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INVESTMENT AND ECONOMIC ASPECTS OF THE TRANSITION OF MARITIME TRANSPORT TO LOW-CARBON TECHNOLOGIES

Abstract. *The article discusses the investment and economic aspects of transitioning maritime transport to low-carbon technologies within the framework of global climate initiatives and the evolving regulatory environment. It analyzes the costs associated with fleet modernization, financing mechanisms for environmental solutions, and the impact of the CII indicator and carbon taxation on maritime transportation expenses. An investment model is presented that considers operational savings, emission reductions, and the payback period. Scenario modeling shows that adopting a slow sailing strategy, combined with technical measures, can lower the total voyage cost while also reducing the carbon footprint. Key implementation risks, such as high CAPEX, insufficient infrastructure, and technological uncertainty, are identified, and policy and financial recommendations are provided to encourage the green transformation of the maritime sector. These results can contribute to developing a national strategy for decarbonizing shipping and advancing green logistics.*

Keywords: *shipping, low-carbon technologies, maritime transport, decarbonization, CO_2 emissions, energy efficiency, slow motion, investment model, ESG, carbon pricing, green logistics, foreign economic activity, port infrastructure, cargo transportation.*

Relevance. In the context of global climate challenges and the intensification of the green transformation of the transport sector, shipping is becoming one of the key elements of the decarbonization of international logistics. The introduction of the Carbon Intensity Indicator (CII), the expansion of IMO requirements, and growing investor expectations regarding ESG indicators are shaping a new paradigm for maritime carriers. At the same time, the transition to low-carbon technologies is a technical upgrade and a comprehensive economic transformation that includes investments, operating costs, regulatory risks, price competition, and financial sustainability of market players. These aspects require in-depth analysis in the Ukrainian and international context.

Literature review. Recent research in the field of maritime transport decarbonization covers a wide range of aspects, from strategic planning and policy to technical implementation and socio-economic impacts. Sources [1, 10, 17] highlight systemic approaches to the transition, emphasizing the importance of national and global strategies, overcoming carbon lock-in, and addressing hard-to-decarbonize transport segments. Modeling of energy scenarios, including island systems and analysis of climate policies, is presented in detail in [2, 3, 8], where optimization models are proposed and climate instruments are evaluated.

The technical aspects of the transition are discussed in [7, 9, 11, 14], which analyze the characteristics of alternative fuels (LNG, methanol, ammonia, HVO) and their impact on emissions and the economy. Sources [4, 6, 16] focus on selecting environmental solutions based on multi-criteria optimization and address barriers to implementation. The issues of market instruments, particularly ETS, carbon pricing, just transition, and carbon revenues, are analyzed in [5, 12, 13, 15].

Ukrainian researchers' works [17, 18] stand out distinctly. They are applied in nature and focus on implementing environmental solutions at the level of machinery and marine fuels under real operating conditions.

Problem statement. Despite the growing pressure from international environmental initiatives, financial markets and regulators, the process of transition of maritime transport to low-carbon technologies remains uneven, fragmented and economically controversial. Most shipping companies face a lack of clear investment mechanisms, long-term access to green capital, and risks of losing competitiveness in the face of increasing regulatory pressure (e.g., due to the introduction of CII, ETS, FuelEU Maritime). At the same time, market incentives for switching to alternative fuels, new energy installations, or digital monitoring remain weak or unpredictable. There is a significant lack of evidence-based approaches to assessing the cost-effectiveness and investment feasibility of low-carbon solutions in the maritime sector, particularly in the face of growing risks and uncertainty. The challenge is to develop a coherent economic model of the transition that considers the costs, benefits, risks, and systemic constraints of infrastructure, public policy, and the capital market.

Research objective. To assess the economic impacts and investment needs of the transition of maritime transport to low-carbon technologies, considering global environmental trends, regulatory challenges, and financial instruments for decarbonization.

Statistical aspects of global decarbonization of maritime transport. Maritime transport generates a significant amount of CO_2 emissions every year. According to the OECD and IEA, in 2022, international shipping emitted about 858 million tons of CO_2, which is higher than the level of aviation OECD, 2023 IEA, 2023. The breakdown of emissions by ship type (Fig. 1) shows that tankers (28.55%), dry bulk carriers (27.52%), and container ships (24.03%) account for the largest share of pollution.

At the same time, according to Statista, the global shipping industry consumed 8.7 exajoules of energy in 2021, mainly from fossil fuels. Forecasts until 2050 (Fig. 2) show a gradual decline in the share of oil to 50%, with an increase in the use of ammonia (15%), LNG (20%) and biofuels (10%) Statista, 2024.

The presented statistics show that maritime transport remains one of the largest sources of greenhouse gas emissions in global logistics. The largest contribution to total CO_2 emissions comes from tankers, dry bulk carriers, and container ships, due to their scale of

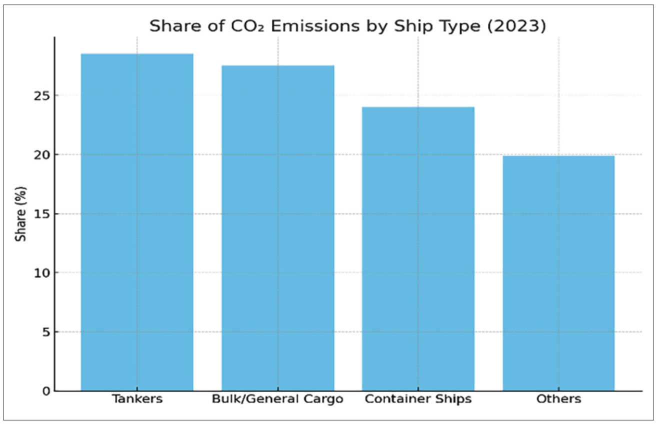

Figure 1. Share of CO_2 emissions by vessel type (2023)

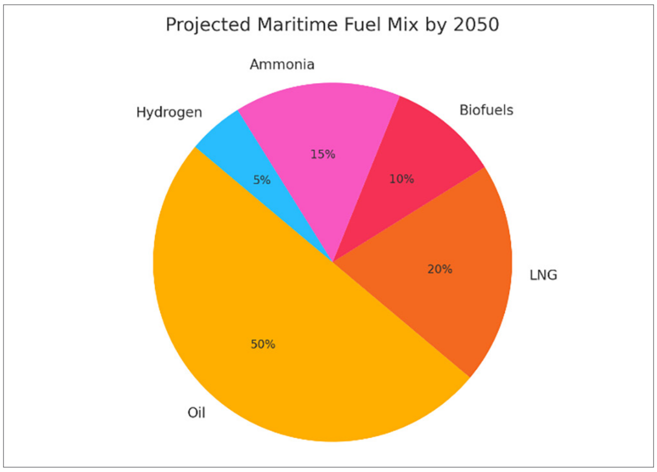

Figure 2. Projected structure of fuel use in maritime transport by 2050

transportation and energy intensity. At the same time, the sector's energy intensity is gradually decreasing, and there is growing interest in the introduction of alternative fuels such as LNG, biofuels, ammonia, and hydrogen. Forecasts to 2050 show a change in the fuel mix, in which fossil fuels, while still dominant, will be complemented by low-carbon solutions. This creates both opportunities and challenges — related to the need for large-scale infrastructure modernization, development of fuel production chains and adaptation of regulatory policies to the new energy reality of maritime transport.

Theoretical and methodological basis of the study. The transition of maritime transport to low-carbon technologies is part of a broader paradigm of decarbonization of the global economy, which the Paris Agreement is shaping, European Union strategies (Green Deal, Fit for 55), initiatives of the International Maritime Organization (IMO), and the green finance market. As part of this transition, key concepts include carbon pricing, emissions externalities, ESG criteria, and institutional support for innovation.

One of the central elements is the carbon pricing system, which, through the CII (Carbon Intensity Indicator), SEEMP, and mechanisms such as the EU ETS, puts financial pressure on ship owners with high emissions. This transforms the cost structure of enterprises and stimulates investment in energy-efficient solutions. The decarbonization economy considers such investments to be long-term, with the effect of strategic protection against future regulatory threats.

From a methodological point of view, the study is based on the principles of institutional economics (analysis of the role of regulators, norms, and incentives), innovation economics (assessment of the impact of technological progress), and applied financial analytics (cost-benefit modeling, sensitivity analysis, NPV/IRR). Basic tools for assessing investment attractiveness are used: calculation of net present value (NPV), internal rate of return (IRR), payback period, and scenario and sensitivity analysis to assess the uncertainty of the regulatory environment, fuel prices and the pace of technological change.

The impact of ESG indicators (environmental, social responsibility, corporate governance) on access to capital is also considered, as shipping companies are increasingly being evaluated according to sustainability criteria. Accordingly, the low-carbon transition is viewed not only as a technical modernization but also as a strategic investment in companies' competitiveness in the context of global logistics transformation.

Investment model for the transition to low-carbon technologies. The transition to low-carbon technologies in maritime transport involves complex investment decisions that encompass both modernizing the technical base and adapting operational strategies. The primary elements of the investment process are initial capital expenditures (CAPEX), anticipated operating savings (OPEX savings), payback period, and the potential to reduce greenhouse gas emissions. This section evaluates the effectiveness of the key technological solutions that shipping companies can implement as part of their decarbonization strategy.

Table 1 presents a selection of essential technologies with potential for reducing carbon footprints, along with their basic investment parameters, cost savings, and environmental impact.

As can be seen from the table, the most capital-intensive option is the conversion of the engine to a dual-fuel mode using LNG (CAPEX — $8.5 million), but also the highest level of emission reduction — up to 22 thousand tons of CO_2 per year. At the same time, the slow-running strategy requires minimal investment ($0.6 million), demonstrates the fastest payback period (0.75 years) and allows for significant emission reductions (15 thousand tons/year), making it extremely attractive in the short and medium term. Other technologies, such as air cushion, hull grinding, or shore power, have moderate investment attractiveness parameters and require a developed infrastructure.

To comprehensively assess the feasibility of implementing such solutions, an integrated environmental and economic efficiency coefficient is used:

$$E_{\text{eco}} = \frac{B_{\text{OPEX}} + \theta \cdot B_{\text{CO}_2}}{\text{CAPEX}}, \tag{1}$$

where: B_{OPEX} — is the annual savings in operating costs; B_{CO_2} — is the annual emission reduction converted to a value equivalent (e.g. €85/ton in the ETS system); θ — carbon value coefficient (depending on the region's policy); *CAPEX* — the amount of initial investment.

The proposed model allows for a comparative analysis of alternatives, taking into account not only the payback period but also the environmental effect integrated

Table 1

Low-carbon maritime technology investments

Technology	Initial CAPEX (USD million)	Expected OPEX savings per year (USD million)	Payback period (years)	CO_2 reduction potential (tons/year)
Dual-fuel LNG engine retrofit	8.5	1.7	5.00	22000
Installation of air lubrication system	2.2	0.5	4.40	8000
Slow steaming strategy implementation	0.6	0.8	0.75	15000
Hull cleaning & coating optimization	0.9	0.3	3.00	5000
Onshore power supply integration	3.0	0.6	5.00	12000

into the financial assessment. This is becoming increasingly important in the context of the transition to the ESG paradigm and sustainable investments.

Case study: The economics of a low-carbon voyage. To illustrate the practical implications of implementing low-carbon measures in maritime shipping, we have conducted a scenario modeling of the cost of a voyage in two variants: a traditional voyage (baseline scenario) and a green voyage with elements of slow running, the use of energy-saving technologies (ESD) and connection to onshore power supply in the port (OPS). Both scenarios assume a fixed route with the same cargo and tariff. The results are shown in Table 2.

The results indicate that, despite the extension of the voyage duration from 7 to 9 days, implementing low-carbon solutions allows for a 17.9% reduction in total costs (from $155,400 to $127,550). This was achieved by lowering fuel consumption by 25% and decreasing CO_2 emissions by 330 tons, which corresponds to $28,050 in carbon tax savings (calculated at €85/ton of CO_2, reflecting the average level in the EU ETS system).

The overall economy of the flight improves even with a slight increase in operating costs (+$500) due to the extended duration. This confirms the effectiveness of slow sailing in conjunction with technical measures as a strategy to simultaneously reduce costs and emissions.

Thus, the scenario analysis illustrates the financial feasibility of green transformation even in the short term, provided there is a regulatory incentive (carbon tax) and support for energy infrastructure in ports.

Risks and barriers to the implementation of low-carbon technologies. Despite the growing relevance of decarbonizing maritime transport, the adoption of low-carbon technologies faces several systemic barriers that impede the large-scale implementation of environmentally efficient solutions. These barriers are both technological, economic and institutional in nature.

1. High initial CAPEX. One of the main obstacles is the high cost of modernizing ships (dual-fuel engines, emission treatment systems, digital monitoring, etc.) In most cases, the payback period exceeds 5 years, which does not correspond to small and medium-sized operators' average financial planning horizon. Access to cheap loans or green financing is limited.

2. Infrastructure constraints. The lack of developed coastal infrastructure (shore power, LNG refueling stations, hydrogen terminals) in many ports limits the ability to effectively use new technologies, even in the case of fleet modernization. This is especially true for developing countries and transit ports.

3. Technological uncertainty. The rapid evolution of IMO standards, the emergence of alternative fuels (ammonium, hydrogen, methanol), and the still unstable regulatory environment lead to a wait-and-see effect: operators postpone investments for fear of obsolescence of already installed solutions.

4. Risks of regulatory fragmentation. There are discrepancies between global IMO requirements and regional systems (EU ETS, FuelEU Maritime). This creates asymmetries in costs and competitiveness between shipping companies operating in different jurisdictions.

5. Shortage of qualified personnel and digital competence. The implementation of most low-carbon technologies requires new competencies of the crew, technical staff and operators — from energy management to working with LNG or hydrogen systems.

Thus, the transition to sustainable maritime transport requires coordinated efforts by the state, the private sector and international organizations, covering not only financing but also standardization, infrastructure development and educational support.

The introduction of low-carbon technologies in maritime transport is a systemic transformation that involves significant costs, changes in business models, and adaptation to new technical and regulatory conditions. For a comprehensive understanding of the problem areas, we propose a framework (Figure 1) that categorizes the main challenges into five key groups: financial barriers, infrastructure constraints, technological uncertainty, human resource gaps, and the need for coordinated policies.

As can be seen from the figure, the central barrier is the high initial CAPEX cost, exacerbated by limited access to green finance, long payback periods and high fleet modernization costs. Infrastructure constraints are particularly critical in developing countries with no LNG/hydrogen terminals or onshore power sources. Technological uncertainty is associated with the emergence of new fuels, rapid changes in IMO requirements, and the risk of obsolescence of implemented solutions. The lack of digital and energy management skills among crew and technicians makes it challenging to integrate modern systems, especially in the LNG and H_2 equipment field. Ultimately, fragmented regulations lead to cost disparities and legal ambiguity, diminishing shipowners' investment incentives.

Table 2

Comparison of flight costs in traditional and low-carbon scenarios

Parameter	Traditional voyage	Low-carbon voyage
Voyage duration (days)	7	9
Fuel consumption (tons)	420	315
Fuel cost (USD)	25,200	18,900
CO_2 emissions (tons)	1320	990
Operational cost (USD)	18,000	18,500
Emission tax (€85/t CO_2)	112,200	84,150
Total voyage cost (USD)	**155,400**	**127,550**

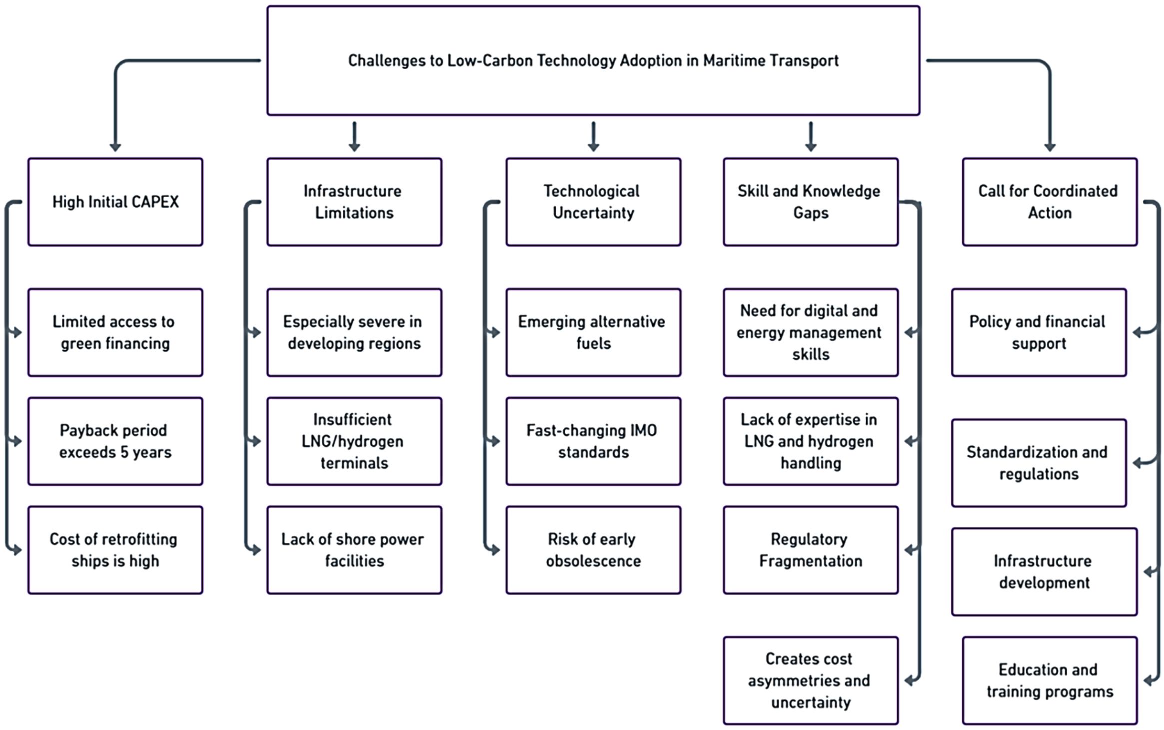

Figure 2. Key challenges to implementing low-carbon technologies in maritime transport

In view of this, implementing low-carbon solutions requires coordinated actions between the state, businesses, and international organizations, including political and financial support, infrastructure development, standardization, and the creation of educational programs. Only if these barriers are removed can the green transformation of maritime transport become systemic and effective.

Policy and management recommendations. Successful implementation of the maritime transport transition to low-carbon technologies requires a systematic, multi-level policy that covers not only financing and regulation, but also infrastructure modernization, training and innovation. This section presents specific recommendations for government policy makers, investors, and industry players, organized into five key areas (Table 3).

First of all, Ukraine needs to adopt a national maritime decarbonization strategy that will be in line with IMO and EU requirements and serve as a basis for regulatory, financial, and infrastructure policies. At the same time, domestic legislation should be harmonized with European mechanisms (EU ETS, FuelEU Maritime) to avoid barriers to access to international markets. To reduce financing barriers, green support instruments, such as subsidies, insurance, tax benefits, and government guarantees, should be created.

In terms of infrastructure, investments are needed in alternative fuel terminals (LNG, methanol, hydrogen), as well as incentives for port electrification, including connecting ships to an onshore power supply (OPS). It is also advisable to develop training programs for crew and managers in digital monitoring, ESG reporting, and energy management.

Market mechanisms, such as introducing carbon pricing or accession to international emissions trading systems (ETS), should be emphasized as they create clear incentives for reducing emissions and investing in clean technologies.

Conclusions. The study results confirm that introducing low-carbon technologies in maritime transport is strategically feasible in terms of both environmental

Table 3

Policy and investment recommendations for low-carbon maritime transition

Category	Recommendation
Policy and Regulation	Adopt a national maritime decarbonization strategy aligned with IMO and EU targets
Policy and Regulation	Harmonize national legislation with ETS and CII requirements
Finance and Investment	Create green financing instruments (e.g., subsidies, credit guarantees)
Finance and Investment	Develop public-private partnerships (PPPs) for fleet modernization
Infrastructure	Invest in LNG, methanol, and hydrogen terminal infrastructure
Infrastructure	Provide incentives for port electrification (OPS) and ESD deployment
Education and Skills	Implement training programs in alternative fuels and digital monitoring
Education and Skills	Integrate ESG skills into maritime education programs
Market Instruments	Introduce carbon pricing mechanisms or emissions trading schemes

impact and economic efficiency. Despite the high start-up costs, the scenario analysis demonstrates a reduction in total operating costs and greenhouse gas emissions with the transition to slower speeds, the introduction of alternative fuels, shore power, and energy-saving systems. At the same time, the identified barriers — financial, infrastructural, human resources, and regulatory — require a comprehensive support policy. Creating the conditions for attracting green capital, harmonizing legislation with European standards, developing port infrastructure, and training specialists are key prerequisites for a successful transition. The green transformation of maritime transport should be viewed as a multisectoral investment strategy for sustainable development that combines technological innovation, market mechanisms, and public policy.

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ІНВЕСТИЦІЙНІ ТА ЕКОНОМІЧНІ АСПЕКТИ ПЕРЕХОДУ МОРСЬКОГО ТРАНСПОРТУ ДО НИЗЬКОВУГЛЕЦЕВИХ ТЕХНОЛОГІЙ

Анотація. *У статті розглядаються інвестиційні та економічні аспекти переходу морського транспорту до низьковуглецевих технологій у контексті глобальних кліматичних ініціатив та трансформації регуляторного середовища. Проведено аналіз витрат на модернізацію флоту, механізмів фінансування екологічних рішень, впливу індикатора CII та вуглецевого оподаткування на вартість морських перевезень. Представлено інвестиційну модель з урахуванням операційної економії, скорочення викидів та періоду окупності. Сценарне моделювання демонструє, що стратегія повільного ходу у поєднанні з технічними заходами дозволяє зменшити загальні витрати рейсу при зниженні вуглецевого сліду. Визначено ключові ризики впровадження (високий CAPEX, нестача інфраструктури, технологічна невизначеність), а також сформульовано політичні та фінансові рекомендації для стимулювання зеленої трансформації морського сектору. Результати можуть бути використані для формування національної стратегії декарбонізації судноплавства та розвитку екологічної логістики.*

Ключові слова: *судноплавство, низьковуглецеві технології, морський транспорт, декарбонізація, викиди CO_2, енергоефективність, повільний хід, інвестиційна модель, ESG, вуглецеве ціноутворення, зелена логістика, зовнішньоекономічна діяльність, портова інфраструктура, вантажні перевезення.*