet the emission limits.

EU flagged coastal vessels not only have to comply with the MARPOL limits, but also to the EU Emission Trading System (EU-ETS) if it concerns cargo and passenger vessels above 5000 GT and the Fuel-EU Maritime. Next to these, there is the Monitoring, Reporting and Verification (MRV) regulation for cargo, passenger, and offshore vessels above 400 GT. Fossil LNG has a slight reduction in emissions compared to diesel and will result in slightly less costs for ETS compliance. However, usage of LNG could not be sufficient to meet the emission reduction targets for Fuel EU Maritime from the year 2035 and certainly is not enough anymore from 2040 onwards. Therefore, Bio-LNG can provide added value as ‘drop-in fuel’ to reach the emission targets on medium/long term.

7.3 Vessel type specific scenarios

7.3.1 IWT

For larger inland fuel-consumers, (Bio-)LNG is competitive with other renewable options and offers real emission-reduction potential. The practical catch is the cryogenic tank: methane must be stored at -162 °C, and even modest LNG volumes require a substantial on-board tank. This requirement effectively rules LNG out for the smaller IWT vessel types and push boats.

When a cryogenic tank does fit, LNG can be cost-competitive with diesel for large fuel consumers, depending on the actual prices. The catch is that the LNG-diesel price gap is volatile and has disappeared in recent years – a pure LNG strategy is therefore risky in isolation. The picture changes with the Bio-LNG outlook: Bio-LNG is currently expected to be cheaper than methanol, HVO or hydrogen on a per-MJ basis, which restores the medium to long term business case. The realistic candidates are new push boats and existing or new larger tankers, motor vessels and coupled convoys.

7.3.2 Coastal vessels

LNG is a mature fuel that has already been adopted in parts of the coastal fleet. Its strengths are clear NOx, SOx and PM reductions and relatively low fuel cost. Its limitation is methane slip, which caps the long-term GHG-reduction potential and positions LNG as a transitional fuel until roughly 2035/2040, with FuelEU Maritime targets in mind for vessels above 5000 GT. The vessel-side requirements are also significant: cryogenic storage and insulation, dedicated fuel-treatment systems, and lower volumetric energy density than diesel, which translates into either reduced autonomy or reduced payload.

For ferries, LNG is well-researched and operationally proven, and the bunkering network is comparatively well-developed — both clear advantages over other alternative fuels. Momentum has slowed somewhat because of prices increases of LNG relative to diesel and also because of the IMO and EU concerns over methane slip emissions, also in the well-to-tank scope, which compromise the overall GHG savings. For OSVs, LNG offers a relatively cost-effective short to medium term solution when

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compared to HVO, methanol, hydrogen. For fishing vessels, LNG is less attractive: the complexity, CAPEX and safety requirements of cryogenic systems (especially the tank) do not match the limited on-board space and tight economic margins typical for this segment[71]. For dry cargo vessels, LNG outperforms other alternative fuels on volumetric energy density, fuel cost and bunkering-infrastructure maturity[72], but still significantly reduces voyage distance and cargo attainment rates [73], limiting the applicability for coastal dry-cargo operators.

Retrofits of conventional diesel engines are feasible, but safety measures, tank placement and structural changes drive significant cost[74]. Furthermore, research on improving engine efficiency, optimising ignition timing, and recovering energy from the cryogenic storage, as well as combining LNG propulsion with CCS to improve emissions reduction is ongoing[75].

LNG is most attractive for vessel owners who seek a cost-effective, proven technology for short-term emission reduction and compliance with IMO and EU regulation as long as these vessels have sufficient space for cryogenic tanks and fuel treatment or benefit from more well-developed LNG bunkering infrastructure. However, methane slip can partly reduce climate benefits, which makes a step to Bio-LNG or e-methane (RFNBO) required for the long-term compliance. Furthermore, CAPEX and volume are increased due to cryogenic storage, insulation, and safety systems. Additionally, application could risk lock-in as policy focus shifts to zero-carbon fuels.

Overall, LNG has been one of the most-researched and most-applied alternative fuels of the past decade, offering short-term benefits in emissions and operating costs. However, LNG is increasingly positioned as a bridging solution, rather than a final pathway toward compliance, although the perspectives for Bio-LNG are promising if compared to other renewable alternatives such as methanol, hydrogen or renewable diesels.

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[71] Fadaie, Sina, Patricia Thornley, and Jean-Baptiste Souppez. “A Systematic Review of Technologies, Measures, and CO2 Emission Reduction Potential for Maritime Transport Decarbonisation.” *Advances in Applied Energy* 20 (December 2025): 100255. https://doi.org/10.1016/j.adapen.2025.100255.

[72] Zhang, Wanying, Jing Wang, Geng Qin, Satpathi Kuntal, Fuzhong Gong, and Ran Yan. “Review of the State-of-the-Art of Alternative Marine Fuels: A Viable Approach to Zero-Carbon Shipping.” *Cleaner Logistics and Supply Chain* 16 (September 2025): 100232. https://doi.org/10.1016/j.clscn.2025.100232.

[73] Law, Li Chin, Epaminondas Mastorakos, and Stephen Evans. “Estimates of the Decarbonization Potential of Alternative Fuels for Shipping as a Function of Vessel Type, Cargo, and Voyage.” *Energies* 15, no. 20 (2022): 7468. https://doi.org/10.3390/en15207468.

[74] 1Zhang, Wanying, Jing Wang, Geng Qin, Satpathi Kuntal, Fuzhong Gong, and Ran Yan. “Review of the State-of-the-Art of Alternative Marine Fuels: A Viable Approach to Zero-Carbon Shipping.” *Cleaner Logistics and Supply Chain* 16 (September 2025): 100232. https://doi.org/10.1016/j.clscn.2025.100232.

[75] Park, Chybyung, Insik Hwang, Hayoung Jang, et al. “Comparative Analysis of Marine Alternative Fuels for Offshore Supply Vessels.” *Applied Sciences* 14, no. 23 (2024): 11196. https://doi.org/10.3390/app142311196.

7.4 Example cases

7.4.1 IWT

ARGONON

Operator: Deen Shipping
Operation area: Rotterdam (Netherlands) to Basel (Switzerland)
Year of construction: 2011
Source: [76]

Vessel type: Motor vessels liquid cargo (L ≥ 110 m)
Vessel size: Length 135 m, 16.2 m, draught 4.95 m
Propulsion system: It has two LNG Dual-Fuel engines with each a power of 1135 kW using 80 % LNG and 20 % diesel. It also includes two microturbines of each 30 kW fully powered by LNG for water heating and central heating.
Benefits: The LNG Dual-Fuel system offers flexibility in diesel and LNG use, it can facilitate autonomies of multiple days without having to bunker, and it reduces emissions especially when Bio-LNG is used while still being competitive with sailing on 100 % diesel.

Somtrans LNG

Operator: Somtrans
Operation area: ARA-area
Year of construction: 2019
Source: [77]

Vessel type: Motor vessels liquid cargo (L ≥ 110 m)
Vessel size: Length 135 m, Width 22.8 m, Draught 5.1 m
Propulsion system: It has two LNG power engines with each a power of 1500 kW and two electrical Bow thruster with a power of 400 kW each supplied by a 90 m^3 LNG tank.
Benefits: It reduces emissions by sailing on LNG without having to sacrifice a significant part of its maximum autonomy. This is especially useful for these types of large energy consuming vessels.

Blue Marjan

Operator: Chartered by Shell and operated by VT Group
Operation area: ARA-area
Year of construction: 2021
Source: [78]

Vessel type: Motor vessels liquid cargo (L ≥ 110 m)
Vessel size: Length 110 m, Width 11.45 m, Draught 3.25 m
Propulsion system: It has two Stage V LNG power engines with each a power of 495 kW, a 277 kW Stage V diesel generator as backup, and two electrical Bow thruster with a power of 425 kW each supplied by a 60 m^3 LNG tank.
Benefits: It runs solely on LNG which reduces emissions without having to sacrifice a significant part of its maximum autonomy.

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[76] Wayback Machine (picture), Argonon | Deen Shipping

[77] scheepvaartwest - Somtrans LNG - ENI 02337993 (picture)

[78] Concordia Damen levert met Blue Marjan eerste van 40 LNG-tankers - Binnenvaartkrant (picture)

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Ms Willem de Vlamingh

Operator: Rederij Doeksen
Operation area: between Terschelling and Harlingen (Netherlands)
Year of construction: 2020
Source: [79]

Vessel type: Ferry
Vessel size: Length 70.6 m, Width 17.3 m, Draught 2.6 m
Propulsion system: hybrid LNG vessel that has 2 LNG engines with each a power of 1492 kW, a heat recovery generating 154 kW worth of electricity and a battery pack of 900 kWh. It also includes two electrical Bow thrusters.
Benefits: The hybrid LNG configuration gives the large fuel consuming ferry enough energy without time loss by using LNG outside the harbour area while the electric part ensures zero emission sailing in residential areas. This combines to low emission, improved human health and unchanged bunker schedules. It is estimated that the electricity part saves about 260.000 liters of LNG fuel which translates into 318 tons of CO2e per year per vessel.

7.4.2 Coastal vessels

ULSAN TAEHWA

Operator: Ulsan ICT Promotion agency
Operation area: Ulsan (South-Korea)
Year of construction: 2022
Source: [80]

Vessel type: Ferries (2000 kW ≤ P < 3000 kW)
Vessel size: Length 89.1 m, Width 12.8 m, Draught 3.3 m
Propulsion system: It has two LNG dual-fuel engines with each a power of 1300 kW supplied by a 60 m^3 LNG tank and a 50 m^3 MGO tank. It also has a fixed battery onboard for zero emission sailing in sensitive areas like the ports.
Benefits: With combination of a LNG dual-fuel engine, a fixed battery onboard, and an optimised energy management system the vessel can reduce emissions by up to 40 % and increase the efficiency by 6 %.

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[79] WILLEM DE VLAMINGH 2020 - IMO 9807580 » Shipdata & Photos (picture), LNG-veerboot Willem de Vlamingh nu hybride — Harlingenboeit, Optimised energy recycling on board: Clean, energy-efficient ferries commence their journeys on the Wadden Sea with waste heat recovery technology from Orcan Energy - en

[80] RINA (Small) Significant Ships catalogus (picture)

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ARMAND-IMBEAU II

Operator: Société des Traversiers du Québec
Operation area: Québec (Canada)
Year of construction: 2018
Source: [81]

Vessel type: Ferries (4000 kW ≤ P < 8000 kW)
Vessel size: Length 92m, Width 26.4m, Draught 4.5m
Propulsion system: double-ended vessel with 4 LNG dual-fuel engines of which two have a power of 1056 kW and two a power of 1584 kW supplied by a 91.8 m^3 LNG tank and a 58.3 m^3 MDO tank. It also has two thrusters each with a power of 2200 kW.
Benefits: By using high LNG blend the NOx, PM and SOx emissions are significantly reduced, where in case that the vessel sails on 100 % LNG the NOx is reduced by 90 % and the PM and SOx are roughly zero**.**

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[81] RINA (Small) Significant Ships catalogue (picture)

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8. Energy efficiency solutions

Summary on energy efficiency solutions:

Suitable for: All vessel types as a "no-regret" complementary measure: solar panels on vessels with sufficient unused deck space or hatch covers, propulsor optimisation on many IWT vessels, aftship replacement on elongated inland cargo hulls, trim optimisation on coastal vessels.

Not suitable for: energy-efficiency measures alone do not deliver zero emissions; they enable other pathways rather than replace them and provide synergetic effects.

Open points: CCNR/CESNI and PLATINA4Action voluntary efficiency instruments for IWT; consistency of EEDI/EEXI/CII benchmark methodology over time; state-aid programmes for efficiency measures, impacts are very much specific for the vessel and operational profile and make generalisation difficult and requires a tailor-made approach.

Alongside new propulsion systems and renewable energy carriers, energy-efficiency measures matter independently. Renewable fuels are expensive and not always available, so cutting the energy demand of the vessel directly improves the business case for every other pathway in this Handbook. This chapter therefore briefly addresses the most relevant efficiency measures.

There are various approaches to achieving better efficiency, such as optimised voyage planning (smart steaming and reduced speeds), as well as optimising load factors and avoiding empty voyages. Another approach involves optimising ship capacity (dimensions), hull shape and propulsion systems (hydrodynamics). All ships, regardless of type, size, transport task or even their energy system, benefit directly from reduced ship resistance and power demand.

The following sections present the technologies with the highest relevance for SYNERGETICS. This includes some information on photovoltaic systems on-board, which is not an efficiency measure per se but helps to reduce the overall GHG intensity of ship operation. As the surface area available for solar panels on typical ships generally yields only a small amount of power relative to the demand for propulsion, photovoltaics is treated here not as a propulsion technology but as an energy-saving option.

Wind-assisted propulsion systems (WASPs) are also experiencing increasing attention for maritime and coastal applications. However, since there are dedicated projects developing different sail systems, ship integration and weather routing, WASPS are left out of scope herein.

8.1 Solar panels

Switching to alternative fuels is the most visible way to cut emissions, but it is also the most capital-intensive. With lower investment, smaller measures offer a useful entry point and sometimes short payback periods. Solar panels are one of those measures – modest impact individually, but cheap, simple to operate, and complementary to almost every onboard energy system. In many cases the PV system has no link to the main propulsion system, but covers a significant part of the auxiliary demand for electric energy. More detail is available in the SYNERGETICS catalogue factsheet (the overall positioning of energy-efficiency measures is described in the Decision matrix in the Executive Summary)[82].

Solar panels fit coastal vessels best: standardised deck layouts make systems cheaper to install and higher-performing per m². On IWT vessels with hatches, solar systems are also feasible but typically need a tailor-made design, which raises cost and lowers power output relative to coastal installations.

The main benefit of solar panels is reduced fuel consumption, with the biggest payoff for vessels that have long idle periods or frequent anchoring. Operationally, solar produces no direct emissions and no

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[82] Solar - Fact Sheet No.6

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noise – an advantage in harbours, densely populated and ecologically sensitive areas where rules tighten and where the vessel operates close to people and habitats. For coastal vessels do not have access to shore power for extended periods, solar can keep the battery state-of-charge up, reduce generator hours and stabilise charging cycles – which in turn extends battery life. Maintenance is low because solar systems have no moving parts, and modern flexible / semi-rigid marine panels allow installation on curved surfaces, so systems can be scaled to deck space and energy demand.

The main limitation of solar is obvious: it depends on sunlight. Output varies with time of day, weather, season and panel orientation, and is effectively zero at night. Solar therefore cannot serve as a standalone power source for most vessels – it always sits alongside batteries, generators or shore power. Available deck area is also limited by safety, operations, shading from masts/equipment and visual requirements, which caps installed capacity. Pay-back times depend on usage pattern, fuel price and local irradiation: vessels operating in Southern Europe can benefit from faster payback periods compared to vessels in Northern Europe.

8.2 Hydrodynamic improvements

Propulsion power demand is dominated by two variables: ship size and operating speed. Larger as well as slender ships have a lower specific resistance (resistance per unit of displacement) thanks to favourable scaling, while speed drives power demand non-linearly – a small increase in speed produces a much larger increase in required power. For inland waterway transport, the picture is further complicated by confined waterways, small under-keel clearance, and the frequent speed and course adjustments typical of IWT operations.

Beyond size, hydrodynamic efficiency is influenced by hull form, loading condition, water depth and the interaction between hull and propulsor. Newbuilds allow extensive hydrodynamic optimisation from scratch; retrofits are by definition more constrained. Even so, several practical measures deliver measurable efficiency gains on existing inland and coastal vessels.

The most accessible retrofit is propeller replacement or modification. As inland waterway vessels are in service for extremely long periods, there is a high probability that their propulsion systems offer scope for optimisation. There are many reasons for this. Depending on when the vessel was fitted out, different configurations were common, which did not necessarily result in the highest efficiency. These initially included propellers without a duct and later, in some cases, excessively long ducts or ducts with an unfavourable profile, which, whilst providing good mechanical protection for the propeller, contribute little to the overall thrust. Furthermore, depending on the operating area, significant wear caused by floating debris or gravel occurs more or less quickly, which is accompanied by a loss of efficiency. Last but not least, it should be noted that the propulsors should be designed to suit both the characteristics of the main engine and the operating conditions. Modern, custom-designed propulsors can result in efficiency gains of up to 20 %, if the replaced propeller(s) and/or duct(s) are worn or do not match the application. Recent research on so-called Tubercle-Assisted Propulsors, e.g. in the Horizon Europe project RESHIP, showed significant energy-saving potential for suitable cases.

For coastal ships, optimising the trim can yield hydrodynamic benefits. By adjusting the longitudinal centre of gravity (LCG) by means of adjusted cargo positioning, operators can reduce resistance and improve propeller immersion, thereby enhancing propulsive efficiency. Inland vessels, however, often face operational constraints: for safety reasons, in rivers, especially when water depth results in a risk of grounding they typically operate with a forward trim (bow-down) when sailing upstream and a trim by stern downstream.

Among the most comprehensive retrofit measures is the replacement of the entire aftship section. While most hydrodynamic improvements for existing vessels are incremental, aftship replacement allows for near-newbuild levels of optimisation. This approach is particularly feasible for inland cargo vessels, given their elongated hull forms. The process involves constructing a new, optimised aftship section—complete with propulsion, accommodation, wheelhouse and steering gear—while the existing vessel remains in operation. Once the new section is ready, the vessel is dry-docked or lifted on a slipway, and the old

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aftship is cut off (typically just forward of the engine room bulkhead). The new section is then welded in place and integrated with the existing midship and forebody, including all mechanical, electrical, and hydraulic systems.

Aftship replacement is more than a hydrodynamic upgrade: it also can reset propulsion technology, bridge equipment and accommodation spaces at the same time. Additional benefits include:

- The new configuration can also accommodate batteries, fuel cells or alternative-fuel tanks (see chapters 4-7).
- Enhanced shallow-water suitability, e.g., by converting a single-screw vessel to a twin-screw configuration with smaller propellers and lower risk of ventilation.
- Integration of adaptive tunnels (Flex Tunnel) to reduce power demand at sufficient draft and ventilation at minimum draft.

With inland vessels often in service for 40 years or longer, fleet renewal based on newbuild ships alone cannot meet the ambitions of the Mannheim Declaration and the EC objectives as mentioned in the EU Green Deal and NAIADES III. Retrofitting existing vessels with alternative energy carriers and prime movers often requires extensive conversion work. Furthermore, this could not be achieved quickly enough, at least not with current European shipbuilding capacity. Therefore, aftship replacement is a credible fleet-modernisation pathway. The cargo sections, the construction of which in Europe would involve high costs, prolonged occupation of shipyard capacity and space, can be reused and fleet renewal comes with a reduced risk of overcapacity. Nevertheless, CAPEX costs for aftship replacement can exceed 60 % of the costs of a complete newbuild ship. Therefore, without CAPEX funding only a limited share of ship owners will make use of this approach. Accordingly, Austria and Germany already run state-aid programmes to incentivise it.

Regulatory point: the ENI (European Number of Identification) is “permanent” with the oldest section of the hull, so it stays even when major sections (bow or aftship) are replaced. The vessel does need to be re-inspected against ES-TRIN after such modifications, and the Union Certificate or Rhine Vessel Inspection Certificate must be updated by the competent national authority to reflect the new data.

Hydrodynamic improvements alone do not deliver zero emissions, but they reduce energy demand – and that matters more every year. Historically, inland and coastal shipping were optimised for transport capacity, CAPEX and crew cost rather than fuel efficiency. With rising fuel prices and tightening regulation, that weighting is now shifting and efficiency is moving up the design agenda. – which lowers the size of any alternative-fuel system needed (see chapters 4-7).

The low energy density of alternative energy storage and fuels (e.g., batteries, hydrogen) and the high capital costs associated with their storage and power systems mean that hydrodynamic optimisation is often a prerequisite for economic viability. By reducing propulsion power requirements, operators can downsize engines and energy storage systems, lowering both CAPEX and operational expenditures (OPEX).

However, efficiency gains should be used to reduce fuel consumption at constant speed rather than to enable faster operation since increases in speed lead to disproportionately higher power demands (typically following a cubic or higher-order relationship). This means, exemplary optimisation can lead to a reduction in energy demand by 20 % or an increase in speed by 5 %.

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In maritime shipping, hydrodynamic improvements also feed directly into the international energy-efficiency metrics:

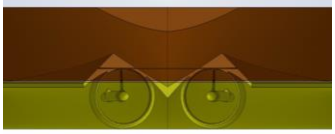
- Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI), which assess the energy efficiency of ship designs and existing vessels, respectively.
- Carbon Intensity Indicator (CII), which measures the CO2 emissions per unit of transport work.

For inland vessels there is no equivalent regulatory framework yet, but CCNR/CESNI and the PLATINA4Action project are developing voluntary instruments to measure energy-efficiency and emissions performance (both GHG and air pollutants).

Hydrodynamic optimisation—whether through propeller upgrades, trim adjustments, or radical measures like aftship replacement—can offer a cost-effective and immediate pathway to reduce energy consumption in inland and coastal shipping. While the technical potential varies by vessel type and operational profile, the economic and environmental imperatives are clear: every percentage point of efficiency gained translates directly into lower fuel costs, reduced emissions, and improved compliance with current and future regulations. As the shipping industry navigates the transition to zero-emission technologies, hydrodynamic improvements will remain a cornerstone of sustainable fleet modernisation.

8.3 Example cases

Hirschhorn / Leonie Deymann
Operator: Reederei Deymann
Operation area: Between Andernach and Basel (Germany)
Year of construction: **2026** (retrofit year)



Vessel type: Motor vessels dry cargo (L ≥ 110 m)
Vessel size: length 135 m, width 11.45 m
Propulsion system: The single screw/Diesel-direct aftship of Hirschhorn was replaced with a twin-screw Diesel-electric with hull-lines designed by DST.
Benefits: With the new aftship the minimum draft without ventilation was reduced by more than 15 % together with a small reduction in power demand.

Ernst Kramer

Operator: RHENUS
Operation area: Rhine corridor and connected waterways
Year of construction: 1974

Vessel type: Dry cargo vessel
Vessel size: Length 105 m, Width 9.5 m
Propulsion system: The vessel was used for a case study on the potential of aftship replacement. Virtually, the existing diesel-direct drivetrain was replaced with a father/son configuration acting through a shared gearbox.
Benefits: Based on hydrodynamic optimisation alone a reduction in power demand between 15 and 30 % was shown depending on load case and water depth without a reduction of cargo capacity and changing the minimum draft. Further potential was shown with the optimised powertrain with right-sized engines for different operational requirements.

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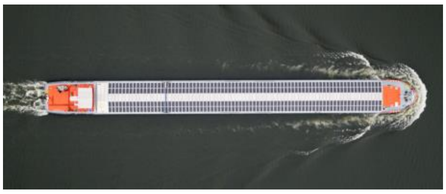
Blue Marlin

Operator: HGK
Operation area: Germany
Year of construction: 2025
Source: [83]

Vessel type: Motor vessels dry cargo (80 m ≤ L < 110 m)
Vessel size: Length 86 m, Width 9.5 m, Draught 1.1 m.
Propulsion system: The hybrid vessel has two 510 kW electrical propulsion engines and a 405 kW thruster at the frond of the vessel, which are supplied by 4 diesel generators, 192 solar panels with 51 kWp and a battery pack.
Benefits: The solar panels deliver up to 51 kW in optimal conditions and are linked to the propulsion system with a 120 kWh battery. It can also cover the hotel loads when berthed, which reduces the need for diesel generators, reducing both emissions and noise in ports independent from onshore power supply.

HS Helios

Operator: HGK
Operation area: Rhine corridor and connected waterways
Year of construction: 2023
Source [84]



Vessel type: Motor vessels dry cargo (L ≥ 110 m)
Vessel size: Length 135 m, Width 11.45 m, Draught 3.8 m
Propulsion system: The hybrid vessel has a total installed power of 2.3 MW supplied by diesel generators with a total power of 1.72 MW, 312 solar panels with a maximum power of up to 117 kW and a battery with a capacity of 109.2 kWh.
Benefits: The solar panels are not linked to the propulsion systems so they can be used either to recharge the battery or to facilitate the energy for the auxiliary and hotel loads. This can save both emissions in sensitive areas and also reduces noise.

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[83] Blue Marlin - Schepen (picture), BLUE MARLIN | 02340620 | Motorvrachtschip | Binnenvaart.eu, Wattlab en HGK Shipping 's werelds eerste hybride binnenvaartschip op zonne-energie - Kijk op Zuid-Holland

[84] MS HELIOS, MS Helios - Blommaert Aluminium Constructions (picture), HELIOS | 02340356 | Motorvrachtschip | Binnenvaart.eu

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