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Study on alternative propulsion on the Danube

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Executive Summary

This study investigates the potential and challenges of adopting alternative propulsion technologies in the inland waterway transport (IWT) sector along the Danube River. It highlights the environmental and economic pressures facing the sector, particularly in the context of the European Union’s ambitious climate goals.

The Danube’s inland fleet, largely dependent on diesel propulsion, significantly contributes to CO_2 and pollutant emissions. However, the aging fleet and slow adoption of new technologies present both challenges and opportunities for transitioning to greener propulsion methods.

Key alternative propulsion technologies evaluated in this study include biofuels, electric propulsion, hydrogen, methanol, and ammonia. Each technology is analyzed based on its technical feasibility, economic viability, environmental impact, and social consequences. The study also identifies the pilot projects and best practices currently being implemented in Europe.

The study makes several important conclusions:
- Biofuels present a short-term solution due to their compatibility with existing engines and infrastructure, but their long-term adoption will depend on sustainable production and regulatory support.
- Electric propulsion offers zero-emission benefits but is constrained by current battery technology and infrastructure challenges, making it suitable mainly for short-range operations.
- Hydrogen and methanol are seen as mid- to long-term solutions for decarbonizing the sector, though they require substantial investments in storage, safety systems, and distribution infrastructure.
- Ammonia shows promise, but its toxicity and handling complexity make it less feasible in the short term.

The report emphasizes the need for significant investment in infrastructure, such as fuel bunkering stations and supply chains, to support these alternative fuels. Collaboration between governments, private stakeholders, and international organizations is essential to achieving a greener future for the Danube’s inland waterway transport.

In conclusion, while the transition to alternative propulsion systems is complex and costly, it is necessary for reducing emissions and aligning with the EU’s decarbonization targets. The report provides strategic recommendations for both short-term and long-term actions, including public-private partnerships, regulatory incentives, and pilot projects that can lead the way towards a more sustainable IWT sector on the Danube.

1. Introduction

The inland waterway transport (IWT) sector along the Danube River plays a crucial role in Europe's logistics network, yet it faces increasing pressure to decarbonize in response to both regulatory and environmental demands. This study explores the potential for alternative propulsion technologies to significantly reduce emissions in this sector. By evaluating current propulsion systems, as well as examining cutting-edge alternatives, the report provides a detailed roadmap for transitioning toward greener, more sustainable solutions.

The structure of the study is designed to guide the reader through the key aspects of this transition, starting with an assessment of the current state of the Danube's inland fleet and propulsion systems and moving toward an analysis of potential alternative technologies. The report also focuses on the infrastructural, logistical, and social challenges that must be addressed to make this transition viable.

Chapter 2:
Current Propulsion Systems: Evaluation of the Predominant Propulsion Systems

This chapter provides an in-depth assessment of the current propulsion systems used in Danube shipping, primarily focusing on diesel engines. It includes a breakdown of vessel types, operational profiles, and environmental impacts. By establishing the baseline emissions and performance of the current fleet, this chapter sets the stage for understanding the urgency of moving toward alternative technologies.

Chapter 3:
Alternative Propulsion Technologies: New Horizons

This chapter explores a range of alternative propulsion technologies, including biofuels, electric drives, hydrogen, methanol, and ammonia. Each alternative is assessed for its technical feasibility, economic implications, environmental impact, and potential social consequences. The chapter also highlights pilot projects and case studies, providing real-world examples of how these technologies are being implemented.

Chapter 4:
Infrastructure and Logistics: Preparing the Groundwork for Change

The successful adoption of alternative propulsion systems requires significant changes in fuel supply chains and infrastructure. This chapter evaluates the current state of fuel infrastructure along the Danube, particularly focusing on bunkering for traditional fuels like diesel. It then examines the infrastructural requirements for biofuels, hydrogen, methanol, and other alternatives, and discusses potential strategies for preparing the Danube to support these new fuels.

Chapter 5:
Comparison of Alternative Propulsion Systems

This chapter compares the alternative propulsion systems discussed earlier in the report, evaluating them based on key factors such as costs, emissions, scalability, and infrastructure needs. The goal is to provide a clear understanding of the advantages and limitations of each technology and how they can be integrated into the Danube's inland waterway system.

Chapter 6:
Conclusions and Outlook: Reflecting on the Journey Ahead

In the final chapter, the report reflects on the key takeaways and looks ahead to the future of inland waterway transport. It emphasizes the need for continued innovation and collaboration to meet the ambitious decarbonization goals set for the sector, while also acknowledging the challenges that lie ahead.

2. Current propulsion systems: Evaluation of the Predominant Propulsion Systems

The foundation of any transition to alternative propulsion systems must begin with a thorough understanding of the current landscape. In this chapter, we will evaluate the predominant propulsion systems currently in use for cargo shipping on the Danube: diesel. By focusing on diesel engines and their associated environmental impact, we will establish a baseline from which future improvements can be measured.

This chapter will set the stage for analyzing alternative propulsion technologies by highlighting the estimated impact of existing diesel dominance, which will help to understand the urgency for sustainable change.

2.1 Danube fleet: numbers

Based on information from Danube Commission-statistics[1], here is an overview of the inland fleet sailing on the Danube, including the distinction between self-propelled and non-propelled vessels:

The Danube fleet consists of approximately 3,500 vessels in total[2].
This can be broken down as follows:

- About 2,652 dry cargo vessels
- 204 liquid cargo vessels
- 642 push boats and tugs

A key characteristic of the Danube fleet is the distribution between self-propelled and non-propelled vessels[3]:

- Self-propelled vessels: approximately 480 vessels (18% of the fleet)
- Non-propelled vessels (barges): about 2,376 vessels (82% of the fleet)[4]

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[1] The Danube Commissions is currently in a process to update statistics including methodology (October 2024)
[2] Web: https://navigation.danube-region.eu/working-groups/wg-3-fleet-modernisation
[3] This contrasts significantly with the Rhine fleet, where about 78% of vessels are self-propelled.
[4] Web: https://pure.tudelft.nl/ws/portalfiles/portal/114634710/s12544_022_00526_5.pdf

The Danube fleet is characterized by several notable features: it is relatively old compared to vessels operating on the Rhine waterway and very few new vessels have been put into operation on the Danube in the last 20 years, i/e 70% of push-boats are over 40 years old. The long lifetime of inland barge engines (15-20 years) results in slow uptake of new engines.

The share of self-propelled vessels is gradually increasing as barges get decommissioned and are replaced by second-hand self-propelled Rhine vessels. The gradual shift towards more self-propelled vessels and the slow but steady introduction of innovative technologies suggest a fleet in transition, adapting to changing economic and environmental demands. That said, modernization and greening measures have been implemented only to a limited extent so far.

2.2 Vessel types: operational profiles per stretch

The Danube River, one of Europe's key waterways, supports a diverse fleet of vessels that operate under unique conditions. From self-propelled cargo ships to pushed convoys, vessels navigate through locks, ports, and varying water levels. Their operational profiles are influenced by factors such as cargo type, seasonal changes, and infrastructural challenges. Understanding these profiles is essential for optimizing transport efficiency, vessel design, and addressing environmental concerns.

Navigating the Danube presents challenges due to its diverse characteristics along its 2,850 km length.

Bottlenecks, such as fairway depths below 2.5 meters, and seasonal fluctuations, restrict vessel drafts and reduce navigable days. The river's infrastructure, with 75 ports and numerous locks, helps manage these challenges, though vessels often require flexible configurations to maintain efficiency year-round.

The Danube is traditionally divided into three sections:

- Upper Danube: From the Black Forest to the Hungarian Gates Gorge, this section features a narrow, rocky bed and meandering channels influenced by alpine tributaries.
- Central Danube: Extending to the Iron Gate Gorge, it has a wide, shallow riverbed and fluctuating depths, traversing plains and receiving major tributaries.
- Lower Danube: From the Iron Gate to the Black Sea, this broad, slow-moving river flows across plains, contributing to the Danube Delta.

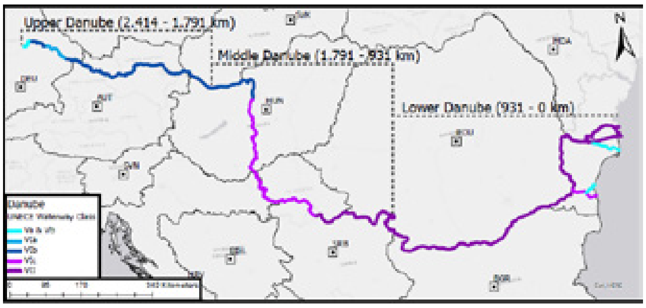

Figure 1: The Danube is traditionally divided into 3 stretches

The Danube fleet comprises a variety of vessel types, particularly larger cargo vessels and push boats, essential for transporting goods efficiently, with pushed convoys being the most common. These consist of pushers and non-motorized barges, optimized for maneuverability. Self-propelled vessels, such as motor cargo ships and tankers, are less prevalent but still significant. Lock sizes put a limit on ship dimensions.

The Danube fleet is operated by a mix of companies: large operators mainly ship dry bulk on long-term contracts and often make use of barge convoys. Smaller companies serve niche markets and short-term contracts. Danube dry cargo vessels typically transport goods like steel, grain, and ore, with capacities between 1,000 and 2,000 tons. Tankers, primarily transporting hazardous materials, have capacities of around 2,000 tons. Container transport is less common but does occur incidentally. Metal products dominate transport on the Danube, followed by agricultural goods. Around 75% of total transport occurs on the Lower Danube, with the Romanian fleet playing a significant role, particularly in dry cargo transportation.

For the entire navigable Danube between Kelheim (Germany) and the Black Sea, including the Danube-Black Sea Canal and Sulina Canal, the cargo transport volume typically ranges between 34 and 40 million tonnes per year[5]. Environmental factors, such as water levels, significantly influence transport volumes, for instance: whereas in 2019 on the Austrian part of the Danube 8.5 million tonnes were transported, this number dropped to 6.0 million in 2023[6].

The fleet continues to evolve, responding to both operational challenges and environmental demands. Two main vessel operational profiles remain and can be categorized based on size, propulsion power, the cargo they carry and the stretch on which they sail:

1. **Push boats**, responsible for moving barge formations, vary in propulsion power, with larger convoys requiring boats exceeding 2,000 kW to handle heavy loads like construction materials, agricultural products, and petroleum. Operating in the Lower and Middle Danube.
2. **Motor cargo vessels**, often over 110 meters long, transport dry and liquid cargo in large volumes, crucial for long-distance transport. Equipped with powerful engines, they navigate the Danube's challenging conditions, such as fluctuating water levels. Although less common, passenger vessels also operate, supporting the region's tourism industry.

2.3 Environmental impact status quo (representative journeys based on data from PROMINENT)

Now that the numbers and vessel types have been identified, it is worth the attempt to make an estimate of the effects of their propulsion systems, primarily diesel engines. To achieve this, several intermediate steps and assumptions must be made. Fortunately, a significant amount of research has already been conducted in this area, providing us with assumptions and important default values that can be utilized to make accurate estimates. By leveraging these research findings, we can model the environmental impact of diesel engines on inland vessels, considering fuel consumption, emission factors, and operational characteristics. This allows us to make educated assumptions about fuel consumption and – thus – CO_2 emission outputs.

For this study, an important primary dataset originates from the European research project PROMINENT[7], which offers extensive data on inland waterway transport, vessel types, operational hours and installed power of representative journeys across the Danube Region. PROMINENT is widely regarded as one of the most detailed and structured sources of information available for European inland waterways, including the Danube. However, it is important to note that the dataset used in this analysis is from 2013, which introduces certain limitations[8]. This dataset should be considered as a foundational reference, providing a first impression of the 'current' state of Danube cargo shipping propulsion systems as a theoretical maximum. While it remains a valuable source of data available at present, stakeholders should be aware that the findings derived from this dataset may not fully reflect the most recent developments in technology, regulation, or industry practices.

Baseline estimation

The following analysis will serve as a preliminary benchmark for the assessment of alternative propulsion systems. The PROMINENT data, referring to Danube Commission data of 2013, contains more detailed information on power installed per vessel family/operational profile. For the representative Danube journeys, the typical vessel used is:

- Pushed convoys with 9 barges (4 barges for one journey)
- CEMT Class VI
- Operational hours per year: 4,318
- 2 installed engines
- Total engine power: 2 x 1,000 kW = 2,000 kW

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[5] Web: https://www.ccr-zkr.org/files/documents/om/om23_II_en.pdf

[6] Web: https://www.viadonau.org/fileadmin/user_upload/Annual_Report_on_Danube_Navigation_2023.pdf

[7] https://cordis.europa.eu/project/id/633929/de

[8] Most journeys in PROMINENT span only two or three segments, resulting in very pronounced peaks of the profiles. These operational profiles provide insight into the power distribution of inland vessels during the most representative journeys and thereby the power needed for these journeys. Also there are some limitations to the operational profiles that were generated, e.g. there were not yet good speed-power distributions for the Danube pushers available.

Some key characteristics of the Danube fleet:

1. Pushers:

- Lengths ranging from 20.72m to 34.66m
- Widths from 7.78m to 11.04m
- Engine powers from 2 x 300 kW to 2 x 1,249 kW

2. Self-propelled vessels:

- Lengths ranging from 64.92m to 105.04m
- Widths from 8.99m to 11.5m
- Engine powers from 383 kW to 2 x 940 kW
- Payloads from 902 tonnes to 2,095 tonnes

3. Most common vessel types on the Upper Danube:

- Motor cargo vessels 110m long (1,150 kW)
- Motor cargo vessels 105m long (950 kW)
- Motor cargo vessels 80m x 8.2m (600 kW)
- Motor cargo vessels 85m x 9.5m (750 kW)
- Pushers 57m long (1,470 kW)

Fuel Consumption Rate:

- Push convoys likely consume around 0.25-0.35 liters of diesel per kWh in general, on the Danube expert opinion consider it to be less → 0.15 liters per kWh
- Self-propelled vessels likely consume around 0.20-0.30 liters of diesel per kWh → 0.25 kWh

Based on the Danube Commission and CCNR statistics provided on their websites[9], this table summarizes the fleet of vessels sailing on the Danube. This table is derived from the following information:

- There were 409 self-propelled dry cargo vessels on the Danube.
- The push boats and tug boats combined totaled 642 (400 push boats and 242 tugs).
- There were approximately 2,100 non-propelled dry cargo barges in the Danube fleet.

It's important to note that these statistics are from 2017, which was the most recent data available in the provided search results. The composition of the fleet may have changed slightly since then, but this gives a good overview of the Danube fleet structure. Now we add operating time and average power installed per vessel type based on the PROMINENT data.

Vessel Type	Number of Vessels	Operating Hours	Average Power Installed (kW)
Self-propelled vessels	409	4,318	1,242
Push boats and tugs	642	4,318	1,153

Notes on the calculations:

1. For self-propelled vessels:

The average power per vessel type is calculated from total power installed divided by number of vessels*:

- Motor vessels dry cargo ≥ 110m length: 1,742 kW
- Motor vessels liquid cargo ≥ 110m length: 1,780 kW
- Motor vessels dry cargo 80-109m length: 764 kW
- Motor vessels liquid cargo 80-109m length: 954 kW
- Motor vessels < 80 m. length: 302 kW

Taking an average of these values:
(1,742 + 1,780 + 764 + 954 + 302) / 5 ≈ 1,242 kW

2. For push boats and tugs:

The average power of 1,153 kW is calculated from:

- Push boats < 500 kW: 247 kW
- Push boats 500-2,000 kW: 847 kW
- Push boats ≥ 2,000 kW: 3,458 kW

Taking an average of these values:
(247 + 847 + 3,458) / 3 ≈ 1,153 kW

These are approximate averages based on the available data. The actual average power may vary depending on the specific distribution of vessels within each category.

Vessel Type	Number of Vessels	Operating Hours	Total Operating hours	Average Power Installed (kW)	Operating Hours x Average Power (kWh)	50% Workload (kWh) [10]	Fuel Consumption per kWh (liters)	Total Fuel Consumption (liters)	CO$_2$ Emissions (kg)
Self-propelled vessels	409	4,318	1,766,062	1,242	2,193,449,004	1,096,724,502	0.25	274,181,125	860,928,734
Push boats and tugs	642	4,318	2,772,156	1,153	3,196,295,868	1,096,724,502	0.15	239,722,190	752,727,677

The total CO$_2$ emissions from the vessels, based on the provided data, amount to **1,613,656 tonnes of CO$_2$**[11]

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[*] Danube Commission, 2013 - https://www.prominent-iwt.eu/wp-content/uploads/2015/06/2015_09_23_PROMINENT_D1.1-List-of-operational-profiles-and-fleet-families-V2.pdf

[9] Web: https://www.ccr-zkr.org/files/documents/om/om21_II_en.pdf

[10] Average power used on the Danube: 50%, figure based on expert opinion

[11] By comparison: Vienna's transport, building and heating, electricity and waste sectors release an estimated 7.8 million tonnes of carbon dioxide each year. Which means the total emissions of the Danube fleet as a theoretical maximum equals about less than 20% of Vienna's annual emissions, see https://www.climate-kic.org/success-stories/viennas-journey-to-carbon-neutrality/

3. Alternative Propulsion Technologies: New Horizons

As the shipping industry strives to reduce its environmental impact, alternative propulsion technologies are gaining traction. This chapter will provide an exploration of several promising alternatives, including biofuels, electric drives, hydrogen, methanol, ammonia, and hybrid systems.

Each of these technologies presents unique opportunities and challenges. By examining their potential, we aim to offer insights into the feasibility of these alternatives and their applicability to cargo shipping on the Danube. This exploration will form the backbone of our discussion on transitioning to greener propulsion systems.

3.1 Biofuels

Biofuels are increasingly recognized as a key solution for reducing emissions in the inland waterway transport (IWT) sector. Fuels such as Hydrotreated Vegetable Oil (HVO) and Liquid Bio Methane (LBM) are particularly well-suited to contribute to emission reductions in the short to medium term. These biofuels offer a practical advantage by being compatible with existing vessel engines and bunkering infrastructure, allowing for a more immediate transition to cleaner energy sources without the need for significant capital investments in new technologies.

Unlike other zero-emission alternatives, such as hydrogen fuel cells or battery-electric propulsion, which require substantial infrastructure changes and higher operational costs, biofuels can be integrated into the current system with relative ease (‘drop-in’). This makes them a feasible option for the inland waterway sector to achieve near-term reductions in greenhouse gas emissions.

Clean combustion engine technologies are expected to continue evolving over the coming decades, with biofuels playing a crucial role in this transition. While the long-term goal is to shift towards zero-emission technologies, biofuels provide an essential bridge, offering a lower-emission option that can be adopted now. However, the cost and availability of biofuels, particularly those derived from sustainable feedstocks, will be critical in determining the extent of their adoption across the sector.

This analysis evaluates the technical feasibility, economic factors, environmental characteristics, and social consequences of biofuel adoption in inland navigation, with a focus on key challenges and opportunities.

3.1.1 Technical Feasibility

Biofuels, particularly Hydrotreated Vegetable Oil (HVO), are emerging as a promising solution to reduce emissions in inland waterway transport. HVO, a second-generation biofuel, can be used directly in existing diesel engines, offering a practical way to reduce carbon emissions without significant modifications to vessels. This “drop-in” fuel is considered carbon-neutral because the carbon dioxide released during combustion is offset by the CO_2 absorbed by the feedstock plants during growth, making it a more sustainable alternative to fossil fuels.

One of the primary advantages of biofuels is their compatibility with existing engines and infrastructure, allowing for relatively easy integration into the current fleet. This contrasts with zero-emission alternatives, such as hydrogen and ammonia, which require extensive modifications to vessels and port facilities. Biofuels provide an immediate solution for emission reduction without the high upfront costs of retrofitting or developing new technologies.

However, there are technical considerations associated with biofuels, particularly with FAME (Fatty Acid Methyl Ester). These fuels require careful management to avoid potential challenges to engine systems. Strict quality standards, attention to fuel storage conditions, and appropriate temperature management are necessary to ensure the successful use of biofuels in inland waterway transport. Extra tests are currently (summer 2024) being performed, e.g. on the winter proofness of the fuel.[12]

Regulations and engine manufacturers allow for up to 37% biofuel content in most diesel engines, consisting of 7% FAME and about 30% HVO mixed with conventional diesel. Stage V engines can potentially use higher blends up to 100% FAME or HVO if included in type approval, but it’s uncertain if manufacturers will pursue this due to limited market size[13]. Technical risks mainly relate to FAME blends and fuel storage/supply systems on ships. Risks are considered acceptable but require good maintenance practices.

3.1.2 Economic Analysis

Biofuels offer a cost-effective solution for reducing emissions in the short term, particularly due to their compatibility with existing infrastructure. This compatibility reduces the need for significant capital investment, making biofuels an attractive option for operators looking to achieve near-term emission reductions.

However, the cost and availability of biofuels, particularly those derived from sustainable feedstocks, remain critical challenges. The production of biofuels is influenced by the availability of raw materials, which can be limited. Sustainable production of biofuels requires careful management of resources, and the cost of production may fluctuate based on feedstock availability and market demand.

Compared to alternatives like ammonia and hydrogen, biofuels are currently more affordable and can be deployed more rapidly, providing a bridge solution while zero-emission technologies are still in development. However, in the long term, the widespread adoption of biofuels may be constrained by supply limitations and the need for continued investment in sustainable feedstock production.

Biofuel demand could increase significantly, especially for international shipping and aviation, potentially reaching 248 PJ in 2030 under ambitious scenarios. The inland shipping sector’s biofuel needs (3-5 PJ) are relatively small compared to overall demand, which means competition with other

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[12] Web: https://binnenvaartkrant.nl/kbn-goede-hoop-op-probleemloze-bijmenging-fame-winterkwaliteit

[13] Web: https://publications.tno.nl/publication/34637419/wHTZ8b/TNO-2020-R11455.pdf

sectors is strong. Biofuel costs are considerably higher than conventional diesel, potentially increasing fuel costs for inland shipping by 9-24% depending on the scenario and feedstock used[14].

3.1.3 Environmental Characteristics: Emissions and Sustainability

When evaluating biofuels as an alternative to conventional diesel for inland navigation, they offer several advantages in terms of emissions, especially when produced from sustainable sources. Biofuels, such as biodiesel or Hydrotreated Vegetable Oil (HVO), are considered carbon-neutral because the CO_2 released during combustion is offset by the CO_2 absorbed during the growth of the feedstock.

While biofuels significantly reduce greenhouse gas emissions compared to fossil fuels, they are not completely emissions-free. Biofuels still emit pollutants, including nitrogen oxides (NOx) and particulate matter (PM), though typically at lower levels than diesel. This makes biofuels a more environmentally friendly option, though not as clean as hydrogen or ammonia, which can potentially achieve zero emissions when properly managed.

3.1.4 Social Consequences

The adoption of biofuels in the IWT sector has significant social implications. One of the key advantages is the ability to reduce emissions without requiring significant retraining of the workforce or investment in new skills, as biofuels can be used with existing engines. This eases the transition to cleaner fuels and reduces the disruption to employment in the sector.

However, to maximize the impact of biofuels, supportive policies and incentives will be essential. A consistent regulatory framework across Europe will help create a level playing field, encouraging wider adoption. Additionally, ensuring that sustainable production of biofuels is scaled up, alongside certification of engines and increased awareness among users, will be key to their successful integration into the IWT sector.

There are also broader social considerations linked to the sourcing of biofuels. The use of food crops for fuel production raises ethical concerns, and careful attention must be paid to the sustainability of feedstock sourcing to avoid negative social impacts, such as increased food prices or land-use conflicts.

Characteristic	Biofuels	Diesel
Greenhouse Gas Emissions	Lower than diesel; CO_2 emissions are often offset by the CO_2 absorbed during biomass growth	High (CO_2, methane, nitrous oxides, etc.)
Air Pollution	Lower than diesel, but can still emit particulate matter and NO_x	High (NO_x, particulate matter, sulfur oxides)
Energy Source	Renewable (derived from plants, algae, or waste materials)	Fossil fuel (non-renewable)
Efficiency	Similar to diesel in combustion engines, higher in advanced biofuel applications	Lower efficiency in internal combustion engines (25-30%)
Production Impact	Impact varies; lower than fossil fuels, but land use and crop production can have environmental impacts	High impact, includes extraction, refining, and distri-bution
Water Usage	High (irrigation and processing can require significant water)	Significant (in extraction, refining, cooling processes)
Noise Pollution	Similar to diesel in combustion engines	High (diesel engines are noisy)
Toxicity	Less toxic than diesel but can vary based on production methods and feedstocks	Toxic (diesel fumes contain carcinogens)
Lifecycle Emissions	Lower than diesel, but depends on feedstock and production methods	High (emissions from extraction to end-use)
Resource Availability	Renewable, but limited by land, water, and feedstock availability	Finite (limited fossil fuel reserves)

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[14] Web: https://publications.tno.nl/publication/34637419/wHTZ8b/TNO-2020-R11455.pdf

3.1.5 Pilot projects

A series of innovative pilot projects have emerged across Europe, focusing on the use of biofuels to decarbonize inland waterway vessels. These projects explore the potential of bio-based fuels like HVO (Hydrotreated Vegetable Oil), FAME (Fatty Acid Methyl Esters). The projects vary in scale and scope, but all share the common goal of promoting sustainability, improving fuel efficiency, and reducing the carbon footprint of inland vessels. Below is a detailed look at some of the leading biofuel pilot projects.

HGK Shipping HVO100 Pilot

Year: 2024

Overview: HGK Shipping, Europe's largest inland shipping company, is running a pilot using HVO100 biofuel on its fleet in Germany. The fuel requires no technical modifications to engines, even for older vessels, and offers up to a 90% reduction in CO_2 emissions. This project highlights HVO's feasibility as a short-term solution for decarbonizing inland waterway transport while reducing dependency on fossil fuels.[15] This project showcases the immediate benefits of HVO100, providing a blueprint for potential use along the Danube. However, private parties call for subsidies to bridge the moment in which mechanisms are in place that can control the extra costs.

Royal Koopmans HVO100 Barge Project

Year: 2024

Overview: In a joint project, NPRC and Royal Koopmans transported the first barge of Nedertarwe wheat powered by 100% HVO biofuel. This journey, from Utrecht to Rotterdam, demonstrated HVO's potential to decarbonize inland waterways without requiring engine modifications. This project marked a significant step in reducing emissions across Dutch inland shipping and serves as a model for HVO use in other regions.[16]

VT Group with FAME[17]

Year: 2023

Overview: VT Group partnered with FinCo Group to test 100% FAME biodiesel on the inland vessel MTS Vlissingen. Over nine months, the pilot demonstrated up to 89% CO_2 reduction using biodiesel derived from animal fats and used cooking oil, with minimal technical adjustments. Both companies gathered valuable operational data, with no significant technical issues arising during the test. Following the success, VT Group plans to implement FAME on other vessels, starting with the world's largest bunkering ship, MTS Vorstenbosch.

The MS"Westenwind" of Kuehne+Nagel Euroshipping, Regensburg.

MS Westenwind started sailing May 2024 after a main engine overhaul, using HVO100. It is known to be the first German inland vessel to transport its cargo from the Amsterdam-Rotterdam-Antwerp (ARA) region to Austria and vice versa. Operating totally on HVO100, a reduction in carbon footprint up to 90% is achieved.[18]

These projects provide strong evidence for the scalability and applicability of HVO in inland shipping. On the topic of FAME technical concerns still remain. The Expertise and Innovation Centre Barging (EICB)[19] highlights several concerns regarding the use of FAME in inland shipping. Many existing engines are not fully compatible with FAME without modifications, which can lead to technical issues and engine damage. Another concern is the variability in FAME quality due to differences in feedstock, impacting storage and performance. FAME is also more prone to oxidation and microbiological growth, especially in the humid environments of inland vessels, making proper storage practices essential to maintain fuel quality. Stricter emission regulations further emphasize the need for adaptation in the sector.

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[15] https://biofuels-news.com/news/hgk-shipping-welcomes-the-approval-for-hvo100/

[16] https://nprc.eu/royal-koopmans-with-first-nedertarwe-barge-on-hvo100-biofuel/?lang=en

[17] https://vtgroup.nl/nl/productieve-pilot-met-100-fame-voor-de-binnenvaart/

[18] https://www.linkedin.com/posts/daniel-j-j-bell-521b8116a_binnenschifffahrt-binnenvaart-hvo-activity-7192129058728550400-9aiu/

[19] https://www.schuttevaer.nl/nieuws/actueel/2024/09/10/binnenvaart-moet-snel-voldoen-aan-strengere-emissieregels/

3.2 Electric propulsion

Electric drives are increasingly recognized as a key solution for the future of zero-emission propulsion in inland waterway transport. These systems, which convert electrical energy into mechanical motion, offer significant advantages in terms of efficiency, often reaching 85% compared to approximately 40% for traditional diesel engines. This high efficiency, combined with the ability to maintain consistent performance across different operating conditions, makes electric propulsion highly adaptable to various vessel types and operational needs.

Electric propulsion systems can be powered by batteries, fuel cells, or hybrid configurations that integrate conventional engines. Battery-electric systems are particularly effective for shorter routes, such as ferries and small excursion ships, while hybrid configurations can serve longer distances by blending electric and traditional propulsion. Successful implementations in major ports like Rotterdam and Antwerp have demonstrated the feasibility of electric drives for IWT. Additionally, these systems contribute to overall energy efficiency by smoothing demand peaks during high-energy consumption periods, making them particularly valuable for energy management in busy ports.

As the IWT sector continues to evolve, electric propulsion offers a scalable and efficient solution for decarbonizing inland waterway transport, contributing to immediate reductions in greenhouse gas emissions without the need for complex retrofitting or infrastructural changes.

3.2.1 Technical Feasibility

Electric propulsion systems, particularly battery-electric solutions, have proven to be technically feasible for a wide range of vessel types. The 85% efficiency rate of electric motors significantly outperforms diesel engines, allowing for better energy use and lower operational costs in the long run. This higher efficiency means that electric propulsion systems can maintain consistent power output across varying operating conditions, which is especially beneficial for vessels operating in urban or environmentally sensitive areas.

Electric propulsion systems are particularly suited for vessels operating on short routes, such as river ferries or port-based cargo transport. Hybrid systems, which combine battery-electric propulsion with conventional engines, offer the flexibility to extend the range of operations for vessels on longer journeys, optimizing fuel use and emissions reduction. Furthermore, ongoing technological advancements, such as high-temperature superconductors and optimized motor control systems, are expected to further improve the performance and adaptability of electric drives in the maritime sector.

However, the widespread adoption of electric propulsion in IWT is currently limited by the energy storage capabilities of batteries and the availability of charging infrastructure. For short to medium-range operations, battery systems are sufficient, but for long-range vessels, significant advancements in battery technology or hybrid solutions will be necessary to meet operational demands.

3.2.2 Economic Analysis

Electric propulsion offers long-term economic benefits, primarily through reduced fuel and maintenance costs. Electric motors are less complex than internal combustion engines, resulting in fewer moving parts and lower maintenance requirements. Over time, these savings can offset the higher initial capital costs associated with electric propulsion systems, particularly the cost of batteries.

Currently, battery costs remain one of the main economic challenges for full electrification. However, as battery technology continues to evolve and economies of scale reduce production costs, the cost-effectiveness of electric propulsion is expected to improve significantly. Advances in battery technology– such as higher energy density and faster charging capabilities – will further enhance the economic feasibility of electric propulsion in the IWT sector.

For operators, the total cost of ownership for electric propulsion systems will likely become increasingly competitive with conventional diesel engines, especially when factoring in potential government incentives for adopting zero-emission technologies.

Additionally, using renewable energy sources to power electric vessels can further reduce operating costs, particularly in regions with low-cost access to wind or solar energy.

Compared to alternatives like hydrogen or ammonia, electric propulsion systems have the advantage of immediate deployment, leveraging existing electricity infrastructure in many regions. However, for longer journeys, hybrid systems or future advancements in battery storage will be crucial for ensuring cost-effective operations.

3.2.3 Environmental Characteristics: Emissions and Sustainability

One of the most significant advantages of electric propulsion is its potential to eliminate direct emissions. Unlike combustion engines, electric propulsion systems do not produce CO_2, NOx, or particulate matter (PM) during operation, making them ideal for zero-emission transport in environmentally sensitive areas such as urban waterways or protected ecosystems.

When powered by renewable energy sources, such as wind, solar, or hydropower, electric propulsion can achieve true zero-emission operation. This makes it one of the most sustainable options for decarbonizing the IWT sector. The widespread adoption of electric propulsion would have a substantial impact on improving air quality in cities, reducing waterway pollution, and meeting regulatory requirements for emission reduction.

However, the environmental benefits of electric propulsion are closely tied to the source of electricity. In regions where electricity is primarily generated from fossil fuels, the indirect emissions from electricity generation must be considered. While still lower than diesel or other fossil fuels, indirect emissions from non-renewable energy sources can reduce the overall environmental advantage of electric propulsion. As countries transition to cleaner energy grids, the sustainability of electric propulsion systems will improve.

3.2.4 Social Consequences

The shift to electric propulsion in IWT carries significant social and economic implications. As electric propulsion systems become more common, new infrastructure such as charging stations and grid upgrades will be necessary, creating jobs and stimulating investment in green technologies. Additionally, electric propulsion systems reduce noise and air pollution, which can improve the quality of life for communities living near busy inland waterways.

However, the transition to electric propulsion will require a degree of retraining for crews and maintenance personnel to operate and maintain electric systems effectively. Governments and industry stakeholders will need to collaborate to provide the necessary support and training programs to ensure a smooth transition.

Incentives, such as subsidies or tax breaks, will be critical for encouraging operators to adopt electric propulsion, particularly given the high upfront costs of battery systems. A consistent regulatory framework across Europe, combined with financial incentives, will help create a level playing field and encourage wider adoption.

3.2.5 Pilot projects

1. Port-Liner: Electric Cargo Ships

- Year: 2018
- Project Overview: Port-Liner developed fully electric cargo ships, aiming to reduce emissions in inland waterways. These vessels, powered by large battery packs, are designed for short and medium-distance shipping in the Netherlands and Belgium.
- Key Vessels: Electric cargo vessels with capacity for up to 280 containers.
- Pilot Location: Netherlands and Belgium.
- Website: port-liner.com

2. Zero Emission Services (ZES) Project

- Year: 2021
- Project Overview: ZES introduced “ZESpacks”, battery containers that can be easily swapped to power electric inland vessels. The project aims to make inland waterway transport more sustainable by offering a flexible, zero-emission solution.
- Key Vessel: Alphenaar, the first vessel to use ZESpacks.
- Pilot Location: Netherlands (Rotterdam, Alphen aan den Rijn).
- Website: zeroemissionservices.nl

3.2.6 Conclusion

Electric propulsion presents a scalable and effective solution for reducing emissions in the IWT sector. Its high efficiency, combined with the elimination of direct emissions, makes it a crucial component in the transition to zero-emission transport. However, the challenges related to battery storage, charging infrastructure, and the source of electricity must be addressed to maximize its potential.

While electric propulsion is already suitable for short- to medium-range operations, ongoing advancements in battery technology and grid infrastructure will enable its expansion to longer routes. Hybrid systems, combining electric propulsion with conventional engines, will play an essential role in bridging the gap until full electrification is feasible. As the technology develops, electric propulsion will become an increasingly important solution for sustainable inland waterway transport.

3.3 Hydrogen

Hydrogen has emerged as a promising energy carrier in the quest to achieve zero-emission goals across various sectors, including inland waterway transport. As countries and regions intensify efforts to reduce greenhouse gas emissions, hydrogen's potential in the maritime sector, especially for inland and short-sea shipping, has gained significant traction. Since 2019, numerous pilot projects and innovations have been launched to explore hydrogen's feasibility as a sustainable fuel alternative, positioning it as a crucial component of future energy solutions in waterways.

3.3.1 Technical Feasibility

Hydrogen technology in inland waterways is technically feasible, as proven by the Rotterdam based company Future Proof Shipping with the launch of the H2 Barge One in 2023, though it remains in the early stages of adoption. Hydrogen can be used in various forms, such as compressed gas, liquid hydrogen, or as part of chemical compounds like ammonia or methanol. Each form has distinct technical considerations, such as storage, handling, and energy conversion efficiency. Fuel cells, particularly proton exchange membrane (PEM) fuel cells, are often favored for their efficiency and low emissions when using hydrogen. However, integrating hydrogen systems into ships poses challenges, such as space constraints for fuel storage and the need for specialized refueling infrastructure[20].

The development of suitable infrastructure, such as hydrogen bunkering stations and onboard storage solutions, is critical to overcoming these challenges. Pilot projects have demonstrated that

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[20] https://www.eicb.nl/wp-content/uploads/2020/07/2020-07-EICB-Rapport-Waterstof-in-de-binnenvaart-en-short-sea.pdf

hydrogen-powered vessels can operate effectively on inland waterways, but scalability and widespread adoption depend on technological advancements and infrastructure development.

3.3.2 Economic Analysis

The economic viability of hydrogen for inland shipping hinges on several factors, including the cost of hydrogen production, infrastructure investments, and operational costs. Currently, hydrogen, especially green hydrogen produced from renewable energy, remains more expensive than traditional fossil fuels. According to HyXchange, a market place for hydrogen, the costs of green hydrogen are about to equal those of grey hydrogen[21].

High upfront costs for retrofitting vessels or constructing new hydrogen-powered ships also pose economic barriers. As a reference point, retrofitting the H2 Barge One required a 6 – 7 million euro investment (2023). The second hydrogen project, MS Antonie, even required a 10 million euro investment which is app. twice as much as a conventional vessel.

Public-private partnerships, government subsidies, and long-term contracts with shippers are seen as essential to bridging the economic gap. The Dutch government (2024) for instance, is preparing to provide subsidies for 18 hydrogen vessels with a budget of 75 million euro. Agreement within the value chain on standardization, e.g. on pressure levels, are essential to reach a suitable economy of scale leading to lower prices and market acceptancy.

Demonstration projects have shown that as the hydrogen economy scales, costs could decrease, making hydrogen a more competitive option for the inland waterway sector. However, clear business models and financial incentives are needed to encourage investment in hydrogen technologies[22].

3.3.3 Environmental Characteristics and Emissions

Hydrogen offers significant environmental benefits, primarily due to its potential for zero emissions when produced from renewable energy sources. Hydrogen-powered vessels emit no carbon dioxide (CO_2), nitrogen oxides (NOx), or particulate matter during operation, which can drastically reduce air pollution and contribute to improving air quality in regions reliant on inland waterways. This makes hydrogen an attractive alternative to diesel and other fossil fuels traditionally used in shipping.

However, the environmental impact of hydrogen depends on its production method. While green hydrogen (produced via electrolysis using renewable energy) is ideal for achieving zero emissions, other forms of hydrogen, such as grey hydrogen (produced from natural gas with CO_2 emissions), offer fewer environmental benefits. Therefore, scaling up the production of green hydrogen is essential for maximizing environmental gains.

Characteristic	Hydrogen	Diesel
Greenhouse Gas Emissions	Zero (if produced from renewable sources)	High (CO_2, methane, nitrous oxides, etc.)
Air Pollution	None (if pure hydrogen combustion or fuel cell)	High (NOx, particulate matter, sulfur oxides)
Energy Source	Can be renewable (e.g., electrolysis using solar/wind)	Fossil fuel (non-renewable)
Efficiency	High efficiency in fuel cells (40-60%)	Lower efficiency in internal combustion engines (25-30%)
Production Impact	Potential for low impact if from renewables, but can be high if produced from natural gas	High impact, includes extraction, refining, and distribution
Water Usage	Moderate (in electrolysis)	Significant (in extraction, refining, cooling processes)
Noise Pollution	Very low (fuel cells)	High (diesel engines are noisy)
Toxicity	Non-toxic	Toxic (diesel fumes contain carcinogens)
Lifecycle Emissions	Can be near zero if produced from renewables	High (emissions from extraction to end-use)
Resource Availability	Abundant (if produced from water or biomass)	Finite (limited fossil fuel reserves)

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[21] https://www.portofrotterdam.com/nl/nieuws-en-persberichten/hyxchange-variabele-kostprijs-groene-waterstof-komt-dichter-bij-grijze

[22] https://www.inlandports.eu/media/Making%20hydrogen%20a%20success%20for%20Inland%20Ports.pdf

From a sustainability perspective, hydrogen is seen as a long-term solution that can contribute to energy independence and reduce the reliance on fossil fuels. The deployment of hydrogen technologies in inland shipping aligns with broader sustainability goals by promoting cleaner transport options and supporting the transition to a low-carbon economy. The integration of renewable energy sources with hydrogen production, such as using solar or wind power to produce hydrogen through electrolysis, enhances the sustainability profile of hydrogen-powered transport.

3.3.4 Social consequences

Sustainable hydrogen solutions also depend on the circular economy concept, where waste and residual energy from other processes is utilized to produce hydrogen. Inland ports, acting as multimodal hubs, can play a crucial role in this by generating hydrogen from excess renewable energy, thus contributing to a more sustainable energy network.

The transition to hydrogen in inland waterways has several social implications. On the positive side, adopting hydrogen technologies can create new jobs in the hydrogen supply chain, from production to distribution and vessel maintenance. Inland ports, as key hubs in the hydrogen economy, can foster local economic development by attracting new industries and investments related to hydrogen.

However, challenges such as safety concerns, regulatory uncertainties, and the need for workforce retraining may arise. Hydrogen is a highly flammable gas, requiring stringent safety protocols and training for personnel involved in its handling and storage. Additionally, the shift to hydrogen may affect existing jobs in traditional fossil fuel-based industries, necessitating policies that support a just transition for affected workers.

3.3.5 Pilot projects

Hydrotug: Hydrogen-powered Tugboat (Port of Antwerp)

- Year: 2021
- Project Overview: *Hydrotug* is one of the world's first hydrogen-powered tugboats, designed to assist in port operations while reducing emissions. The vessel uses a combination of hydrogen fuel cells and diesel, making it a hybrid vessel.
- Key Vessel: *Hydrotug*.
- Pilot Location: Port of Antwerp, Belgium.
- Website: portofantwerp.com

H2 Barge 1 & 2 Projects

- Year: 2023
- Project Overview: The H2 Barge 1 project involves converting an existing inland barge into a hydrogen-powered vessel. The barge is equipped with hydrogen fuel cells and is expected to operate primarily along the Rhine River in the ARA-region and, focusing on bulk cargo transport.
- Key Vessel: Hydrogen-powered barge.
- Pilot Location: ARA-region.
- Website: h2barge.com

MS Letitia

- Year: 2024
- Project Overview: The fully zero-emission vessel Letitia, the first of its kind in inland shipping, operates on both hydrogen and ZES or onboard batteries. This innovative ship marks a major step toward emission-free transport, offering sustainable alternatives for both urban areas and heavy-duty operations on the Rhine.
- Key Vessel: MS Letitia
- Pilot Location: Rhine

3.3.6 Conclusion

In summary, while hydrogen holds great promise for transforming inland waterway transport into a zero-emission sector, its widespread adoption depends on overcoming technical, economic, environmental, and social challenges.

3.4 Methanol

Methanol has been identified as a promising alternative fuel for inland waterways, contributing to the reduction of greenhouse gas (GHG) emissions in the shipping industry. It stands out as a potential solution due to its versatility and the possibility of producing it from renewable sources, offering a pathway toward sustainable maritime operations[23].

3.4.1 Technical Feasibility

Methanol technology is ready for large-scale adoption in the maritime sector. Existing engines can be modified to use methanol with relatively minor adjustments, and new methanol-powered vessels are already being built. Dual-fuel engines that can operate on methanol and traditional fuels are available, making the transition smoother for shipowners. Methanol's liquid state at ambient temperatures and pressures simplifies storage and handling compared to other alternative fuels like hydrogen or ammonia, requiring fewer modifications to existing infrastructure.

Retrofitting existing vessels to use methanol is feasible, though it may require changes to fuel tanks and other systems, potentially impacting cargo space. However, examples such as the successful conversion of vessels like the Stena Germanica demonstrate that these modifications can be implemented effectively.

3.4.2 Economic Analysis

Methanol offers a cost-effective pathway to decarbonization compared to other alternative fuels. The capital expenditure (CAPEX) for methanol-powered ships is significantly lower than for other alternatives like hydrogen or ammonia. Methanol's existing global infrastructure further reduces costs associated with fuel production and distribution, as methanol is already available in over 100 ports worldwide. However, the cost of renewable methanol remains higher than fossil methanol, and scaling up renewable methanol production is essential for long-term economic viability.

Public-private partnerships, governmental incentives, and regulatory support will be crucial in bridging the economic gap and encouraging the adoption of methanol as a sustainable fuel. Large shipping companies, such as Maersk, are investing in methanol-powered vessels, indicating confidence in methanol's economic potential as a marine fuel.

[23] https://publications.tno.nl/publication/34640817/zpBGh5/gerritse-2023-green.pdf

3.4.3 Environmental Characteristics and Emissions

Methanol is considered a low-emission marine fuel, particularly when produced from renewable sources. Green methanol can reduce well-to-wake greenhouse gas emissions by up to 99% compared to traditional marine fuels. Additionally, methanol significantly lowers other harmful emissions, such as nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter, making it an environmentally friendly alternative to conventional fuels.

Despite its carbon content, burning renewable methanol does not contribute to net increases in atmospheric carbon dioxide, as the carbon released during combustion is balanced by carbon capture during production. This makes methanol an attractive option for reducing the overall carbon footprint of inland waterway transport.

From a sustainability perspective, methanol offers multiple advantages. It can be produced from a wide range of feedstocks, including biomass and renewable electricity, making it resilient to supply disruptions and price shocks. Methanol's role in the transition to a circular economy is also significant, as it can be produced from waste materials and recycled carbon, contributing to resource efficiency.

Methanol is seen as a scalable solution that can be integrated into the existing maritime fuel infrastructure with minimal modifications, supporting the broader sustainability goals of reducing reliance on fossil fuels and promoting renewable energy sources in the transport sector.

3.4.4 Social Consequences

The adoption of methanol in inland waterways has several social implications. On the positive side, it can create new jobs in the renewable fuel production sector and enhance the sustainability credentials of shipping companies, which may improve their reputation and relations with stakeholders. The shift to methanol could also reduce pollution in port cities and along waterways, leading to improved public health outcomes.

However, challenges such as workforce retraining and safety concerns related to handling methanol must be addressed. Methanol is toxic and flammable, requiring strict safety protocols and specialized training for those involved in its storage and use. Additionally, the transition to methanol may impact jobs in traditional fossil fuel industries, necessitating policies that support affected workers during the energy transition.

Characteristic	Methanol	Diesel
Greenhouse Gas Emissions	Lower than diesel, can be near zero if produced from renewable sources	High (CO_2, methane, nitrous oxides, etc.)
Air Pollution	Lower than diesel but can produce formaldehyde and CO during combustion	High (NO_x, particulate matter, sulfur oxides)
Energy Source	Can be produced from renewable sources (e.g., biomass) or fossil fuels	Fossil fuel (non-renewable)
Efficiency	Higher than diesel in fuel cells, lower in combustion engines	Lower efficiency in internal combustion engines (25-30%)
Production Impact	Depends on production method; renewable methanol has lower impact than fossil methanol	High impact, includes extraction, refining, and distribution
Water Usage	Moderate (depending on production process)	Significant (in extraction, refining, cooling processes)
Noise Pollution	Lower than diesel engines	High (diesel engines are noisy)
Toxicity	Toxic (methanol is highly toxic if ingested or inhaled)	Toxic (diesel fumes contain carcinogens)
Lifecycle Emissions	Can be near zero if produced from renewable sources, higher with fossil-based production	High (emissions from extraction to end-use)
Resource Availability	Potentially renewable (from biomass or waste), but also produced from natural gas	Finite (limited fossil fuel reserves)

In summary, methanol presents a viable and sustainable alternative to traditional marine fuels, with significant potential to reduce emissions in inland waterway transport. However, its widespread adoption will require overcoming economic, technical, and social challenges, supported by continued innovation and regulatory frameworks.

3.4.5 Pilot project

Chemical tanker Stolt IJssel

- Year: 2024
- Project Overview: The *Stolt IJssel* chemical tanker is being retrofitted to operate on methanol as part of a pilot project aimed at reducing emissions in inland waterway transport. The project focuses on demonstrating the feasibility and environmental benefits of methanol as a marine fuel.
- Key Vessel: Stolt IJssel
- Pilot Location: Rhine
- Website: stolt-nielsen.com

FASTWATER

- Year: 2021
- Project Overview: The FASTWATER project aims to demonstrate the feasibility and benefits of using methanol as a sustainable fuel in inland and coastal shipping. It focuses on converting existing vessels to methanol propulsion, significantly reducing emissions such as sulfur, carbon, and particulates. The project highlights methanol's practicality for small craft and larger vessels in ports and inland waterways.
- Key Vessel: Methanol-powered pilot boat operated by the Swedish Maritime Administration (SMA).
- Pilot Location: Stockholm Harbour, Sweden
- Website: fastwater.eu

3.5 Ammonia

In the context of inland navigation, ammonia faces distinct challenges and opportunities compared to its application in maritime shipping. The feasibility of ammonia as a fuel for inland waterways is influenced by several factors, including infrastructure needs, vessel design, and operational profiles.

3.5.1 Technical Feasibility

Ammonia is a widely traded chemical commodity that has long been transported in liquefied petroleum gas (LPG) tankers, which are also capable of carrying ammonia. Despite its promise as a green fuel, ammonia presents challenges, particularly due to its toxicity at low concentrations. This poses health and safety risks for crew members, making it essential for shipowners to implement stringent safety protocols and ensure compliance with applicable regulations.

The toxic and corrosive nature of ammonia raises serious safety concerns for its use in IWT. Handling ammonia requires stringent safety protocols, specialized training, and new regulations. In confined inland environments, where vessels operate close to populated areas, any leakage poses significant health risks. Compared to diesel, which is more familiar and less hazardous, ammonia requires more sophisticated containment systems and safety measures, increasing the complexity and cost of its adoption.

Ammonia has a lower energy density than diesel, meaning that more ammonia is required to achieve the same energy output. For inland vessels, which often have limited space for fuel storage, this can be a significant drawback. Larger fuel tanks reduce cargo capacity, negatively impacting the economic feasibility of operations. Diesel, with its higher energy density, allows for more compact storage solutions, making it more suited to the space constraints typical of inland vessels.

Adapting existing vessels to use ammonia as fuel would require extensive retrofitting, particularly in terms of engine modifications and storage systems. Retrofitting costs for ammonia are considerably higher than for diesel, which can be used with minimal changes to existing infrastructure. New vessel designs optimized for ammonia would need to account for larger storage requirements and ensure that safety systems are fully integrated. This raises the initial capital expenditure for operators considering a switch to ammonia.

3.5.2 Economic Analysis

While ammonia benefits from existing storage infrastructure and a worldwide terminal network, its adoption in inland navigation faces significant hurdles due to the lack of existing refueling infrastructure. Developing refueling stations across inland ports will require substantial investment. Unlike diesel, which benefits from an established global supply chain, ammonia's distribution networks are still underdeveloped, particularly for inland applications. Maritime ports are more equipped to handle ammonia due to existing industrial uses, but replicating this infrastructure in inland waterways, particularly in smaller and less commercially active ports, presents a challenge.

Inland vessels generally operate over shorter distances than their maritime counterparts but face unique constraints related to fuel storage and energy density. Ammonia's lower energy density compared to conventional fuels, such as diesel, necessitates larger storage tanks, which can be a significant limitation for vessels operating in confined spaces, such as rivers and canals.

Ammonia is currently more expensive than diesel on a per-unit energy basis. The price of ammonia, largely influenced by production costs and nascent infrastructure, is approximately 930 euro per ton, while diesel costs around 558 euro per ton. This price difference is exacerbated by the additional costs associated with retrofitting vessels and developing new infrastructure for ammonia, making it a less attractive option in the short term compared to diesel. However, as ammonia production scales up and green ammonia (produced from renewable energy sources) becomes more available, prices may decrease over time, potentially narrowing the gap.

3.5.4 Environmental Characteristics: Emissions and Sustainability

From an emissions perspective, ammonia offers significant advantages over diesel in terms of carbon dioxide (CO_2) emissions but presents challenges with nitrogen oxide (NOx) emissions.

Ammonia does not emit CO_2 during combustion, making it a zero-carbon fuel in this respect. However, the production of NOx during ammonia combustion is a significant concern, as it can contribute to air pollution unless effectively managed with after-treatment technologies such as selective catalytic reduction (SCR). Diesel, on the other hand, produces both CO_2 and NOx in significant quantities, making it a less environmentally friendly option overall.

3.5.4 Social Consequences

The adoption of ammonia as a fuel in the inland waterway transport sector has several social implications. The increased need for specialized training and safety protocols may create new job opportunities but also impose additional responsibilities on crew members. Furthermore, transitioning to ammonia could result in economic shifts within communities reliant on traditional fuels, necessitating support and adaptation measures to ensure a smooth transition. However, the long-term benefits of reduced emissions and improved environmental quality are likely to have a positive impact on public health and the overall well-being of communities living near waterways.

Characteristic	Ammonia	Diesel
Greenhouse Gas Emissions	Zero CO_2 emissions when used in combustion or fuel cells, but N_2O (a potent greenhouse gas) can be emitted	High (CO_2, methane, nitrous oxides, etc.)
Air Pollution	Lower than diesel, but ammonia combustion can release nitrogen oxides (NO_x)	High (NO_x, particulate matter, sulfur oxides)
Energy Source	Can be produced from renewable energy (green ammonia) or fossil fuels (gray ammonia)	Fossil fuel (non-renewable)
Efficiency	Higher in fuel cells, lower in internal combustion engines	Lower efficiency in internal combustion engines (25-30%)
Production Impact	Depends on production method; green ammonia has lower impact compared to fossil-based production	High impact, includes extraction, refining, and distribution

3.5.5 Pilot projects and best practices

Ammonia Inland Shipping Pilot (Port of Antwerp)

- Year: 2021 – Ongoing
- Project Overview: The Port of Antwerp has launched an ammonia pilot to assess the feasibility of using ammonia as a marine fuel for inland vessels. The project involves retrofitting an inland barge to run on ammonia while also developing safety protocols and bunkering infrastructure for the fuel. This is part of the port's broader sustainability agenda.
- Key Vessel: Inland cargo barge.
- Pilot Location: Antwerp, Belgium.
- Website: portofantwerpbruges.com

Apollo Project

- Year: 2024
- Project Overview: The Apollo Project focuses on converting the Viking Energy platform supply vessel to use ammonia as a marine fuel. The project, funded by the EU's Horizon Europe programme, aims to reduce greenhouse gas emissions by over 70%, demonstrating the feasibility of ammonia as a clean fuel for maritime and inland navigation.
- Key Vessel: Viking Energy platform supply vessel.
- Pilot Location: European waters, with the potential to expand to inland waterways.
- Website: apollo-project.eu

3.5.6. Conclusion

While maritime shipping can more easily accommodate large-scale ammonia storage and refueling infrastructure due to the global nature of ports and shipping networks, inland navigation requires more localized solutions. Retrofitting existing vessels with ammonia-compatible systems or designing new vessels optimized for ammonia is a more complex and gradual process in the inland sector.

Ammonia may ultimately prove to be more appropriate for deep-sea cargo ships rather than short-sea, passenger, or inland waterway operations. Nevertheless, ammonia remains a viable alternative, especially for larger inland vessels operating on major waterways like the Danube, where longer distances and larger cargo capacities justify the use of this alternative fuel.

The technical and economic analysis shows that while ammonia holds promise as a zero-emission fuel for inland navigation, it faces significant challenges in terms of infrastructure development, safety concerns, and retrofitting costs. Ammonia is currently more expensive than diesel, and its adoption would require extensive investment in new technology and regulatory frameworks. From an environmental perspective, ammonia offers clear advantages in terms of CO_2 emissions but must address the challenge of NOx emissions to be a viable long-term alternative. As ammonia production scales up and infrastructure develops, it may become a more feasible option for the IWT sector.

3.6 Hybrid systems

Dual fuel systems in inland waterway transportation refer to propulsion systems capable of operating on two types of fuel, typically a combination of conventional fossil fuel, such as diesel, and a cleaner alternative fuel like liquefied natural gas (LNG), hydrogen, or methanol. These systems provide operational flexibility by allowing vessels to switch between fuels depending on factors like availability, cost, or emission regulations. Dual fuel systems are designed to improve fuel efficiency and reduce emissions by incorporating cleaner fuels, thus enabling vessels to comply with environmental regulations while maintaining performance.

One of the key advantages of dual fuel systems is their flexibility. Operators can switch between fuel types, optimizing for cost or regulatory constraints. For example, a vessel may use electric propulsion when operating in emission-restricted zones and switch to diesel once possible. This adaptability is particularly beneficial for inland waterway vessels that operate across various regions with differing fuel infrastructure. In addition to flexibility, dual fuel systems contribute significantly to emission reduction. Cleaner fuels such as hydrogen produce far fewer carbon dioxide (CO_2), nitrogen oxides (NOx), and sulfur emissions compared to diesel, which can help vessels meet increasingly stringent environmental standards.

In Europe, several inland waterway vessels are already using dual fuel systems such as diesel-electric propulsion. Similarly, hydrogen-diesel dual fuel systems are being piloted in projects like the Hydrotug in Belgium, which uses hydrogen as the primary fuel while relying on diesel as a backup. Methanol-diesel dual fuel systems are also emerging as a viable option, given methanol's lower carbon content and the potential for it to be produced from renewable sources.

Despite these advantages, dual fuel systems face challenges. The initial investment required to install such systems is higher than for traditional engines, due to the complexity and need for additional fuel storage. Furthermore, the availability of alternative fuels, such as methanol, ammonia or hydrogen, is still limited in many regions, which restricts the widespread use of these systems. However, as infrastructure for cleaner fuels expands, the practical application of dual fuel systems is expected to increase.

In summary, dual fuel systems offer a practical solution for reducing emissions in inland waterway transport, providing a balance between environmental responsibility and operational flexibility. While they are not yet a universal solution, they represent an important step toward sustainable shipping practices, particularly as fuel infrastructure continues to develop.

3.7 Estimated costs

The following table shows **average costs in EUR** for various alternative propulsion pilot projects, along with relevant website sources for further reference:

Alternative Propulsion	Pilot Project Type	Average Cost per Vessel (EUR)	Key Cost Factors	Website Sources
Biofuels (e.g., HVO, FAME)	Retrofitting vessels to use biofuels	€500.000 – €2 million	Fuel infrastructure, engine modifications, operational testing	goodfuels.com, portofantwerpbruges.com
Electric Propulsion	Battery-electric vessels (new build or retrofit)	€900,000 – €4.5 million	Battery systems, electrical infrastructure, hybrid systems	zeroemissionservices.nl
Hydrogen Propulsion	Hydrogen fuel cells (new build or retrofit)	€1.8 million – €6.3 million	Hydrogen storage, fuel cell technology, safety measures, infrastructure	futureproofshipping.com, elektra-boat.com
Ammonia Propulsion	Ammonia engines or fuel cells (new build or retrofit)	€2.7 million – €7.2 million	Engine modifications, ammonia storage systems, safety infrastructure	shipfc.eu, portofantwerpbruges.com
Methanol	Methanol-fueled vessels (conversion or new build)	€1.5 million – €5 million	Fuel storage modifications, engine retrofitting, emission control systems	sustainableworldports.org, op.europa.eu

Notes:

- **Biofuels:** These are relatively affordable since they can often be used with existing engines. Costs come from infrastructure and modifications. The cost of retrofitting vessels to use biofuels such as HVO (hydrotreated vegetable oil) and FAME (fatty acid methyl ester) in inland shipping typically falls between €500,000 and €2 million per vessel. These expenses vary based on several factors, including necessary engine modifications and the availability of sustainable biofuel feedstocks, which significantly impact both market price and regulatory compliance. More info at GoodFuels and Port of Antwerp-Bruges.
- **Electric Propulsion:** Costs are driven by battery size and vessel capacity. Larger vessels require higher-capacity batteries. Details can be found at Port-Liner and ZES.
- **Hydrogen Propulsion:** Hydrogen projects are costlier due to storage and safety infrastructure. See also Future Proof Shipping and Elektra.
- **Ammonia Propulsion:** Ammonia projects require significant investment in safety and fuel handling. Find more details at SHIPFC and Port of Antwerp-Bruges.
- This estimate for methanol includes costs associated with necessary safety measures, such as double-walled fuel lines, conversion of existing engines, and emission control systems. The costs reflect the findings from pilot projects like the *Stena Germanica* conversion and feasibility studies. These estimates provide a comparison of the costs for implementing different alternative propulsion technologies in the inland waterways sector, including both retrofitting and new vessel builds.

4. Infrastructure and Logistics: Preparing the Groundwork for Change

A major hurdle for IWT's energy transition is the current lack of infrastructure to support alternative fuels like hydrogen, electricity, or biodiesel. Traditional fuels such as diesel are still the norm, and the existing network of bunkering and charging facilities is insufficient for the demands of cleaner energy sources. The shift toward cleaner energy and increased digitalization in inland waterway transport thus presents several critical infrastructural challenges that must be addressed to ensure a successful energy transition.

4.1 Current state of fuel infrastructure (Danube)

As the inland shipping industry pushes toward greener, more sustainable fuels, the development of bunkering infrastructure for alternative propulsion systems, including biofuels, hydrogen, and methanol, is gaining importance. That said, marine diesel remains the dominant fuel for vessels navigating the Danube. The infrastructure for diesel bunkering is well-established, with numerous ports offering refueling services to inland vessels. Key diesel bunkering locations along the Danube include:

- **Port of Vienna region (Austria)**: One of the busiest ports along the Danube, offering comprehensive refueling services for marine diesel nearby.
- **Port of Bratislava (Slovakia)**: A major port with refueling services for vessels operating along the Danube.
- **Port of Budapest (Hungary)**: A central hub for inland shipping, providing diesel bunkering facilities for both cargo and passenger vessels.
- **Port of Novi Sad (Serbia)**: Offers marine diesel bunkering for vessels traveling through the lower Danube region.
- **Port of Ruse (Bulgaria)**: A key port in Bulgaria with established diesel bunkering facilities for vessels navigating the Danube's lower stretches.
- **Port of Constanta (Romania)**: Romania's largest port and a key point for vessels transitioning between the Black Sea and the Danube. Constanța is a strategic bunkering hub for marine diesel.

Figure 3 Locations of diesel bunker stations and bunker vessels along the Danube

4.2 Preparing for alternative fuel bunkering infrastructure along the Danube

Figure 3 presents a map of the current diesel infrastructure, showing both stations and vessels. Compared to the Upper and Lower Danube, Hungary has fewer stations per kilometer. While this is not a major issue for diesel, as vessels can travel long distances on a single bunkering, the situation may not be as viable for alternative fuels with lower energy densities, such as hydrogen or electric batteries.

Since these cleaner energy solutions require more frequent refueling or recharging, a denser network of fueling stations and charging points will be essential. Without sufficient infrastructure in regions like Hungary, the transition to alternative fuels could be significantly hindered.

As each alternative fuel—whether biofuels, hydrogen, or methanol—presents unique challenges and needs, ranging from production and storage facilities to specialized safety systems or supply chains, below is an overview of the key areas where investments are required to establish and scale up bunkering infrastructure for alternative fuels.

4.2.1 Biofuels (HVO, FAME)

Biofuels offer a relatively easy transition from traditional marine diesel due to their availability, as well as the possibility of using existing engine technologies with minor modifications. However, investments are still needed to establish dedicated biofuel bunkering infrastructure on a larger scale. Key investment areas include:

- Storage Tanks and Pipelines: Adjustments must be made to ensure compatibility with biofuels' chemical properties. Investment in corrosion-resistant materials and specialized pipelines is necessary.
- Fuel Blending and Distribution Centers: Establishment of fuel blending stations and transportation logistics to move biofuels from production facilities to bunkering stations.
- Retrofit of Existing Bunkering Stations: Retrofitting marine diesel bunkering stations to handle biofuels requires investments in safety protocols and storage compatibility.
- Fuel Production and Supply Chain: Increased biofuel production capacity along the Danube requires investment in local production plants.

Two major players are currently leading this transition along the Danube corridor: OMV and MOL Group.

- OMV, the Austrian integrated oil, gas, and petrochemical company, has established a strong presence in the Danube region. The company offers HVO100 fuel and operates in several countries along the river. In a significant move towards sustainability, OMV Petrom, a subsidiary of OMV, has announced a EUR 750 million investment at its Petrobrazi refinery in Romania[24]. This investment will transform the refinery into the first major producer of sustainable fuels in Southeast Europe, with a focus on producing Sustainable Aviation Fuel (SAF) and renewable diesel (HVO). The new facility will have a production capacity of 250 kt/year of SAF and HVO, along with bio-naphtha and bio-LPG.
- MOL Group, a Hungarian oil and gas company, has also been making strides in biofuel production, including FAME. The company operates in multiple countries along the Danube, positioning itself to supply biofuels to the inland shipping sector. In a recent development[25], MOL Group has started innovative biofuel production at its Danube Refinery. This initiative involves co-processing bio feedstock, such as vegetable oils, used cooking oils, and animal fats, with fossil components during fuel production to create more sustainable diesel.

Both companies are not only focusing on production but also on the entire value chain of sustainable fuels. For instance, OMV Petrom has acquired a 50% stake in "Respiră Verde", a leader in the collection of used cooking oil in Romania, to ensure a reliable source of raw materials for biofuel production.

These developments signify a major shift in the Danube region's energy landscape, with potential benefits for the inland shipping sector. As these companies continue to invest in and expand their sustainable fuel offerings, inland shipping operators along the Danube will have increasing access to cleaner fuel options, contributing to the overall reduction of carbon emissions in the transport sector.

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[24] https://www.romania-insider.com/omv-petrom-petrobrazi-producer-sustainable-fuels-2024

[25] https://molgroup.info/en/media-centre/press-releases/strategy-in-action-mol-group-starts-innovative-biofuel-production-at-danube-refinery

While both HVO (Hydrotreated Vegetable Oil) and FAME (Fatty Acid Methyl Esters) present promising cleaner alternatives for propulsion in inland transport, there are important distinctions to consider. One key concern with HVO is the European Union's dependency on external sources, which exposes the region to geopolitical and geoeconomic risks beyond its control. This reliance on imports could lead to supply shortages and unpredictable cost increases. Furthermore, as the aviation sector ramps up its use of HVO to meet sustainability targets, the inland transport sector will face heightened competition for this fuel. This growing demand could drive prices even higher, creating additional challenges for cost-effective implementation in inland waterway transport.

4.2.2 Hydrogen (H2)

Hydrogen is one of the most promising zero-emission fuels, but the infrastructure required to support hydrogen bunkering is complex and costly. Hydrogen can be produced through electrolysis and stored as either compressed gas or liquid. While hydrogen can be considered zero emission from a tank-to-wake perspective, the origin of production and the environmental costs associated with the supply chain determine whether hydrogen could be classified grey or green and could therefore be considered zero emission (or not) from a well-to-wake perspective.

Two studies can serve as reference as to what the consequences are from an infrastructural point of view: H2 meets H20 focussing on the Danube, and RH2INE with focus on the Rhine river.

H2 meets H20

Findings from the "H2 meets H2O" project, presented by Pro Danube International[26], explores the potential of hydrogen as a sustainable fuel source for inland waterway vessels on the Danube. This initiative aims to develop a comprehensive roadmap for implementing hydrogen technology in Danube shipping, addressing both the challenges and opportunities presented by this innovative approach.

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[26] https://www.gsv.co.at/wp-content/uploads/2023%2005%2004%20Rafael%20Pro%20Danube%20International.pdf

One of the key innovations proposed by the project is the use of pressurized containers filled with hydrogen as a storage solution. This approach offers a practical method for handling hydrogen fuel, like the way shipping containers are managed. By allowing easy exchange of these containers, the system addresses some of the major challenges associated with onboard hydrogen storage and the need for extensive refueling infrastructure along the Danube.

Despite its potential, the implementation of hydrogen technology in Danube shipping faces several challenges. These include the limited hydrogen refueling infrastructure along the river, the suboptimal nature of current hydrogen storage systems for inland vessels, and the high investment costs required for both vessels and infrastructure development.

However, the opportunities presented by this technology are considered to be significant, including substantial reductions in greenhouse gas emissions, improved energy efficiency through fuel cell technology, and potential synergies with other transport modes and industries. To address these challenges and capitalize on the opportunities, the project outlines a phased roadmap. In the short term (by 2025), the focus will be on research, development, and demonstration projects. The medium-term phase (2025-2035) aims to scale up hydrogen production and distribution infrastructure. The long-term goal (beyond 2035) envisions widespread adoption of hydrogen technology in inland navigation.

The "H2 meets H2O" project underscores the potential of hydrogen as a clean fuel for Danube shipping while acknowledging the hurdles that need to be overcome. The innovative approach of using exchangeable pressurized hydrogen containers offers a promising solution to some of the infrastructure and storage issues. Ultimately, the success of this initiative will depend on coordinated efforts among various stakeholders to develop the necessary infrastructure and technology, paving the way for a more sustainable future in inland waterway transport.

Learnings from RH2INE kickstart studies

The CEF funded RH2INE Kickstart studies[27] provided detailed estimates on the number of a similar system of hydrogen containers, filling stations, and the anticipated hydrogen demand in different port areas under various scenarios on the Rhine river. The study projects the number of filled hydrogen containers required per port area per day for the years 2030 and 2040, under low, medium, and high demand scenarios. These numbers may not be representative for the Danube area, but they give an idea.

For 2030
(High Demand Scenario with 300-bar Containers):

- Rotterdam Area: Approximately 148 filled containers per day
- Duisburg Area: Approximately 111 filled containers per day
- RheinCargo Area (Neuss/Düsseldorf and Cologne): Approximately 56 filled containers per day

For 2030
(Low Demand Scenario with 300-bar Containers):

- Rotterdam Area: Approximately 15 filled containers per day
- Duisburg Area: Approximately 12 filled containers per day
- RheinCargo Area: Approximately 6 filled containers per day

These numbers are based on projected hydrogen demand for inland vessels operating along the Rhine corridor and consider factors like vessel types, operational profiles, and energy consumption. The study also outlines hydrogen consumption projections under three scenarios (Low, Medium, High) for the years 2030 and 2040:

Total Hydrogen Demand in 2030:

- Low Scenario: Approximately 5,000 tonnes per year
- High Scenario: Approximately 48,000 tonnes per year

Total Hydrogen Demand in 2040:

- Low Scenario: Approximately 10,000 tonnes per year
- High Scenario: Approximately 104,000 tonnes per year

These demand estimates are meant to help in planning the required infrastructure, such as filling stations and storage facilities along the Rhine river. Infrastructure investments and requirements identified are as follows:

- Hydrogen Filling Stations: The study emphasizes the need for strategically located hydrogen filling plants near ports. While it doesn't specify an exact number, it suggests that existing container terminals can initially handle the swapping of hydrogen containers, minimizing the need for new infrastructure in the short term.
- Scaling Up Infrastructure: For future expansion, the study recommends investing in more centralized container solutions and possibly developing greenfield sites or utilizing bulk terminals to accommodate increased demand.
- Standardization Needs: The study highlights the importance of standardizing container types, pressures (300 or 500 bar), and handling equipment to improve efficiency and reduce costs as the number of hydrogen-powered vessels increases.

The RH2INE Kickstart Studies provided quantitative assessments of the infrastructural needs for hydrogen implementation in inland navigation. By estimating the number of hydrogen containers required per day and projecting future hydrogen demand, the study offers a foundation for planning and investment decisions necessary to support the transition to hydrogen as a fuel for inland vessels. Please note the study was performed some years ago, 2019-2020, and the process of drawing a plan as to set up a next step, for a so-called supply facilitated by a entity taking care of the 'tanktainer pool', is just about to start in 2024. This is an indication that the process of getting the infrastructural boundary conditions right is time consuming, partly due to the chicken-and-egg problem: without demand there is no base for supply, but without adequate supply the demand will not increase. Excellent stakeholder management, public support and entrepreneurial spirit seems to be the vital ingredients in this case. As new momentum grows in the Rhine area, it is advised to keep a close eye on the developments especially since standardization is considered a necessity to maintain momentum and speed up the process of market up-take.

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[27] www.rh2ine.eu

Points of attention on the landside

Investment[28] in electrolyser facilities is critical to enable large-scale production of green hydrogen. These facilities will rely on renewable energy sources, such as solar or wind power, to generate hydrogen through water electrolysis, ensuring a sustainable supply for inland vessels. Specialized storage tanks, designed to handle hydrogen under high pressure or cryogenic conditions, are also essential for safe and efficient storage. These tanks must accommodate the unique properties of hydrogen, requiring advanced materials and technologies to maintain its stability. Investment is also needed in distribution systems, such as pipelines or trucks, to transport hydrogen from production sites to bunkering stations. These systems play a pivotal role in creating a reliable hydrogen supply chain for inland navigation. Finally, hydrogen fueling stations must be equipped with the necessary safety protocols to handle the gas securely. Bunkering stations require robust fueling systems capable of managing hydrogen's properties while ensuring the safety of both personnel and infrastructure.

Points of attention for vessels

For smaller vessels, such as motor cargo vessels (MCVs), hydrogen-powered operations are feasible with one or two bunkering stops on a typical route. For example, between Budapest and Regensburg, a motor cargo vessel would need just one stop in Vienna or Linz to refuel, using three 20-foot hydrogen containers for the trip[329]. However, for larger pushed convoys, more frequent refueling would be required—potentially two stops along the same route—due to their higher energy consumption. The same evaluation also shows that smaller vessels with lower energy demands are more compatible with hydrogen technology in its current stage. For example, motor cargo vessels operating in the A1 operational mod (up to 14 hours of continuous sailing) on the Upper Danube are ideal candidates for hydrogen fuel. However, larger pushed convoys, which require more energy, face challenges due to the volume and mass of hydrogen storage tanks, making their operation less efficient on hydrogen without further technological advancements.

In terms of regions, the port density along the Upper Danube is sufficient for hydrogen adoption, with maximum distances between ports of about 100 to 150 kilometers, making it feasible for hydrogen-powered vessels to refuel without major interruptions. Hydrogen thus presents a promising future for decarbonizing inland navigation on the Danube, especially for smaller vessels operating on shorter routes. For a more general application, expanding port infrastructure and addressing the logistical demands of hydrogen bunkering will be key to the widespread adoption of hydrogen as a fuel for Danube navigation.

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[28] Estimated Investment Range: €10 million to €50 million per location (depending on whether compressed or liquid hydrogen is used and the scale of the electrolyser and storage facilities). Sources: Hydrogen Council report on hydrogen infrastructure investment (2021), Fuel Cells and Hydrogen Joint Undertaking (FCH JU) cost analysis for hydrogen refueling infrastructure (2020).

[29] Evaluation of the applicability of hydrogen as fuel in Danube navigation, J. Schweighofer 2023, Institute of Thermodynamics and Sustainable Propulsion Systems, Graz University of Technology

Infrastructure: identifying gaps

As current container handling facilities can play a crucial role in the implementation of the swappable tanktainer concept, it is worth taking a look at the current state of play on container handling facilities along the Danube. Here is an overview of the main ports along the Danube that have container handling facilities, listed by country:

1. Germany
   - Port of Deggendorf: An important container terminal for the Bavaria region, located on the upper Danube.
2. Austria
   - Port of Vienna: The largest container handling facility in Austria, playing a key role in international container transport.
   - Port of Linz: An industrial port with extensive container handling capabilities.
   - Port of Enns: Austria's largest inland terminal, located at the confluence of the Enns and Danube rivers.
3. Slovakia
   - Port of Bratislava: Important for container handling in the region and connected to international markets.
4. Hungary
   - Port of Budapest (Csepel): The largest and most developed container handling location in Hungary, connected by rail and road transport.
   - Port of Baja: A smaller but strategically significant container port in southern Hungary.
5. Croatia
   - Port of Vukovar: The only major container handling location in Croatia on the Danube.
6. Serbia
   - Port of Belgrade: A key container handling location and logistics hub for the region.
   - Port of Novi Sad: An industrial port with container facilities.
7. Bulgaria
   - Port of Ruse: One of Bulgaria's largest ports on the Danube, with container handling facilities.
   - Port of Vidin: A smaller port with container handling capabilities.
8. Romania
   - Port of Constanța: Connected to the Danube via the Danube-Black Sea Canal. It is Romania's largest seaport and an important hub for container transport to the hinterland.
   - Port of Giurgiu: A key Romanian inland port with container facilities.
   - Port of Galati: The largest port on the Danube in Romania with a significant container terminal.
   - Port of Drobeta-Turnu Severin: A smaller container handling location.
9. Ukraine
   - Port of Reni: Strategically located near the Danube estuary, with container facilities.

Map data ©2024 GeoBasis-DE/BKG (©2009), Google, Inst. Geogr. Nacional, Mapa GISrael

Figure 4 Container handling facilities along the Danube

This overview highlights the major container handling locations along the Danube. Some ports have large terminals with extensive facilities, while others offer smaller-scale container handling for local or regional transport.

To have an adequate infrastructure for hydrogen tanktainers, one would ideally have a container handling facility every 200 kilometers along the Danube. Currently, the point-to-point gap between container handling facilities along the Danube is as follows:

From	To	Distance (km)
Deggendorf	Linz	**150**
Linz	Krems	**112**
Krems	Vienna	**83**
Vienna	Bratislava	**51**
Bratislava	Budapest	**221**
Budapest	Baja	**169**
Baja	Vukovar	**146**
Vukovar	Novi Sad	**79**
Novi Sad	Belgrade	**84**
Belgrade	Drobeta-Turnu Severin	**239**
Drobeta-Turnu Severin	Vidin	**140**
Vidin	Ruse	**296**
Ruse	Giurgiu	**6**
Giurgiu	Galati	**334**
Galati	Reni	**23**
Reni	Constanța	**132**

Identifying ports that could help close the gaps where the distance between existing container facilities exceeds 200 kilometers:

1. Bratislava to Budapest (221 km)

- This stretch is over 200 km, so an intermediate port would be necessary to meet the infrastructure goal. Potential Ports:
- Komárom (Hungary): Located approximately halfway between Bratislava and Budapest, Komárom is a key candidate for container handling development. It has an industrial port that could be expanded.
- Esztergom (Hungary): Situated north of Budapest, Esztergom could be a secondary candidate for port development.

2. Belgrade to Drobeta-Turnu Severin (239 km)

- This gap exceeds 200 km, so an intermediate facility would improve coverage. Potential Port:
- Smederevo (Serbia): Located east of Belgrade along the Danube, Smederevo has a port and could be considered for container handling facilities.
- Veliko Gradište (Serbia): Another potential option, though smaller than Smederevo.
- Kladovo (Serbia): Positioned closer to Drobeta-Turnu Severin, this could also bridge the gap.

3. Vidin to Ruse (296 km)

- This is a significant gap, and developing a port between these two would be essential. Potential Ports:
- Lom (Bulgaria): Located halfway between Vidin and Ruse, Lom already has a port and could be upgraded with container handling facilities.
- Svishtov (Bulgaria): Another possible option located further downstream, Svishtov has port facilities that could be expanded.

4. Giurgiu to Galati (334 km)

- This is the longest gap, and it's crucial to have an intermediate container facility. Potential Port:
- Călărași (Romania): Positioned roughly halfway between Giurgiu and Galati, Călărași could be a strategic port for development.
- Brăila (Romania): Another possible option near Galati, Brăila already has port infrastructure and could be adapted for container handling.

Summary of Candidate Ports for upgrading facilities as to be able to support a hydrogen tanktainerpool infrastructure:

- Bratislava to Budapest: Komárom, Esztergom
- Belgrade to Drobeta-Turnu Severin: Smederevo, Veliko Gradište, Kladovo
- Vidin to Ruse: Lom, Svishtov
- Giurgiu to Galati: Călărași, Brăila

These ports are located within the long gaps and have potential for development to ensure a more consistent container handling infrastructure every 200 kilometers.

4.2.3 Methanol

To make methanol a viable alternative fuel for inland waterway transport on the Danube, significant infrastructural developments are required. First and foremost, refueling stations must be established along the river, strategically placed in key locations where vessel traffic is highest. These stations would need to store methanol safely and be equipped to handle frequent refueling needs, as methanol has a lower energy density compared to diesel, requiring more frequent refueling stops. Infrastructure development should include not only ports but also methanol production and supply chains, ensuring an uninterrupted fuel supply for vessels operating on the Danube.

Furthermore, the storage and safety infrastructure on vessels themselves needs to be upgraded to accommodate methanol. Methanol is a liquid fuel that can be stored more easily than hydrogen, but it is toxic and requires specialized tanks and handling procedures to ensure safe transport and use. Vessels will need to undergo significant retrofits to integrate methanol-compatible engines and storage systems. Safety protocols for methanol handling, spill response, and emissions control must be introduced to comply with environmental and safety standards, further driving the need for widespread training and investment in both onboard systems and port facilities.

Finally, the successful adoption of methanol as an alternative fuel depends heavily on the development of supporting infrastructure, such as methanol production plants and transportation logistics for delivering the fuel to refueling stations. Collaboration between governments, fuel producers, and logistics providers is essential to establish a reliable supply chain. Additionally, regulatory frameworks that incentivize the use of methanol and provide subsidies for infrastructure upgrades will be crucial in ensuring methanol's feasibility as a green fuel for inland waterway transport on the Danube.

Key Investment Areas[30]:

- Storage Tanks: Methanol requires tanks made from compatible materials like stainless steel.
- Bunkering Stations: Fueling systems need spill containment, leak detection, and vapor recovery systems for methanol handling.
- Fuel Distribution Infrastructure: Investment in a reliable supply chain for methanol, including potential partnerships with chemical producers.
- Retrofit of Existing Bunkering Stations: Modifications to existing fueling infrastructure for methanol handling.

Methanol production along the Danube is minimal due to the lack of large-scale chemical industries typical of the Rhine. Methanol production traditionally relies on natural gas or coal feedstocks, which are not widely available along the Danube corridor. However, projects exploring green methanol production using renewable feedstocks are emerging in Europe, though they are still in early stages and concentrated outside the Danube region.

Ports along the Danube have limited methanol storage facilities, as most are not yet equipped to handle alternative fuels beyond conventional diesel and biofuels. Some Austrian ports are considering methanol storage solutions due to methanol's relatively easy storage requirements compared to LNG (non-cryogenic, liquid at ambient temperatures), which makes it a more viable alternative for future bunkering. Vienna, for instance, is assessing methanol's feasibility as part of its alternative fuel initiative, though full-scale bunkering stations are still pending.

Investing in methanol bunkering facilities in ports like Vienna, Budapest, Novi Sad, Ruse, Galati and Agiega/Constanța ensures coverage along the entire Danube, from the upper to lower stretches. These locations are crucial for facilitating long-distance inland waterway traffic and ensuring that vessels have access to alternative fuels, which is essential for the decarbonization of the shipping sector. Each port offers unique advantages based on traffic volume, industrial presence, and logistical connectivity, making them ideal for such investments.

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[30] Estimated Investment Range: €1 million to €10 million per location (depending on the scale of the storage and bunkering facility).
Sources:Methanol Institute report on methanol bunkering (2021), FASTWATER Project reports on methanol infrastructure and retrofit costs (2022).

4.2.4 Ammonia

By converting hydrogen into ammonia, it can be easily transported over long distances. To make ammonia a viable fuel for inland shipping along the Danube, key infrastructure investments are critical. First, specialized bunkering stations must be established at strategic ports such as Vienna, Budapest, Novi Sad, Ruse, Galati and Agiega/Constanța . These ports, given their heavy traffic, are ideal locations to create refueling points for vessels. The construction of safe storage facilities for ammonia, equipped with advanced safety systems like leak detection and emergency protocols, will be essential.

Moreover, the infrastructure must include retrofits for existing vessels or investments in new ammonia-powered vessels. These ships will require safe and efficient storage and handling systems, given ammonia's toxicity. Port staff and crews will need to be trained in specialized handling techniques, which is another layer of infrastructural preparation.

Lastly, a reliable supply chain for ammonia is crucial, which could involve building production plants near industrial hubs along the Danube. Investments in pipelines or specialized transport solutions will also be needed to ensure a steady supply of ammonia to the bunkering stations. Without these infrastructure developments, ammonia's potential as a sustainable alternative for inland shipping will be limited.

HGK Shipping is pioneering a project in inland waterway transportation with the development of a new vessel called “Pioneer”. This innovative ship is designed to revolutionize the transport of liquefied gases, specifically cold liquefied ammonia (NH3) and liquefied carbon dioxide (LCO_2), along Europe's inland waterways. The Pioneer, measuring 135 meters in length and 17.5 meters in width, represents a significant leap forward in cargo capacity compared to current gas tankers. Its innovative tank and loading systems are tailored for the efficient handling of gases in their liquefied forms. One of the vessel's most remarkable features is its ability to transport cold liquefied ammonia at temperatures as low as -33 degrees Celsius, eliminating the need for energy-intensive heat treatment processes at ports.[31]

This project aims to set new standards for the safe and efficient transportation of ammonia derived from “green” hydrogen, as well as facilitating the removal of unavoidable carbon dioxide from industrial production sites. The vessel's diesel-electric drive concept and shallow-water design make it ideal for traffic between the Amsterdam-Rotterdam-Antwerp (ARA) ports and destinations further up the Rhine. By providing efficient alternatives to pipeline transport for hydrogen derivatives and carbon dioxide, it aligns with carbon capture and storage (CCS) methodologies.

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[31] https://swzmaritime.nl/news/2024/04/18/hgk-develops-inland-tanker-for-shipping-ammonia-and-lco2/

4.3 Common infrastructure investments for all fuels

To support the adoption of alternative fuels in inland shipping, several common infrastructural elements are necessary, regardless of the specific fuel chosen. First, port infrastructure upgrades are essential. Ports will need to expand and adapt their facilities to handle alternative fuels safely. This includes creating designated safety zones, updating fuel storage facilities, and allocating more space for refueling operations.

Additionally, intermodal logistics play a critical role in the supply of alternative fuels to inland vessels. Investment in logistics hubs that connect road, rail, and waterways will be key to ensuring efficient fuel transportation and distribution. These hubs will allow seamless integration of multiple transport modes, supporting fuel supply chains from production sites to refueling points.

Moreover, the adoption of advanced digitalization and monitoring systems is required. These systems will monitor fuel levels, detect leaks, and optimize fuel distribution, ensuring safety and efficiency in the handling of alternative fuels like hydrogen, ammonia, or methanol. The digitalization of the fuel supply chain will also enhance real-time tracking of fuel availability and distribution across ports.

Finally, cross-border collaboration is crucial for the success of alternative fuel adoption. Countries along the Danube will need to harmonize regulations, safety standards, and legal frameworks to ensure the seamless movement of vessels using alternative fuels. Investment in establishing these international agreements and safety protocols will foster smoother operations across borders, reducing bureaucratic obstacles and ensuring uniform safety practices. Together, these infrastructural investments will pave the way for a cleaner and more efficient inland shipping sector.

4.4 Other relevant infrastructure for Alternative Propulsion on the Danube: Shoreside Electrification and Lessons from LNG

In advancing sustainable propulsion on the Danube, a realistic approach emphasizes tangible pilot projects and lessons learned from past initiatives. Here’s a closer look at ongoing shoreside electrification efforts and the challenges faced with LNG infrastructure in the region.

Shoreside Electrification Projects

Shoreside electrification provides immediate emission reductions by allowing vessels to connect to the electrical grid while docked, reducing the need for onboard diesel engines. Thanks to two shore power units a cleaner, more sustainable docking experience is available for cargo vessels on Austrian Danube since June 19, 2023.
On the banks of the Austrian Danube, at two public mooring places, Linz (river-km 2,129.2 – 2,129.0; right bank) and Wildungsmauer (river-km 1,895.1 – 1,894.8; right bank), now stand two shore power units, each operating at 400 V. These state-of-the-art units boast three 16 A, 32 A, and 63 A-connections (CEE) on their underside, offering connectivity for mooring in multiple rows.[32]

LNG in the Danube Region

LNG was previously considered a “bridging fuel” for cleaner propulsion along the Danube. However, several projects encountered setbacks, causing stakeholders to rethink LNG’s viability in this region. The LNG Masterplan for Rhine-Main-Danube (2013 - 2018) for instance: this extensive plan envisioned a cross-European LNG network, including the Danube. However, it faced significant economic barriers, with fluctuating LNG prices and insufficient demand deterring uptake. Operators ultimately found the cost savings to be minimal, limiting the plan’s impact.[33]

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[32] https://www.inlandwaterwaytransport.eu/shore-power-danube/
[33] http://www.upper-rhine-ports.eu/images/UpperRhinePorts/LNG_MP_Booklet_FINAL.pdf

5. Comparison of alternative propulsion systems & regulations

By assessing the environmental impact, as well as the social implications of each alternative, we will provide a comprehensive overview of how these technologies can contribute to a greener and more socially responsible future for cargo shipping on the Danube. We will also look at the practical side: what is allowed from a regulatory point of view, and what is not (yet)?

5.1 Ammonia, hydrogen and methanol

When analyzing the potential of alternative fuels for inland navigation, ammonia and hydrogen stand out as significant contenders for reducing carbon emissions, though each presents unique challenges. Ammonia, for example, does not produce CO2 during combustion, making it an attractive option for decarbonizing inland waterway transport. When produced using renewable energy, ammonia becomes “green ammonia,” a zero-carbon fuel that is environmentally friendly from production to use meaning zero emissions also from a well-to-wake perspective. This offers shipowners a fuel option with the potential for no well-to-wake CO2 emissions, helping to meet even the most stringent long-term emissions reduction targets. However, its adoption faces hurdles such as infrastructure requirements and safety concerns due to its toxicity and corrosiveness. Ammonia also generates nitrogen oxides (NOx) during combustion, which necessitates advanced after-treatment systems to mitigate emissions.

Hydrogen, similarly, offers the promise of zero CO_2 emissions, particularly when produced from renewable sources. However, like ammonia, it requires significant infrastructure investments, particularly in storage and refueling capabilities. Hydrogen has the added advantage of producing no NOx or particulate matter during use, which makes it an even cleaner alternative from an emissions standpoint, though it faces higher upfront costs related to its production and distribution.

Fuel Type	**CO_2e (g/MJ)**	**NO_x (g/MJ)**	**PM (g/MJ)**
Diesel	90.5	0.5	0.03
Ammonia	0.0	0.7	0.02
Hydrogen	0.0	0.0	0.0
Methanol	20.6	0.3	0.01

Methanol, another alternative fuel, presents a lower carbon footprint compared to diesel, especially when derived from renewable sources. Methanol’s emissions profile is more favorable than diesel, with significantly lower CO_2, NOx, and particulate matter emissions. However, it still produces more emissions than ammonia and hydrogen, which have the potential for zero or near-zero emissions depending on how they are produced and utilized.

The economic feasibility of adopting these fuels also varies. Ammonia typically requires lower initial capital expenditure than hydrogen due to its existing production and distribution infrastructure, although handling and safety measures introduce ongoing costs. Methanol, while less complex to store and handle compared to ammonia, is more expensive than conventional diesel but less costly than hydrogen.
Considering the emissions and costs associated with these fuels, the choice between ammonia, hydrogen, and methanol will largely depend on balancing the environmental benefits against the economic implications and operational requirements of inland navigation. Here is a comparison of key emissions factors for diesel, ammonia, hydrogen, and methanol:

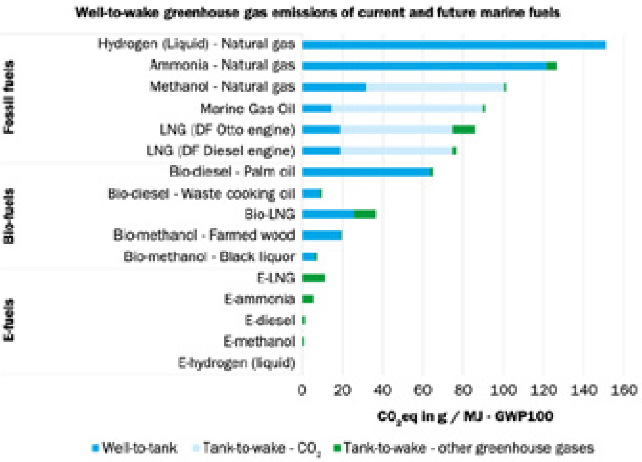

Figure 5 TNO, https://publications.tno.nl/publication/34640817/zpBGh5/gerritse-2023-green.pdf

This table (figure 5) illustrates the environmental trade-offs between different fuel types, highlighting ammonia and hydrogen's clear advantages in reducing CO_2 emissions, while also pointing out the need for managing other pollutants, such as NOx and particulate matter, to achieve comprehensive environmental benefits.

Ammonia vs. hydrogen

Ammonia and hydrogen are both promising alternative fuels for inland waterway transport as the industry moves toward decarbonization. However, they differ in several key aspects, which influence their suitability for different applications within IWT.

1. **Energy Density and Storage:**

- **Ammonia:** Ammonia has a higher energy density by volume than hydrogen, which means it can store more energy in a given space. This is particularly advantageous for inland vessels that need to carry enough fuel for long journeys on waterways like the Danube. Ammonia can be stored in liquid form under moderate pressure or at low temperatures, making it easier to handle than hydrogen, which requires extremely high pressures or cryogenic temperatures for storage.
- **Hydrogen:** Although hydrogen has a higher energy density by weight, its volumetric energy density is much lower than ammonia's. This means that storing sufficient hydrogen on board a vessel requires more space or complex high-pressure systems, which can be a limiting factor for vessels where space is at a premium.

2. **Infrastructure:**

- **Ammonia:** The existing infrastructure for handling and transporting ammonia is more developed than that for hydrogen, particularly because ammonia is already widely used in the agricultural sector as a fertilizer. This existing infrastructure could potentially be adapted for use in the maritime industry, making it easier to scale up ammonia as a fuel for IWT.
- **Hydrogen:** Hydrogen infrastructure, especially for refueling, is still in the early stages of development, particularly in the IWT sector. Significant investment is required to build the necessary production, storage, and distribution networks for hydrogen, which could delay its widespread adoption.

3. **Safety and Handling:**

- **Ammonia:** Ammonia is toxic and corrosive, which raises significant safety concerns, particularly in the confined and heavily populated environments often associated with inland waterways. Proper safety measures and handling protocols must be rigorously enforced to prevent leaks and ensure the safety of crew and nearby populations.
- **Hydrogen:** Hydrogen is highly flammable and requires careful handling, especially due to its tendency to leak from storage systems because of its small molecular size. However, hydrogen's lack of toxicity and the extensive research into safe handling practices give it an advantage in terms of safety over ammonia.

4. **Environmental Impact:**

- **Ammonia:** Ammonia does not emit carbon dioxide during combustion, making it a zero-carbon fuel in that respect. However, burning ammonia can produce nitrogen oxides (NOx), which are harmful pollutants. This issue can be mitigated with after-treatment technologies like selective catalytic reduction (SCR), but it adds complexity to its use as a fuel.
- **Hydrogen:** Hydrogen fuel cells generate electricity with water as the only byproduct, meaning that they produce zero emissions at the point of use. This makes hydrogen a cleaner option from an emissions standpoint compared to ammonia, especially when considering NOx production.

5. **Adoption and Future Prospects:**

- **Ammonia:** Ammonia's existing industrial infrastructure, coupled with its energy density advantages, makes it a strong candidate for the near-term adoption in IWT. It is particularly suited for vessels operating on longer routes where refueling opportunities are limited, such as on the Danube.
- **Hydrogen:** Hydrogen is seen as a longer-term solution for zero-emission transport, particularly in cases where infrastructure can be developed to support its use. Hydrogen fuel cells are an attractive option for IWT in areas where shorter trips or readily available refueling infrastructure make storage less of a concern.

Ammonia and hydrogen each have distinct advantages for inland waterway transport, and the choice between them depends on factors such as operational range, vessel size, and the development of supporting infrastructure. Ammonia offers greater energy density and benefits from existing infrastructure, making it a more immediate solution for long-range applications. Hydrogen, with its zero-emission profile and advanced fuel cell technology, is a cleaner option, but it faces challenges with storage and infrastructure that need to be overcome for widespread adoption.

5.2 Readiness according to ES-TRIN status

ES-TRIN (European Standard laying down Technical Requirements for Inland Navigation vessels) is crucial for the deployment of new technologies, developed under supervision of the European Committee for Drawing up Standards in Inland Navigation (CESNI), in inland waterways for several reasons. ES-TRIN provides[34] a harmonized regulatory framework that ensures the safe and efficient operation of inland waterway vessels. When new technologies, such as alternative propulsion systems (hydrogen, biofuels, batteries) or autonomous navigation, are introduced, ES-TRIN helps define the technical standards that must be followed to ensure safety. These regulations cover critical aspects such as fuel storage, engine design, fire safety, and emission control.

ES-TRIN sets performance and operational standards for modern technologies like fuel cells, electric propulsion systems, and hybrid engines. By providing guidelines for integrating these technologies, ES-TRIN helps promote the modernization of the inland waterway fleet, leading to improved fuel efficiency and lower emissions. For alternative fuels like hydrogen, methanol, and ammonia, ES-TRIN outlines specific requirements that address their unique characteristics, such as low flashpoints or complex storage needs. The standard ensures that new fuels are integrated safely into the fleet, preventing accidents while encouraging a transition from traditional diesel engines to greener alternatives.

Since ES-TRIN is applied across European countries, it ensures consistent standards for all inland waterway vessels. This harmonization is essential for cross-border operations, enabling vessels equipped with new technologies to navigate seamlessly through different countries and waterways without facing technical barriers. As new technologies are tested through pilot projects, ES-TRIN enables flexibility by allowing for derogations and exceptions in special cases (e.g., pilot projects or innovative vessels). This flexibility is key for evaluating new technologies on a smaller scale before wider implementation.

Per January 1st of 2024, ES-TRIN 2023 is in force. The ES-TRIN 2023 replaced the 2021 edition and serves as a technical annex for the European Directive ED/2016/1629. ES-TRIN is periodically updated per 2 years. In 2025 a new edition will be developed.

Work programme

In the CESNI Work Programme (2022-2024)[35], alternative propulsion and fuels are addressed through several key initiatives aimed at reducing emissions and promoting innovative technologies in inland navigation:

1. Standards for Alternative Fuels: CESNI is working on drafting and adopting technical standards for the use of alternative fuels on inland navigation vessels, including methanol, hydrogen (both liquefied and gaseous), and compressed natural gas (CNG). These standards cover fuel

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[34] ES-TRIN is not binding per se but CCNR, EU, international organisations and States can apply ES-TRIN by referring to it in their respective legal frameworks

[35] https://www.cesni.eu/wp-content/uploads/2023/12/CESNI-work-programme-REV_231213_en.pdf

storage and the adaptation of internal combustion engines to alternative fuels
2. Electric Propulsion Systems: The programme includes a review and update of the requirements for electric propulsion systems, taking into account the experience gained in the sector. This is a significant move toward integrating electric solutions and transitioning to zero-emission propulsion
3. Zero-Emission and Green Technologies: CESNI supports the deployment of batteries and electric propulsion systems as part of the fleet's move towards zero-emission operations. The organisation is also facilitating innovation by reducing administrative barriers to these new technologies

The ES-TRIN 2023 includes several amendments, with some relevant to alternative fuels. In ES-TRIN, hydrogen is recognized as a potential fuel for inland waterway vessels. However, the regulatory framework for its use is still under development. Annex 8 of ES-TRIN outlines requirements for handling low-flashpoint fuels like hydrogen. Key challenges include ensuring safe hydrogen storage and bunkering, as well as fire safety protocols due to hydrogen's properties.

Chapter 30 (general requirement for all low flashpoint fuels) and Annex 8 (different sections for storage and use of different fuels) of ES-TRIN 2023 address these topics, which are particularly relevant for methanol and hydrogen use in inland navigation. While not included in ES-TRIN 2023, storage and use of methanol will most probably be part of ES-TRIN 2025/1, expected entry into force in January 2026.[36]

The European Committee for Drawing up Standards in Inland Navigation works closely with various international bodies, including the Central Commission for the Navigation of the Rhine (CCNR), to develop and harmonize technical standards for inland navigation. While the Danube Commission focuses on the Danube region, it aligns its regulations and technical requirements with standards developed by CESNI, particularly to ensure consistency across European inland waterways.

CESNI/TP contains a temporary working group on technical requirements for alternative fuels, the meeting schedule can be found here:
https://www.cesni.eu/nl/evenements

Directive (EU) 2016/1629

The ED/2016/1629 regulation, also known as Directive (EU) 2016/1629, lays down technical requirements for inland waterway vessels.

The new Alternative Fuels Infrastructure Regulation (AFIR) introduces targets for shoreside electricity supply in inland waterway ports, which will indirectly impact vessels covered by ED/2016/1629. Regulation (EU) 2016/1628, which is related to ED/2016/1629, encourages the introduction of alternative fuel engines that can have low NOx and particulate pollutant emissions. There is ongoing work to develop regulations and standards for the decarbonization of Inland Waterway Transport in Europe, which will likely influence future updates to ED/2016/1629.

The list of alternative fuels considered in maritime regulations is not exhaustive and could be complemented in the future, suggesting that ED/2016/1629 may need to evolve to accommodate new fuel technologies. As the directive serves as a technical annex alongside ES-TRIN, future updates to ES-TRIN regarding alternative fuels will likely be reflected in amendments to ED/2016/1629.

While ED/2016/1629 doesn't currently have extensive provisions for alternative fuels, it's clear that the regulatory landscape is evolving to address the growing importance of sustainable and alternative fuel solutions in inland navigation. Future revisions of the directive are likely to incorporate more specific requirements and guidelines related to alternative fuels, aligning with broader EU environmental and energy policies.

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[36] https://www.cesni.eu/wp-content/uploads/2023/09/6_Secretariat-du-CESNI.pdf

5.3 RED III and ETS 2

The Renewable Energy Directive III (RED III) and the Emissions Trading System II (ETS-2) are key elements of the European Union's strategy to meet its climate targets and promote cleaner energy use. Both directives are expected to have a significant impact on various sectors, including inland shipping, by pushing them towards adopting renewable energy sources and reducing greenhouse gas emissions.

RED III (Renewable Energy Directive III)

The RED III directive, adopted in 2023, sets a binding target for the EU to source 42.5% of its energy from renewable sources by 2030, with the possibility of reaching 45% if conditions allow. It aims to accelerate the transition to cleaner energy in all sectors, including transport, and focuses on reducing carbon emissions by increasing the use of biofuels, hydrogen, and other renewable fuels.

Impact on Inland Shipping:

- Adoption of Renewable Fuels: RED III will push the inland shipping sector to transition from diesel to low-carbon and renewable fuels like biofuels, hydrogen, and synthetic fuels. This aligns with the EU's broader objective of becoming carbon-neutral by 2050.
- Increased Biofuel Demand: With the entire transport sector, including aviation and shipping, transitioning to biofuels, inland shipping companies may face rising costs due to increased competition for biofuels.
- Timeline: By 2030, inland shipping will need to significantly adopt renewable fuels to comply with the RED III targets. This means that investments in alternative fuel infrastructure will be necessary in the short to mid-term to ensure compliance and cost-effectiveness.

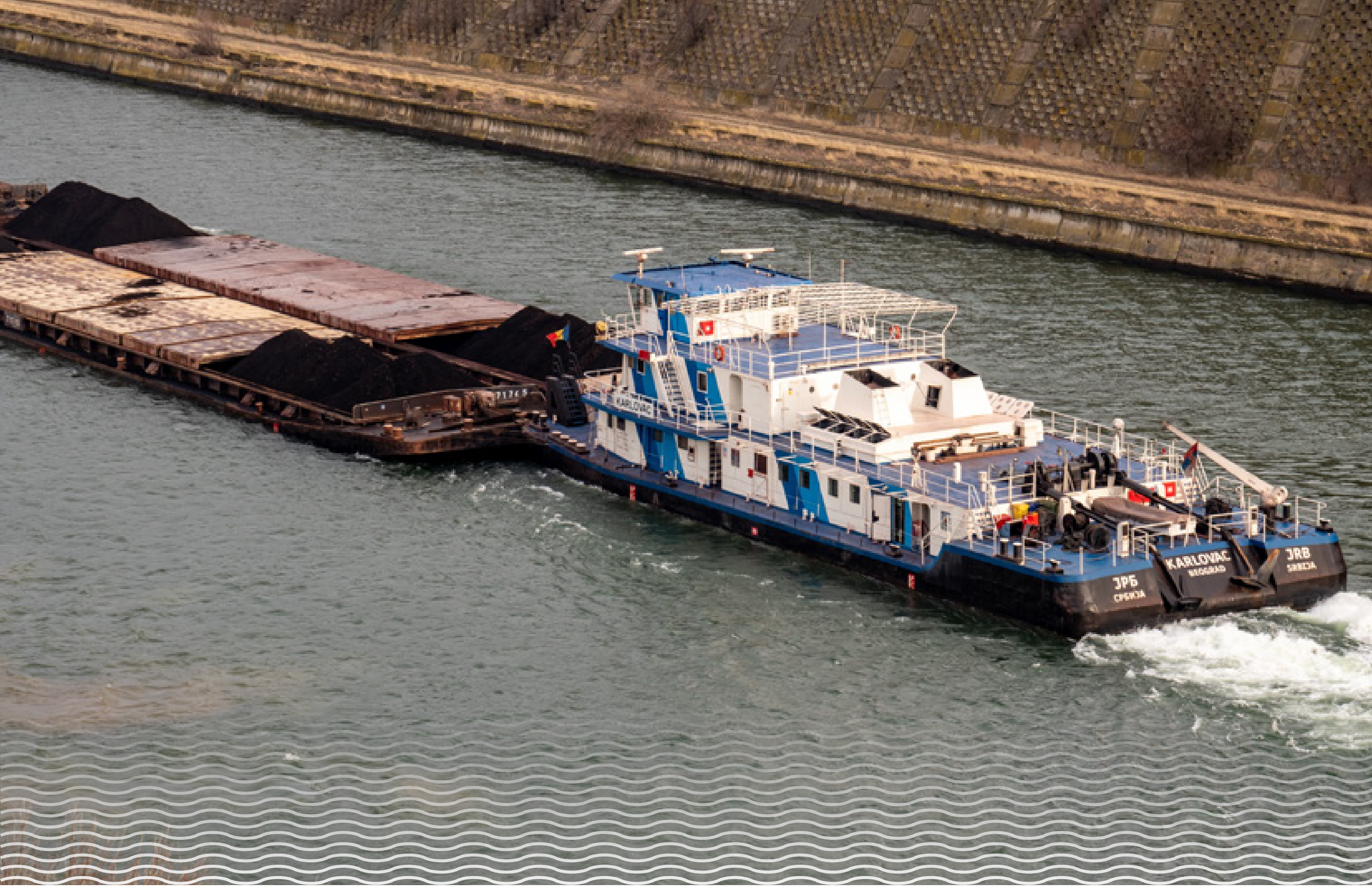
ETS-2 (Emissions Trading System II)

The ETS-2, set to launch in 2027, extends the EU's carbon pricing mechanism to road transport and buildings. Under this system, carbon emissions in these sectors will be capped, and companies will need to buy permits for each ton of CO_2 they emit. Although ETS-2 does not directly cover inland shipping, it will have an indirect impact.

Impact on Inland Shipping:

- Indirect Cost Pressures: While not directly subject to ETS-2, the inland shipping sector could see rising operational costs as the logistics and supply chains that rely on last mile road transportation become more expensive due to carbon pricing.
- Higher Fuel Prices: As road transport faces rising costs for using diesel and other carbon-intensive fuels, this could also affect the cost of fuels used in inland shipping, making traditional fuels more expensive and pushing shipping companies towards renewable alternatives.
- Long-Term Influence: The gradual increase in carbon prices due to ETS-2 will further encourage the inland shipping sector to adopt cleaner fuels and technologies by the end of the decade.

Both the RED III directive and ETS-2 will play critical roles in driving the inland shipping sector toward sustainability. RED III will directly push the sector to adopt renewable fuels by 2030, while ETS-2 will indirectly raise the cost of carbon-intensive fuels starting in 2027, incentivizing a shift to zero-emission technologies.



6. Conclusions and Recommendations for Action: Charting the Path Forward

A successful transition to sustainable propulsion systems requires clear and actionable strategies. In this chapter, we will outline short-term and long-term strategies for the adoption of alternative propulsion technologies in Danube cargo shipping.

Our recommendations will cover both technical and policy measures, providing a comprehensive roadmap for stakeholders to follow. By offering practical steps and policy guidance, this chapter aims to drive forward the implementation of sustainable propulsion systems in the region.

Economic Factors

With the current practice of modernizing the Danube fleet by purchasing inland vessels decommissioned in Western Europe or nearing the end of their economic lifespan, achieving the zero-emission target by 2050 is at risk. While older ships from Western Europe may offer short-term economic benefits compared to the aging fleet (many vessels are over 40 years old), this approach delays incentives to transition to zero-emission vessels.

- As large-scale subsidies in Western Europe accelerate the adoption of zero-emission ships, fleet composition will shift by 2030, with more zero-emission ships in operation. The older ships being replaced will likely find their way into the Danube fleet.
- This relative modernization could be supplemented by drop-in fuels, as new owners are unlikely to invest in costly retrofits that far exceed the value of the vessel.
- Higher blends and regional production of these fuels, along with necessary technical maintenance, present a no-regret option, requiring minimal infrastructural changes compared to other pathways.

An important economic factor to consider is the comparison between diesel prices and alternative fuels, as economies of scale from increased production and demand are expected to lower alternative fuel costs. Conversely, diesel prices are likely to rise due to the impact of larger schemes like ETS-2 and RED III, whose effects on individual businesses[37] remain unclear. Dialogue with sector organizations is essential to maintaining support for long-term ambitions within the industry.

Technological Feasibility
Promising zero-emission solutions like ammonia, methanol, and hydrogen differ in their technological readiness levels (TRL).

- Ammonia is not viable in the short term due to design limitations and toxicity concerns.
- Methanol applications, while promising, are still in their infancy compared to hydrogen.
- Hydrogen is widely recognized as a mid-term solution, though challenges remain in terms of energy density and infrastructure requirements. For optimal hydrogen use, a robust network of supporting infrastructure is needed. Ports should be upgraded accordingly.
- Swappable containers present a viable solution, enabling cheaper hydrogen supply through container transshipment points equipped with adequate safety measures.
- In regions with fewer facilities, hydrogen supply may require integration with industrial pipelines or the establishment of additional strategic hydrogen depots.

Meanwhile, electric propulsion is less applicable. It works well in the West, where energy demands are lower due to canal navigation. However, for regions with stronger currents, like the Danube Delta, the energy requirements for pushed convoys are too high to justify the cost of electric propulsion.

Regulatory Framework Conditions
A strong regulatory framework and stakeholder management are essential. Institutions like the Danube Commission can play a facilitating role. As urgency increases, avoiding fragmentation is crucial. Unlike the Rhine, the Danube benefits from the presence of multiple capitals along its waters, offering higher visibility and political attention. However, due to the relatively low number of vessel movements, inland waterway transport is not always as visible as it should be.

- Investing in public relations and cross-sector cooperation (e.g., with the cruise industry) could improve visibility and lead to more political urgency. Strengthening regional cooperation, similar to the RH2INE model, could also be beneficial.
- Competing for European funding for the necessary infrastructure, supported by prior studies, will be key to success. A strong intermediary field, with specialists who are familiar with Brussels and subsidy administration, is critical.
- As the playing field broadens, inland waterway transport will face stronger competition from other sectors, like aviation, for biofuels. Market dynamics could increase fuel prices and reduce profit margins, making vessel owners vulnerable and in the long term threatening the continuity of the sector as a whole. A level playing field therefore needs to be guaranteed.

Given the size of the Danube fleet (several hundred to over a thousand vessels, depending on sources), a tailored approach might be necessary. Conversations with key vessel owners (e.g., push convoys) could help identify the specific technical and economic needs of the fleet, paving the way for targeted applications for European funding. Specialized advisors could provide detailed insights and actionable advice.

Recognizing the fleet's distribution across countries—where Romania plays a significant role—could open up discussions for more targeted support, in collaboration with relevant authorities. Larger cities and ports could also play a useful role by providing incentives for greener vessels.

Way forward
Significant investment is needed to prepare the Danube region for alternative fuel propulsion. Investments on the water (vessels) and on the land (infrastructure) will be key to making the transition. A critical aspect of this development would be upgrading port facilities to support a hydrogen tanktainer pool infrastructure. Key candidate ports identified for this purpose include Komárom and Esztergom (Bratislava to Budapest), Smederevo, Veliko Gradište, and Kladovo (Belgrade to Drobeta-Turnu Severin), Lom and Svishtov (Vidin to Ruse), and Călărași and Brăila (Giurgiu to Galati). These ports, strategically located within long gaps, have the potential for development to establish a

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[37] Ownership also plays a role in driving fleet modernization. For instance, independent owners nearing retirement may have little incentive to invest in long-term sustainability goals, while fleet owners may have different motivations.

consistent container handling infrastructure approximately every 200 kilometers along the corridor.

Building the necessary infrastructure for alternative energy faces complex permitting and regulatory barriers. These regulations differ between regions and countries, creating fragmented processes that slow down development. To facilitate the energy transition, there is a pressing need for harmonized policies across Europe, especially for permitting and constructing bunkering stations, charging points, and other essential infrastructure for clean energy.

The demand for alternative energy infrastructure from vessel operators remains low due to the high upfront costs of retrofitting vessels and the uncertainty about the reliability of the new energy networks. There is a significant investment gap that must be bridged to build the necessary infrastructure. Governments and private stakeholders need to work together to create financial instruments and incentives that can accelerate the development of a clean energy network for IWT. These investments are vital to meeting the European Union's decarbonization goals.

Longterm and shortterm options:

- For achieving zero emission, hydrogen and methanol offer the potential for long-term zero-emission shipping but require substantial investment in electrolysers, storage, and safety systems.
- Near zero emission would cost less. Biofuels, while easier to integrate into existing infrastructure, still require upgrades to storage and distribution facilities. A combination of HVO100 combined with Stage V can bring 2049 targets within reach by today and is a promising way forward, bearing in mind the new dependencies it creates on suppliers.

Whether the difference in investments can be justified is a subject for further stakeholder consultation.

Some more notes:

- Strong leadership and stakeholder management are critical. Existing institutions like the Danube Commission should facilitate the process. With increasing urgency, fragmentation should be avoided.
- The visibility of inland waterway transport can be enhanced through strategic public relations campaigns, especially in collaboration with the cruise industry.
- Securing European funding for infrastructure is key. This requires skilled intermediaries familiar with Brussels and subsidy procedures.
- Cooperation between industry and transport sectors will become increasingly important as market dynamics change. Biofuel prices may rise due to competition with other sectors, such as aviation.

By addressing these challenges through tailored approaches and strategic planning, the Danube fleet can move towards a greener future, aligning with long-term emission reduction targets.

Summary

Propulsion	Technological Feasibility	Economic Viability	Social Impact	Regulatory Readiness
Biofuels (HVO, FAME)	+ (proven, easy integration)	+ (affordable, some supply concerns)	++ (familiar to industry, minimal retraining)	+ (biofuel mandates exist, but needs sustainability focus)
Electric Propulsion	+ (high efficiency, good for short routes)	0 (high initial investment but lower operating costs)	+ (improves air quality, but requires new infrastructure)	0 (some support, but charging infrastructure needed)
Hydrogen	+ (proven, but storage and safety concerns)	- (high production cost, limited infrastructure)	0 (requires significant re-training, safety concerns)	+ (supportive policies emerging, but infrastructure lacking)
Methanol	++ (easy to retrofit, good storage properties)	+ (lower cost compared to other alternatives, but renewable methanol is pricier)	+ (easier adoption, but some toxicity concerns)	+ (emerging support, widespread adoption possible)
Ammonia	0 (high toxicity, storage and handling challenges)	- (expensive infrastructure, not widely available yet)	-- (significant safety issues, major retraining required)	0 (regulatory frameworks still developing)

Colophon

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