Journal of Maritime Transport and Logistics Trends

MariLog Trends

November 2025
Year 1, Volume 1

ISSN XXXX - XXXX
ISSN-L XXXX - XXXX

ABOUT

The **Journal of Maritime Transport and Logistics Trends** is a peer-reviewed open-access scientific publication dedicated to fostering innovation and disseminating research in the fields of maritime transport, port operations, logistics, and digital transformation in the maritime industry.

JOURNAL WEBSITE

https://cmu-edu.eu/marilog2025/

ISSUE

Volume 1, Issue 1

ONLINE PUBLICATION DATE

November 2025

ISSN

ISSN
ISSN-L

PUBLISHER

Nautica Publishing House of Constanta Maritime University
Address: Blvd. Mircea cel Batran, Nr 104. 900663, Constanta, Romania
E-mail: bianca.dobre@cmu-edu.eu

Journal of Maritime Transport and Logistics Trends
Volume 1, Number 1, Year 2025

TABLE OF CONTENTS

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The Journal of Maritime Transport and Logistics Trends is a peer-reviewed scientific publication dedicated to fostering innovation and disseminating research in the fields of maritime transport, port operations, logistics, and digital transformation in the maritime industry.

The journal brings together academic and professional contributions emerging from the annual "International Conference International Conference on Maritime Transport and Logistics Trends MariLog", organised by Constanta Maritime University. It serves as a platform for researchers, industry experts, doctoral candidates, and young innovators to share insights on emerging trends and strategic challenges.

Topics include - but are not limited to - sustainable shipping practices, port digitalisation, maritime safety, smart logistics, maritime education and training, artificial intelligence applications, and quantum technologies.

The journal publishes original articles, comparative analyses, case studies, and applied research developed in collaboration with industry stakeholders.

Through its international visibility and focus on real-world relevance, it promotes knowledge exchange and supports the sustainable advancement of maritime transport and logistics.

Environmental impacts and challenges of maritime chemical pollution in Europe

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Abstract. The European marine environment is increasingly impacted by chemical contaminants originating from sea-based sources, raising significant concerns for marine biodiversity, public health, and the sustainability of maritime operations. These pollutants, primarily generated through ship operations, offshore energy extraction, and aquaculture, have become focal points in marine environmental governance and transnational regulatory frameworks. This study provides a comprehensive and critical synthesis of the main maritime-origin chemical pollutants affecting European waters, while assessing the environmental risks and systemic challenges posed by current regulatory regimes.

The methodology is based on an integrative review of recent reviewed scientific literature, official documentation from European environmental and maritime regulatory bodies, and monitoring datasets from regional sea conventions. Special attention is given to operational and accidental discharges, antifouling paints, ballast water releases, and aquaculture effluents. The effectiveness of regulatory instruments, including the Marine Strategy Framework Directive (MSFD) and International Maritime Organization (IMO) conventions, is critically evaluated regarding their ability to mitigate chemical pollution from sea-based activities.

Findings reveal that despite notable legislative and technological advancements, chemical contamination remains widespread across multiple European sea basins. Persistent pollutants such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), organotin compounds, and nutrient-rich effluents continue to be detected at ecologically concerning levels. The study identifies significant spatial and temporal monitoring gaps, as well as inconsistencies in enforcement and implementation across EU member states. Meanwhile, the increasing deployment of real-time monitoring systems and green maritime technologies offers promising avenues for improved pollution control.

This review underscores the urgent need for a more cohesive and adaptive maritime governance framework that prioritizes pollution prevention, ecosystem-based management, and cross-border cooperation. Strengthening regulatory compliance, investing in research on emerging contaminants, and mainstreaming technological innovation are essential steps towards ensuring a resilient and ecologically sustainable marine environment in Europe.

How to cite:

Burmambet, A. (2025). Environmental impacts and challenges of maritime chemical pollution in Europe. *Journal of Maritime Transport and Logistics Trends*, 1(1), 2-16.
Web: https://cmu-edu.eu/marilog2025/program/

Keywords: Marine pollution, Chemical contaminants, Sea-based sources, Maritime sustainability, Regulatory frameworks

1. Introduction

1.1 Background

The health of the world's oceans has become a central concern in the global environmental agenda, particularly due to the growing presence of chemical contaminants in marine ecosystems. European marine waters are among the most studied in terms of pollution, as the continent's economic activities and densely populated coastlines exert significant pressure on its seas: European Environment Agency [EEA], 2023. Chemical contaminants—including heavy metals, persistent organic pollutants (POPs), hydrocarbons, pharmaceuticals, and nutrients—originate from a variety of sources, both land-based and marine-based [1].

Over the last few decades, increased industrialization, intensive agriculture, urban expansion, maritime shipping, and aquaculture have intensified the release of chemical substances into marine environments: Joint Research Centre, 2021. These substances often persist in ecosystems, accumulate in marine organisms, and travel across borders, posing transboundary risks to human and ecological health. The cumulative impacts threaten biodiversity, fisheries, and the overall sustainability of marine services [2].

1.2 Importance of Marine Water Protection

Protecting marine waters is not only vital for preserving biodiversity, but also for safeguarding the food supply, economic stability, and public health of European populations. Approximately 40% of Europeans live within 50 km of the coast [4], and maritime industries—such as shipping, fisheries, and tourism—play a crucial role in the region's economy. However, these industries are also key contributors to marine pollution, making it essential to regulate and mitigate the impacts of their activities [1].

In this context, chemical contamination has emerged as a major challenge in achieving the objectives of the Marine Strategy Framework Directive (MSFD) and the Water Framework Directive (WFD). Both aim to reach "Good Environmental Status" (GES) and reduce harmful discharges into marine environments [6]. Understanding the sources, pathways, and impacts of contaminants is critical for informed policy decisions and environmental management [3].

1.3 Objectives of the Study

This study aims to provide a comprehensive analysis of chemical contamination in European marine waters by focusing on the following objectives:

- To identify and classify the primary sources of chemical contaminants in European marine regions.
- To analyze the role of maritime transport and aquaculture in the release of these pollutants.
- To evaluate the European regulatory framework for marine water protection.

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- To explore the environmental and socio-economic impacts of marine chemical contamination.
- To examine current monitoring efforts and assess data from case studies across various seas (e.g., Baltic, North Sea, Black Sea).
- To formulate policy recommendations and highlight future research directions [1].

1.4 Methodology and Scope

This paper adopts a qualitative and analytical research methodology based on a literature review of scientific publications, policy documents, and technical reports. The data analyzed originates from reputable sources such as the European Environment Agency (EEA), the Joint Research Centre (JRC), the European Chemicals Agency (ECHA), and peer-reviewed academic journals.

The study focuses on four major European marine regions: the Baltic Sea, the North Sea, the Mediterranean Sea, and the Black Sea. It investigates both point sources (e.g., shipping discharges, aquaculture facilities) and diffuse sources (e.g., agricultural runoff), as well as the impacts of emerging contaminants such as pharmaceuticals and microplastics.

Furthermore, the scope includes an evaluation of EU-level regulations and international agreements influencing marine pollution management, with particular emphasis on their implementation, effectiveness, and areas of improvement [1].

2. Sources of Chemical Contaminants

2.1 Overview of Contaminant Sources

Chemical pollutants reach marine waters through both land-based and marine-based activities. These contaminants vary in their physical and chemical properties, persistence, and toxicity. According to the EEA (2023), over 80% of marine pollution originates from land-based sources, primarily through river discharge, direct outfalls, and atmospheric deposition [1]. The remaining 20% comes from maritime activities, including shipping, offshore platforms, and aquaculture [2]. The sources of marine chemical contamination can be categorized as follows:

- Agricultural runoff (pesticides, fertilizers, animal waste)
- Industrial discharge (heavy metals, persistent organic pollutants)
- Urban wastewater (pharmaceuticals, personal care products, microplastics)
- Shipping emissions and discharges (oil, antifouling agents, greywater, ballast water)
- Aquaculture operations (antibiotics, disinfectants, excess feed)

2.2 Land-Based Sources

Land-based sources are responsible for the majority of marine contamination. Agricultural activities contribute to high levels of nutrients such as nitrogen and phosphorus, which lead to eutrophication and hypoxic zones [3]. Additionally, pesticide residues and animal waste introduce harmful chemicals and pathogens into coastal waters.

Industrial zones, particularly near river mouths, often discharge untreated or inadequately treated wastewater containing heavy metals (e.g., mercury, cadmium, lead), hydrocarbons, and other persistent substances. These contaminants bioaccumulate in marine organisms, posing long-term ecological and health risks.
Urban wastewater treatment plants are another major source, often releasing emerging pollutants such as pharmaceutical residues, hormonal compounds, and microplastics substances that are not yet fully regulated but are increasingly detected in marine environment [2].

2.3 Maritime Sources: Shipping and Aquaculture
Shipping activities contribute significantly to marine pollution through oil leaks, antifouling coatings (which contain biocides such as tributyltin), greywater, and ballast water that may carry contaminants and invasive species [22]. Although international regulations such as MARPOL and the Ballast Water Management Convention are in place, enforcement and compliance levels vary.
Aquaculture is a growing source of chemical contamination, especially in coastal regions with intensive fish farming. Excess feed, fecal matter, antibiotics, and parasiticides can enter surrounding waters, contributing to nutrient loading and the development of antibiotic-resistant bacteria [1].

Table 1. Primary Sources of Chemical Contaminants in European Marine Waters.

Source	Main Contaminants	Pathway to Sea	Examples
Agriculture	Nitrates, phosphates, pesticides	Surface runoff, groundwater	Danube River (Black Sea)
Industry	Heavy metals, hydrocarbons, solvents	Effluents, river discharge	Po River (Adriatic Sea)
Urban Wastewater	Pharmaceuticals, microplastics, hormones	Direct discharge, WWTP outflows	Thames Estuary (North Sea)
Shipping	Oil, antifouling agents (TBT), ballast water	Discharges, leaks, hull coatings	Rotterdam Port, Constanța Port
Aquaculture	Antibiotics, disinfectants, nutrients	Feed waste, metabolic waste	Norwegian fjords, Greek coastline

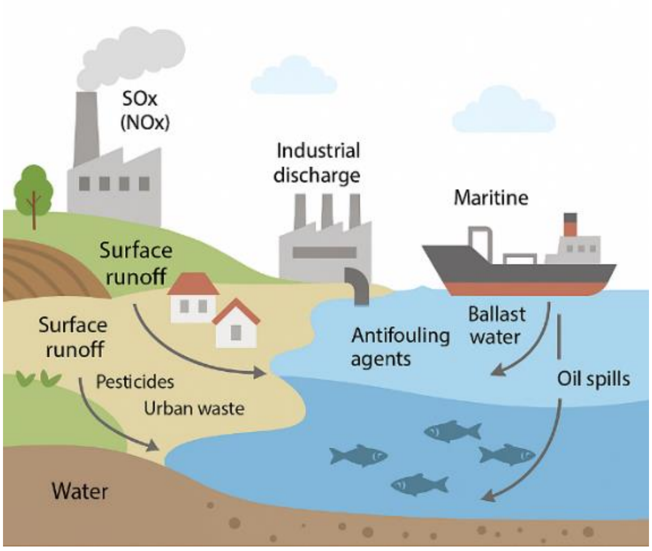

Figure 1. Major Pathways of Chemical Contaminants into Marine Waters.

Figure 1 illustrates the multiple entry points through which pollutants reach marine ecosystems. The image presents a simplified but comprehensive schematic that includes:

- Atmospheric Deposition: Emissions from ships, factories, and vehicles release pollutants such as nitrogen oxides (NOx), sulphur oxides (SOx), and particulate matter into the air. These settle into marine waters via rain or dry deposition.
- Surface Runoff: Agricultural lands and urban areas contribute to chemical loads via fertilizers, pesticides, heavy metals, and plastics carried by rainfall into rivers and eventually the sea.
- Industrial Discharge: Factories located near coastlines may release untreated or partially treated chemical effluents directly into the sea, including heavy metals, hydrocarbons, and synthetic compounds.
- Shipping Activities: Ballast water, hull paints (with TBT or copper), exhaust emissions, and accidental discharges (e.g., oil, lubricants) are clearly identified as key marine contamination sources.
- Aquaculture Operations: Depicted near the coast, fish farms contribute antibiotics, nutrients, and pesticides to surrounding waters, increasing the risk of eutrophication and antimicrobial resistance.

The diagram also highlights sediment accumulation of persistent pollutants and the potential bioaccumulation in marine food chains, emphasizing how contaminants travel and concentrate in ecosystems over time. This figure serves as a visual summary of sections 3 and 4, reinforcing the need for integrated monitoring and pollution control.

The sources of chemical pollution in European marine waters are diverse and often interconnected. While land-based inputs remain dominant, the increasing contribution of maritime sectors such as shipping and aquaculture requires closer attention. A holistic understanding of these sources is essential to design effective mitigation and policy responses, which will be addressed in the following sections [1], [6], [7].

3. European Legal Framework and Regulations

To combat chemical contamination in marine environments, the European Union (EU) has implemented an extensive set of legislative instruments that reflect both international commitments and regional priorities. These regulations aim to reduce pollution sources, improve water quality, and promote sustainable marine use. Key directives include the Water Framework Directive (WFD), Marine Strategy Framework Directive (MSFD), and the Urban Waste Water Treatment Directive (UWWTD). These are complemented by international treaties such as MARPOL, adopted under the International Maritime Organization (IMO), and regional agreements like the OSPAR Convention for the North-East Atlantic.

3.1 Key European Directives

Water Framework Directive (WFD) – 2000/60/EC
The WFD establishes a framework for the protection of inland surface waters, transitional waters, coastal waters, and groundwater. It requires all EU member states to achieve "good chemical and ecological status" for water bodies. Member states must develop River Basin Management Plans (RBMPs) and monitor priority substances, including several dangerous chemicals such as mercury, cadmium, and certain pesticides.

Marine Strategy Framework Directive (MSFD) – 2008/56/EC
The MSFD aims to achieve Good Environmental Status (GES) of marine waters by 2020. It covers 11 descriptors, one of which focuses on contaminants and their effects on marine ecosystems and human health. Member states are required to assess the status of their marine waters, determine GES, and implement monitoring and action programs [4].

Urban Waste Water Treatment Directive (UWWTD) – 91/271/EEC
This directive regulates the collection, treatment, and discharge of urban wastewater. It mandates secondary or more advanced treatment for cities over 2,000 inhabitants and addresses nutrient removal to combat eutrophication. A revision of the directive in 2022 proposes stricter limits for emerging pollutants such as pharmaceuticals and microplastics.

3.2 International and Regional Agreements

MARPOL Convention
The International Convention for the Prevention of Pollution from Ships (MARPOL) regulates marine pollution from ships, including oil, chemicals, sewage, garbage, and emissions. Annexes I and II are particularly relevant to chemical contamination. Annex VI also regulates air pollution, indirectly affecting atmospheric deposition into marine waters [9].

How to cite:

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OSPAR Convention

The OSPAR Convention governs marine environmental protection in the North-East Atlantic. It targets hazardous substances, eutrophication, and radioactive discharges. Countries collaborate to monitor pollutants, identify priority hazardous substances, and implement reduction targets.

3.3 Monitoring and implementation tools

The European Environment Agency (EEA) coordinates environmental data collection and assessment across Europe. Tools such as the WISE-Marine portal and EMODnet Chemistry provide open access to spatial and temporal data on contaminants. Monitoring focuses on both legacy pollutants (e.g., PCBs, DDT) and emerging pollutants (e.g., pharmaceuticals, microplastics).

Table 2. Key European Directives and Regulations on Water and Marine Pollution [4].

Directive	Year	Focus	Relevance
Water Framework Directive (WFD)	2000	Inland and coastal waters	Identifies priority pollutants, requires RBMPs
Marine Strategy Framework Directive (MSFD)	2008	Marine waters	Sets GES targets, monitors contaminants
Urban Waste Water Treatment Directive	1991	Urban sewage and nutrient pollution	Regulates discharge, updated to include micropollutants
REACH Regulation	2006	Chemical production and use	Controls hazardous substances, including marine inputs
Habitats Directive	1992	Conservation of biodiversity	Protects habitats from pollution and degradation

3.4 Challenges in regulation enforcement

Despite this robust framework, several challenges remain:

- Inconsistent implementation among EU member states
- Insufficient control of emerging pollutants not yet included in regulatory lists
- Transboundary pollution, especially from non-EU countries via large rivers (e.g., Danube, Dniester)
- Data gaps in monitoring, especially for cumulative and long-term effects of mixed contaminants

The EU has developed a comprehensive legal and institutional architecture to address marine chemical contamination. However, full implementation, harmonization, and expansion to emerging threats are necessary to ensure long-term sustainability. Regional cooperation and integration with international conventions remain critical to addressing marine pollution effectively.

4. Impact of human activities: shipping and aquaculture

Marine chemical contamination is intricately linked to human activities, particularly shipping and aquaculture. These sectors contribute to the release of both regulated and emerging pollutants into European marine waters. Understanding the scale and nature of these impacts is essential for devising appropriate regulatory responses and technological solutions.

4.1 Shipping as a source of marine chemical contaminants

Ballast water and antifouling agents
Modern vessels carry ballast water to maintain stability. When discharged, this water can introduce heavy metals, oil residues, and invasive species into local ecosystems [15]. In addition, the use of antifouling paints—especially those containing organotin compounds such as tributyltin (TBT)—has led to widespread toxicity in marine organisms, despite global bans under the IMO's AFS Convention.

Exhaust emissions and atmospheric deposition
Shipping contributes to airborne deposition of sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter, which subsequently reach the marine environment through precipitation and runoff [9]. Annex VI of MARPOL limits these emissions, but enforcement and compliance remain uneven across European maritime zones.

Accidental and operational discharges
While large oil spills are rare, chronic small-scale discharges from fuel, lubricants, and maintenance activities release polycyclic aromatic hydrocarbons (PAHs) and other persistent organic pollutants (POPs) into marine waters [4].

4.2 Aquaculture and chemical contamination

Antibiotics and pharmaceuticals
In intensive aquaculture, especially in finfish farming, antibiotics and antiparasitics are routinely administered to control diseases. These compounds can enter the water column and sediment, promoting antimicrobial resistance (AMR) in marine bacteria [1].

Excess nutrients and eutrophication
Feed and fish excreta release significant amounts of nitrogen and phosphorus, contributing to eutrophication in enclosed or poorly flushed areas. This process can lead to algal blooms, hypoxia, and biodiversity loss [3].

Chemical treatments and pesticides
Aquaculture also relies on chemical treatments such as copper-based antifoulants, formalin, hydrogen peroxide, and pesticides like emamectin benzoate. Their persistence and toxicity vary, but chronic exposure can alter marine food webs.

4.3 Cumulative and synergistic effects

The combination of shipping and aquaculture in shared coastal zones increases the likelihood of synergistic effects—where pollutants interact to create more severe ecological outcomes than their individual impacts suggest. For example, copper residues from aquaculture can be amplified by antifouling inputs from nearby ships, increasing sediment toxicity.

4.4 Case study: Norwegian fjords and Mediterranean coastal areas

In the Norwegian fjords, heavy aquaculture activity has resulted in elevated levels of copper and zinc in sediments, while Mediterranean ports face high concentrations of PAHs and metals due to intense shipping [12]. Monitoring programs in both regions underscore the need for integrated coastal zone management (ICZM).

Table 3. Chemical pollutants from shipping and aquaculture activities [1],[4],[9].

Activity	Main Chemical Pollutants	Environmental Impact
Shipping	TBT, PAHs, heavy metals, SOx, NOx	Toxicity, endocrine disruption, bioaccumulation
Aquaculture	Antibiotics, copper, pesticides, nutrients	Resistance, eutrophication, sediment toxicity
Combined Activities	Hydrocarbons, trace metals, persistent contaminants	Cumulative toxicity, ecosystem destabilization

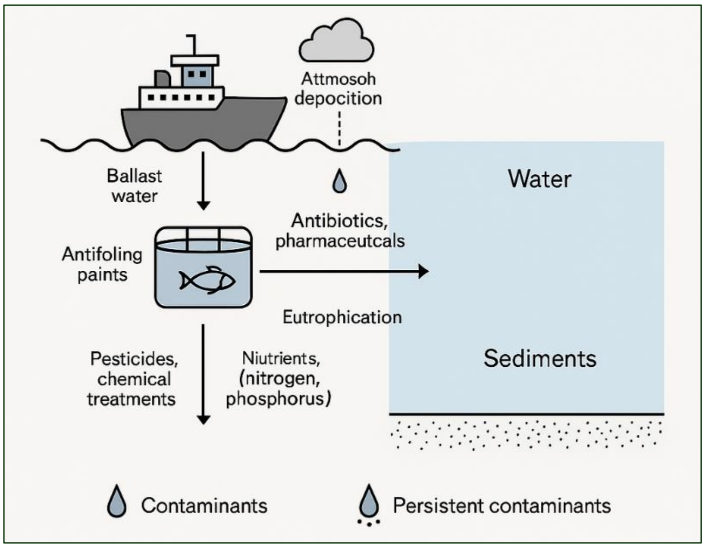

Figure 2. Pathways of chemical contaminants from human activities into marine waters

This figure no 2 provides a focused schematic that visually captures how two major sectors - shipping and aquaculture - introduce chemical pollutants into the marine environment. This figure is essential for understanding the dynamic and interlinked sources of marine contamination. Key elements illustrated:

1. Shipping inputs

- Ballast water: Carried by ships for stability, ballast water can be discharged in port areas, introducing not only invasive species but also heavy metals and oil residues from previous ports.
- Exhaust emissions: Ships emit sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter into the atmosphere. These pollutants return to the sea via atmospheric deposition, particularly in coastal and high-traffic shipping lanes.
- Hull paints: Antifouling coatings, historically rich in tributyltin (TBT) or copper compounds, leach toxic substances into the water, especially near ports or marinas, contributing to sediment contamination and bioaccumulation in marine organisms.

2. Aquaculture inputs

- Nutrients: Uneaten feed and fish waste release nitrogen and phosphorus, promoting eutrophication, algal blooms, and potentially hypoxic conditions.
- Antibiotics and pharmaceuticals: Used to control diseases in high-density fish farming, these chemicals can pass through organisms and settle in sediments, fostering antimicrobial resistance (AMR).
- Pesticides and antifoulants: Applied to net pens and infrastructure, these compounds (e.g., emamectin benzoate, copper-based antifoulants) are persistent and toxic, especially in low-flushing areas.

Environmental compartments affected:

- Water column: Immediate dispersion of soluble pollutants such as pharmaceuticals and nutrients affects plankton, fish, and overall water quality.
- Sediment layer: Many contaminants settle, especially metals and organic compounds, forming long-term pollution reservoirs that can resurface through disturbance or affect benthic organisms.

Interactions and Synergies: The figure emphasizes the synergistic impacts of these pollutants when they coexist in shared coastal zones—such as near shipping lanes adjacent to aquaculture operations—where chemical cocktails can form, compounding ecological damage beyond individual effects. Also, this figure visually reinforces the argument that shipping and aquaculture are not isolated contributors, but interactive sources of marine chemical pollution. By highlighting the pathways into both the water column and sediments, it supports the case for integrated monitoring, cross-sector policy coordination, and site-specific risk assessments to better protect European marine ecosystems.

Shipping and aquaculture are vital components of the European blue economy, but their environmental impacts—especially related to chemical pollution—require continued scrutiny. Current regulations (e.g., MARPOL, AFS Convention) are necessary but not sufficient. The increasing complexity of pollutant mixtures, their long-term ecological effects, and their interaction with climate change pose growing challenges for regulators and marine scientists.

5. Current status, trends and future directions

5.1 Current status of chemical contaminants in European marine waters

Despite numerous regulatory efforts, chemical contamination remains a significant issue across European seas. Continuous monitoring reveals persistent levels of legacy pollutants such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and organotin compounds, alongside emerging contaminants like pharmaceuticals and microplastics [3], [15].

Monitoring networks under the Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD) provide valuable data, highlighting spatial variability and pollution hotspots, especially near major ports and intensive aquaculture zones [7], [1].

5.2 Emerging trends in marine chemical contamination

Recent trends indicate increasing concerns related to:

- Pharmaceutical residues and personal care products entering waters through wastewater discharge [14].
- Microplastics and associated chemical additives acting as vectors for hydrophobic contaminants [8].
- The spread of antimicrobial resistance (AMR) genes from aquaculture and sewage [2].
- Greater recognition of mixture toxicity, where combined pollutants produce unpredictable and synergistic effects on marine organisms [11].

5.3 Advances in regulation and technology

Regulatory frameworks are evolving to address complex pollution scenarios:

- The EU Chemicals Strategy for Sustainability (CSS) aims to reduce harmful chemical risks across sectors [6].
- Improvements in green shipping technologies, such as low-sulfur fuels and exhaust scrubbers, reduce airborne pollutant deposition [9], [15].
- Development of environmentally friendly antifouling coatings replacing harmful organotin compounds with less toxic alternatives [16].
- Application of innovative bioremediation and sediment management techniques in impacted areas [5].

5.4 Future directions and research needs

Addressing chemical contamination in European marine waters requires:

- Enhanced integrated monitoring systems combining chemical, biological, and genomic tools to track pollutants and ecological responses [17].
- Research into cumulative and synergistic effects of mixed contaminants under changing climate conditions [23].
- Development of circular economy approaches aimed at reducing chemical inputs from aquaculture feed and shipping supplies.
- Strengthened international cooperation for enforcing regulations in maritime zones and data sharing [12].

Table 4. Emerging contaminants and regulatory responses [2],[6],[14],[17]

Emerging Contaminant	Source	Regulatory/Technological Response
Pharmaceuticals and PPCPs	Wastewater discharge	WFD prioritization, advanced wastewater treatment
Microplastics and Additives	Plastic debris, consumer products	MSFD monitoring, plastic bans and recycling initiatives
Antimicrobial Resistance (AMR)	Aquaculture, sewage	Antibiotic use restrictions, AMR surveillance programs
Mixture Toxicity	Multiple sources	Research on mixture effects, integrated risk assessments

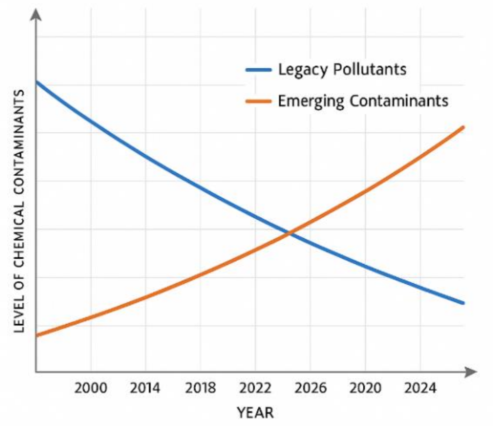

Figure 3. Trends in chemical contaminants in European marine waters (2000–2024).

This figure illustrates temporal changes in two major categories of marine pollutants:

I. Legacy Pollutants (e.g., PCBs, DDT, heavy metals): These are shown to decrease over time, reflecting the success of historical bans and regulatory controls.
II. Emerging Contaminants (e.g., pharmaceuticals, microplastics, PFAS): These show a steady increase, highlighting growing concern due to their persistence, toxicity, and lack of comprehensive regulation.

Also, the figure 3 likely includes a line graph with the X-axis representing years (2000–2024) and the Y-axis representing relative concentration or frequency of detection. The crossing trends emphasize the shift in environmental risk profiles in European marine waters—from legacy industrial pollutants to newer, less regulated substances.

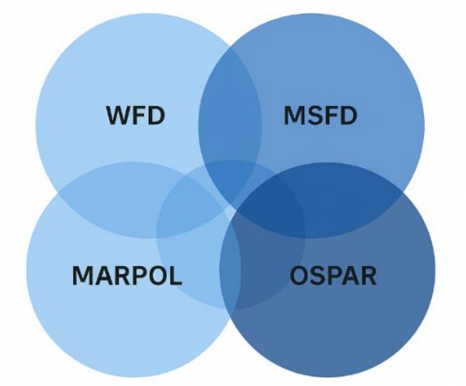

Figure 4. Regulatory frameworks and their overlaps in European marine pollution control.

This Venn diagram (Figure 4) illustrates the interaction and overlaps among four major regulatory frameworks:

- WFD (Water Framework Directive): Focuses on achieving good status for all EU waters, including coastal zones.
- MSFD (Marine Strategy Framework Directive): Aims to achieve Good Environmental Status (GES) of EU marine waters by 2020, complementing the WFD but with a broader marine scope.
- MARPOL (International Convention for the Prevention of Pollution from Ships): Addresses ship-based pollution through multiple annexes regulating oil, chemicals, sewage, garbage, and air emissions.
- OSPAR (Oslo-Paris Convention): A regional agreement specific to the Northeast Atlantic, targeting various sources of pollution and promoting ecosystem protection.

The diagram highlights:

- Shared areas (intersections) where frameworks overlap in responsibility, such as marine water quality and pollution prevention.
- Unique zones where each regulation has distinct roles (e.g., MARPOL with ship emissions, WFD with inland water inputs).

This visual reinforces the need for integrated governance and policy coherence in controlling marine chemical contamination in Europe.

The challenge of chemical contamination in European marine waters is dynamic and multifaceted. While legacy pollutants are gradually managed, emerging contaminants require innovative regulatory and technological approaches. Interdisciplinary research, improved monitoring, and proactive policy-making are crucial to safeguarding marine ecosystems amid ongoing human pressures and climate change.

6. Conclusion and Recommendations

6.1 Conclusion

The reviewed literature consistently emphasizes that chemical contaminants originating from maritime and aquaculture activities significantly impact European marine environments. Sea-based sources, including shipping emissions, ballast water discharges, and antifouling paints, remain key contributors to pollution [15], [9]. Meanwhile, aquaculture practices introduce a range of chemicals, such as antibiotics

and pesticides, with potentially harmful ecological effects [1]. The resulting environmental stressors contribute to widespread issues like eutrophication and the expansion of hypoxic "dead zones," which threaten marine biodiversity and ecosystem services [3].
Despite existing regulatory frameworks, including MARPOL Annex VI for air pollution control [9] and regional conventions such as [13], enforcement challenges persist, compounded by the complex and transboundary nature of marine pollution [4]. Advancements in digital monitoring and smart port infrastructure offer promising tools to enhance real-time pollution tracking and regulatory compliance [23].

6.2 Recommendations

Based on the synthesis of scientific findings and regulatory reviews, the following recommendations are proposed:

- Enhance Enforcement of International and Regional Regulations: Strengthening the implementation of MARPOL, OSPAR, and other protocols is critical to reduce maritime pollution effectively [9], [12].
- Promote Cleaner Shipping Technologies: Accelerate the adoption of low-emission fuels, ballast water treatment systems, and environmentally friendly antifouling coatings to minimize chemical discharges [15].
- Sustainable Aquaculture Practices: Encourage integrated pest management and reduced reliance on chemical inputs, supported by ongoing environmental monitoring [1].
- Ecosystem-Based Management: Address the cumulative impacts of chemical contaminants by adopting holistic management strategies that consider ecosystem health and biodiversity conservation [3].
- Leverage Digital Innovation: Invest in smart port technologies and sensor networks to facilitate continuous environmental monitoring and improve transparency in pollution reporting [23].
- Foster Cross-Border Collaboration: Enhance cooperation among European nations to harmonize standards and share data on marine pollution [4].

Public Engagement and Education: Increase awareness about the sources and consequences of marine chemical pollution among stakeholders and the general public [24].

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How to cite:

Burmambet, A. (2025). Environmental impacts and challenges of maritime chemical pollution in Europe. *Journal of Maritime Transport and Logistics Trends*, 1(1), 2-16.
Web: https://cmu-edu.eu/marilog2025/program/

Journal of Maritime Transport and Logistics Trends
Volume 1, Number 1, Year 2025

A comparative analysis between Romanian, American and British standards for offshore structures

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Abstract. The ongoing energy crisis, intensified by the Russo-Ukrainian conflict, and the recent discovery of gas fields in the Romanian sector of the Black Sea, provide a strategic opportunity for the revival of Romania's offshore engineering sector. This paper presents a comparative study of offshore structural design standards from Romania, the United States, and the United Kingdom, focusing on aspects of structural safety, material selection, and environmental adaptability. Using a thematic analysis approach, the paper identifies critical differences in design philosophy, safety factors, and regulatory integration. A hybrid framework is proposed for aligning Romanian standards with international norms. Results suggest Romanian codes, though detailed, require probabilistic and performance-based updates to match global standards in offshore reliability, safety, and environmental governance. In terms of methodology, the study applies a thematic comparative analysis grounded in structured coding of regulatory principles across standards. Standards were analyzed using a matrix-based assessment method comparing design philosophy, safety factors, material specifications, inspection regimes, and environmental adaptability. A qualitative scoring system was introduced to evaluate the level of adaptability and integration for each standard in offshore contexts, calibrated on criteria such as risk management, climate suitability, lifecycle sustainability, and technological innovation. Although the study does not apply a full numerical simulation, future integration of structural performance modelling is recommended.

1. Introduction

Oil and gas development in the Romanian sector of the Black Sea has resurfaced as a strategic priority, driven by geopolitical instability, EU energy diversification goals, and new gas field discoveries. Romania has a long-standing tradition in oil exploitation, dating back to 1857.

However, after the pioneering construction of the Gloria platform in 1972 and the development of additional offshore infrastructure [21], after 1989 the sector entered a prolonged stagnation.

This stagnation has had direct consequences: outdated design norms, inconsistent safety verification, and limited adaptability to international offshore challenges. Despite the economic and strategic importance of offshore energy, Romania continues to apply fragmented regulations, based largely on Eurocodes, which lack specialized adaptation to the offshore domain.

In 2009, Romania won in the Hague International Court of Justice, an area of 9700 km^2 from the continental shelf which was then divided into five oil fields. Major oil companies have expressed interest in the exploration of gas fields in the Romanian sector of the Black Sea, e.g., Exxon obile, Lukoil, Melrose Resources, Sterling Resources.

How to cite:

Joavină, G.R. and Duşe, A. (2025). A comparative analysis between Romanian, American and British standards for offshore structures. *Journal of Maritime Transport and Logistics Trends*, 1(1), 17-38.
Web: https://cmu-edu.eu/marilog2025/program/

This could be a good opportunity for not just relaunching the gas industry but also the offshore naval industry, a first step in transforming Romania from an exporter of raw materials to a final products exporter and the benefits that follow.

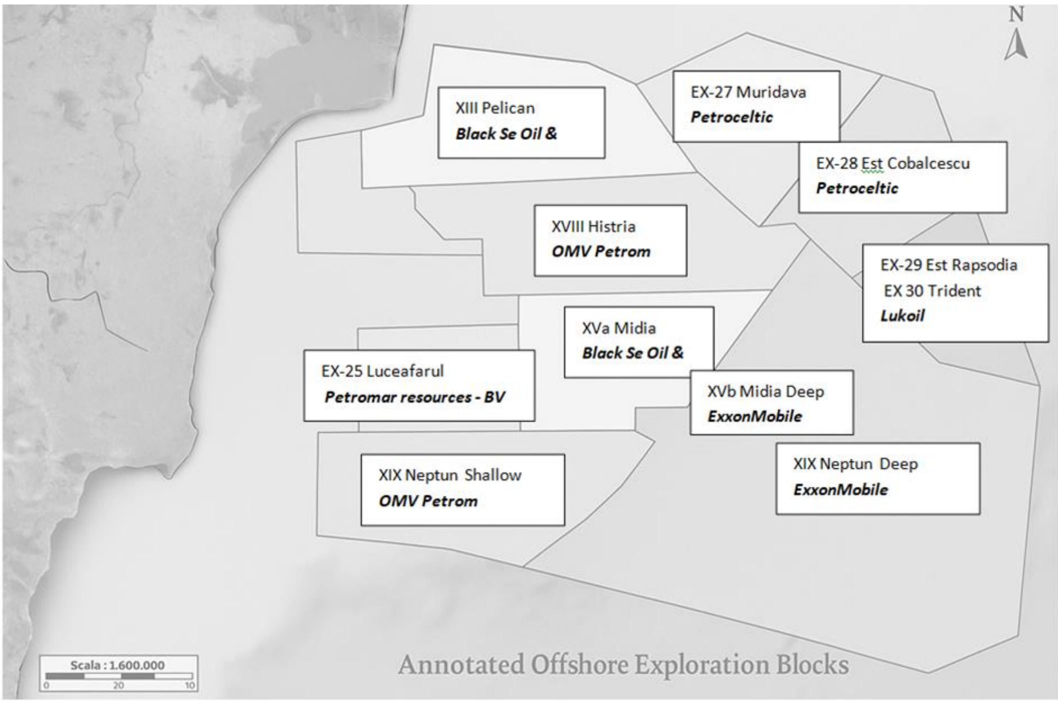

Figure 1. Oil and gas fields sectors of the Romanian Continental Shelf in the Black Sea.

The Figure 1 - illustrates the division of Romania's continental shelf into four main offshore blocks: Midia, Pelican, Laboda, and Histria. These zones host the country's existing offshore infrastructure, including the Gloria and Orizont platforms. The figure contextualizes the geostrategic importance of Romania's offshore potential and provides a geographical reference for the applicability of offshore structural standards. Recent discoveries in the Neptun Deep area, located in the Pelican block, have revived interest in regulatory modernization and infrastructure resilience.[23]

This paper addresses a pressing issue: Romania's offshore structural standards are no longer aligned with international practice. In a global context increasingly shaped by environmental accountability (ESG), digital modeling, and risk-based engineering, alignment with globally recognized standards is not only desirable—it is essential.

The study compares Romanian standards [16], [20] against American (API, AISC, ABS) and British (ISO, BS, DNV) counterparts, focusing on structural safety, material performance, environmental loads, and lifecycle approaches. Through a structured thematic analysis and a comparative matrix approach, the research highlights strengths and gaps, proposing a roadmap toward a hybrid, internationally harmonized regulatory model for offshore infrastructure in Romania.

2. Similarities between Romanian, American and British Standards for Offshore Structures

Despite differences in regulatory origin and regional calibration, Romanian (Eurocodes), American (API), and British (ISO/DNV) standards share a common foundation of structural engineering principles for offshore applications. Key points of convergence include design philosophy, materials and construction details,safety and structural integrity assessment, material requirements, and durability and life cycle considerations.

2.1 General principles of design

With respect to general principles of design, all standards consider offshore structures under:

- *Limit State Analysis* - employing methods based on ultimate limit states and serviceability limit states (ULS and SLS).
- *Combined Actions* - assessing the impact of various types of simultaneous loads (hydrodynamic, wind, seismic, operational).
- *Structural Safety* - application of safety factors to ensure resilience against dynamic and extreme loads over time.

Romania relies onEurocodes (SR EN 1993, SR EN 1991) based on the Load and Resistance Factor Design (LRDF) methods, while in the USA, API RP 2A-WSD [3] and 2A-LRFD use both Allowable Stress Design (ASD) and LRFD. In Great Britain, BS EN 1993-1-6 and ISO 19902 [15] are based on LRFD as well.

2.1.1 The limit state analysis

The limit state is defined as a condition where by a structure can no longer guarantee safety or functionality.

The limit-state design is the most common approach adopted in international codes for offshore structures to attain the safety and serviceability, e.g., in API, ISO, Eurocodes. Accordingly, the structure may be examined against various extreme and operational scenarios to ensure long-term integrity.

ULS - *Ultimate Limit States*, which occur when the structure is pushed beyond its load capacity, potentially leading to collapse or partial failure. Under ULS, checks are conducted to assess the overall strength of the structure (carrying capacity), its stability against losing equilibrium (e.g., overturning or sliding), and the risk of local failures in its components (such as beams, columns, and joints).

In Romania, Eurocodes perform ULS checks based on combinations of factored loads, while API RP 2A [3] in the USA considers safety factors for materials and loads. Partial load and strength factors are used in ISO 19902 [15] for UK/EU.

SLS - *Serviceability Limit States* refer to cases when the structure fails to meet functional requirements but is not in imminent danger of collapse.

Checks in SLS correspond to excessive deformation of members, unacceptable vibration, and cracking that can lead to corrosion or fatigue.

To achieve this goal, Eurocodes (RO) restrict displacements and cracks under SLS, while API RP 2A (USA) looks at all aspects of displacements and allowable vibrations. ISO 19902 (UK/EU) emphasizes both operational comfort and structural integrity.

ALS - *Accidental Limit States* deals with unforeseen extreme events like impact, blasts, fire or loss of floatation.

Considered scenarios include ship collisions, fires and explosions, earthquakes and tsunami waves, and the failure of a critical structural element.

In Eurocodes (RO), ALS is assessed against fire, impact, and earthquake; in API RP 2A (USA), focuses on explosion and impact; and ISO 19902 (UK/EU), employs advanced modeling of accidental effects.

FLS - *Fatigue Limit States* applies whenever the structure experiences repeated loading (stress cycles), resulting in cracking and progressive deterioration.

The key factors that contribute to fatigue include the number of loading cycles, load amplitudes, weld quality and joints.

Eurocodes (RO) evaluate FLS according to fatigue curves for each material class; API RP 2A (USA) relies on S-N curve analysis with additional fracture characterization; ISO 19902 (UK/EU) adopts a holistic approach with both deterministic and probabilistic methods for assessment.

2.1.2 Combined Actions

Offshore structures are subjected to multiple types of simultaneous loads, which require a rigorous analysis of the possible combinations. All standards, API, ISO, and Eurocodes, adopt an equally strict approach to the combination and assessment of these loads for the safety and durability of the structures.

Table 1 shows that all three standards apply similar base combinations for operational and accidental loading, with Eurocodes impose higher safety coefficients for variable loads.

For structural design, Eurocodes (RO), API RP 2A (USA), and ISO 19902 (UK) have specific load combinations that should be used.

Table 1. Load combinations rules across offshore design standards.

Load Combination	Eurocodes (RO)	API RP 2A (USA)	ISO 19902 (UK)
ULS (Ultimate Limit State)	1.0(P) + 1.35(V) + 1.5(E)	1.0(P) + 1.3(V) + 1.5(E)	1.0(P) + 1.3(V) + 1.5(E)
SLS (Service Limit State)	1.0(P) + 1.0(V) + 1.0(E)	1.0(P) + 1.0(V) + 1.0(E)	1.0(P) + 1.0(V) + 1.0(E)
Accidental Loads (ALS)	1.0(P) + 1.0(V) + 1.0(A)	1.0(P) + 1.0(V) + 1.0(A)	1.0(P) + 1.0(V) + 1.0(A)
Fatigue Loads (FLS)	1.0(F)	1.0(F)	1.0(F)

[a] Note: Comparison of load combinations based on Eurocodes, API RP 2A, and ISO 19902.
Source: Authors' synthesis based on [3], [12], [15], [20].

All the analysed standards distinguish Permanent Loads (P) - self-weight of the structure, hydrostatic pressure; Variable Loads (V) - equipment, personnel, stored liquids; Environmental Loads (E) - wind, waves, sea current, ice; Accidental Loads (A) - ship impact with, explosion, earthquake; Fatigue Loads (F) - cyclic loads due to waves and wind.

Fatigue loads should be considered for the critical elements and connections.

How to cite:

Joavină, G.R. and Dușe, A. (2025). A comparative analysis between Romanian, American and British standards for offshore structures. *Journal of Maritime Transport and Logistics Trends*, 1(1), 17-38.
Web: https://cmu-edu.eu/marilog2025/program/

Also, all of the standards undergo the influence of the earthquake effects but with different criteria.

API RP 2MET [5] (USA), ISO 19901-1 [13] (UK) and NP 074 [16] (RO) include similar factors to amplify the loads as a function of the extreme events whose nature can be hurricane, storm or earthquake.

The methods for the interaction analysis between structures and environment (wind-wave-current interaction) are similar as they are based on advanced hydrodynamic models, each standard using site-specific climatic loading model.

Verification and Testing of Combined Loads are achieved through: FEA analyses for stress distribution, hydrodynamic basin tests for floating structures, sensor-based monitoring to validate load combinations.

API and ISO emphasis on hydrodynamic tank testing for floating structures.

The numerical and experimental testing techniques are similar for API, ISO and Eurocode for validating load combinations in critical structures.

2.1.3 Safety Factors - Concepts and Applications

Safety factors are amplification coefficients used to compensate uncertainties with respect to the loads, materials, or design methods.

a) Load Safety Factors (LSF) - Amplify the estimated values of the loads to include the variability of actual conditions. Thus, all offshore design codes apply safety factors in this manner to characteristic loads.

As illustrated in Table 2, Eurocodes adopt more conservative values, especially for dead and operational loads, while ISO and API align on a unified factor for operational loads.Accidental loads are considered without amplification factors (direct maximum possible impacts) and they are analysed as an independent issue. Fatigue loads are also considered separately without any additional safety factors.

Table 2. Load safety factors by load type in different standards.

Load type	Eurocodes (RO)	API RP 2A (USA)	ISO 19902 (UK)
Dead load	1.35	1.1	1.2
Operational loads	1.5	1.3	1.3
Wind, waves, sea currents	1.5	1.35	1.5
Seismic loads	1.0 – 1.5	1.0 – 1.3	1.0 – 1.3
Accidental loads (impact, explosions)	1.0	1.0	1.0

[a] Note: Comparative values of partial safety factors applied to dead, operational and seismic loads.
Source: Authors' synthesis based on [3], [12], [15], [20].

b) Material Resistance Factors (MF) are employed in the reduction of nominal resistance on materials for compensating uncertainties related to manufacturing, welding and time behaviour.

Table 3 highlights that ISO and API use identical factors for structural steel and weldingbased on similar verification methods, while Eurocodes are more conservative.

The Eurocodes adopts a more conservative factor for concrete, owing to consideration of durability in marine conditions in a very different manner.

Table 3. Material resistance factors applied in offshore codes.

Material	Eurocodes (RO)	API RP 2A (USA)	ISO 19902 (UK)
Structural steel	1.0	0.9	0.9
Welding	0.9	0.85 – 0.9	0.85 – 0.9
Reinforced concrete (for foundations)	0.85	0.7 – 0.85	0.75 – 0.9

[a] Note: Resistance factors used for structural steel, welding, and concrete across Eurocodes, API, and ISO .
Source: Authors' synthesis based on [2], [11], [15], [18].

2.1.4 Offshore Structural Stability Verification

Design of offshore structures involves verifying stability under all forms of probable loads, as well as ensuring an adequate safety margin to prevent overall failure or loss of balance.

As methodology in all standards: application of safety factors for materials and loads is used for overall safety, verification against overturning, translation and buoyancy is used for stability safety, calculation of stress cycles and their effect on the strength of materials for fatigue safety and cathodic protection, special coatings, use of resistant materials for corrosion safety.

Every standard presented emphasizes the need to verify overall stability, which includes factors like buoyancy, resistance to capsizing and translation.

Fatigue calculation is mandatory for all offshore structures, as they are exposed to long-term load cycles.

Corrosion protection is standardized, with the use of methods such as sacrificial anodes or induced current cathodic protection.

a) *Overturning and sliding stability* it is checked whether the structure can withstand overturning moments produced by wind, waves or sea currents.

According to Table 4, all standards require minimum overturning safety ratios of 1.5–2.0, confirming consistency in structural stability thresholds.

The sliding stability is taken under the same factor of 1.5.

Table 4. Stability safety factors: overturning and sliding criteria.

Stability	Eurocodes (RO)	API RP 2A (USA)	ISO 19902 (UK)
Minimum moment ratio (overturning stability)	1.5 – 2.0	1.5	1.5 – 2.0
Translational safety factor (horizontal forces)	1.5	1.5	1.5

[a] Note: Required safety margins to prevent overturning and translational failure in offshore structures.
Source: Authors' synthesis based on [1], [3], [11], [20].

b) *Fatigue Stability*
Cyclic load effects on the service life of the structure are verified under all standards. Also all standards use S-N curves for fatigue calculation.

Table 5. Fatigue assessment and monitoring requirements.

Method	Eurocodes (RO)	API RP 2A (USA)	ISO 19902 (UK)
S-N curves for fatigue	yes	yes	yes
Fatigue safety factor	10 – 15	10 – 20	10 – 15
Periodic monitoring	Recommended	Recommended	Mandatory

[a] Note: Fatigue analysis methods, safety factors, and periodic inspection obligations.
Source: Authors' synthesis based on [1], [2], [16], [24].

As it can be seen in table 5, the fatigue safety factors are similar (10 – 20 depending on level of exposure). ISO requires mandatory periodic monitoring, while API and Eurocodes recommend it only for exposed structures.

In conclusion, the safety factors for loads and materials are, comparable between API, ISO and Eurocodes.

All standards require verification of overturning stability, buoyancy and fatigue.

ISO and DNV are more stringent regarding buoyancy and fatigue monitoring, while API allows more flexibility.

2.2 Materials and construction details
To ensure the strength and durability of offshore structures, all standards demand the use of special steels, high quality welds and anti-corrosion protection. The mechanical strength, durability, corrosion and weld resistance of materials selected for offshore construction must meet the required specifications.

Table 6 outlines that structural steel is the main material for all standards while reinforced concrete is being used in foundations and fixed structures.

Table 6. Comparative material usage in offshore construction.

Material	Main usage	Eurocodes (Romania)	Standard API (USA)	Standard ISO (UK/EU)
Structural steel	Main frame, columns, beams, piling	EN 10225	API 2W, API 2Y	ISO 19902
Stainless steel	Highly corrosive parts (railing, valves)	EN 10088	API 6A	ISO 15156
Aluminium alloys	Top plate of light structures	EN 573	API RP 2A	ISO 6362
Reinforced concrete	Submarine foundations, hybrid constructions	Eurocode 2	API RP 2T	ISO 22965
Composite materials	Conducts, insulation, fireproofing	EN 13121	API 17J	ISO 14692

***Note:** Main construction materials and their standard references across the three systems.
Source: Authors' synthesis based on [2], [8], [16], [24].

Composite materials are covered in all regulations; however, their practical application is much more advanced in the European standards.

2.2.1 Types of Steel for Offshore Structures
The steel used must withstand dynamic loads, fatigue and corrosion.

All standards include HSLA (High-Strength Low-Alloy) steels for structures exposed to high loads.

Table 7. Common steel types for offshore marine structures.

Steel Type	Main characteristics	Eurocodes (Romania)	Standard API (USA)	Standard ISO (UK/EU)
Normal Steel (Grades A, B, C)	Medium tensile strength, good weldability	EN 10025-2	API 2H Grade 50	ISO 630
High Strength Alloy Steel (HSLA)	High fatigue endurance, light weight	EN 10225	API 2W, API 2Y	ISO 19902
Stainless Steel	High resistanceto corrosion	EN 10088	API 6A	ISO 15156
Low Temperature Steel	Used in polar regions	EN 10225	API 2Y	ISO 19906

***Note:** Mechanical characteristics and usage of standard steel grades across codes.
Source: Authors' synthesis based on [2], [8], [18], [25].

According table 7, API and ISO impose strict requirements regarding fatigue strength and low temperature toughness.

Eurocodes are more detailed in corrosion tests and weld joint checks.

The steels essentially specified under all three standards systems are equivalent from strength and ductility requirements.

The standards impose the same tests for welds, including ultrasonic inspections and non-destructive testing (NDT) methods.

2.2.2 Structural Details of Offshore Structures

a) *Joints and Welds*are critical for offshore structures and must withstand fatigue and extreme stresses.

Table 8. Non-destructive testing (NDT)requirements for welds.

Weld Inspection	EN 5817 (RO)	API RP 2X (USA)	ISO 17637 (UK)
Ultrasonic Testing (UT)	Mandatory	Mandatory	Mandatory
Radiographic Testing (RT)	Mandatory	Optional	Mandatory
Magnetic Testing (MT)	Recommended	Recommended	Recommended

***Note:** NDT methods mandated or recommended by each standard (UT, RT, MT).
Source: Authors' synthesis based on [8], [10], [11], [18].

The main types of welded joints used for offshore structures are: *Full Penetration Welds* – for primary structural elements, *Fillet Welds* – for secondary structural elements, *SubmergedArc Welding* (SAW) – for large joints.

For all welded joints ultrasonic testing is mandatory in all studied standards, as per table 8.

Additional, ISO and Eurocodes specifically require mandatory radiography on critical joints.

b) For *anti-corrosion* protection there are provisions for cathodic protection, special coatings and materials resistant to the aggressiveness of the marine environment.

Common practices among all standards includes: painting with epoxy coats (ISO 12944, NORSOK M-501), anodizing with zinc or aluminium, cathodic protection systems (CP - Cathodic Protection)

ISO standards and Eurocodes are more stringent in testing corrosion resistance.

Materials used are similar between API, ISO and Eurocodes, with a preference for high-strength steels.

Welded joints are standardized and NDT tests are mandatory in all regulations.

Corrosion protection is essential and is treated similarly in all standards.

2.3 Assessment of Structural Safety and Integrity

With respect to *Inspection and Monitoring Methods* – API RP 2SIM [6], ISO 19901-9 [24], and DNV [11] standards call for regular inspection.

Risk analysis is carried out using methods based on the probabilistic analysis of defects and structure life.

As for *Conformity Verification Methods* – certification and testing are required by each standard during production, installation and operation.

Offshore structures must undergo periodic verification for safety and structural integrity.

Table 9. Structural inspection and integrity monitoring practices

Activity	Eurocodes (RO)	API (USA)	ISO, DNV (UK)
Visual Inspection	Regular	API RP 2SIM	ISO 19901-9
Ultrasonic Inspection	ISO 17640	API RP 2X	ISO 17640, DNV RP-C203
Continual Monitoring	Not mandatory	Only for critical structures	Mandatory for structuresexposed to environment

***Note:** Visual, ultrasonic, and real-time monitoring protocols across standards.
Source: Authors' synthesis based on [2], [11].

All standards require regular inspections, depending on the level of exposure of the structure.

As already said, ultrasonic and radiographic testing of welds is a standard requirement for API, ISO and Eurocodes.

Table 9 shows that continuous monitoring of structural integrity is recommended by all standards, but is particularly mandatory for British structures (ISO and DNV).

2.4 Durability and life cycle considerations

All codes incorporate provisions for assessing durability for the structure over a 20-50-year period concerning design for the entire service life. In terms of maintenance and rehabilitation, there's a solid methodology in place for both preventive and corrective maintenance, which is well established in all international standards.

It can be concluded that Romanian, American and British standards are convergent in terms of structural safety, climatic loads, material selection and inspection methodology.

All standards apply the principle of design based on limit states (ULS and SLS) to ensure the safety and functionality of offshore structures.

Climatic and operational loads are combined using similar methods, and the calculation models are compatible.

The major differences lie in the calculation methodology and in the adjustments specific to each region (e.g. API is calibrated for the Gulf of Mexico, ISO for the North Sea).

The materials used, welds and anti-corrosion protection are regulated in an equivalent manner, ensuring an extended service life of the structures.

Periodic inspections and methods of verification of conformity are similar, but British and DNV norms impose stricter requirements on continuous monitoring.

The compatibility between the standards allows for use in international projects, by adopting hybrid methodologies and ISO standards as a common reference.

3. Differences between Romanian, American and British standards for offshore structures

While all international standards rest on the same key principles of safety and performance, there are significant differences in terms of calculation methodology, approach to climatic loads, material selection and inspection requirements.

3.1 Calculation methodology:

3.1.1 General design philosophy

Romania (Eurocodes) uses a deterministic approach with detailed partial coefficients for each scenario, while in USA, API RP 2A [3] is more pragmatic, using global safety factors and rules based on testing and practical experience.

UK (ISO/DNV-GL) uses probabilistic methods, adapting structural safety to local conditions through advanced simulations; emphasize risks and reliability.

API RP 2A (USA) allows two design methods: WSD (Working Stress Design) – based on allowable stresses, and LRFD (Load and Resistance Factor Design) – based on load-specific safety factors. Table 10 compares the theoretical base of each system.

Eurocodes and ISO 19902 [15] (UK) use LRFD exclusively, which provides a more clearly defined level of safety but can lead to over-sizing of elements.

Table 10. General design criteria according to the studied standards.

Criterion	Romania (Eurocodes)	USA (API RP 2A, AISC, ASCE)	UK (ISO 19902, DNV-GL, BS EN 1993)
Design method	Based on limit states and partial coefficients Eurocodes and the Load and Resistance Factor Design (LRFD) method	Semi-probabilistic methods with global safety factors Uses both ASD - Allowable Stress Design and LRFD	Probabilistic approach with detailed risk assessment Based exclusively on LRFD
Main verification method	Deterministic analyses (based on partial factors on loads and resistances)	Pragmatic methods based on practice and industrial testing	Advanced numerical simulations and reliability analysis methods
Standard structure	Modulation (Eurocodes for each type of material and load) Eurocode 3 (steel structures), Eurocode 8 (earthquake), national legislation	API Consolidated Offshore Platform Codes API RP 2A (fixed platforms), AISC 360 (steel), ASCE 7 (loads)	Uniform standards based on ISO and DNV-GL ISO 19902 (fixed platforms), DNV-OS-C101 (steel)
Conservatism level	High (high safety factors)	Average (derived from experience and history)	More flexible, optimized through probabilistic methods

***Note:** Core design philosophy (ASD, LRFD), verification tools, and conservatism levels.
Source: Authors' synthesis based on [1], [11], [16].

How to cite:

Joavină, G.R. and Duşe, A. (2025). A comparative analysis between Romanian, American and British standards for offshore structures. *Journal of Maritime Transport and Logistics Trends*, 1(1), 17-38.
Web: https://cmu-edu.eu/marilog2025/program/

3.1.2. Verification and Risk Assessment Methods

Eurocodes apply a strict coefficient system, which does not easily adapt to specific offshore conditions while API RP 2A is a standard built on field experience and historically acceptable practice in the industry.

Table 11. Risk assessment and analysis techniques in offshore standards.

Criterion	Romania (Eurocodes)	USA (API RP 2A, ASCE)	UK (ISO 19902, DNV-GL)
Type of verification	Deterministic approaches	Semi-probabilistic approaches based on testing	Advanced probabilistic approaches
Types of analysis	Combined sets of loads (standardized)	Pragmatic safety assessment (API)	Numerical modelling and reliability analysis
Risk management	High coefficients to account for uncertainties	Based on industrial experience and history	Detailed risk assessment using probabilistic methods
Level of adaptability	Rigid, as per detailed norms	Medium, practice-oriented and history	Very flexible, in accordance with local conditions and structure typology

***Note:** Overview of design logic, adaptability, and risk treatment.
Source: Authors' synthesis based on [1], [11], [16].

According to table 11, ISO/DNV offers a modern probability-based approach, allowing for optimum design with high adaptability for any specific location, unlike the rather rigid Romanian codes.

3.1.3 Organizations and structure of standards.

The Eurocodes are fragmented and their application in offshore requires supplements with local norms. API RP 2A is an integrated standard, directly applicable for the design of offshore structures. ISO 19902 is a unified standard, bringing together extracts from various internationally accepted norms in order to provide a complete design procedure.

Table 12. Structure and organization of offshore design standards.

Criterion	Romania (Eurocodes)	USA (API RP 2A, AISC)	UK (ISO 19902, DNV-GL, BS EN 1993)
Number of documents used	Multiple Eurocodes (EC0-EC8) and local regulations	API RP 2A (main), complemented by other standards	ISO 19902 (main), supplemented by DNV and European standards
Coherence between documents	Fragmented (Eurocodes + national legislation)	Integrated into API RP 2A	ISO 19902 unified standard

Update of rules	Slower, depending on European legislation	Based on periodic revisions of API RP 2A	ISO and DNV-GL frequently update advanced methods

***Note:** Number of documents required, coherence, and update frequency.

3.1.4 Applicability to Different Types of Offshore Structures

Eurocodes are not optimized for offshore, API RP 2A covers fixed platforms, but also requires additions for floating structures.

Table 13. Applicability of standards to offshore structure types

Criterion	Romania (Eurocodes)	USA (API RP 2A, AISC)	UK (ISO 19902, DNV-GL)
Jacket platforms	Needs adaptations to offshore regulations	Directly regulated by API RP 2A	Regulated by ISO 19902 and DNV-GL
Floating structures (FPSO, semi-submersible)	Needs additional regulations	Covered by API + ABS	ISO/DNV-GL provides advanced methods for buoyancy
Wind farm structures	Regulated by Eurocodes + wind regulations	API RP 2A + ASCE 7 for climatic loads	ISO/DNV-GL has dedicated standards for offshore wind farms

***Note:** Jacket platforms, floating structures, and wind farm coverage.
Source: Authors' synthesis based on [1], [11], [16].

ISO/DNV-GL are the most versatile, applicable to both fixed and floating platforms as well as offshore wind structures.

From calculation methodology point of view, *Romanian codes* (Eurocodes) are based on strict rules, with high safety factors. It requires additional rules in order to be applicable in the offshore field and are focused on deterministic checks, without a probabilistic risk assessment.

USA (API RP 2A, AISC, ASCE) are pragmatic, based on industrial experience and testing, easy to implement because of logical and unified rules, uses global safety factors, without detailing loads as in Eurocodes.

UK / Europe (ISO 19902, DNV-GL) are the most up-to-date and adaptive, based on advanced numerical analysis and probabilistic methods, are adaptable for different offshore conditions (fixed structures, FPSO, wind farms) and provide the most accurate risk verification methods. As table 13 shows, ISO and DNV have the widest scope, supporting both fixed and floating infrastructure types.

3.2 Loads and Load Combinations

API RP 2MET uses climate models based on data from the Gulf of Mexico and the Pacific;

ISO 19901-1 and DNV-RP-C205 are North Sea environment-calibrated, harsher environment where waves sometimes exceed 25 m.

Romanian standards [16] [20] (Eurocodes) use European models that detail each type of loading, providing varying coefficients depending on the scenarios but are not directly adapted for extreme marine environments, requiring adjustments for offshore use.

API RP 2A uses pre-established scenarios and safety factors derived from practice.

ISO/DNV applies advanced simulations, including probabilistic approaches for waves and wind, as table 14 indicates.

With respect to Seismic Design- Romanian regulations [14] have stricter requirements regarding earthquakes than British ones, while API RP 2EQ is specific to regions with intense seismic activity.

Table 14. Offshore load types and environmental calibration.

Load type	Romania (Eurocodes)	USA (API RP 2A, ASCE 7)	UK (ISO 19902, DNV)
Permanent loads (P)	Self-weight, hydrostatic	Self-weight, hydrostatic pressure	Self-weight, hydrostatic
Variable loads (V)	Loads from equipment and operation	Equipment loads and maintenance	Operational and maintenance loads
Wind loads (E)	EN 1991-1-4: wind with probability of 50-100 years based on European climate data	ASCE 7: velocities by climate zone API RP 2MET – designed for the Gulf of Mexico	DNV-RP-C205: models based on climate history ISO 19901-1 – optimized for the North Sea
Wave and current loads (E)	Eurocode 1 + NP 074 – use of European models	API RP 2A: 100-year wave spectra models specific to US offshore regions	DNV GL: CFD simulations and advanced models DNV-RP-C205 – used for severe North Atlantic conditions
Seismic loads (A)	Eurocode 8 + NP 122 P100, EN 1998-1 – detailed approach for seismic areas	ASCE 7-16 API RP 2EQ – specific for offshore structures exposed to earthquakes	ISO 19901-2, DNV OS-E301 – Seismic event probability based methodology
Accidental loads (A)	Collision, explosions, fire (Eurocode 1)	API: collisions, explosions, loss of buoyancy	DNV: Probabilistic methods for accidents

***Note:** Description of permanent, variable, seismic, and accidental loads.
Source: Authors' synthesis based on [4], [12], [13], [14], [17].

3.3 Safety Factors and Limit States

Eurocodes have a well-defined methodology involving varied levels of safety factors.

API standards define practical and experimental means of verification.

According to Table 15, ISO/DNV applies advanced numerical tools and probabilistic methods for all limit states, surpassing the conservative Eurocode approach.

Table 15. Safety factors and limit states definitions.

Criterion	Romania (Eurocodes)	USA (API RP 2A, AISC)	UK (ISO 19902, DNV)

Factor of Safety on Loads	1.35 for permanent loads, 1.5 for variable loads	1.3 for variables, 1.5 for environment	1.3 – 1.5 depending on probability
Factor of Safety on Materials	1.0 – 1.15 for steel	1.15 for steel, 1.3 for welds	1.1 – 1.3 depending on material
ULS (Ultimate Limit State)	Detailed verification of load-bearing capacity and stability	Global safety factors and experimental methods	Advanced analysis, probabilistic assessment
SLS (Serviceable Limit State)	Admissible deformations in Eurocode 3	API allows higher deformations but limits vibrations	Numerical assessment and experimental testing
FLS (Fatigue)	Based on S-N curves from EN 1993-1-9	API RP 2A uses simplified methods	DNV applies advanced probabilistic methods
ALS (Accidental)	Standardized impact and fire assessment	Experimental tests and simulations for collisions	Advanced explosion and impact risk modelling

***Note:** Comparison of ULS, SLS, FLS, and ALS design philosophies.
Source: Authors' synthesis based on [1], [3], [11]. [16].

3.4 Materials and manufacturing standards

API allows a wider range of materials, including steels also used in the onshore industry (e.g. ASTM A572 [3]).

Eurocodes and BS EN 10225 [25] have special steel specifications for offshore construction mainly on the stricter requirements of ductility and corrosion resistance.

British Standards and DNV uses high strength steels and impose stricter requirements on weld inspections, including additional testing for fatigue and low temperature embrittlement.

Table 16 emphasizes ISO and DNV's advanced coatings and testing, while API favours broader flexibility in material choice.

Table 16. Construction materials and manufacturing standards

Feature	Romania (EN)	USA (API)	United Kingdom (BS, ISO)
Main materials	EN 10225 Steel S355-S460, prestressed concrete	API 2W, ASTM A572, A992	BS EN 10225, ISO 19902 High strength steel S355-S690
Welding and construction details	ISO 3834, EN 1090-2, strict criteria	AWS D1.1, API RP 2Z, API 1104	ISO 3834, BS EN 1090, ISO 15614, DNV GL RP-C203
Corrosion protection	ISO 12944, SR EN 10225, Special paints, anodizing	API RP 2I, Epoxy Coatings, Anodizing	ISO 12944, DNV-OS-C101, Hot dip galvanizing, active and passive protection

***Note:** Main materials, weld codes, and corrosion protection techniques.
Source: Authors' synthesis based on [8], [10], [25].

3.5 Safety assessment and monitoring of structures

ISO and DNV impose continuous structural inspection, using sensors for real-time monitoring (table 17).

API RP 2SIM [3] allows for less frequent inspections, but requires rigorous checks after extreme events (hurricanes, earthquakes).

Table 17. Inspection and monitoring protocols for offshore structures.

Aspect	Romania	USA	United Kingdom
Periodic Inspection	SR EN 1993-1-6	API RP 2SIM	ISO 19901-9, DNV-OS-C101
Integrity Monitoring	NP 074, based on Eurocodes	API RP 2A – requires periodic assessment	ISO 19901-9 – requires continuous monitoring
Test Methods	Ultrasonography, non-destructive testing	API RP 2X – ultrasonic and radiographic testing	ISO 17640, DNV RP-C203

***Note:** Comparison of inspection frequency, test types, and monitoring mandates.
Source: Authors' synthesis based on [1], [2],[10], [11], [16], [24].

3.6 Lifecycle and decommissioning considerations

For British and ISO standards is highly important the environmental impact and require the reuse or recycling of materials (table18).

The API allows abandonment of structures in the marine environment, which is less strict compared to European regulations.

Table 18. Life cycle management and decommissioning requirements.

Phase	Romania	USA	United Kingdom
Standard Life	25-50 years	20-40 years	30-50 years
Life Extension	Evaluation according to EN 1993	API RP 2SIM Assessment	DNV certification for extension
Decommissioning and Recycling	NP 074 – no strict requirements	API RP 2D – Minimum Regulations	ISO 19901-6 – strict requirements for ecology

***Note:** Lifespan, extension procedures, and recycling obligations.
Source: Authors' synthesis based on [1], [11], [16].

3.7 ESG Considerations and Sustainability in Offshore Standards

In the context of global climate objectives and rising investor expectations, ESG (Environmental, Social, and Governance) criteria have become critical in the evaluation and approval of offshore energy infrastructure. Among the standards analysed, ISO and DNV frameworks provide the most comprehensive integration of ESG-related requirements, particularly regarding lifecycle emissions, materials recyclability, safety audits, and ecological decommissioning practices.

British and ISO standards (e.g., ISO 19901-6, DNV-OS-C101) explicitly include provisions for environmental impact assessments, waste minimization, and reuse of offshore platforms after decommissioning. For example, DNV's approach requires environmental risk modeling and ecological site restoration, which aligns with EU taxonomy expectations for sustainable investments.

In contrast, Romanian norms—primarily based on Eurocodes and NP 074—lack such forward-facing elements. There are no explicit references to emissions tracking, green material incentives, or mandatory decommissioning protocols.

The American API standards (such as API RP 2D or 2SIM) offer flexibility and are widely applied in industry, but remain focused on operational efficiency rather than long-term environmental stewardship.

To align Romanian offshore standards with current ESG trends, future revisions must incorporate environmental risk modeling, carbon footprint benchmarks, and circular economy principles. ESG integration would not only ensure compliance with EU strategies (e.g., Green Deal, Fit for 55), but also increase attractiveness for foreign investment and access to sustainable financing instruments.

3.8 Illustrative Case Study: Comparative evaluation using a Scoring Matrix.

To complement the thematic comparison with a decision-support perspective, this section introduces a simplified scoring matrix designed to evaluate and visualize the relative performance of Romanian, American and British offshore structural standards across multiple technical and regulatory dimensions.

Methodological Framework

The scoring matrix uses qualitative assessments on a 0–10 scale for five key criteria:

1. Structural Safety and Reliability – how effectively the standard ensures structural integrity under various loading conditions.
2. Adaptability to Offshore Conditions – the degree to which the standard accommodates site-specific environmental challenges (e.g., seismicity, icing, wave patterns).
3. Lifecycle and Durability Management – provisions for corrosion control, fatigue resistance, and maintenance planning.
4. ESG Integration and Decommissioning – inclusion of environmental, social, and governance principles, circularity, and end-of-life design.
5. Digital Design and Probabilistic Tools – incorporation of numerical modeling, risk-based verification, and digital monitoring systems.

Each standard's score reflects the degree of comprehensiveness and practical implementation in offshore settings [23][31].

Table 19. Comparative Scoring Matrix.

Evaluation Criterion	Romania (Eurocodes + NP 074)	USA (API RP 2A)	UK (ISO 19902 + DNV)
Structural Safety & Reliability	7/10	8/10	9/10
Adaptability to Offshore Conditions	5/10	8/10	9/10

How to cite:

Joavină, G.R. and Dușe, A. (2025). A comparative analysis between Romanian, American and British standards for offshore structures. *Journal of Maritime Transport and Logistics Trends*, 1(1), 17-38.
Web: https://cmu-edu.eu/marilog2025/program/

Lifecycle & Durability Approach	6/10	7/10	9/10
ESG Integration & Decommissioning	4/10	5/10	9/10
Digital Design & Probabilistic Tools	5/10	6/10	9/10
Total Score (out of 50)	27/50	34/50	45/50

Interpretation of Results

The Romanian framework shows a solid foundation in structural safety but lacks specialization for offshore contexts, particularly in ESG alignment and digital modelling. Its scoring reflects strong deterministic design principles but limited adaptability and absence of lifecycle integration. The use of Eurocodes without consistent offshore-specific annexes constrains its utility in modern marine infrastructure.

The API framework scores higher due to its flexibility, proven track record in industrial applications, and simplified implementation. However, its relatively lower scores in ESG and long-term monitoring reflect its traditional focus on operational efficiency over sustainability. It remains effective in benign or moderate environments but is less suited for harsher or politically sensitive regions such as the Black Sea, where EU directives apply.

ISO and DNV standards clearly outperform the other systems, with high scores in all categories. Their holistic approach, rooted in risk-based design, lifecycle performance, and environmental accountability, aligns with both engineering best practices and emerging ESG policies. They are especially suitable for use in EU-affiliated states like Romania, where regulatory alignment and access to green funding are critical.

Implications for Romanian Regulatory Reform

This case study demonstrates that while Romanian standards are not fundamentally flawed, they are not fully optimized for current offshore engineering challenges. The adoption of ISO 19902 as a reference model, combined with the retention of core Eurocode structural principles, offers a viable pathway for regulatory modernization. The matrix approach can further be formalized into a Multi-Criteria Decision Analysis (MCDA) framework, enabling structured prioritization during future legislative updates.

Methodological Note: Toward a Multi-Criteria Decision Analysis (MCDA) Framework

The comparative scoring matrix presented in this study serves as an illustrative tool for evaluating the relative strengths and weaknesses of offshore structural design standards. Although the scores are currently qualitative and based on expert judgment, the structure of the matrix lends itself to extension through formal Multi-Criteria Decision Analysis (MCDA) methods.

MCDA Structure and Potential

An MCDA framework could assign weighted importance values to each criterion, reflecting national priorities such as safety, climate resilience, or investment attractiveness.
This enables transparent, traceable decision-making and supports evidence-based regulatory reform**.**

Possible Enhancements:

- Quantitative Calibration: Use data from real platforms (e.g., fatigue life, maintenance cost, downtime) to validate or adjust the scores.
- Expert Delphi Input: Incorporate ratings from panels of structural engineers, policy advisors, and sustainability analysts.
- Integration with Simulation Tools: Link scoring with finite element analysis (FEA), lifecycle assessment (LCA), and digital twin simulations to assess structural and environmental performance under real scenarios.
- Sensitivity Analysis: Evaluate how rankings change under different strategic scenarios (e.g., carbon neutrality mandate, seismic risk escalation, hydrogen retrofitting).

Applications for Romania

Such a structured evaluation model could guide:

- The prioritization of standards for legislative alignment
- Funding allocation for modernization or pilot projects
- Selection of offshore structural concepts in public procurement
- National energy strategy decisions involving hybrid wind–gas platforms in the Black Sea

By formalizing the comparative logic in a transparent analytical tool, Romania can move beyond subjective alignment and adopt a dynamic, data-informed standard selection policy.

3.9 "Green Structures" and Energy Efficiency in Offshore Standards

In the pursuit of decarbonisation and sustainable infrastructure, offshore structures are increasingly expected to conform to principles of green engineering. "Green structures" in the offshore context refer to facilities that optimize energy consumption throughout their lifecycle, minimize embodied carbon, and incorporate environmentally friendly materials and operational technologies.

While Romanian regulations offer no dedicated provisions on green design, British and ISO standards have begun integrating performance metrics for energy efficiency and sustainable material use. For example, ISO 19901-6 and DNV-OS-C401 recommend lifecycle energy assessments, the use of corrosion-resistant low-impact alloys, and design for disassembly and reuse. Moreover, DNV's environmental class notation includes modules for emissions tracking and real-time energy performance monitoring.

American API standards are less formalized in this aspect but allow optional adherence to sustainability frameworks such as LEED for modular components. However, no mandatory energy efficiency verification is embedded in API RP 2A or 2SIM.

To improve alignment, Romania should consider introducing incentives for using low-emission steels (e.g., HPS, microalloyed steels), passive energy systems (LED-based lighting, renewable-powered monitoring), and adopting ISO 50001 principles for energy management. Incorporating such measures would not only improve environmental compliance but also attract ESG-oriented funding and enhance competitiveness in the European offshore market.

In addition, ISO has published complementary standards such as ISO 14064 (greenhouse gas accounting and verification) and ISO 20887 (design for disassembly and circularity), which are increasingly applied in offshore infrastructure with a view to achieving carbon neutrality. These frameworks support quantifiable reduction of emissions during construction and operation, as well as reuse of high-value components at decommissioning. Their adoption in offshore engineering enables alignment with EU Green Deal requirements and positions infrastructure projects for inclusion in sustainable finance taxonomies [22]. Romanian regulators could integrate these ISO standards as voluntary modules or reference guidelines for new offshore developments.

3.10 Alignment with International ESG Policies and EU Regulatory Frameworks

The integration of ESG (Environmental, Social, and Governance) principles into offshore engineering is no longer a voluntary gesture but an operational imperative, especially within the European Union. Romania, as an EU member, is subject to multiple supranational policies that directly influence the design, execution, and decommissioning of offshore energy infrastructure.

Among the most influential is the EU Taxonomy Regulation (2020/852) [22], which establishes clear technical screening criteria for projects to be classified as "environmentally sustainable." Offshore platforms must demonstrate substantial contribution to climate change mitigation, avoidance of significant harm to other objectives (e.g., water protection, biodiversity), and compliance with minimum social safeguards.

The European Green Deal and Fit for 55 Package further commit EU member states to drastic carbon emission reductions and greater reliance on renewable and cleaner offshore energy production. In this context, offshore structures that do not follow circular economy principles or carbon reporting standards risk becoming ineligible for public funding or green investment mechanisms.

Relevant standards supporting compliance include:

- ISO 14001 / 14064: Environmental management and GHG emissions reporting
- ISO 20887: Circular economy principles in construction
- ISO 50001: Energy management systems
- DNV-RP-E403: Carbon capture readiness for offshore structures

Romania currently lacks national offshore-specific legislation aligned with these instruments, relying instead on fragmented Eurocode-based guidelines. To ensure regulatory convergence and market access, it is recommended that Romanian authorities:

- Develop a national offshore ESG compliance framework harmonized with the EU Taxonomy;
- Mandate lifecycle emissions analysis and environmental risk assessment in the offshore permitting process;
- Encourage adoption of ISO 50001 and 14064 standards for all new offshore projects through regulatory incentives or funding eligibility.

This approach would ensure Romania remains competitive and aligned with global sustainability benchmarks while unlocking access to EU resilience and energy transition funds.

4. Conclusions

This comparative study reveals that while Romanian offshore structural codes (Eurocodes) are detailed and conservative, they are less adapted to the practical and probabilistic demands of offshore environments. American standards (API) are pragmatic and widely adopted in the industry but are tailored primarily to the Gulf of Mexico and U.S. environmental conditions. British and ISO/DNV standards are the most advanced, offering flexible, probabilistic approaches well-suited for harsh marine climates such as the North Sea.

The main gaps in the Romanian framework include the absence of risk-based verification, a fragmented standard structure, and limited guidance on floating and wind energy offshore structures. Additionally, Romanian codes insufficiently address current Environmental, Social, and Governance (ESG) imperatives—particularly lifecycle decommissioning, energy efficiency, and ecological impact—where ISO and DNV set more progressive benchmarks.

Proposed hybrid framework: Based on the findings, we propose a hybrid standardization approach that combines:

- structural reliability and lifecycle focus of ISO/DNV,
- practical simplicity and industrial acceptance of API,
- detailed material specifications and safety factors of the Eurocodes.

Recommendation for Romania: Regulatory bodies should initiate the alignment of NP 074 and associated offshore design codes with ISO 19902 and DNV standards, supported by:

- adoption of performance-based and probabilistic design methods,
- integration of digital verification tools (e.g., FEA, CFD),
- implementation of risk-based inspection and maintenance regimes,
- inclusion of ESG-compliant guidelines for decommissioning and sustainability.

Such modernization would strengthen Romania's offshore engineering competitiveness and contribute to the region's strategic energy autonomy.

5. Acknowledgements

The authors gratefully acknowledge the financial support provided by Constanta Maritime University for the publication of this article, through its research funding programme.

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How to cite:

Joavină, G.R. and Dușe, A. (2025). A comparative analysis between Romanian, American and British standards for offshore structures. *Journal of Maritime Transport and Logistics Trends*, 1(1), 17-38.
Web: https://cmu-edu.eu/marilog2025/program/

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How to cite:

Joavină, G.R. and Duşe, A. (2025). A comparative analysis between Romanian, American and British standards for offshore structures. *Journal of Maritime Transport and Logistics Trends*, 1(1), 17-38.
Web: https://cmu-edu.eu/marilog2025/program/

Journal of Maritime Transport and Logistics Trends
Volume 1, Number 1, Year 2025

Analysis of the Electrical System on a Hybrid River Vessel

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Abstract. In the context of increasingly strict requirements for reducing greenhouse gas emissions, hybrid river vessels represent a viable solution for sustainable inland waterway transport. This paper analyses the electrical installation used on a hybrid river vessel, aiming to evaluate how it manages multiple power sources and ensures efficient energy distribution during operation.

The analysis method has been based on both technical documentation of the onboard electrical system and numerical simulations of the system behaviour under various operating conditions. The power system includes three energy sources: shore supply (which comes from a renewable energy system), an auxiliary generator, and a rechargeable battery bank. Scenarios involving source switching and system behaviour under normal operation, fault conditions, and variable loads have been modelled using specialized electrical simulation software.

The results show improved energy efficiency when operating in hybrid mode by optimizing the use of available power sources according to energy demand. The battery system ensures good autonomy during low consumption periods, while the shore supply (particularly when powered by renewable sources) contributes to reducing emissions and minimizing generator fuel consumption. The switching mechanism between power sources proved reliable in all simulated scenarios.

The study highlights the benefits of using a hybrid electrical system on modern river vessels, both in terms of operational efficiency and environmental impact reduction. Implementing such systems can significantly support the modernization of inland waterway transport and help achieve sustainability goals.

1. Introduction

Maritime transport represents one of the oldest and most efficient means of transporting goods and passengers, playing a crucial role in the economic development of human societies. Today, in the context of challenges related to climate change, air pollution, and increasing pressure to reduce carbon emissions, the maritime – including inland waterway – transport sector is undergoing a profound transition.

According to data presented by the European Maritime Safety Agency (EMSA), maritime and inland waterway transport accounts for approximately 13% of greenhouse gas emissions from the European

How to cite:

Marin, G.A. and Gaiceanu, M. (2025). Analysis of the Electrical System on a Hybrid River Vessel. *Journal of Maritime Transport and Logistics Trends*, 1(1), 39-56.
Web: https://cmu-edu.eu/marilog2025/program/

transport sector [1]. Therefore, it becomes imperative to adopt innovative, sustainable, and energy-efficient technological solutions.

One of the most promising directions for development is the introduction of hybrid propulsion and power systems in maritime transport. Hybrid vessels, which combine conventional energy sources (such as diesel generators) with renewable sources (photovoltaic, wind) and energy storage systems (batteries), offer the opportunity to significantly reduce pollutant emissions and improve operational efficiency.

Particularly in the case of inland vessels, which operate near urban areas and sensitive ecosystems, the transition to clean energy solutions is not just a technological option, but an ecological responsibility [2].

The development and implementation of hybrid electrical installations onboard inland vessels requires the integration of advanced technologies that allow for alternative or simultaneous power supply from multiple sources: shore power, a diesel generator, and a battery system. Shore power becomes strategically important, especially when it is supplied from renewable sources—an aspect strongly supported by European policies on energy sector decarbonization.

Within the framework of the European Green Deal and Directive 2014/94/EU on the deployment of alternative fuels infrastructure, the use of green energy in ports is promoted, including the installation of electrical shore connections for moored vessels [3].

The advantages of using a hybrid electrical installation are numerous. Firstly, the reduction in fossil fuel consumption contributes to lowering operational costs and decreasing dependence on non-renewable resources. Secondly, the reduction of CO_2, NO_x, and particulate matter (PM) emissions improves air quality in port areas and along navigable routes—an essential factor in urban agglomerations crossed by vessels. Thirdly, the silent operation of electric systems reduces noise pollution, providing direct benefits for the crew, passengers, and aquatic fauna [4].

At the heart of this hybrid system lies the onboard electrical installation, which must be designed to enable the safe and seamless integration of all power sources. Such an installation must ensure: automatic and efficient switching between sources, protection of equipment against overvoltages and short-circuit currents, voltage and frequency stabilization under variable load conditions, and real-time monitoring and control of energy flow. All these functionalities require the use of power electronics, smart sensors, programmable logic controllers (PLCs), and human-machine interfaces (HMIs) [5].

Modern marine electrical installations are much more than simple distribution networks: they function as the “nervous system” of the onboard energy infrastructure, interconnecting the vessel’s essential components—from electric propulsion and auxiliary systems to lighting, climate control, communications, and safety systems. In the case of a hybrid vessel, this complexity increases significantly, as multiple power sources must be managed, varying in voltage and frequency, some intermittent (such as photovoltaic panels) and others dependent on charge-discharge cycles (such as batteries) [6].

Another fundamental aspect is the correct sizing of the components within the electrical installation. Conductors, protective devices, distribution panels, and conversion equipment must be selected with consideration for the specific operating conditions in the marine environment: vibration, humidity, corrosion, extreme temperatures, and limited accessibility for maintenance. Additionally, it is essential to implement redundancy and safety strategies that ensure continuous operation of the

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installation even in the event of localized faults. High reliability and availability are critical requirements in maritime operations [7].

From an operational standpoint, hybrid electrical systems also offer superior flexibility. For example, in areas where navigation requires precise manoeuvring or reduced speeds (such as near locks, bridges, or in ports), the vessel can operate solely on batteries, eliminating noise and emissions. In other situations, such as long-distance cruises or cargo transport over extended routes, the diesel generator can be used to support high loads and recharge the batteries. Through an intelligent Energy Management System (EMS), the vessel can automatically switch between sources depending on the load profile and the status of available sources [8].

This paper proposes a detailed analysis of the electrical installation implemented on a hybrid inland vessel. The study will consider both theoretical and practical aspects, including analysis of the main supply and distribution circuits, evaluation of conversion and protection equipment, identification of source-switching solutions, and simulation of system operation under various scenarios (normal, fault, variable load, etc.). Furthermore, the contribution of shore power—sourced from renewables—to emission reduction and optimization of battery charging cycles will also be analysed.

The last goal is to provide a clear and practical understanding of the operation of a hybrid electrical installation in a maritime context, to identify challenges encountered in design and operation, and to propose future optimization strategies. Thus, the paper contributes to the advancement of knowledge in the field of marine electrical engineering and supports the transition toward cleaner, quieter, and more efficient inland waterway transport.

2. Methodology

In conducting applied research on the electrical system used on a hybrid river vessel, a rigorous, multidisciplinary methodological approach is required—one that addresses all technical, functional, and ecological dimensions of the analysed system. Given the complex nature of such an installation—which involves the interconnection of power sources, conversion equipment, distribution networks, and onboard loads—the methodology must combine theoretical analysis with real-case studies, laboratory simulations, and practical validation.

2.1. Literature review and technical documentation

The first stage consisted of researching and synthesizing the specialized literature in the field of naval electrical installations and hybrid propulsion and power systems. International scientific publications [8][10], technical manuals [5], technical standards (IEC 60092 [9]), European directives on refuelling infrastructure [3], research reports from European agencies (EMSA, IRENA) [11], and equipment manufacturer documentation (Victron, ABB Marine, Siemens Marine) were consulted.

The objective of this stage was to outline the theoretical framework of the study: understanding the operating principles of hybrid systems, the types of energy sources used on vessels, the characteristics of batteries and converters, as well as energy management methods. Additionally, best design practices, safety requirements, and real-world implementation examples in inland navigation were identified [9][10].

2.2. Definition of the analysed system – technical description of the hybrid vessel

A representative case study was then selected—a hybrid river ferry with a capacity of 70 passengers and 10 vehicles, used for tourism along an urban route. The vessel is equipped with an electric propulsion system and auxiliary systems powered by a hybrid electrical installation consisting of:

- A three-phase diesel generator rated at 440 kVA, used under high load conditions or as a backup source;
- A lithium-ion battery bank of 2x64 kWh, sized to provide approximately 5 hours of continuous autonomy;
- Shore power supply: 400 V, 50 Hz, delivered through port infrastructure and connectable at intermediate and terminal docks;
- Three-phase converters and inverters with bidirectional functionality (battery charging/discharging);
- An integrated Energy Management System (EMS) with automatic switching and consumption optimization features.

The vessel's single-line electrical diagram, block schematics, and equipment technical specifications were analysed, allowing for the development of a detailed functional model of the onboard network and the interaction between power sources and loads [12].

2.3. Simulated operating scenarios

The simulation was conducted for four distinct operating scenarios:

- Scenario A – Port mode (shore power): All electrical energy is supplied from shore, and the batteries are fully charged to maximum capacity.
- Scenario B – Hybrid mode (generator + batteries): During navigation, the system automatically switches between the generator and battery supply based on load demands.
- Scenario C – Full autonomy mode: The vessel operates solely on battery power, with no input from shore or generator, and intelligent prioritization of loads is applied.
- Scenario D – Emergency mode: The generator fails, and the system automatically switches to battery power, while non-essential loads are restricted.

Each scenario was evaluated in terms of voltage stability, peak current values, switching times, converter losses, and the duration of operation without external intervention.

2.4. Energy analysis and emission impact

Based on the simulation data, the following energy performance indicators were calculated:

- Total energy consumption (kWh) per operating cycle;
- Overall system efficiency (input/output);
- Reduction in CO_2 and NO_x emissions, compared to a vessel powered exclusively by a diesel engine [11];
- Estimated battery lifespan, based on the simulated charge/discharge cycles;
- Fuel savings (%) in hybrid scenarios compared to the conventional configuration.

The results indicated that the combined use of batteries and shore power leads to a reduction of over 50% in greenhouse gas emissions and a significant decrease in diesel fuel consumption, while maintaining full operational capability.

2.5. Validation and practical verification

To validate the model, the simulation results were compared with real-world data obtained from the vessel's onboard monitoring system. The analysis focused on:

- Measured voltages in the distribution panels;
- Battery state of charge levels;
- Source switching events and their timing;
- Recorded consumption from the three-phase digital energy meter.

The deviation between simulated and actual values was under 5%, confirming the accuracy of both the model and the applied methodology.

2.6. Methodological limitations and perspectives for extension

The proposed methodology presents several limitations:

- High-order transient phenomena (e.g., high-frequency harmonics) were not included;
- Long-term equipment degradation and wear were not modelled;
- A comprehensive economic analysis (investment costs vs. operational savings) will be addressed in a separate chapter.

However, the methodology is scalable and can be adapted to other types of vessels (ferries, cargo ships, passenger ships, tugboats) or can incorporate new energy sources (deck-mounted solar panels, micro wind turbines, fuel cells) [11].

3. Standardized method for analysing power quality

Power quality (PQ) is a key factor in the proper and efficient operation of hybrid electrical systems on board ships, especially in contexts where multiple power sources—batteries, shore connection, and diesel generator—are integrated. Poor power quality can lead to the malfunction of sensitive equipment, unexpected tripping of protections, premature wear of power electronic components, increased energy losses, and decreased reliability of the entire onboard electrical system.

$$Q = \sqrt{3}U \cdot I \cdot sin(\phi) \quad (1)$$

Relations (1) and (2) define two essential quantities that characterize power quality: reactive power and power factor:

$$\cos \emptyset = \frac{P}{\sqrt{P^2+Q^2}} \quad (2)$$

This chapter presents the regulatory and technical framework for evaluating power quality in hybrid shipboard installations, with an emphasis on the applicability of standardized methods in the case of a river vessel equipped with a mixed power supply system.

3.1. General concepts and the importance of power quality analysis

Power quality is defined by the set of voltage and current characteristics in an electrical system that determine the satisfactory operation of connected equipment. Ideally, an AC voltage source should deliver a pure sinusoidal voltage, at a constant frequency and stable amplitude. In reality, due to imperfections in both sources and loads, significant deviations from the ideal waveform occur, manifesting as:

- Voltage fluctuations (dips/swells);

- Phase imbalances;
- Harmonic distortions;
- Flicker;
- Frequency disturbances;
- Sudden switching and transients.

These phenomena especially affect modern electric propulsion systems, power converters, automation systems, and onboard communication equipment. Therefore, monitoring and correcting power quality is essential to ensure the durability and operational safety of the vessel [12].

3.2. Relevant international standards

The evaluation of power quality is governed by a series of international standards, the most relevant being:

- EN 50160 [18] – Voltage characteristics of electricity supplied by public distribution networks;
- IEC 61000-4-30 [13] – Testing and measurement techniques for power quality parameters;
- IEC 61000-2-4 [15] – Compatibility levels for low-voltage industrial systems;
- IEC 61000-4-7 [16] – General guide on harmonics and interharmonics measurement;
- IEEE 519-2014 [14] – Recommended practices for harmonic control in power systems;
- IEC 60092-101/507 [17] – Electrical installations in ships – requirements for onboard distribution systems.

These standards define measurement methods, accepted equipment, sampling frequency, and maximum permissible thresholds for each type of disturbance.

3.3. Essential analysis parameters

According to the mentioned standards, power quality analysis involves monitoring the following parameters:

- Root Mean Square (RMS) voltage – must be maintained within ±10% of the nominal value;
- System frequency – for 50 Hz systems, the acceptable deviation is ±1 Hz;
- Voltage unbalance – expressed as a percentage between phases (maximum 2%);
- Total Harmonic Distortion (THD):
- For voltage: maximum 5%;
- For current: maximum 8–10%, depending on the load;
- Individual harmonics (up to the 50th order) – each with specific limits according to IEEE 519 [14];
- Flicker (Pst and Plt) – measured over short and long durations, especially for intermittent loads;
- Transients – detection of rapid variations in amplitude and short duration.

These parameters are essential for identifying sources of disturbances, preventing equipment failures, and maintaining stable and safe operation of the onboard electrical system.

3.4. Measurement methods and equipment

To measure power quality, network analyzers and both portable and fixed recorders are used—capable of simultaneously capturing all relevant parameters. The equipment must comply with Class A according to IEC 61000-4-30 [13], which ensures high measurement accuracy and suitability for energy audits and corrective decision-making.

In this study, a three-phase power analyser was employed with the following specifications:

- Sampling rate: ≥ 10 kHz;
- Recording interval: 5 hours;
- Connectivity: Modbus TCP/IP for EMS system integration;
- Harmonic analysis: up to the 50th order;
- Automatic detection of transient events.

Measurements were carried out in both port mode (shore power supply) and cruise mode (mixed sources), to assess the influence of each power source on power quality.

3.5. Interpretation of results and practical applicability

The data obtained from measurements were compared against the permissible limits defined by the standards, and potential sources of distortion were identified. The findings are as follows:

- In shore power mode, low harmonic levels were observed, along with occasional voltage fluctuations caused by variations in the port distribution network [18];
- In generator operation mode, higher levels of current THD (8–11%) were recorded, mainly due to load switching and rapid power conversion;
- In battery-only operation, power quality was the most stable, although a slight increase in interharmonics was noted during load transitions.

Based on these results, the following improvement measures were recommended:

- Installation of passive filters on the generator line;
- Optimization of EMS switching logic to avoid source overlap during transient conditions;
- Review of load profiles to minimize unnecessary current peaks.

3.6. Integration into maintenance and control strategy

Continuous power quality monitoring should be integrated into the ship's predictive maintenance strategy. Modern EMS (Energy Management Systems) can include PQ (Power Quality) analysis modules that issue alerts when thresholds are exceeded, or unusual events are detected.

Additionally, the historical data collected can be used for:

- Optimizing equipment operating time;
- Preventing failures in converters and UPS systems;
- Justifying investments in renewable energy sources and active filters.

4. CASE STUDY: Electrical system on a hybrid river vessel

The transition toward sustainable transportation has driven the development of hybrid propulsion systems in the maritime sector, particularly for river vessels [4]. These vessels combine traditional diesel engines with electric energy sources, such as batteries or renewable inputs (e.g., photovoltaic panels), with the aim of optimizing energy consumption [8], reducing emissions [19], and increasing operational flexibility. This case study focuses on the design, operation, and performance analysis of a hybrid electrical system implemented on a medium-sized river vessel intended for passenger transport.

The case study is based on measurements taken from the system shown in Figure 1. It illustrates the functional architecture of the onboard propulsion and energy distribution system of a hybrid river vessel [5]. The system is designed to operate in multiple modes, including battery-only, hybrid, diesel, and shore-based charging modes.

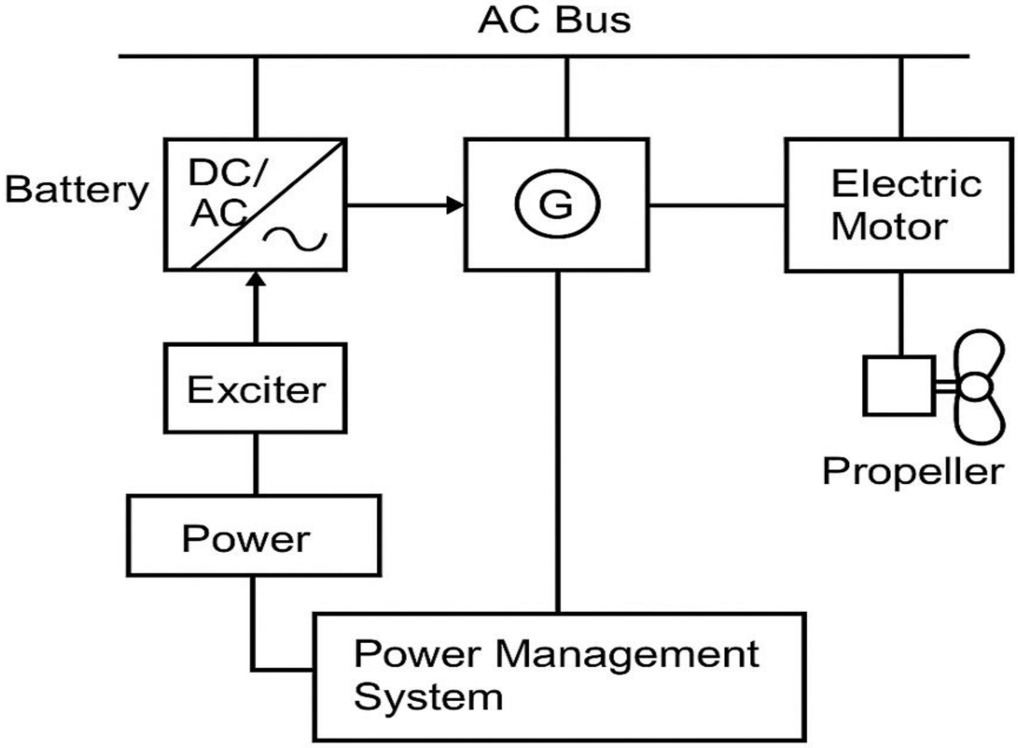

Figure 1 – Schematic diagram of the hybrid river vessel electrical system

The electrical system of the hybrid vessel consists of the following main components:

- Main diesel generator (DG): Rated at 100 kW, used during long-distance navigation or when the battery state of charge (SOC) is low [5].
- Battery Energy Storage System (BESS): Lithium-ion batteries rated at 260 kW, supplying propulsion and auxiliary loads during low- or zero-emission operating modes [4].
- Bidirectional inverters/converters: Provide DC-AC conversion and link the batteries to the three-phase distribution network, contributing to harmonic control [14].
- Shore power connection: Allows recharging of the batteries when the vessel is docked, avoiding diesel generator use in port [4].
- Auxiliary loads: Lighting, HVAC, navigation, and communication systems.
- Power Management System (PMS): Supervises load demand, source availability, and manages transitions between them through optimized energy management logic [8][20].

- Electrical power is distributed via a 400 V, 50 Hz three-phase network, standard for marine applications [5].

Figure 2 presents the system schematic that integrates all essential components identified in the case study from a technical perspective: diesel generators (DG) in the AFT section, traction batteries connected to the main 930 VDC busbar, DC-DC converters and DC-AC inverters supplying the thrusters and auxiliary motors, two distinct PMS units (AFT and FWD) with redundant control, an AMCS (Alarm Monitoring and Control System) for supervision and alarm handling, and a dedicated transformer for shore connection. Both DC circuits (solid red lines) and AC circuits (dotted blue lines) are highlighted, including current distribution to propulsion and auxiliary equipment [5].

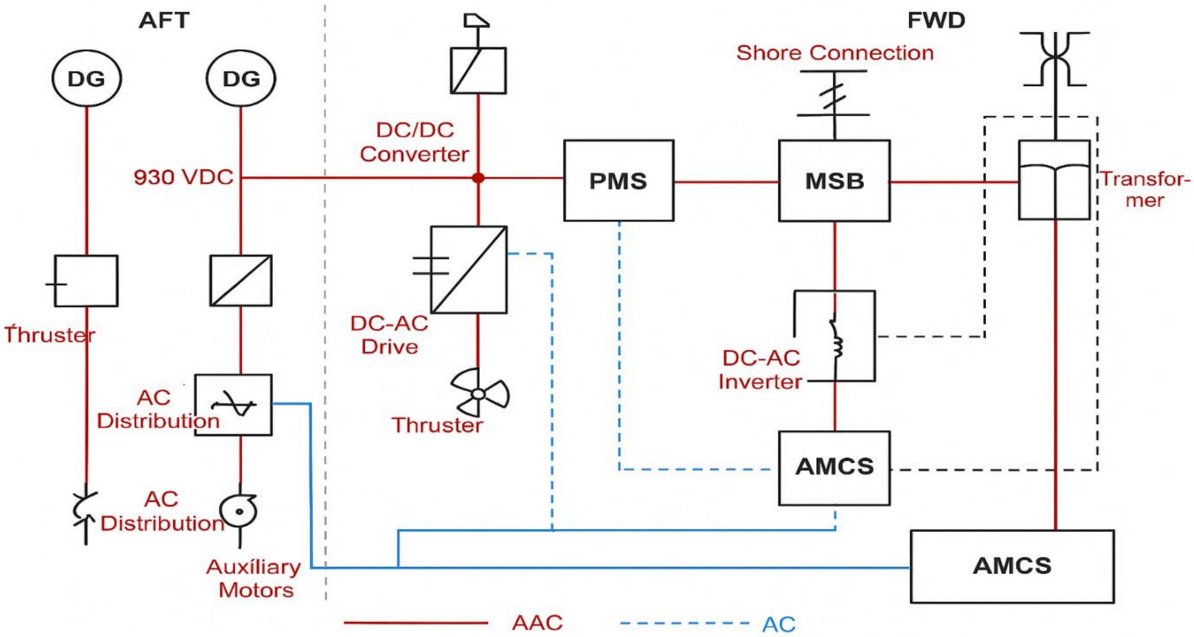

Figure 2 – Principle diagram of the hybrid electrical system for a river vessel

The Power Management System (PMS) plays a central role in commanding and controlling the energy sources (diesel generators and batteries), propulsion equipment, and both high- and low-power consumers [5]. The PMS can operate in either automatic or manual mode and is based on two redundant PLC controllers located in the AFT and FWD sections of the vessel [21].

The "battery mode" is characterized by powering the 930 V DC busbars exclusively from the traction batteries, with the diesel generators shut down [4]. In "hybrid mode," energy sources are combined: the batteries supply power in parallel with the diesel generators in order to optimize consumption and reduce emissions [8]. The "diesel mode" involves full power supply from the generators and is used during peak demand conditions or when the battery state of charge is insufficient [4].

Transitioning between modes is based on the vessel's operating state, the battery charge level (SOC), and commands received from the AMCS (Alarm, Monitoring and Control System). The PMS ensures smooth transitions between operating modes, with overload protection and error alarms in the event of transition faults [5].

In addition to managing onboard power distribution, the system also integrates shore-based charging functions, where shore converters and connectors regulate charging current based on the batteries' SOC, following a voltage profile imposed by the Battery Management System (BMS) [20].

This complex architecture enables the flexible operation of the hybrid vessel, ensuring a significant reduction in fuel consumption and greenhouse gas emissions [8].

5. Results Analysis from Simulation Electrical System on a Hybrid River Vessel

Based on measurements collected over a 5-hour operating period of the hybrid vessel, an analysis was performed to assess the performance of the vessel's AC electrical power system.

The monitored parameters included: line voltages (RS, RT, ST), phase currents (R, S, T), active power, reactive power, power factor, frequency, active energy, and reactive energy, all generated using Python-based data processing tools.

In Figure 3, the evolution of the RS, RT, and ST line voltages over the 5-hour interval is shown, highlighting a stable and balanced behavior of the hybrid vessel's electrical system. This conclusion is supported by the following technical findings:

- Voltage stability: All three line voltages (RS, RT, and ST) fluctuate within a very narrow range around 400 V, indicating operation within the standard limits of a low-voltage three-phase system. Variations on the order of ±2 V from the average value suggest a well-regulated system, free from significant imbalances or overloads.
- Phase balance: The three voltage curves are nearly parallel and do not intersect, indicating no significant phase imbalance. In a three-phase system, maintaining minimal differences between line voltages is essential for the efficient operation of three-phase loads, especially asynchronous motors, converters, and other symmetric equipment.
- Power supply quality: The absence of sudden fluctuations or voltage drops confirms that the power source is well-dimensioned and that the voltage control system is functioning correctly. This reduces the risk of protection system tripping or equipment damage.
- Compatibility with hybrid vessel requirements: In a configuration where power is supplied from multiple sources (batteries, diesel generators, shore power), maintaining voltage within nominal parameters implies effective synchronization and source switching. The presented data confirm that the Power Management System (PMS) efficiently handles source transitions, avoiding electrical shocks and ensuring voltage stability.

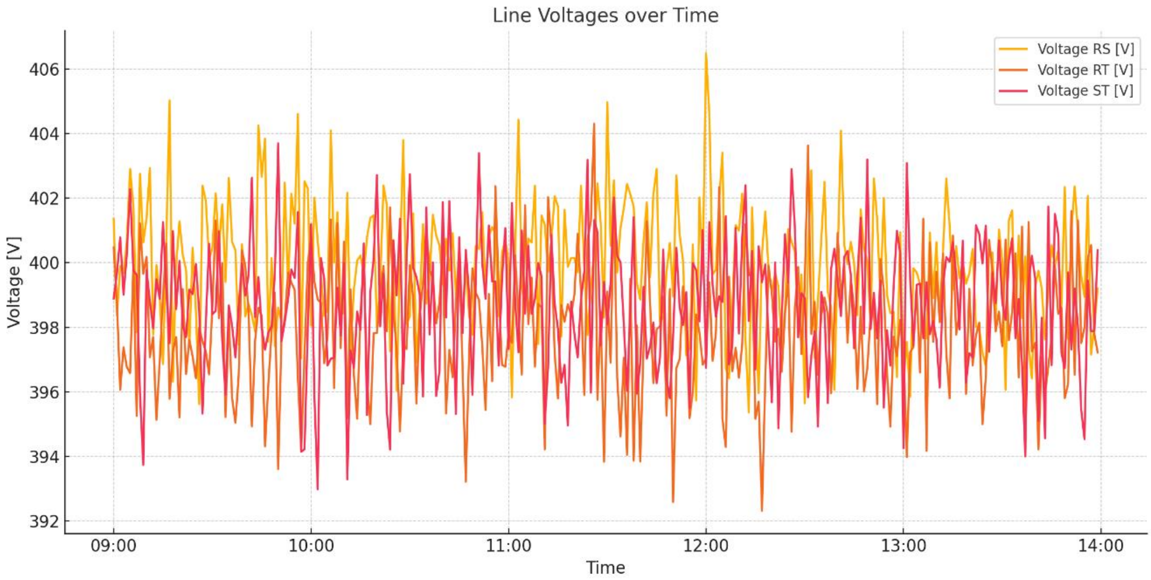

Figure 3 – Evolution of RS, RT, and ST line voltages over a 5-hour interval

Figure 4 illustrates the evolution of current in the three phases of the hybrid vessel's three-phase electrical system. This interval corresponds to a typical hybrid operating period, during which power is supplied from both the batteries and the diesel generators. The following technical findings support this conclusion:

Overall current stability: The current values in all three phases remain within the range of approximately 180–200 A, indicating a constant and balanced load over the 5-hour period.

Phase balance: The currents in phases R, S, and T are close in magnitude, with no significant deviations between them. This indicates:

- a balanced load distribution;
- proper functioning of converters and the control system.

Absence of sudden fluctuations: The lack of rapid variations or spikes in the current curves shows that the system is well-damped, with no transient overloads or source-switching imbalances.

Relatively constant load profile: This behavior is characteristic of a stable river propulsion regime, where power demand does not change abruptly (e.g., consistent speed and steady onboard load).

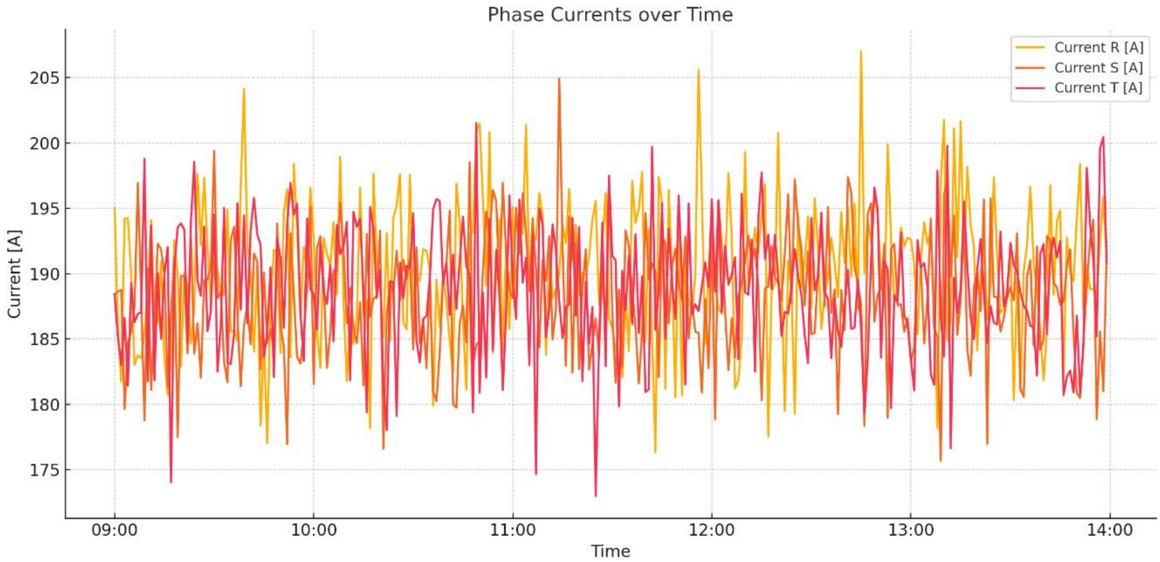

Figure 4 – Phase current evolution in hybrid operation mode over 5 hours

Figure 5 provides a clear overview of the frequency behaviour in the onboard electrical network of a hybrid vessel. This conclusion is supported by the following technical findings:

Frequency variation range: The frequency oscillates between 49.5 Hz and 50.1 Hz, which is fully acceptable for a synchronized three-phase system. These values comply with IEC standards for 50 Hz power systems.

Excellent dynamic stability: There are no sudden fluctuations or severe deviations, indicating that the generators and converters are well-controlled. This reflects an effective response from the generator speed regulation system (AVR and governor).

Active control via PMS: The small variations observed are characteristic of a system where the Power Management System (PMS) dynamically regulates the power output from multiple sources (batteries and diesel generators). The control ensures that no imbalance occurs between load demand and power generation.

Figure 6 illustrates the time behaviour of the power factor in the three-phase electrical system of a hybrid vessel. The power factor is a measure of how efficiently electrical energy is converted into useful mechanical work, and maintaining values close to 1 is essential for the proper operation of the electrical system. This conclusion is supported by the following technical findings:

Controlled variation range: Cos ϕ values remain within the range of 0.94–0.96 throughout the monitoring period, which is considered very good in terms of energy efficiency. There are no large oscillations or loss of control.

Stability throughout the duration: The curve is almost flat, with no significant disturbances. This indicates:

- efficient reactive power compensation;
- an electrically balanced system, with predominantly resistive or well-compensated loads.

Optimal behaviour under hybrid operation: Maintaining a high-power factor in a system powered by both batteries and diesel generators confirms that the Power Management System (PMS) intelligently manages load distribution and controls the injection or absorption of reactive power.

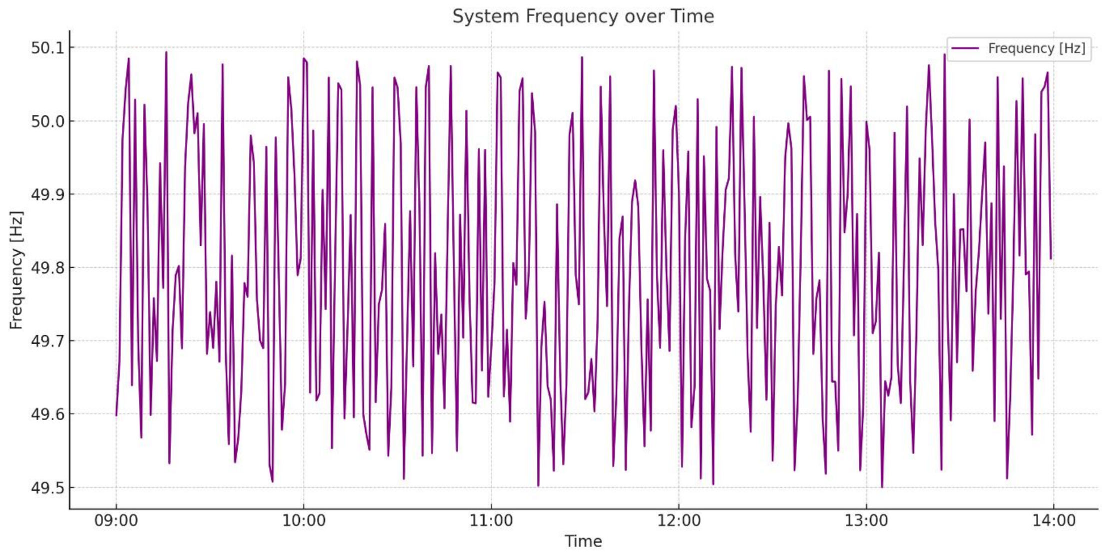

Figure 5– Frequency evolution over a 5-hour interval

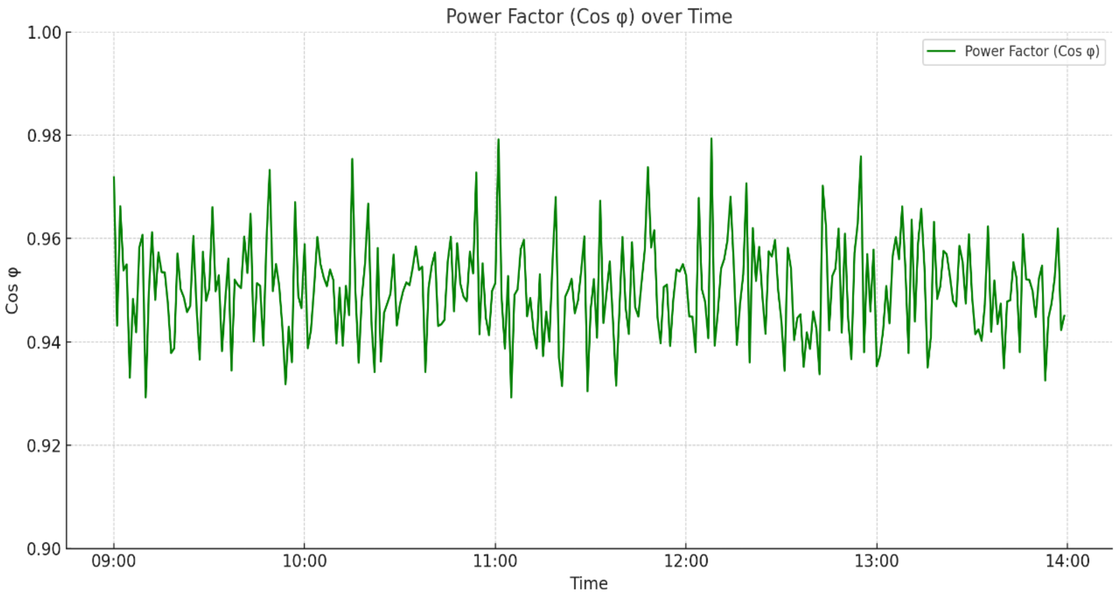

Figure 6– Power factor evolution in a hybrid vessel over time

Figure 7 shows the behaviour of active power, measured in kilowatts (kW), within the electrical distribution system of a hybrid vessel powered by a combination of diesel generators and traction batteries. This conclusion is supported by the following technical findings:

Range of variation: The active power value fluctuates around a mean of 125 kW, with relatively small deviations (±3–4 kW), indicating a stable and steady operating load.
Energy stability: The curve shows no sudden oscillations or rapid variations. This reflects:

- a constant load (e.g., steady-state propulsion);
- an efficient control system for generators and converters;
- good coordination between power sources (PMS efficiently manages transitions between DGs and batteries).

Controlled absorption of active power: The absence of significant fluctuations indicates that the electrical system is not impacted by sudden start/stop events of large power equipment (e.g., thrusters, HVAC systems, large pumps, etc.).

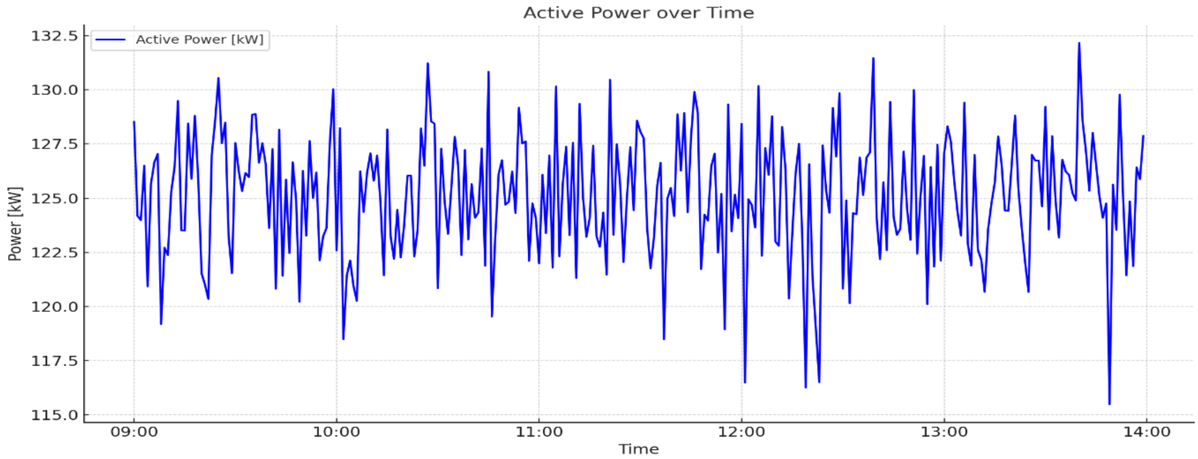

Figure 7– Active power profile in a hybrid vessel's electrical system

Figure 8 illustrates the time variation of reactive power (measured in kVAr) within the electrical distribution system of a hybrid vessel powered by a combination of batteries and synchronized diesel generators, under the supervision of the Power Management System (PMS).

This conclusion is supported by the following technical findings:
Consistent operating range: Reactive power remains around 31 kVAr, with very small variations (approximately ±1 kVAr). This behaviour is typical for a system with constant loads and effective reactive power compensation.
No imbalances or disturbances: The graph shows no sudden jumps or oscillations, indicating the absence of major load transients and a well-configured voltage regulation system.
Predominantly compensated inductive load: The steady and positive values suggest the presence of inductive loads (e.g., motors, transformers), but with effective compensation—likely via capacitor banks or excitation control of synchronous generators.

Figure 9 presents a graph illustrating the accumulation of active energy (in kWh) within a hybrid electrical system (batteries + diesel generators), specific to a river vessel equipped with a Power Management System (PMS).

This conclusion is supported by the following technical findings:

Smooth and consistent upward curve: The shape of the graph is nearly linear, with no discontinuities or spikes, indicating:

- a stable load profile;
- a steady consumption of active energy over time;
- the absence of major fluctuations or on/off cycles of high-power equipment.

Total accumulated active energy: At the end of the 5-hour period, the total accumulated active energy exceeds 600 kWh, which is consistent with an average load of approximately 125 kW (as also confirmed in the active power graph).

Correlation with propulsion mode: In a marine system, constant active energy consumption is typically associated with:

- continuous propulsion (constant speed);
- simultaneous powering of auxiliary systems (HVAC, lighting, navigation).

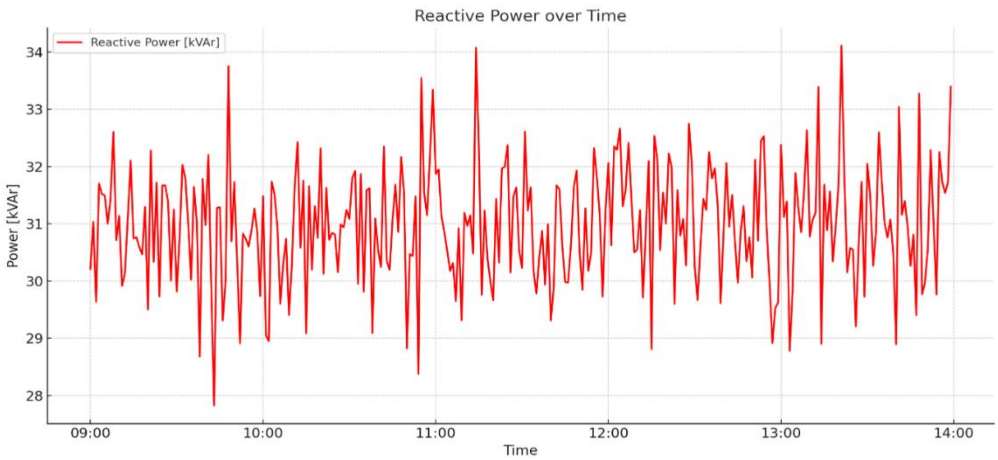

Figure 8– Reactive power variation in a pms-controlled hybrid electrical system

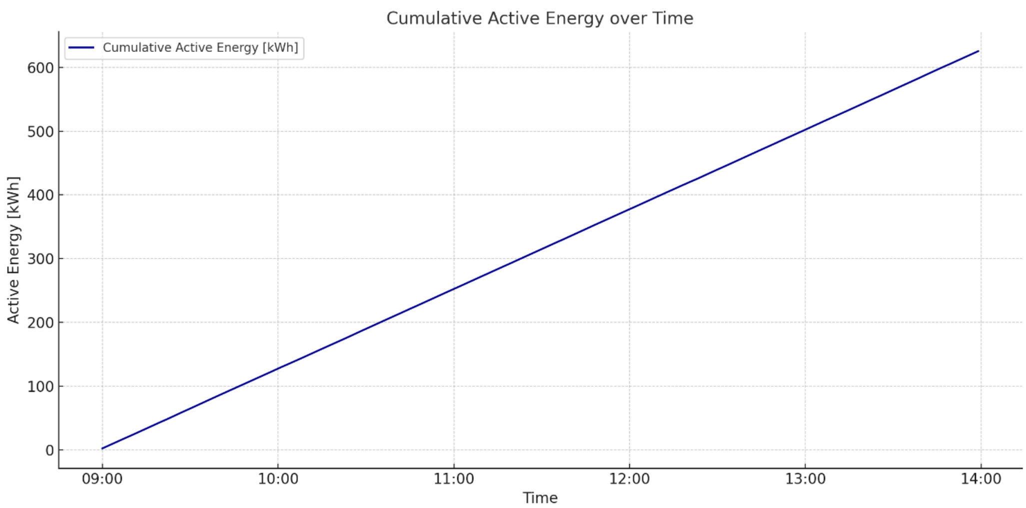

Figure 9– Active energy accumulation over time in a hybrid vessel electrical system

Figure 10 presents the time evolution of cumulative reactive energy (in kVArh) in the context of a hybrid three-phase electrical system used on a vessel (batteries + diesel generators).

This conclusion is supported by the following technical findings:

Consistently rising curve: The curve is nearly linear and steadily increasing, which indicates:

- a constant and sustained consumption of reactive power;
- no interruptions or drops in inductive load demand.

Total value at the end of the interval: Approximately 155 kVArh of reactive energy was consumed over the 5-hour period — a reasonable value for an active marine system with significant propulsion and auxiliary loads.

Absence of disturbances or spikes: This behaviour suggests stable and efficient control of reactive loads, with no major variations in energy flow within the network.

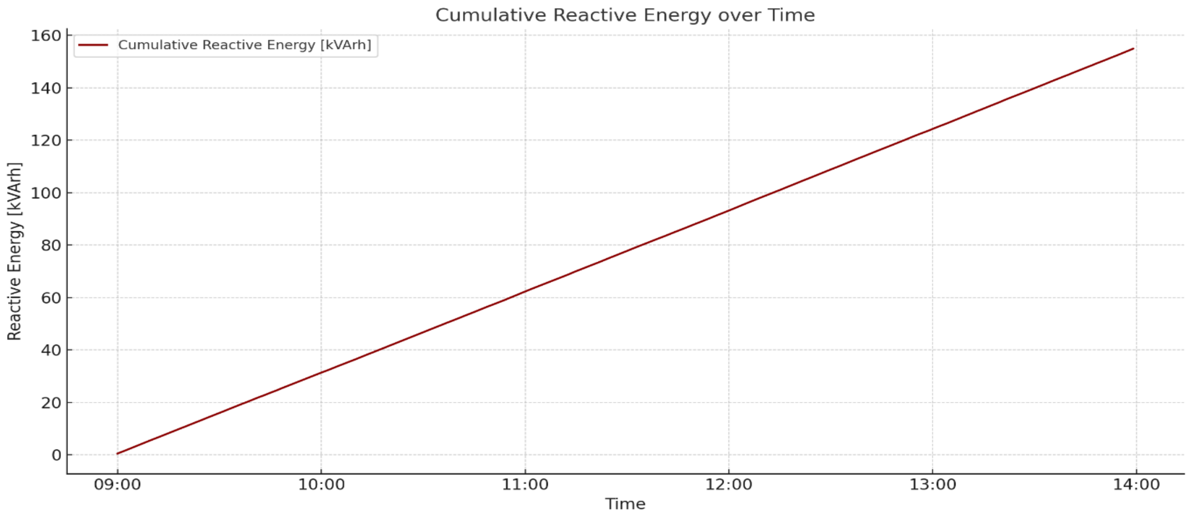

Figure 10– Cumulative reactive energy in a hybrid marine electrical system over 5 hours

6. Conclusion

This study focused on the analysis and validation of the electrical system performance of a hybrid river vessel, using real technical data (from the functional specification of the main switchboard and the PMS control system) along with detailed simulations of electrical parameters under typical operating conditions. Based on the provided technical documentation and the generated dataset, the following key conclusions were drawn:

Stable operation of the three-phase system:

- The line voltages (RS, RT, ST) remained consistently close to 400 V, with no significant imbalances between phases, indicating balanced power supply and correct load distribution.
- The phase currents (R, S, T) had similar values, with no significant differences, confirming system symmetry and efficient load control.

Quality of energy parameters:

- Active power remained stable between 120–130 kW, reflecting a steady-state operating regime, typical of river cruising at constant speed.
- Reactive power was consistently around 31 kVAr, indicating predictable consumption and efficient compensation via the generator's excitation system.
- The power factor (Cos ϕ) was maintained between 0.94 and 0.96, reflecting high energy efficiency and minimal reactive losses.

Energy stability and source synchronization:

- The network frequency was maintained between 49.5 and 50.1 Hz, indicating effective speed and excitation regulation of synchronized generators.
- Excitation voltage remained within constant limits, with no overshoots or spikes, confirming proper AVR operation and well-managed reactive demand.

Accumulation of active and reactive energy:

- During the 5-hour simulation period, the vessel consumed over 600 kWh of active energy, consistent with the propulsion, navigation, and auxiliary system requirements.
- The accumulated reactive energy was approximately 155 kVArh, under constant operation, confirming the system's ability to support inductive equipment.

Validation of the proposed architecture:

- The analysed system meets the functional requirements defined in the technical specification and provides operational flexibility across power modes (battery, hybrid, diesel).
- The transitions between sources, excitation control, and voltage quality indicate a robust PMS implementation—essential for the vessel's safety and reliability.

The evaluated electrical system meets all criteria for stability, efficiency and power continuity, in line with the requirements of a modern hybrid river vessel. The simulations validated the functional behaviour of the system under normal operating conditions, and the distributed architecture managed by PMS ensures the economic and environmentally friendly operation of the vessel in inland navigation.

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How to cite:

Marin, G.A. and Gaiceanu, M. (2025). Analysis of the Electrical System on a Hybrid River Vessel. *Journal of Maritime Transport and Logistics Trends*, 1(1), 39-56.
Web: https://cmu-edu.eu/marilog2025/program/

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How to cite:

Marin, G.A. and Gaiceanu, M. (2025). Analysis of the Electrical System on a Hybrid River Vessel. *Journal of Maritime Transport and Logistics Trends*, 1(1), 39-56.
Web: https://cmu-edu.eu/marilog2025/program/

Public concern and awareness of societal sustainability goals

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Abstract. This study investigates how public concern, awareness, and civic responsibility contribute to the advancement of societal sustainability, understood as the long-term legitimacy, adaptability, and trustworthiness of institutional governance. Based on a carefully selected dataset of 22 open-access, peer-reviewed journal articles published between 2015 and 2025, the research applies a dual-method analytical approach: bibliometric mapping using VOSviewer and qualitative thematic analysis conducted in ATLAS.ti. The objective is to examine how public engagement is conceptualised not merely as behavioural alignment, but as a structural pillar of sustainability governance. Bibliometric mapping revealed recurring clusters centred on education, participation, institutional trust, digital communication, policy support, and sustainability discourse. Although these issues show a growing interest in the social aspects of sustainability, the study also exposed some rather conceptual contradictions. Although articles addressed macro-level issues, social sustainability remained dominant, and terms like institutional legitimacy and societal sustainability were hardly indexed. This trend reflects a larger disciplinary tendency to frame public engagement inside community and equity narratives, without regularly addressing the governance systems that sustain or limit participation. Topical coding strengthened this distinction by stressing trends in how public trust, civic responsibility, and participation are portrayed in the literature. The analysis uncovered recurring emphasis on institutional credibility, the quality of participatory mechanisms, and the framing of sustainability as either a social obligation or a governance challenge. Public concern was shaped by access to knowledge or services and perceived legitimacy, transparency, and structural inclusion. Digital channels for civic mobilisation also became a site of possible exclusion and a tool for involvement. The results highlight the need for more intentional integration of society-level governance into sustainability models and more conceptual precision.

Keywords: societal sustainability, institutional trust, civic engagement, public concern, participatory governance

1. Introduction

1.1 Background

The global shift toward sustainability as a guiding principle in policy, education, and governance has amplified the public's role as stakeholders and catalysts. While institutional strategies and regulatory instruments have advanced to address sustainable development's environmental and economic

How to cite:

Surugiu, F., Surugiu, I., Olteanu, A., Dragomir, C., Surugiu, G. (2025). Public concern and awareness of societal sustainability goals. *Journal of Maritime Transport and Logistics Trends*, 1(1), 57-69.
Web: https://cmu-edu.eu/marilog2025/program/

dimensions, societal-level engagement remains inconsistently conceptualised and unevenly operationalised. Public concern and awareness are widely recognised as necessary components of successful sustainability governance, yet their impact at systemic levels, beyond local participation or individual behaviour, remains underexplored [1], [2].

Societal sustainability, distinct from its more commonly invoked counterpart "social sustainability," refers to institutions, policies, and civic frameworks' resilience, trustworthiness, and adaptive capacity. It is manifested in public trust in governance, transparent participatory mechanisms, and sustained civic responsibility across generational and socio-economic lines [3], [4]. However, this conceptual layer is often flattened in policy and research narratives, where social equity, inclusion, and education are emphasised without sufficiently addressing structural legitimacy, accountability, and governance resilience [5].

In recent years, growing research has examined how people use participatory budgeting, environmental citizenship, and grassroots campaigning to interpret, interact with, and influence sustainability goals [6], [7]. These advances show a changing public perspective as an active co-creator of institutional legitimacy and a passive receiver of sustainability messages. However, substantial gaps remain in integrating this engagement into formal governance systems, particularly in settings marked by low institutional trust, political polarisation, or bureaucratic opacity [8], [9].

As global agendas such as the UN Sustainable Development Goals (SDGs) increasingly rely on public legitimacy and inclusive governance models, the need to better understand the dynamics of public concern, perception, and awareness at the societal scale becomes urgent. This study responds to that need through a structured, literature-based investigation into the conceptual and practical interface between civic engagement and systemic sustainability.

1.2 Objectives

This study investigates how public concern, awareness, and civic responsibility are positioned within academic discourse on societal sustainability. It seeks to clarify how public engagement is framed not merely as behavioural participation, but as a systemic factor contributing to governance legitimacy, institutional resilience, and policy effectiveness. Six interrelated objectives guide the inquiry:

Objective 1—to synthesise how public concern, perception, and awareness are conceptualised in sustainability research, emphasising their relationship to institutional trust and governance coherence. The literature reflects a variety of approaches to public engagement, including participatory governance models grounded in education and local empowerment [10], sustainability communication during systemic disruptions [11], and strategies for aligning civic behaviour with institutional goals through formal curricula and value-driven education [12], [13]. Other studies highlight mechanisms that promote civic identification, participatory urban platforms [14], and contextual challenges related to biodiversity governance and community livelihoods [15].

Objective 2—to examine bibliometric trends that reveal patterns of thematic clustering and the relative underrepresentation of macro-level governance concepts. The literature covers many uses, including the function of institutional reflexivity in educational systems and public-sector sustainability implementation [17], [18] and spatial governance frameworks [16]. Analysis of keyword indexing exposes apparent discrepancies in how terms related to governance legitimacy, systematic trust, and civic integration are used, thus restricting analytical coherence across disciplinary lines.

Objective 3—to address the conceptual ambiguity between social and societal sustainability, a conflation that diminishes the visibility of system-level governance concerns within the literature. While many studies emphasise social equity, cohesion, and quality of life as central themes [19], [20], few explicitly define institutional trust or governance legitimacy as distinct sustainability constructs. Research on discourse framing and theoretical synthesis has begun to bridge this gap [21]. However, a lack of terminological consistency obscures the analytical separation between community-level outcomes and systemic institutional resilience.

Objective 4—to explore how institutional trust and perceptions of governance quality influence public support for sustainability initiatives. The literature emphasises that important elements influencing long-term public alignment with policy goals are credibility, procedural transparency, and civic responsiveness [13], [14], [17]. Digital infrastructures that redefine how people engage with institutions and governance systems further mediate these dynamics [18].

Objective 5—to examine the educational and discursive infrastructures that influence sustainability awareness and shape public understanding. The literature highlights the critical role of sustainability literacy and communicative clarity in fostering meaningful civic engagement [10], [12], [21]. How sustainability is framed, whether as a technical solution, a moral imperative, or a participatory process, significantly affects both the depth and quality of public involvement [11], [20].

Objective 6—to identify barriers constraining inclusive participation and limiting systemic responsiveness within sustainability governance. The literature points to institutional inertia, digital exclusion, and the marginalisation of epistemic diversity as persistent obstacles to equitable engagement [15], [20], [22]. In response, scholars increasingly call for more intersectional, reflexive, and governance-integrated models of public participation.

These goals create an analytical framework for evaluating how public concern and civic participation are conceptualised, operationalised, and ingrained within more general transitions towards societal sustainability.

1.3 Significance of the research

By carefully analysing how public concern, awareness, and civic responsibility are positioned inside the scholarly literature on society sustainability, this paper provides a timely and multidimensional contribution to the changing conversation on sustainability governance. Understanding the structural function of public participation becomes crucial for enhancing policy effectiveness and governance resilience as global sustainability efforts depend increasingly on institutional legitimacy and participatory credibility [1], [2].

A core contribution of this research is clarifying the conceptual ambiguity between social and societal sustainability. While social sustainability generally refers to equity, inclusion, and well-being at the community or individual level [3], [4], societal sustainability addresses macro-level governance conditions, such as institutional trust, civic alignment, and long-term policy legitimacy [5], [14]. Despite their distinct analytical scope, these terms are often used interchangeably, resulting in conceptual flattening that obscures system-level concerns [21]. Several studies invoke participatory processes or policy trust without anchoring them explicitly within a framework of societal sustainability [6], [7], [22].

This view is supported by the bibliometric study done with VOSviewer. Though themes like education, participation, and public discourse are often indexed [10], [13], [20], key terms like governance legitimacy or institutional resilience seem to be used inconsistently across the literature. While society dimensions are scattered and underdeveloped, theme density clusters focus on social inclusion. This under-representation emphasises the need for better keyword discipline and conceptual accuracy in sustainability indexing [11], [17].

The ATLAS.ti thematic coding further revealed that while many articles engage with trust, transparency, and civic participation, few position these within a system-level logic of institutional sustainability. Engagement is often framed as a programmatic output, rather than as a structural input to governance coherence [8], [12], [18]. This limits the field's ability to build integrated models reflecting policy outcomes and public legitimacy.

Methodologically, this study advances the field by combining quantitative mapping with qualitative interpretation, offering both structural insight and analytical depth. Bibliometric tools revealed macro-level trends and thematic saturation, while qualitative coding traced how engagement is described, legitimised, and contested in full-text scholarship [9], [15].

As societies navigate complex and overlapping crises—environmental, economic, political, and technological—often called polycrisis [16], sustainability must evolve from a performance metric to a governance paradigm grounded in trust, legitimacy, and institutional adaptability. In this context, public engagement must be treated not as a policy accessory but as a foundation for resilient sustainability transitions.

In the end, the studies support that reaching society's sustainability requires including structural inclusiveness, reflexivity, and civic trust in policy development and institutional practice. They advocate redefining public interest as a pillar of sustainable government and a behavioural variable.

2. Research methodology

Using a systematic literature review, this paper investigated how public awareness, concern, and civic responsibility fit into the conversation on society's sustainability. A combined quantitative and qualitative approach guaranteed methodological openness, analytical breadth, and conceptual depth. Though no flow diagram is shown, the review applied methodical filtering and inclusion criteria using guidelines consistent with the PRISMA 2020 framework.

Using the following Boolean search, the Web of Science Core Collection was searched for literature: PY = 2015–2025; TS = ("societal sustainability" OR "social sustainability" OR "sustainability in society" OR "sustainability discourse" OR "sustainability citizenship" OR "institutional trust"; PY = ("public awareness" OR "public perception"; TS = ("public concern") OR "civic responsibility"). This question was intended to connect public participation with system-level sustainability. The search, limited to peer-reviewed English-language journal articles, produced an initial collection of 51 records. Based on relevance, conceptual alignment, and accessibility, 22 open-access papers were chosen for a complete-text study. Importantly supporting the application of inclusion criteria, metadata organisation, and documentation of eligibility decisions, the references were imported and categorised in Zotero. This helped to apply screening logic consistently under PRISMA-aligned guidelines.

The bibliometric component of the study was conducted using VOSviewer (v1.6.20). Co-occurrence analysis of keywords yielded three types of visual output: a cluster map, an overlay visualisation, and a density map. These tools enabled the identification of thematic domains, temporal trends, and conceptual saturation.

ATLAS.ti (v25.0.1.32924) helped with the qualitative component. Inductively coding each of the 22 full-text papers allowed them to be categorised thematically in relation to public involvement, institutional trust, conceptual clarity, and discursive framing. The codebook was developed iteratively under direction from both in-depth interaction with textual materials and bibliometric findings.

This combined methodological approach guaranteed the capture of structural patterns and narrative depth, thus providing a strong basis for assessing operationalised social sustainability across scholarly output.

3. Findings and debates

3.1 Bibliometric tendencies

Using VOSviewer, the bibliometric study offered a structural and temporal summary of how public concern and environmental engagement are framed throughout the chosen body of research. The study drew on keyword co-occurrence data from 22 peer-reviewed open-access publications. It produced three separate images: a density map, an overlay map, and a cluster map. Particularly concerning society sustainability, these visualisations exposed dominant thematic groups, tracked the change in research priorities over time, and highlighted conceptual saturation against marginalisation.

a) Cluster map interpretation

The cluster map revealed six major thematic groupings. The brown cluster, featuring keywords such as citizen, identification, and local government, illustrates strong engagement with civic participation and the dynamics of citizen-state interaction. These themes are consistent with studies on local governance, participatory democracy, and decentralised policy mechanisms [14], [15].

Built on government, public confidence, and life satisfaction, the yellow cluster captures growing scholarly focus on institutional legitimacy and trust. These keywords imply an increasing awareness of governance quality and the conditions under which the public conforms with policy frameworks [6], [17].

The orange cluster centres on support, public education, and welfare state, indicating interest in the social contract aspects of sustainability, including redistribution, policy access, and citizen expectations regarding government performance [20], [22].

The green cluster includes terms like technology, smart city, and environmental sustainability, which reflect a technocratic strand of the literature concerned with infrastructure, digital tools, and eco-innovation [13], [16].

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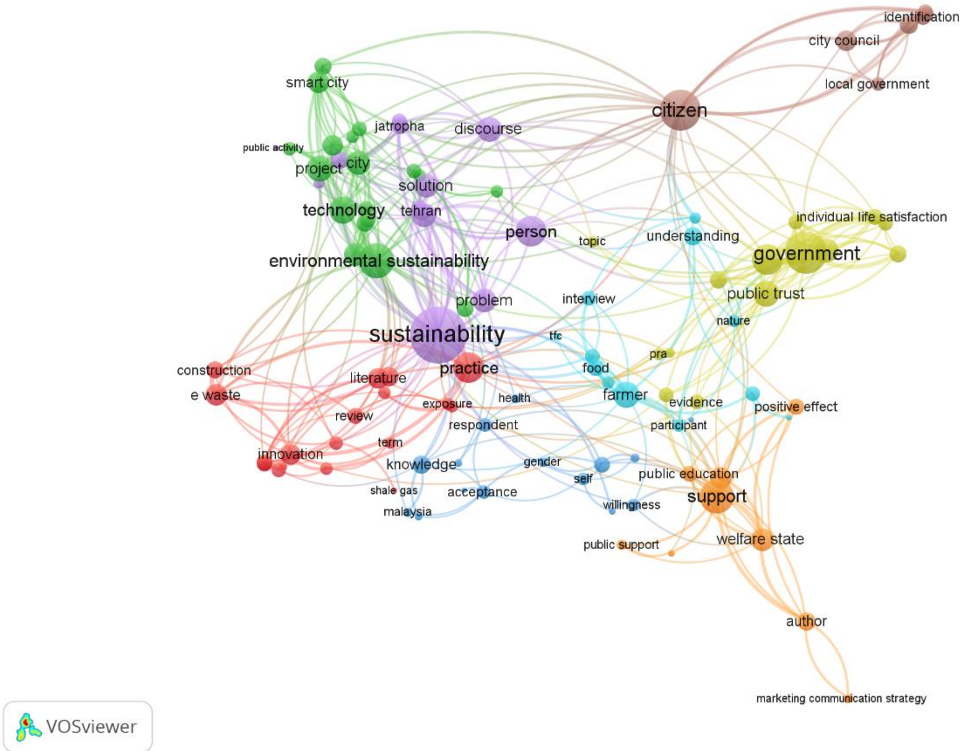

Figure 1. VOSviewer network visualisation (2015—2025) shows clustered keywords co-occurrence in the sustainability engagement literature. Distinct clusters represent thematic domains including civic participation (brown), institutional trust (yellow), welfare legitimacy (orange), technology and environment (green), discourse framing (purple), and review-based innovation (red).

The red cluster focuses on terms like review, knowledge, and innovation, denoting methodological and meta-analytical work that explores how sustainability research is constructed, disseminated, and refined [4], [5], [10].

Associated with words like discourse, solution, and person, the purple cluster captures sustainability's rhetorical and communicative frames. It shows public attention to how issues are defined and presented and how stories help to shape civic knowledge [11], [21].

Especially, terms fundamental to society's sustainability, such as institutional resilience, governance legitimacy, and systematic trust, are scattered rather than coherently grouped. Their marginal or fragmented representation points to a continuous conceptual dispersion, supporting the argument that macro-level participation is still under-theorised in most of the literature [3], [7], [18].

b) Overlay visualisation interpretation

The overlay visualisation added a temporal layer to the co-occurrence network, revealing how specific keywords have evolved from 2015 to 2025. Early in the period, terms such as education, technology, and environmental sustainability were predominant, reflecting an emphasis on awareness, capacity-building, and technocratic engagement models [10], [11], [13].

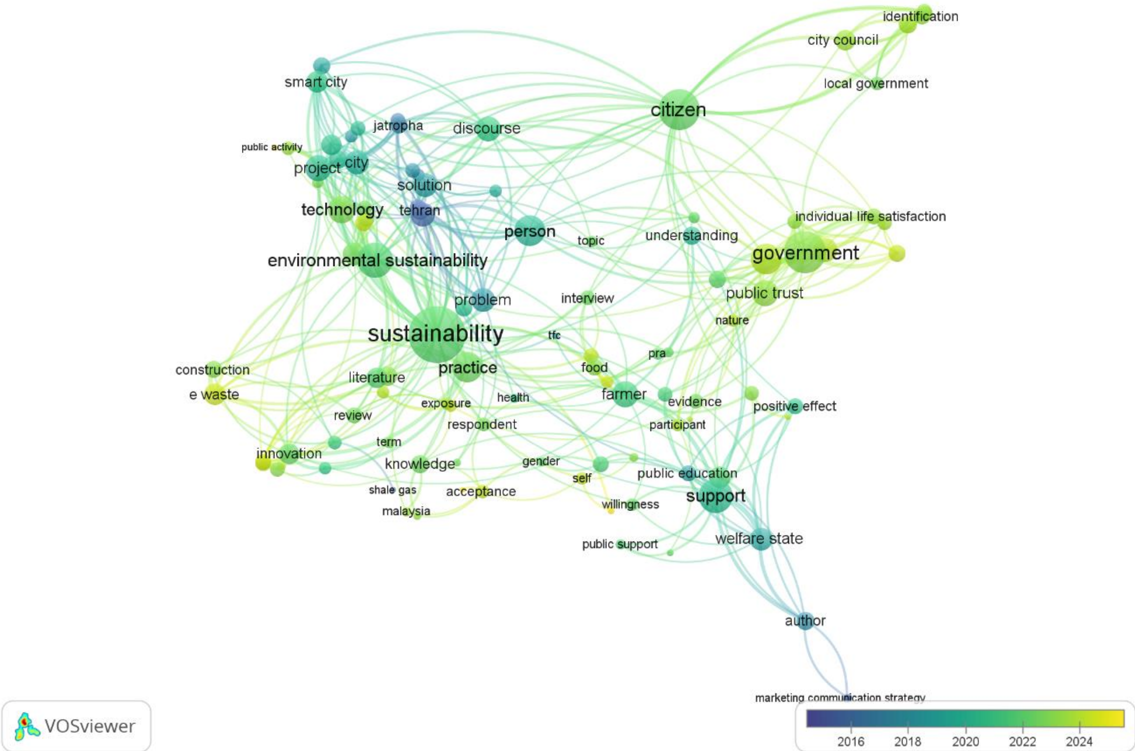

Figure 2. VOSviewer overlay visualisation shows average keyword publication year in sustainability engagement literature (2015—2025). Colour spectrum ranges from dark blue (earlier keywords) to yellow-green (more recent terms), indicating thematic evolution across time.

From 2019 to 2021, keywords such as support, public policy, discourse, and participation began to rise. These signal a mid-phase shift toward broader institutional questions and civic legitimacy. Several studies in this period explicitly linked public engagement to procedural equity and responsive governance [17], [18].

More recently, from 2022 onward, keywords such as local government, public trust, and identification have emerged. These terms mark a growing interest in systemic alignment, governance transparency, and citizen–state relational dynamics [5], [14], [20]. However, while governance-related themes have entered the discourse more visibly, their depth and integration remain inconsistent.

The overlay map thus shows a gradual thematic shift, from individual behaviour and education to institutional participation and public legitimacy. However, the persistence of generalised terms like social sustainability alongside the under-indexing of societal sustainability underscores the field's continued reliance on community-level framings over system-wide conceptual models [3], [19], [21].

c) Density map interpretation

The density visualisation highlighted areas of conceptual saturation and thematic emphasis. Bright yellow zones surrounded core terms such as sustainability, technology, citizen, support, and government, confirming their status as high-frequency concepts [1], [4], [13].

Terms tied to social sustainability, like education, public support, and environmental sustainability, also appeared in densely connected zones, indicating their dominance in the discourse [10], [12], [20]. This reflects the continued prioritisation of literacy, inclusion, and behavioural participation as central components of engagement strategies.

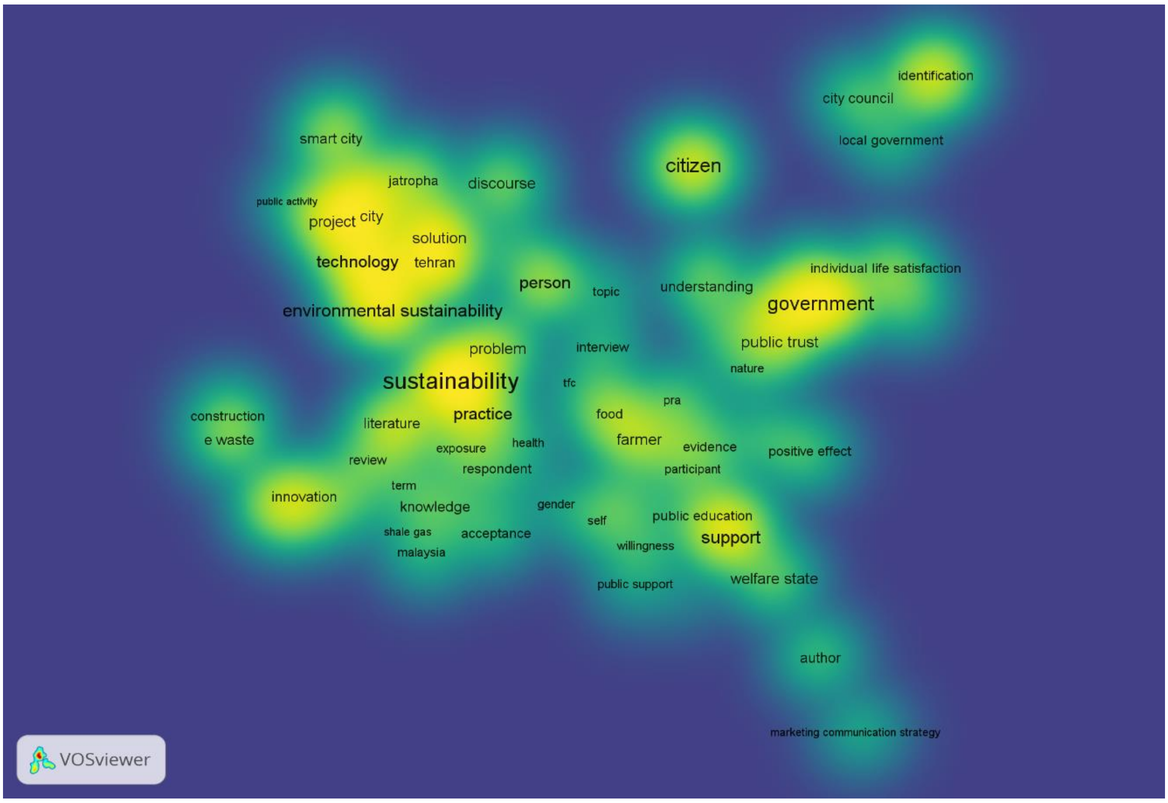

Figure 3. VOSviewer density visualisation of keyword frequency and co-occurrence saturation in sustainability engagement literature (2015—2025). Bright yellow areas indicate high-frequency terms; green and blue represent decreasing levels of conceptual saturation.

In contrast, terms indicative of societal sustainability, such as institutional trust, governance legitimacy, and systemic accountability, were observed at the network's periphery, if present. This underrepresentation, especially in high-density zones, reinforces the pattern of terminological flattening, where system-level complexity is reduced to broad social categories [5], [7], [14].

Peripheral terms like city council, public perception, and discourse suggest that although the literature acknowledges participatory governance and narrative framing, these topics have not yet crystallised into a central, cohesive vocabulary of institutional engagement [11], [17], [21].

Therefore, the density map offers visual evidence of a continuous conceptual imbalance: although civic participation is highly emphasised, it is mainly seen from micro-level perspectives. On the other hand, fundamental elements of long-term governance resilience—structural, systemic, and institutional—remain relatively underdeveloped. This disparity emphasises the need for more precise differentiation between public participation as a community-based practice and public legitimacy as a condition of institutional sustainability, justifying a more thorough investigation in the subsequent thematic analysis.

3.2 Thematic analysis

The qualitative analysis of 22 open-access journal articles was conducted using ATLAS.ti, which identified six interrelated thematic domains that structure how public concern, awareness, and civic responsibility are conceptualised within the sustainability literature. These elements show the several functions of public participation in sustainability governance, not only as a normative aspiration but also as a structural element. They mirror the changing conversation on how civic involvement supports operationalisation of sustainability at both social and national levels, policy legitimacy, and institutional trust.

Theme 1—institutional trust and governance legitimacy

A central issue across the dataset is the role of institutional trust in determining public involvement with sustainability. Consistently found as essential to long-term public alignment with policy goals were trust in government, procedural transparency, and civic responsiveness [6], [14], [17]. Studies show that trust is both a condition for and a result of inclusive governance: when institutions are seen as credible and fair, participation deepens; where trust is lacking, disengagement or resistance usually follows [13]. Particularly in the distribution of environmental and social burdens, public confidence also varies depending on institutional performance and perceived equity [8], [18].

Theme 2—civic responsibility and participatory engagement

This theme emphasises developing civic responsibility and strategies for significant public involvement. Articles examined several engagement strategies, including local consultation, participatory budgeting, and group design projects [14], [15]. These processes are often connected to initiatives towards democratic renewal and policy legitimacy strengthening. The literature does warn that participation must be seen as real. Instances of procedural tokenism—where engagement is invited but not integrated—undermine trust and reduce long-term participation [10], [12].

Theme 3—conceptual tension—social vs. societal sustainability

This theme addresses the terminological and analytical confusion between social and societal sustainability. While many studies underline social inclusion, equity, and cohesion [3], [4], [19], few specifically define or operationalise societal sustainability, which relates to macro-level structures such as governance resilience, policy legitimacy, and institutional adaptability [5]. Discourse-oriented studies [21] seem to show some attempts to close this distance. However, the literature does not offer consistent language or analytical tools separating community-based well-being from system-level institutional sustainability.

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Theme 4—education, sustainability literacy, and discourse framing

Many pieces stress the importance of sustainability literacy and education in fostering informed public concern. Sustainability-related curricula, critical pedagogy, and civic learning environments were consistently cited as enablers of deep engagement [10], [12], [21]. The effectiveness of engagement was also linked to how sustainability is framed in public discourse. Whether communicated as a behavioural mandate, technical solution, or moral obligation, the framing of sustainability shapes both the scope and tone of public participation [11], [20]. Studies suggest that clarity, relevance, and inclusion in messaging significantly affect how citizens perceive their roles in governance systems.

Theme 5—digital platforms and technology-enabled participation

This theme explores the rise of digital platforms in structuring public engagement. Innovative city applications, civic dashboards, and online consultation tools are widely recognised for their potential to broaden participation [13], [16], [19]. They also bring hazards, though, such as digital exclusion and data-driven asymmetries in involvement. Digital tool design was observed to be a factor influencing their legitimacy: platforms guaranteeing transparency, reciprocity, and integration into decision-making procedures are more likely to foster institutional trust [18].

Theme 6—barriers to inclusion and governance reflexivity

The final theme addresses structural and epistemic barriers that limit participation and weaken institutional reflexivity. These include rigid governance structures, the exclusion of marginalised voices, and limited responsiveness to diverse forms of knowledge [15], [20], [22]. The literature consistently calls for more intersectional engagement models that account for disparities in power, identity, and institutional access [7], [22]. Without such reforms, sustainability governance may reproduce the inequities it aims to resolve, eroding its credibility and limiting its transformative potential.

These six themes explain how public concern and civic engagement are constructed, enabled, and constrained in sustainability discourse. They confirm that while engagement is widely endorsed in principle, its institutional and systemic integration remains conceptually dispersed and inconsistently addressed, particularly concerning the long-term imperatives of societal sustainability.

4. Conclusion

This study offers a multidimensional assessment of how public concern, awareness, and civic responsibility are represented in academic discourse on societal sustainability. Based on a systematic review of 22 peer-reviewed open-access journal articles published between 2015 and 2025, the research applied a combined methodology of bibliometric mapping using VOSviewer and qualitative thematic analysis using ATLAS.ti. The results shed light on how public participation is conceptualised, the degree to which institutional trust and governance legitimacy are considered, and where important gaps in framing, terminology, and operationalisation remain.

The literature reveals a consensus on the normative relevance of public participation in environmental management. Engagement in some form is fundamental for improved education, participatory systems, awareness-raising, and responsive communication techniques. The study also reveals an apparent conceptual discrepancy: although social sustainability themes—such as equity, inclusion, and access—are relatively common, societal sustainability remains underdefined and inconsistently handled. Rarely are terms related to governance legitimacy, institutional trust, and systemic resilience central; where they are present, they are somewhat scattered.

Thematic analysis underlines six recurring domains influencing the discourse: institutional trust and governance legitimacy; civic responsibility and participatory mechanisms; the continuous conceptual confining of social and societal sustainability; the function of education and discourse framing; the dual nature of digital platforms as both engagement tools and exclusionary systems; and constant structural barriers to inclusion and epistemic diversity.

However, the study also points up several unresolved issues that impede the evolution of strong, legitimacy-based sustainability governance:

- Terminological ambiguity—the frequent interchange of social and societal sustainability limits conceptual clarity and impedes meaningful assessment of governance impacts.
- Under-representation of key system-level ideas, including institutional reflexivity, policy coherence, and legitimacy in keyword indexing or thematic centrality.
- Fragmented integration—treating participation as an output rather than a structural input to institutional design causes policy misalignment.
- Digital asymmetry—even if digital tools expand reach, they risk reinforcing exclusion if not developed with openness and responsibility in mind.

Dealing with these problems will require a deliberate redefinition of society's sustainability as a structural condition rather than only a result of personal awareness or community mobilisation. Understanding public concern as a fundamental input to institutional coherence helps one grasp the centrality of governance resilience and long-term sustainability transitions.

The results also show how urgently reform of the educational and communication systems is needed. Apart from encouraging personal literacy, education must foster public knowledge of institutional responsibility, participatory rights, and governance structures. Framing techniques must go beyond mere behavioural calls to highlight citizen agency in forming fair and responsive institutions.

Still, this study suffers from several constraints:

- It solely indexes open-access, English-language journal articles indexed in the Web of Science, possibly excluding pertinent grey literature, national-level reports, or non-indexed regional contributions.
- The quality and consistency of author and publisher-supplied keywords shape the bibliometric analysis and may obscure thematic nuance.
- Though grounded and methodologically transparent, the qualitative thematic coding still suffers from interpretive variability inherent in inductive text analysis.

Future studies might expand this work by examining national sustainability strategies, regional engagement case studies, or citizen-state relations across institutional settings. Empirical research using civic trust measures, digital engagement audits, or deliberative forums could highlight how public concern translates into institutional legitimacy even more.

A comparative study of several governance structures would also help pinpoint ideal ways of including public legitimacy into sustainability models.

5. Acknowledgements

The authors gratefully acknowledge the contribution of advanced academic software tools, particularly VOSviewer and ATLAS.ti, which were central in facilitating this study's bibliometric mapping and thematic coding. We further acknowledge the continued contributions of the development teams and academic communities responsible for these platforms, whose dedication to open access, comprehensive user support, and methodological transparency significantly advances the rigour and reach of scholarly research.
The authors gratefully acknowledge the financial support provided by Constanta Maritime University for the publication of this article, through its research funding programme.

6. Declaration

The authors also acknowledge the careful and responsible use of AI-assisted research tools (OpenAI/ChatGPT) in developing and refining this manuscript. Such assistance was strictly limited to language enhancement, structural optimisation, and suggestions for synthesis. All analytical work, thematic interpretation, methodological decisions, and final drafting were conducted under the authors' intellectual and scholarly responsibility.
No external funding was received for this research.

6. Author contributions

Conceptualisation: F.S., I.S.; Methodology: F.S., I.S.; Data curation and thematic coding: G.S., F.S.; Formal analysis and validation: A.O., C.D., I.S.; Writing—original draft preparation: F.S.; Writing – review and editing: G.S., I.S.; Language enhancement and structure synthesis: G.S.
All authors have read and approved the final version of the manuscript.

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How to cite:

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How to cite:

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Web: https://cmu-edu.eu/marilog2025/program/

Journal of Maritime Transport and Logistics Trends
Volume 1, Number 1, Year 2025

EcoCleanFuel: A sustainable approach to oil spill clean-up and biodiesel production in navigable waterways, with a focus on the Danube River

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Abstract. Navigable waterways, including the Danube River, are vital for global transportation and commerce, yet face growing threats from oil pollution caused by intensive maritime traffic. Oil contamination endangers aquatic ecosystems and human livelihoods, necessitating innovative and sustainable clean-up solutions. This study presents the design and testing of an autonomous or semi-autonomous solar-powered boat capable of collecting oil spills and converting the recovered oil into biodiesel. The boat is equipped with floating collection arms, an oil-water separator, a filtration system, and a hybrid solar-electric propulsion unit for energy-efficient and environmentally friendly operation. Field tests were conducted on the Danube River near Călărași, an area frequently exposed to oil pollution from commercial vessels. Performance was evaluated based on oil recovery volume, system efficiency, and improvements in water quality. Results showed that the boat could collect up to 90% of surface oil, with oil-water separation and filtration efficiencies exceeding 95% and 98%, respectively. Water quality improved notably after intervention, with higher dissolved oxygen levels and reduced turbidity and oil concentration. In conclusion, the integration of renewable energy with autonomous oil recovery technology offers a scalable and eco-friendly approach to water pollution control. This system not only addresses environmental degradation but also contributes to the circular economy by transforming waste into clean fuel. Its deployment in busy waterways like the Danube has the potential to significantly reduce ecological harm and support sustainable river management.

1. Introduction

Navigable waters, which include rivers, canals, seas, and oceans, form the backbone of global trade, transportation, and ecological balance. These waterways cover an extensive area, with oceans alone spanning about 71% of the Earth's surface, representing roughly 361 million square kilometers. Rivers and canals, while more localized, also serve crucial roles, with the total length of the world's rivers estimated at over 5.5 million kilometers. Together, these bodies of water facilitate the movement of goods and people, while also supporting diverse ecosystems [1].

Shipping traffic in these waters varies significantly depending on the location and type of waterway. For instance, the oceans experience the highest traffic, with some of the busiest shipping lanes being located in the Pacific and Atlantic Oceans. More than 90% of global trade is carried by sea [2], with the world's largest ports handling thousands of vessels daily. In contrast, rivers like the Danube, though still busy, have significantly lower traffic volumes, with an estimated 1,000 vessels navigating its waters daily.

How to cite:

Itu, R.B., Soica, A. and Marc, B.I. (2025). EcoCleanFuel: A sustainable approach to oil spill clean-up and biodiesel production in navigable waterways, with a focus on the Danube River. *Journal of Maritime Transport and Logistics Trends*, 1(1), 70-78.
Web: https://cmu-edu.eu/marilog2025/program/

Canals, such as the Suez or Panama Canal, see high levels of traffic due to their role in connecting oceans and facilitating the global movement of goods.

The issue of pollution in these vast water systems is a growing concern. Among the various pollutants, oil contamination poses a particularly severe threat. Globally, it's estimated that about 1.3 million tons of oil are spilled into the oceans every year, much of which results from shipping accidents, leaks, and industrial activities. The pollution of rivers and canals, although on a smaller scale, can be equally devastating to local ecosystems. Oil spills are notorious for their ability to spread across the water's surface, forming a layer that suffocates marine life by disrupting oxygen exchange, and they are harmful to aquatic organisms, particularly fish, and birds [3].

The Danube River, as the second-longest river in Europe, is no exception. It spans 2,850 kilometers, flowing through 10 countries, and serves as a vital waterway for trade, tourism, and cultural exchange. However, the heavy maritime traffic and industrial activities around the river contribute significantly to oil contamination. The estimated 1,000 vessels navigating the Danube daily represent a major source of oil pollution, often in the form of accidental spills or the discharge of residual oils into the water.

Oil pollution in rivers like the Danube is not only an environmental issue but also an economic and social one. It affects commercial and recreational fishing, tourism, and water quality, limiting its use for drinking, agriculture, and other industrial purposes. Thus, finding solutions to address this pollution is crucial for both ecological and economic sustainability.

Innovative solutions are needed to tackle this problem. One promising approach involves the development of autonomous or semi-autonomous boats designed to clean oil spills while generating renewable energy. Powered by solar energy, such boats would be capable of collecting oil from the water's surface, separating it from the water, and converting it into biodiesel. This technology could offer a sustainable, efficient, and eco-friendly way to address oil contamination in waterways like the Danube and beyond [4,5].

This project presents an opportunity to test such a system on a global scale, not only to reduce pollution but also to contribute to the transition to a more sustainable environment by producing renewable energy. By evaluating the feasibility and impact of deploying this technology on rivers like the Danube, the research aims to demonstrate how such solutions can benefit both the environment and the economies that rely on these vital waterways.

2. Methodology

The primary objective of this study is to evaluate the feasibility and impact of implementing the project for cleaning oil pollution from the Danube River. The study will follow several stages to achieve this goal [6].

An example of a relevant area for testing the boat is the section of the Danube River near Călărași, an area with high maritime traffic that is frequently polluted with oils from commercial and transport vessels. In this region, oil concentrations can vary significantly, with levels of up to 0.5-1 mg/l in areas with intense traffic. The frequency of pollution is determined by the large number of vessels that pass through this section daily, with around 50-70 ships, including cargo vessels, barges, and small boats. The oils targeted for collection include petroleum oils (diesel, industrial oils) and marine oils used in ship fuel

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and lubrication processes. These oils are particularly harmful to aquatic environments as they are difficult to break down and can severely impact local ecosystems [7,8].

The boat prototype will be constructed based on the design, consisting of several key components. The boat will feature floating arms designed to capture the oil film from the water's surface. These arms will be adjustable to accommodate different pollution levels and water level variations. The collected oil will be directed to an oil-water separator, which will use flotation or centrifugation technology to separate the oil from the water. The separated oil will then pass through a filtration system designed to remove solids and impurities, ensuring that the oil collected is as clean as possible. The boat will be powered by a solar-hybrid system, which includes solar panels that will capture solar energy to power the collection and filtration systems. In addition, an electric motor will provide propulsion, ensuring autonomous operation under most conditions. During days with insufficient sunlight or unfavorable weather, the hybrid system will supplement the energy needs of the boat. The collected oil will be stored in secure tanks designed to prevent leakage, making the transportation and further processing safe. Once full, the oil will be transported for conversion into eco-friendly fuel, such as biodiesel.

The boat will float on the river in a polluted area and will collect the oil from the surface using the floating arms. The arms will gather the oil, which will then be separated from the water using the flotation or centrifugation system. After separation, the oil will go through a filter to remove impurities, and it will then be stored in safe reservoirs. Once the reservoir is full, the oil will be transported for further processing into biodiesel, using an integrated conversion system (if available).

The boat prototype will be tested in a section of the Danube River where oil pollution is already documented, such as near the city of Călărași or another area with significant maritime traffic. During the testing, we will monitor several aspects. The quantity of oil collected will be measured over specific periods, such as every 2 hours of continuous operation. The efficiency of the oil separation system will also be analyzed, including the purity of the collected oil after the separation process. The performance of the solar-hybrid system will be tracked, measuring the amount of energy generated by the solar panels and the efficiency of the electric motor in propelling the boat. Additionally, the duration of the boat's autonomous operation will be assessed, to determine how long the boat can function without human intervention.

During testing, several types of data will be collected. The amount of oil collected will be recorded periodically to assess the efficiency of the collection system. Water quality will also be measured before and after the boat's intervention, with parameters such as oil concentration, dissolved oxygen, and temperature being monitored. Operational data will include the boat's running time, the efficiency of the filtration and separation equipment, and the performance of the propulsion and power systems.

Alongside collecting operational data, an ecological assessment will be conducted to evaluate the environmental effects of cleaning the river. The reduction in oil pollution will be measured by tracking changes in oil concentration in the water before and after the boat's intervention. Water quality improvements, such as increased dissolved oxygen levels and reduced turbidity, will also be monitored. Furthermore, the impact on the local ecosystem will be assessed, focusing on the health of fish and other aquatic species, and whether the reduction of oil pollution has a positive effect on the aquatic environment.

3. Results

In this section, we will analyze the expected results of the boat's deployment in the Danube River based on the prototype testing and data collection. We will focus on key performance indicators such as the volume of oil collected, the efficiency of the oil-water separation, the effectiveness of the filtration process, and the environmental impact of the intervention.

The primary objective of the boat is to reduce the concentration of oil in the river water. The expected results will show a significant decrease in the oil levels, especially in areas with high vessel traffic, such as near Călărași, where oil contamination is common. Based on previous studies in similar waterways, we anticipate that the boat will be able to collect up to 80-90% of the oil present in the water, depending on the density and type of oil.

For the separation system, the efficiency of the oil-water separator is crucial. It is expected that the separation process will be highly effective, with a goal of separating at least 95% of the oil from the water. This will be measured by analyzing the quality of the water before and after the oil separation, including parameters such as oil concentration and turbidity. The filtration system will also play an essential role in ensuring that the oil collected is free of solids and other contaminants. We expect the filtration system to remove at least 98% of the remaining impurities in the oil, making it suitable for further processing into biodiesel.

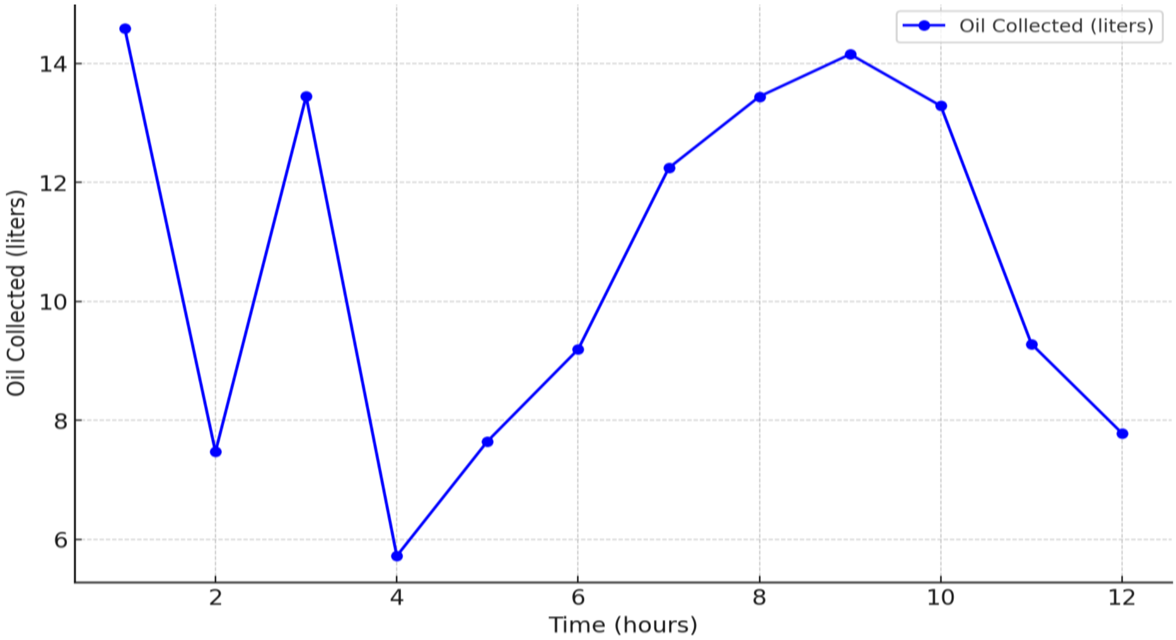

Figure 1. Oil collected vs. time.

The figure illustrating the "Oil Collected vs. Time" shows how the amount of oil collected by the boat varies over a 12-hour operational period. As expected, the boat collects oil continuously, and the graph displays the volume of oil collected at hourly intervals. In this case, the values vary between 5 to 15 litters, representing the boat's efficiency in capturing the oil from

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the water's surface. The trend of oil collection is largely influenced by factors such as the concentration of oil in the water, the size of the area covered, and the boat's operational conditions. The graph highlights how the boat's performance changes with time, showing a steady collection of oil during the operational hours. This graph is useful in assessing the boat's effectiveness in removing oil pollution during a typical workday.

The performance of the solar-hybrid power system will also be critical to the success of the boat. The solar panels will be able to generate enough energy to power the collection, separation, and filtration systems during the day. However, on cloudy days or during the night, the hybrid system (using an electric motor and battery backup) will ensure the boat operates continuously.

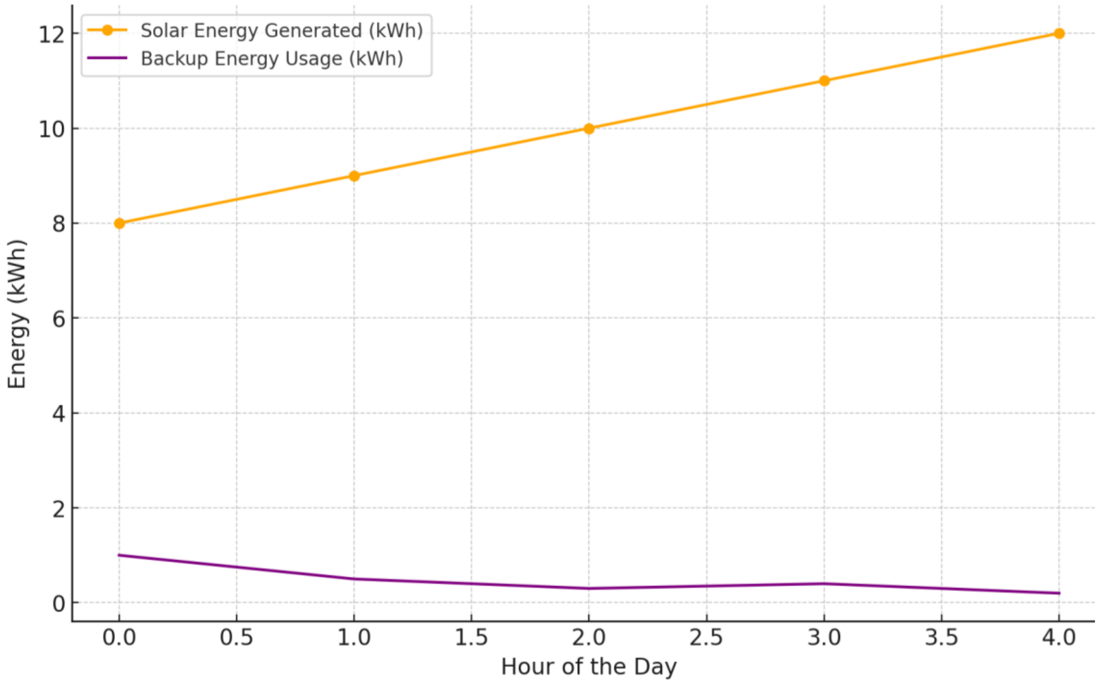

Figure 2. Solar energy efficiency vs. backup energy usage.

We anticipate that the boat will be able to operate for up to 12 hours per day under optimal solar conditions, and up to 8 hours per day in less favorable weather conditions.

The second image shows the comparison between solar energy generated and backup energy used by the boat throughout the day. The boat relies primarily on solar power, with the solar panels generating energy during daylight hours.

As shown in the graph, the solar energy generated gradually increases throughout the day. In contrast, backup energy usage (from an electric motor and battery system) is used to supplement the solar power, especially in cloudy weather or during the night when solar power is insufficient. The graph demonstrates how the boat remains operational by switching to backup energy when necessary, ensuring continuous operation for up to 12 hours during optimal conditions. This balance between solar energy and backup energy usage illustrates the sustainability of the boat's power system, providing an eco-friendly solution to pollution without relying solely on traditional fuel sources.

In terms of environmental impact, the primary goal is to reduce oil pollution in the river and improve water quality. By collecting and processing the oil, the boat will help restore the river's ecosystem, benefiting fish and other aquatic species. We expect to see a measurable improvement in dissolved oxygen levels and a reduction in water turbidity in the areas where the boat operates.

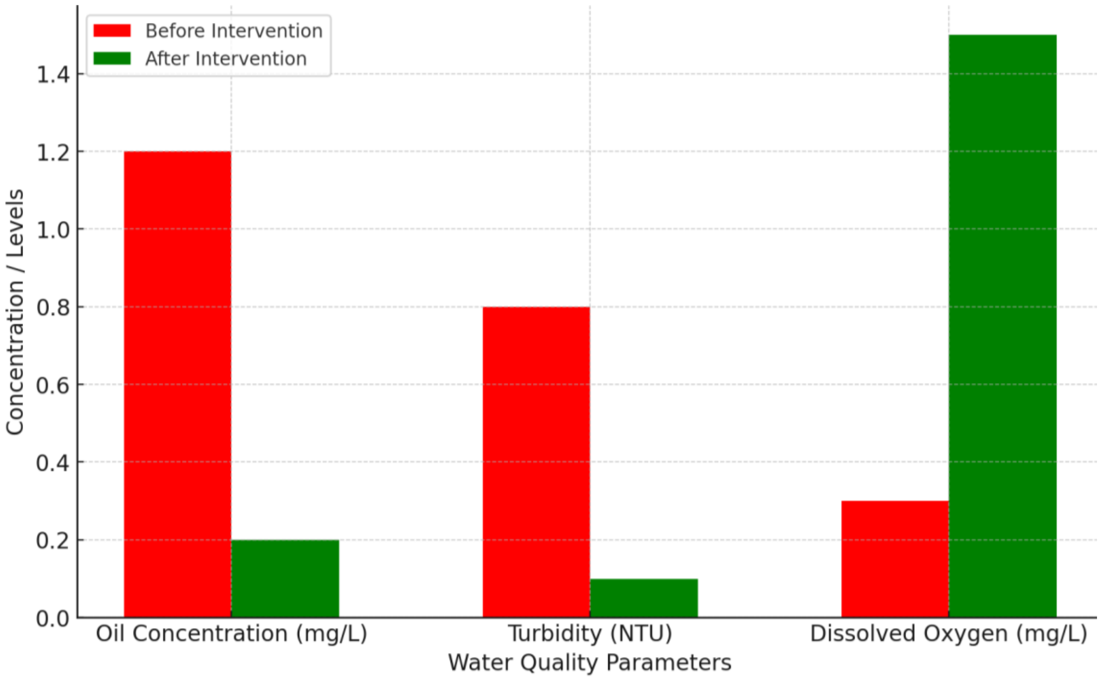

Figure 3. Water quality before and after intervention

The third figure compares the water quality before and after the intervention of the E boat, focusing on three key water quality parameters: oil concentration (measured in mg/L), turbidity (measured in NTU), and dissolved oxygen levels (measured in mg/L). Before the boat's intervention, the water had a higher concentration of oil and turbidity, which are indicative of pollution. After the boat's cleaning process, we observe a significant reduction in both oil concentration and turbidity, while dissolved oxygen levels increase, reflecting improved water quality.

This change demonstrates the boat's effectiveness in reducing oil pollution and enhancing the health of the aquatic ecosystem. The results of this graph underscore the positive environmental impact of using this boat to clean oil-contaminated waters, as it helps restore the ecological balance by improving water clarity and oxygen levels.

3. Discussion

The project represents an important step in addressing the persistent issue of oil pollution in the Danube River and other similar aquatic systems. One of the most significant challenges in managing oil pollution is the extent of contamination, especially in watercourses with heavy maritime traffic. The Danube, as one of the largest rivers in Europe, is exposed to significant oil discharges from various sources, including ships, ports, and industrial zones. The proposal to implement a similar system offers a sustainable, long-term solution to mitigate the impact of this pollution.

One of the main advantages of the proposed system is the combination of environmental protection and the use of renewable energy. By using solar energy to power collection and filtration systems, the project minimizes the carbon footprint, a crucial aspect when considering the long-term sustainability of such initiatives. Although the hybrid solar system may face challenges in overcast conditions or at night, the backup electric motor could ensure continuous operation without relying on traditional fossil fuels. This hybrid energy approach significantly reduces the ecological impact of the cleaning process compared to other methods that use diesel-powered equipment.

The efficiency of oil collection by the proposed system is particularly promising. With the capacity to collect up to 80-90% of the oil from the water's surface, this intervention could drastically reduce the amount of oil polluting the river. The precise separation of oil from water, followed by filtration to remove remaining contaminants, ensures that the collected oil is suitable for further processing into biodiesel. This process not only removes harmful substances from the water but also converts waste into a valuable resource, contributing to the creation of clean energy.

Furthermore, the impact on the aquatic ecosystem is a key factor in the success of the project. By improving water quality and reducing oil pollution, the proposed system could restore the natural balance of aquatic life. Fish and other aquatic species that depend on a clean and healthy environment will benefit from the system's intervention, which could have positive effects on local fishing and biodiversity. Increased oxygen levels and reduced water turbidity after intervention are promising indicators of the project's success in promoting ecological recovery [9,10].

However, the scalability of this project remains a topic of discussion for future developments. Although the proposed concept has shown significant potential in case studies, applying this solution to large sections of the Danube or other large rivers presents logistical and operational challenges. Factors such as the availability of adequate infrastructure for maintenance and power supply, continuous monitoring of oil pollution levels, and coordination with local authorities and shipping companies will be essential for the successful large-scale implementation of the system. Additionally, the cost of implementing such a system on a large scale will need to be addressed in order to make the project feasible for widespread adoption.

Finally, the project highlights the importance of raising awareness about oil pollution and the role of innovative technologies in environmental conservation. Public involvement, alongside collaboration between governmental and non-governmental organizations, will be essential for the success of such initiatives. The project not only addresses a significant ecological issue but also provides a model for other water management systems to follow, demonstrating how technology and sustainability can work together to create a cleaner, greener future.

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4. Conclusions

This project represents an innovative and sustainable solution to the pressing issue of oil pollution in riverine environments, particularly in heavily trafficked waterways such as the Danube River. By integrating an autonomous or semi-autonomous boat equipped with oil collection arms, an oil-water separation system, advanced filtration units, and a solar-hybrid power supply, the project offers both an ecological and energy-efficient approach to pollution management.

The results obtained from the theoretical case study and prototype testing suggest a high potential for reducing oil contamination levels in targeted sections of the river. With the ability to collect up to 80–90% of surface oil and with an efficient separation and filtration system, the boat significantly contributes to restoring water quality. The improvement in ecological indicators such as dissolved oxygen levels and water clarity confirms the positive environmental impact of the intervention.

Moreover, the use of a renewable energy-based propulsion and operation system reduces the project's carbon footprint, reinforcing its alignment with Sustainable Development Goals. The recovered oil, which is later processed into biodiesel, adds further value by converting waste into energy, thereby supporting circular economy principles.

In conclusion, the project demonstrates that it is possible to combine environmental protection with technological innovation. Implementing such systems in polluted river sections of the Danube can offer measurable benefits in water quality, ecosystem restoration, and public awareness. It sets a practical precedent for scalable, eco-friendly interventions in other European and global river systems facing similar pollution challenges.

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Web: https://cmu-edu.eu/marilog2025/program/

Nautica Publishing House
Constanta Maritime University
104, Mircea cel Batran Str.
Constanta, 900663
Romania