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Energy efficiency and decarbonization of maritime and offshore vessels: integration between design, operation and investment decision.

Energy efficiency and decarbonization of maritime and offshore vessels: integrating design, operations and investment decisions

Energy efficiency and decarbonization of maritime and marine ships: integrating design decisions, operations and investment

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SUMMARY

Decarbonizing maritime transport requires decisions that go beyond fuel substitution. This article analyzes the energy efficiency of maritime and offshore vessels as an integrated engineering, operational, and investment problem. The research adopts a qualitative and bibliographic-documentary approach, supported by the International Maritime Organization's 2023 Strategy for reducing greenhouse gas emissions, UNCTAD data, and recent studies on speed, route, trim optimization, hybrid systems, and alternative fuels. The analysis shows that operational and technical measures can produce significant gains, but their results depend on the mission profile, load curve, environmental conditions, energy availability, and asset lifecycle. In offshore vessels, particularly those with diesel-electric propulsion and dynamic positioning, the high power variability makes energy management especially sensitive to generator dispatch and storage. A decision framework is proposed that combines hydrodynamic performance, operational profile, safety, CAPEX, OPEX, emissions, and technological risk. It can be concluded that the low-carbon transition is more robust when energy efficiency, fuel choice, and investment strategy are evaluated together.

Keywords: naval engineering; energy efficiency; maritime decarbonization; offshore vessels; alternative fuels; energy management.

ABSTRACT

The decarbonization of maritime transport requires decisions that go beyond fuel substitution. This article examines vessel energy efficiency as an integrated engineering, operational and investment problem. The study adopts a qualitative bibliographic and documentary approach based on the International Maritime Organization's 2023 GHG Strategy, UNCTAD data and recent research on speed, routing, trim, hybrid power systems and alternative fuels. The analysis indicates that operational and technical measures can provide relevant gains, but their performance depends on mission profile, load curve, environmental conditions, energy availability and asset life cycle.

Offshore vessels, particularly diesel-electric units operating with dynamic positioning, present highly variable power demands and therefore require careful generator dispatch and energy-storage assessment. A decision structure combining hydrodynamic performance, operational profile, safety, CAPEX, OPEX, emissions and technology risk is proposed. The article concludes that low-carbon transition strategies are more robust when energy efficiency, fuel choice and investment decisions are assessed jointly.

Keywords: naval engineering; energy efficiency; maritime decarbonization; offshore vessels; alternative fuels; energy management.

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INTRODUCTION

Over 80% of the volume of international merchandise trade is transported by sea.
which makes the performance of the merchant fleet a relevant part of the global economic infrastructure.
(UNCTAD, 2025). At the same time, the sector faces a regulatory and technological transition that
requires a progressive reduction in emissions without compromising safety, availability and
competitiveness.

The IMO 2023 Strategy establishes, among other levels of ambition, a reduction of at least 40%.
of the carbon intensity of international maritime transport by 2030, compared to 2008,
and the pursuit of net-zero emissions by around 2050. The strategy also introduces checkpoints.
Guidelines for total annual greenhouse gas emissions: a reduction of at least 20%.
Aiming for 30% by 2030, and at least 70%, aiming for 80% by 2040 (IMO, 2023).

These goals increase the pressure on design and operational decisions. A vessel built
Today it could remain in service for decades, weathering regulatory and price changes.
energy and supply infrastructure. The choice of propulsion is therefore no longer just a matter of...
An initial performance decision then becomes one that involves exposure to technological and regulatory risk.

Offshore vessels add complexity to the problem. Platform Supply Vessels, Anchor
Handling Tug Supply vessels and specialized units can alternate transit, waiting, and operation in
Dynamic positioning and demand peaks. This variability means that efficiency is not...
It depends not only on the specific fuel consumption of an engine at a nominal point, but also on its behavior.
of the system throughout the mission.

The objective of this article is to analyze how energy efficiency measures, hybrid systems,
Operational optimization and alternative fuels can be integrated into a decision of
economically sound engineering. The focus is not on indicating a universally applicable technology.
superior, but identify variables that need to be evaluated together.

Figure 1. Checkpoints indicating reductions in total annual GHG emissions from transport.
International maritime traffic in relation to 2008. Source: author's elaboration based on IMO (2023).

2 METHODOLOGY

The research is qualitative, exploratory, and bibliographic-documentary. Priority was given to sources...
Institutional and technical documents published up to July 2025, including the IMO 2023 Strategy, literature
Academic research on energy efficiency and hybrid systems and the US Department of Energy roadmap

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on the operation and maintenance of offshore wind assets. The literature on decarbonization and
The term "alternative fuels" is used as documentary support for the sector, and not as...
evidence of the author's specific professional experience in these areas.
The IMO 2023 Strategy is used as a regulatory benchmark for decarbonization targets.
The context of integrity and offshore asset management, the US Department of Energy roadmap.
(2024) is used to address reliability, maintenance, inspection, costs, risks, digitization,
safety and performance. Although the document focuses on offshore wind, its principles of
O&M and asset integrity offer a transferable technical reference for systems analysis.
offshore. Academic studies were selected for their direct relationship with engineering variables.
such as speed, trim, route, power dispatch, and energy storage.
For offshore vessels, the work of Lindstad, Eskeland and Rialland (2017) is considered.
about batteries in offshore support vessels, and a study published in Applied Energy in 2024 about
Optimizing dispatch and storage systems on Platform Supply Vessels using real data.
These studies are not generalized to the entire fleet, but are used to demonstrate mechanisms.
relevant technical aspects.

The analysis of alternative fuels is presented as a review of technical and regulatory literature.
Available until July 2025, with emphasis on the IMO 2023 Strategy and sectoral sources prior to that.
adopted time limit. These sources are used to map maturity, security requirements,
infrastructure and technological uncertainty, without attributing specific professional experience to the author in
development or implementation of alternative fuels.
The results are organized into four dimensions: hydrodynamic and operational efficiency,
Energy architecture, fuel and infrastructure, and economic and financial viability. Integration.
These dimensions underpin the proposed decision-making structure.

3. EFFICIENCY BEFORE FUEL REPLACEMENT

Decarbonization can be discussed from two complementary perspectives: reducing the energy required.
to execute a mission and reduce the intensity of emissions from the energy consumed. The first
Front-end includes speed, route, trim, hull and propeller condition, power management, and planning.
The first involves operational technology. The second involves fuels, electrification, and new propulsion architectures.
Treating fuel as the sole variable can shift the focus of the problem. A fuel with less fuel...
Carbon intensity does not eliminate hydrodynamic losses, inefficient engine operation, or
Inadequate sizing. The lower the vessel's energy demand, the lower it tends to be.
to be the amount of fuel or alternative energy needed to perform the same function.

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Recent studies show the potential for operational optimization. Luo, Yan and Wang (2024)
They developed a model for optimizing speed under dynamic weather conditions and
They reported a 7.34% reduction in consumption compared to a static speed model.
The result is specific to the ship and the conditions studied, but it demonstrates the importance of integrating...
Meteorology plays a role in operational decision-making.

In another approach, Li et al. (2024) combined route, speed, and trim in a model of
Optimization for energy efficiency and reported reductions of up to 4.54% in consumption in the scenario.
analyzed. Studies on trim optimization using CFDs and neural networks already show how tools
Computational systems can convert complex hydrodynamic analyses into operational support.
(ALVAREZ et al., 2024).

These results should not be added together or treated as guaranteed savings. Each study has its own...
Ship, route, conditions, and specific assumptions. The common point is measurable operational efficiency.
It can be obtained before or in parallel with the fuel change.

4. The Mission Profile of Offshore Vessels

In offshore vessels, the load curve is often marked by strong variability. Operations
transit, approach, dynamic positioning, cargo handling and waiting impose
Different demands. Systems designed to safely respond to peak loads can operate
during extended periods under partial loads.

Lindstad, Eskeland and Rialland (2017) observed that offshore support vessels utilize multiple
Advanced engines and dynamic positioning systems to maintain reliability in different
Sea states. The study highlights that operating multiple engines at low load can increase
local emissions and reduced combustion efficiency.

This characteristic explains the interest in hybrid systems. Storage can absorb
Rapid variations allow for the operation of fewer generator sets in more efficient ranges.
and provide power reserve. The potential advantage, however, depends on the actual load profile and the
System sizing.

A 2024 study in Applied Energy, based on real data from a Platform Supply Vessel.
diesel-electric, concluded that optimizing power dispatch can reduce fuel consumption and CO2 emissions, and
that integrating batteries can produce additional gains. The study also observed effects
distinct factors regarding pollutants, reinforcing that environmental performance should not be reduced to a single factor.
variable.

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For engineering, the consequence is methodological: decisions about batteries or generation should not
Based solely on installed power. Time series of load, duration of operating modes,
Redundancy and transient requirements are key information for evaluating the architecture.

5. SPEED, ROUTE, TRIM AND ENVIRONMENTAL CONDITIONS

Resistance to forward motion and required power vary with speed, displacement, trim, and conditions.
Hull, waves, wind, and current. Therefore, operational efficiency requires a connection between hydrodynamics.
and travel planning.
Weather routing can seek shorter travel times, shorter distances, lower fuel consumption, or a combination of these.
objectives. Palma, Giglio and Tei (2024) highlight the potential of weather routing and discuss
How e-navigation and S-100 standards can improve the information used in route calculation.
Speed optimization is equally sensitive to dynamic conditions. Models that ignore
Weather variations can yield different profiles than those obtained when wind and waves are the only factor.
are incorporated. The work of Luo, Yan and Wang (2024) illustrates this difference by comparing
Dynamic and static optimization.
Trim is another engineering variable with operational potential. Optimization studies
The combined data on route, speed, and trim show that computational models can support decisions.
efficiency, provided that its results remain linked to the ship, the data and the conditions for
which were developed. Li et al. (2024), for example, reported fuel savings of
up to 4.54% in the case study analyzed, without this percentage being automatically transferable.
to other vessels.
These measures have a strategic characteristic: many can be applied without waiting for...
maturity of a new fuel. They also reduce the energy that future low-energy solutions require.
They will need to supply carbon.

6. Hybrid Systems and Energy Storage

Hybrid systems combine energy sources with distinct characteristics. In diesel-powered vessels-
Electrical batteries can be used for peak shaving, spinning reserve, transient support, and optimization.
from the charging of the generators. The benefit does not stem from the presence of the battery itself, but from how
It alters the operation of the set.

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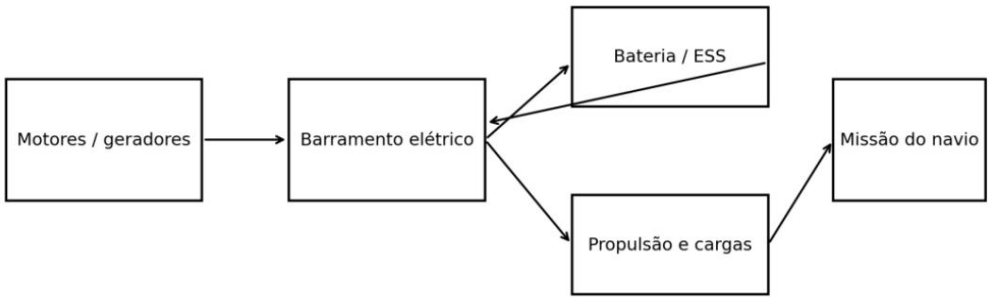

Figure 2. Conceptual architecture of a diesel-electric hybrid system with energy storage.
energy. Source: author's elaboration based on Lindstad, Eskeland and Rialland (2017) and the study
PSV published in Applied Energy (2024).

The study by Lindstad, Eskeland and Rialland (2017) concluded that the combination of batteries and motors
Recycling in offshore support vessels could reduce local pollution and climate impact.
The conditions analyzed. In that economic context, the authors found greater attractiveness for
new vessels rather than retrofitting.
This historical conclusion needs to be interpreted with caution because of the costs of batteries, fuel,
Regulations and technology change. However, it remains relevant by demonstrating that retrofitting and
Newbuild projects have different economics and should not be evaluated using the same logic.
In new projects, integration can begin with the overall layout, electrical distribution, cooling,
Fire protection, weight, and stability. In retrofitting, space, existing interfaces, and limitations are considered.
Structural factors and the remaining lifespan of the asset may limit the solution.
Economic analysis should therefore incorporate not only fuel economy, but also CAPEX.
Maintenance, component replacement, downtime, impact on operational capacity.
and any residual value.

7 Alternative Fuels and Technological Uncertainty

The maritime energy transition does not present a single consolidated route. LNG, biofuels,
Methanol, ammonia, hydrogen, electrification, and hybrid combinations have different levels of
maturity, infrastructure, energy density, storage requirements, and emissions profile.
The IMO 2023 Strategy recognizes that scaling up technologies, fuels and energy sources
having zero or near-zero GHG emissions will be an integral part of meeting the targets of

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sector. The document establishes as a level of ambition that these solutions represent at least 5%, aiming for 10%, of the energy used by international maritime transport by 2030 (IMO, 2023).

This regulatory guideline does not, however, eliminate differences in maturity, availability, cost, and infrastructure among alternatives.

For emerging fuels, the technical assessment needs to consider specific hazards and requirements. of storage, material compatibility, infrastructure and energy source. The IMO itself It determines that the climate assessment should consider well-to-wake emissions, preventing the reduction in one stage of the chain simply shifts emissions to another (IMO, 2023).

Alternatives with a longer operational track record may offer infrastructure advantages and Availability in certain markets, but this does not eliminate the need to assess emissions. throughout the lifecycle, safety, convertibility, and regulatory exposure. The central point of this This section compares decision variables described in the literature, and does not present practical experience of... author with a specific fuel.

Therefore, fuel readiness shouldn't just mean reserved space for a future tank. A robust strategy examines convertibility, material compatibility, safety, Regional availability, price, regulation, and impact on vessel layout.

8 Life Cycle Economics and Investment Decision

The technological choice needs to be connected to the economic life cycle of the asset. CAPEX plus High costs can be rational when they reduce operating expenses or regulatory exposure over years of operation. Similarly, a technically efficient solution may not pay for itself in an asset close to the market value. end of its economic life.

Net present value, total cost of ownership, and scenario analysis are suitable tools. to compare alternatives. The challenge lies in the assumptions: fuel price, annual usage, Carbon costs, infrastructure availability, and residual value can vary significantly. In an environment of uncertainty, a single central projection can mask risk. Conservative scenarios, Base and accelerated versions allow testing of fuel sensitivity, regulatory compliance, and usage. Long-lasting maritime assets and technological flexibility can have economic value even when it doesn't appear directly in the instantaneous efficiency.

Project management also affects the outcome. Late integration of fuel requirements, Safety or electrical systems tend to increase rework and interfaces. Engineering decisions These decisions must be made with governance of scope, risk, and change that is compatible with the complexity of the situation. project.

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The financial perspective, therefore, is not a step that comes after engineering. It helps to select which gains...
The technicians have sufficient value to justify the investment.

9. An Integrated Framework for Decision-Making

Based on the literature reviewed, the decision can be organized into six questions. First, what
What mission does the vessel need to accomplish? Second, what is the actual energy profile of this mission?
Third, what losses can be reduced by operational or hydrodynamic measures? Fourth,
Which generation and storage architecture best follows the load curve? Fifth, which
Are these fuels technically and logistically feasible? Sixth, which alternative best preserves the environment?
What is its economic value under different scenarios?

Order is important. Starting with fuel before understanding energy demand can...
To produce oversizing or choices incompatible with the operating profile. Start by
Capital expenditure alone can eliminate solutions that offer a better total cost.
Safety remains a cross-cutting issue. New fuels introduce specific hazards, while
Batteries alter protection and emergency response requirements. No emissions gains justify the change.
reduction in the level of security.
The structure should also be iterative. A change in operational route can alter the...
Fuel availability; new regulations could change the cost of a retrofit; data
Actual consumption figures can reveal optimization opportunities that were not visible in the design phase.
This approach does not produce a universal answer. Its value lies in reducing fragmented decisions.
and to make explicit the dependencies between engineering, operations, and finance.

10 DISCUSSION

Recent literature converges on one point: maritime efficiency is a multivariable problem. Studies
Speed, route, and trim measurements demonstrate gains in specific cases; research with PSVs shows that...
Dispatch and storage paper; technical documents on fuels show
different maturity levels and barriers.

A distinction also emerges between efficiency and decarbonization. The former is directly connected
the engineering, operation, reliability, and asset performance decisions; the second expands the
Analysis for a regulatory and technological field in transformation. This article discusses
Alternative fuels serves as a technical and documentary context for design decisions and
investment, without presupposing specific professional activity on the part of the author in the implementation of these solutions.

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A vessel can become more efficient without changing fuel, reducing emissions by...
service unit. It can also switch to lower carbon-intensive energy without correction.
Operational inefficiencies. The most robust strategy combines both approaches.
For the offshore segment, load variability and the need for reliability make this...
Integration is especially relevant. The assessment should consider modes of operation, requirements,
Positioning, reserve, dynamic response, and safety.
IMO checkpoints underscore the importance of decisions made in the present.
The vessel, ordered in the mid-2020s, could operate during the milestones of 2030 and
2040. This transforms regulatory risk into a design variable.
However, there are important limitations. Percentage savings results found in studies do not
They must be transported directly to other vessels. Validity depends on data, model,
Route, environmental conditions, and architecture. Case studies should guide hypotheses, not promises of...
performance.
The main implication is the need for data-driven engineering and life cycle analysis.
Measuring before investing, validating models, and testing scenarios are practices that reduce the risk of decisions.
Technically attractive, but economically fragile.

CONCLUSION

Maritime decarbonization cannot be reduced to choosing a new fuel. It begins
by understanding how much energy the vessel needs to accomplish its mission and why that is necessary.
Energy is consumed.
Operational measures such as speed, route, and trim optimization demonstrate potential for reduction.
consumption figures have been released in recent studies, but the percentages are specific to each case and do not constitute a definitive answer.
Performance guarantee.
In offshore vessels, the variable load curve makes power dispatch and storage a priority.
particularly relevant. Studies with offshore support vessels show that hybrid systems
They can reduce fuel consumption and emissions when properly sized and operated.
The choice between newbuild and retrofit requires different economic considerations. Space, integration, life.
Remaining costs and downtime can affect the attractiveness of a solution.
Alternative fuels add another layer of uncertainty. Maturity of onboard technology.
This does not mean the availability of low-carbon fuel, and exhaust performance does not.
It replaces life cycle analysis.

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The IMO 2023 Strategy makes this discussion temporally concrete by setting ambitions for 2030, 2040, and approximately 2050. Long-lived assets need to be valued against this. horizon.

The integration between engineering and finance is therefore necessary. CAPEX, OPEX, availability, Maintenance, regulatory risk, and flexibility need to be assessed along with consumption and emissions. Project management is also part of efficiency. Safety, fuel, and architectural requirements. Energy management systems need to be implemented early in development to avoid late interfaces and rework.

The structure proposed in this article organizes the decision based on the mission, energy demand, and... Opportunities for efficiency, power architecture, fuel, and economic analysis. She It is a conceptual synthesis, not a predictive model.

Future research could further explore the integration between operational data, hydrodynamic models, Weather forecasting and dispatch optimization for offshore vessels, with validation in different mission profiles.

Life cycle studies that incorporate future energy prices and emissions are also needed. Upstream and regulatory changes should be considered, avoiding conclusions based solely on onboard performance.

It is concluded that the low-carbon maritime transition will be more consistent when efficiency is improved. Energy should be treated as a continuous discipline of design and operation, and not as an isolated response to a regulatory goal.

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