RÜZGAR DESTELİ SEVK SİSTEMLERİNİN IMO'NUN GFI REGÜLASYONU KAPSAMINDA DEĞERLENDİRİLMESİ: BİR RO-RO GEMİSİ ÜZERİNE VAKA ÇALIŞMASI

Dr. Buğra Arda ZİNCİR[1]
[1]Galatasaray Üniversitesi, Denizcilik Meslek Yüksekokulu, bazincir@gsu.edu.tr, 0000-0003-1036-2411

Özet

Uluslararası Denizcilik Örgütü'nün (IMO) Ocak 2027'de yürürlüğe girecek yeni Sera Gazı Yakıt Yoğunluğu (GFI) regülasyonu, gemilere, karbon yoğunluğu açısından giderek sıkılaşan gereklilikler getirerek bir dekarbonizasyon yol haritası dayatmaktadır. Rüzgar Destekli Sevk Sistemleri (WAPS) gibi yenilenebilir enerji sistemlerinin kullanımı artmasına rağmen, bu yeni regülasyona uyum sağlamadaki spesifik etkinlikleri henüz ölçülmemiştir. Bu çalışma, ağır yakıt kullanan 30.998 GT'luk bir roll-on/roll-off (Ro-Ro) gemisi için WAPS'ın uyum risklerini azaltma potansiyelini araştırarak bu boşluğu doldurmayı amaçlamaktadır. Geminin 2024 yılı emisyon verileri baz alınarak, farklı ölçeklerde WAPS (küçük, orta, büyük) entegre edilmiş üç farklı uyum senaryosu modellenmiştir. Bulgularımız, WAPS'ın GFI regülasyonu kapsamında mali yaptırımların başlangıcını önemli ölçüde geciktirebileceğini göstermektedir. Analizler, büyük ölçekli bir WAPS'ın 2035'e, orta ölçekli bir sistemin 2033'e ve küçük ölçekli bir sistemin ise 2029'a kadar cezasız uyum sağlayabileceğini ortaya koymaktadır. Bu çalışma, WAPS'ın tek başına nihai bir çözüm olmasa da, oldukça etkili bir geçiş teknolojisi olduğu sonucuna varmaktadır. WAPS, uyum mali yükünü azaltabilir, mevcut gemilerin ömrünü uzatabilir ve alternatif yakıtlar gibi uzun vadeli çözümlerin geliştirilmesi için kritik zaman sağlayabilir. Bu araştırma, GFI uygulamasının erken aşamalarında yol haritası belirleyen gemi sahipleri, operatörler ve politika yapıcılar için değerli bilgiler sunmakta ve pratik uyum stratejileri ile literatüre katkıda bulunmaktadır.

Anahtar Kelimeler: Dekarbonizasyon, Deniz taşımacılığı, Rüzgar Destekli Sevk Sistemi, Sera Gazı Yakıt Yoğunluğu,

ASSESSING THE IMPACT OF WIND-ASSISTED PROPULSION SYSTEM ON COMPLIANCE WITH THE IMO'S GFI: A CASE STUDY ON A RO-RO VESSEL

Dr. Bugra Arda ZINCIR[1]
[1]Galatasaray University, Maritime Vocational School, bazincir@gsu.edu.tr, 0000-0003-1036-2411

Abstract

The International Maritime Organization's (IMO) new Greenhouse Gas Fuel Intensity (GFI) regulation, effective January 2027, imposes stringent carbon intensity requirements on ships, mandating a pathway towards decarbonization. While renewable energy systems like Wind-Assisted Propulsion Systems (WAPS) are being adopted, their specific efficacy in ensuring compliance with this new regulation remains unquantified. This study addresses this gap by investigating the potential of WAPS to mitigate compliance risks for a 30,998 GT roll-on/roll-off (Ro-Ro) vessel operating on heavy fuel oil. Using the vessel's 2024 annual emission data as a baseline, we model three compliance scenarios, each integrating a different scale of WAPS (small, medium, and large). Our findings demonstrate that WAPS can significantly delay the onset of financial penalties under the GFI regulation. The analysis shows that a large-scale WAPS can ensure compliance without penalties until 2035, a medium-scale system until 2033, and a small-scale system until 2029. This study concludes that while WAPS alone is not a complete decarbonization solution, it serves as a highly effective transitional technology. It can reduce the financial burden of compliance and extend the viability of existing vessels, providing critical time for the development and integration of long-term solutions like alternative fuels. This research offers valuable insights for shipowners, operators, and policymakers navigating the early stages of GFI implementation and contributes to the literature on practical compliance strategies.

Keywords: Decarbonization, Greenhouse Gas Fuel Intensity, Maritime transportation, Wind-Assisted Propulsion System

1. INTRODUCTION

According to UNCTAD (2024), maritime transport accounted for nearly 80–85% of global trade in 2023, corresponding to approximately 12,292 million tons of cargo. The sector predominantly relies on fossil-based marine fuels, such as heavy fuel oil (HFO), marine diesel oil (MDO), and marine gas oil (MGO), to meet the energy requirements of vessels. The combustion of these fuels, however, results in significant greenhouse gas (GHG) emissions, primarily carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), which are major drivers of climate change. To address these concerns, the International Maritime Organization (IMO) has progressively tightened environmental regulations over recent decades, with the Greenhouse Gas Fuel Intensity (GFI) regulation being the most recent addition. Introduced under the IMO Net-Zero Framework at the Marine Environment Protection Committee's 83rd session in April 2025, the GFI applies to vessels of 5,000 gross tonnage (GT) and above starting in 2028. The regulation sets two main indicators: the attained GFI and the target GFI, both expressed in grams of CO_2 equivalent per megajoule (gCO_2eq/MJ) on an annual well-to-wake (WtW) basis. The 2008 reference value (GFI_{2008}) is established at 93.3 gCO_2eq/MJ, as shown in Table 1. While each ship must annually report its attained GFI, compliance is assessed against tiered target values: a base target and a stricter direct compliance target, with reduction requirements outlined through 2035. Ships meeting the direct compliance target can generate surplus credits that may be saved for later compliance periods or transferred to other vessels. Vessels falling between the base and direct compliance thresholds are liable for Tier 1 penalties, whereas ships exceeding the base target incur both Tier 1 and Tier 2 penalties. During the first compliance phase (2028–2030), the penalty rates are set at $100 per ton of CO_2 equivalent for Tier 1 and $380 per ton for Tier 2 (IMO, 2025).

Table 1. IMO GFI annual reduction factors for base and direct compliance targets (2028–2035).

Year	Base Target	Direct compliance target
2028	4.0%	17.0%
2029	6.0%	19.0%
2030	8.0%	21.0%
2031	12.4%	25.4%
2032	16.8%	29.8%
2033	21.2%	34.2%
2034	25.6%	38.6%
2035	30.0%	43.0%

A variety of strategies are available to lower GHG emissions in shipping, generally falling into two categories: operational improvements and vessel modifications (Zincir, 2025). Among the most notable approaches is the integration of renewable energy solutions, particularly wind-assisted propulsion systems (WAPS). As of 2025, 71 vessels have been equipped with WAPS, with an additional 84 systems on order (DNV, 2025a). This represents a significant increase compared to 2024, when only 29 ships had WAPS installed and 72 orders were pending (LR, 2024). The surge in adoption is likely linked to the enforcement of the FuelEU Maritime Regulation on 1 January 2025, which offers incentives for the deployment of such technologies.

WAPS have also gained growing attention in recent academic research. For example, Kolodziejski and Sosnowski (2025) provided a comprehensive review of WAPS in maritime transport, discussing their potential for emission reduction, prospects for future application, market developments, and system innovations. Similarly, Chou et al. (2021) reviewed WAPS technologies and reported that energy efficiency gains could range from 0.4% to as high as 60%. Such variability is largely influenced by factors including wind conditions, trade routes, geographic regions, seasonal variations, voyage distances, operational profiles, and routing strategies. In a more technology-specific study, Lu and Ringsberg (2019) examined the performance of Flettner

rotors, estimating fuel savings between 5.6% and 8.9%. Calic et al. (2024) carried out a case study to evaluate the influence of WAPS on both fuel consumption and propeller performance. Their findings indicated a 12.5% reduction in fuel use; however, the ship's operating point shifted into a less efficient propeller region, partially offsetting the benefits. While these studies demonstrate the potential of WAPS, to the best of the author's knowledge, no research has yet examined their implications under the newly introduced GFI regulation. Addressing this gap, the present study evaluates the impact of WAPS on a case ship under three distinct operating scenarios.

2. METHODOLOGY

This study focuses on a roll-on/roll-off (Ro-Ro) vessel as the case ship. Ro-Ro vessels are particularly suitable for WAPS since their open deck areas, which are not typically occupied by cargo, provide ample space for installing such technologies. Ship-specific data were obtained from the MRV-THETIS platform, with details summarized in Table 2. These datasets correspond to 2024 submissions that were verified and approved by accredited agencies. While the platform provides tank-to-wake (TtW) emissions, well-to-tank (WtT) values were derived from the IMO Life Cycle Assessment (LCA) Guidelines (IMO, 2024). For HFO, the WtT emission factor is 16.8 gCO_2eq/MJ, and the lower calorific value (LCV) is 0.0402 MJ/g.

Three scenarios were developed to assess the impact of WAPS on the case ship: (i) installation of a small system achieving 19% fuel savings, (ii) a medium-sized system with 38% fuel savings, and (iii) a large-scale system delivering 57% fuel savings (DNV, 2025b).

Table 2. Case vessel specifications and 2024 verified emission data from MRV-THETIS platform.

Description	Parameter
Vessel Type	Ro-ro
Length overall	209 m
Beam	26.5 m
Max Speed	21.5 knot
Gross tonnage	30,998 GT
Built date	2010
Fuel Type	HFO
Scrubber	Available
Fuel consumption	18,287 tons
CO_2 emissions	57,016 tons
N_2O emissions	3.29 tons
CH_4 emissions	0.91 ton

Prior to performing GFI calculations, the total emissions in gCO_2eq must first be determined. This is done using Equation (1), where the conversion factors for nitrous oxide (CF_{N2O} = 264) and methane (CF_{CH4} = 84) are applied (IMO, 2024). $Energy_{total}$ represents the overall energy consumption from all fuels, expressed in megajoules (MJ).

$$TtW_{gCO_{2eq}/MJ} = \frac{gCO_2 + gN_2O \times CF_{N_2O} + gCH_4 \times CF_{CH_4}}{Energy_{total}} \quad (1)$$

Once emissions are expressed in gCO_2eq, the GFI targets can be derived. The initial step involves calculating the annual base target and direct compliance target values using Equation (2). Here, Z_T denotes the annual reduction factor (as shown in Table 1), and the 2008 reference level (GFI_{2008}) is fixed at 93.3 gCO_2eq/MJ.

$$GFI_T = (1 - \frac{Z_T}{100}) \times GFI_{2008} \quad (2)$$

Subsequently, the attained GFI for a vessel is computed with Equation (3). In this formulation, j refers to the fuel type, J is the total number of fuels consumed, EI_j is the GHG intensity (gCO_2eq/MJ) of fuel j, and $Energy_j$ corresponds to the energy provided by that fuel.

$$GFI_{attained} = \frac{\sum_{i=1}^{J} EI_j \times Energy_j}{Energy_{total}} \quad (3)$$

After calculating the attained value, compliance deficits are assessed in tons of CO_2 equivalent using Equation (4). This step determines whether the vessel satisfies the regulation or becomes subject to penalties.

$$GFI\ compliance\ balance = (Direct\ compliance\ target\ annual\ GFI - Attained\ annual\ GFI) \times Energy_{Total} \quad (4)$$

The compliance framework then distinguishes between two cases. If the attained GFI lies between the direct compliance target and the base target, Tier 1 penalties are applied as defined in Equation (5). However, if the attained GFI exceeds the base target, both Tier 1 and Tier 2 deficits must be determined according to Equations (6) and (7), respectively.

$$Tier\ 1\ compliance\ deficit = (Direct\ compliance\ target\ annual\ GFI - Attained\ annual\ GFI) \times Energy_{total} \quad (5)$$

$$Tier\ 1\ compliance\ deficit = (Direct\ compliance\ target\ annual\ GFI - Base\ target\ annual\ GFI) \times Energy_{total} \quad (6)$$

$$Tier\ 2\ compliance\ deficit = (Base\ target\ annual\ GFI - Attained\ annual\ GFI) \times Energy_{total} \quad (7)$$

Finally, penalty costs are assigned. For the first compliance phase (2028–2030), Tier 1 deficits are priced at \$100 per ton of CO_2eq, while Tier 2 deficits are valued at \$380 per ton of CO_2eq (IMO, 2025). Although penalty rates beyond 2030 have not yet been specified, this study assumes the same cost structure for subsequent years.

3. RESULTS AND DISCUSSION

Table 3 presents the attained GFI values for each case, while Table 4 outlines the annual target GFI levels. The findings show that the base case scenario does not meet even the 2028 requirements. In Case 1, compliance with Tier 1 is achieved only in the first year, after which it fails, though Tier 2 compliance is sustained until 2033. Both Case 2 and Case 3 remain within Tier 2 limits, but Case 2 falls short of Tier 1 compliance after 2034.

Table 3. Attained GFI values for base case and WAPS scenarios.

Case	Attained GFI
Base case	95.55
Case 1	77.39
Case 2	59.24
Case 3	41.09

Figure 1 illustrates the GFI compliance balance for the period 2028–2035. Positive values indicate surplus compliance, which can be banked for subsequent years or transferred to another vessel in the fleet (IMO, 2025). Negative balances, in contrast, represent a compliance deficit, requiring either penalty payments or the transfer of surplus units from another ship. The base case consistently shows a negative balance. Case 1 and Case 2 shift into deficit after 2029 and 2034, respectively, whereas Case 3 consistently maintains a surplus. Table 5 quantifies the Tier 1 and Tier 2 compliance deficits.

Tablo 4. Annual base and direct compliance GFI targets.

Year	Base target (gCO_2eq/MJ)	Direct compliance target (gCO_2eq/MJ)
2028	89.57	77.44
2029	87.70	75.57
2030	85.84	73.71
2031	81.73	69.60
2032	77.63	65.50
2033	73.52	61.39
2034	69.42	57.29
2035	65.31	53.18

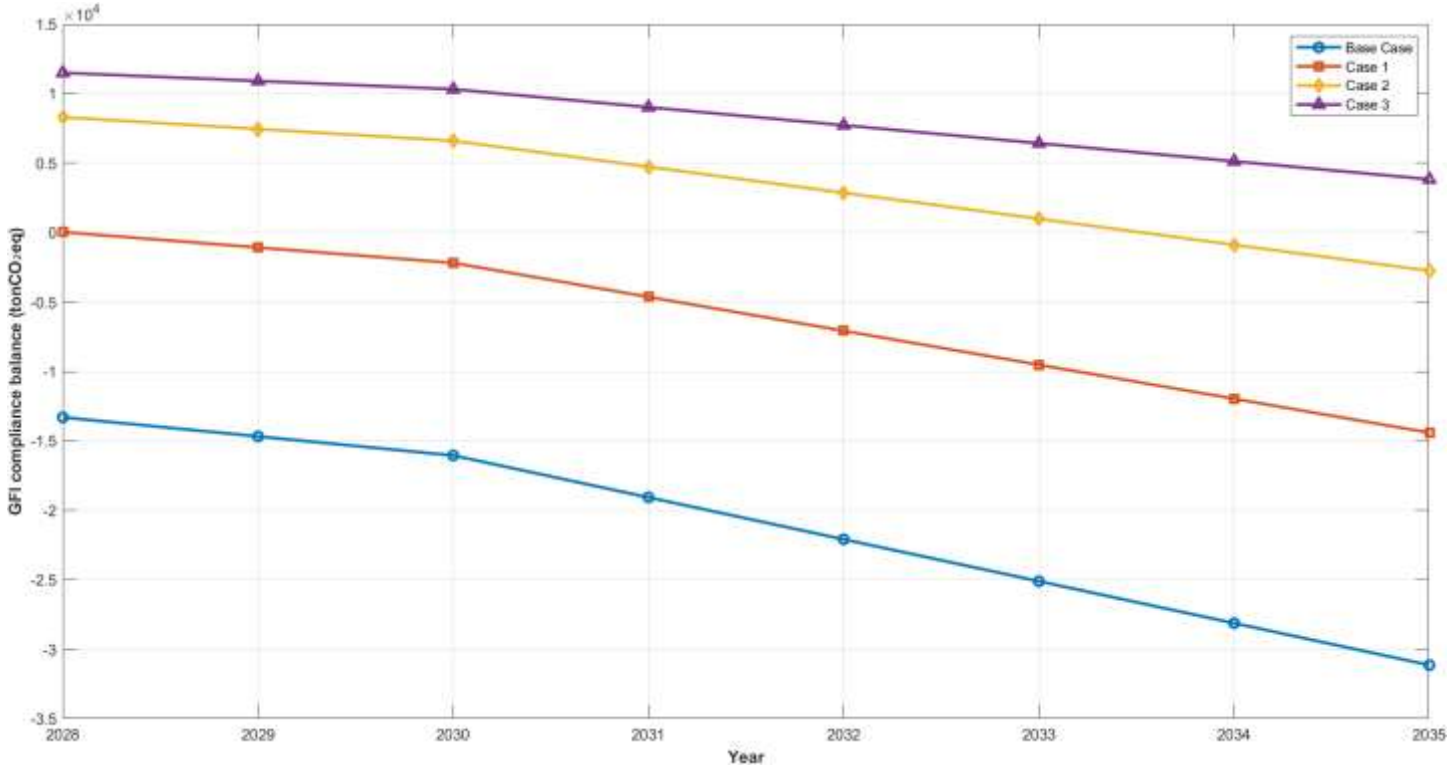


Figure 1. GFI compliance balance for the base case and WAPS scenarios.

The associated penalty costs are shown in Figure 2. As expected, the base case generates the highest penalty, reflecting its substantial compliance deficit. Conversely, Case 3 incurs no penalties since it fully complies with all targets throughout the period. Case 1 begins accumulating penalties from 2029 onward, while Case 2 starts in 2034. It is also notable that Tier 2 penalties represent the larger share of total costs, largely due to the significant difference in remedial unit values between Tier 1 and Tier 2. Consequently, failure to meet the base compliance target results in substantially higher financial burdens. Furthermore, penalty rates are assumed constant beyond 2030 in this study, although future increases are likely.

WAPS are generally estimated to achieve a return on investment of approximately 5.5 years based solely on fuel savings (LR, 2024). Under the GFI regulation, this payback period can be shortened by avoiding penalty costs. For the case Ro-Ro vessel, the cumulative penalty from 2028–2035 amounts to $44,479,281 in the base case. This figure is reduced to $9,084,286 in Case 1 and to $365,266 in Case 2, while Case 3 avoids penalties altogether. According to the European Maritime Safety Agency (EMSA, 2023), the capital expenditure for installing WAPS ranges from 15–25% of a vessel's total value. In addition, annual maintenance costs are estimated at €26,000–79,000, with a one-time crew training cost of around €10,000. Although the high upfront investment may pose challenges, particularly for new entrants, the long-term economic benefits combined with compliance-related savings strongly support the adoption of WAPS.

Tablo 5. GFI compliance deficits (Tier 1 and Tier 2) under each case.

Tier	Year	Base case	Case 1	Case 2	Case 3
Tier 1	2028	-8916.60	-	-	-
	2029	-8916.60	-1084.88	-	-
	2030	-8916.60	-2196.03	-	-
	2031	-8916.60	-4640.55	-	-
	2032	-8916.60	-7085.07	-	-
	2033	-8916.60	-7222.45	-	-
	2034	-8916.60	-7222.45	-890.77	-
	2035	-8916.60	-7222.45	-2761.89	-
Tier 2	2028	-4397.10	-	-	-
	2029	-5768.89	-	-	-
	2030	-7140.67	-	-	-
	2031	-10,158.60	-	-	-
	2032	-13,176.53	-	-	-
	2033	-16,194.46	-2307.14	-	-
	2034	-19,212.38	-4751.66	-	-
	2035	-22,230.31	-7196.19	-	-

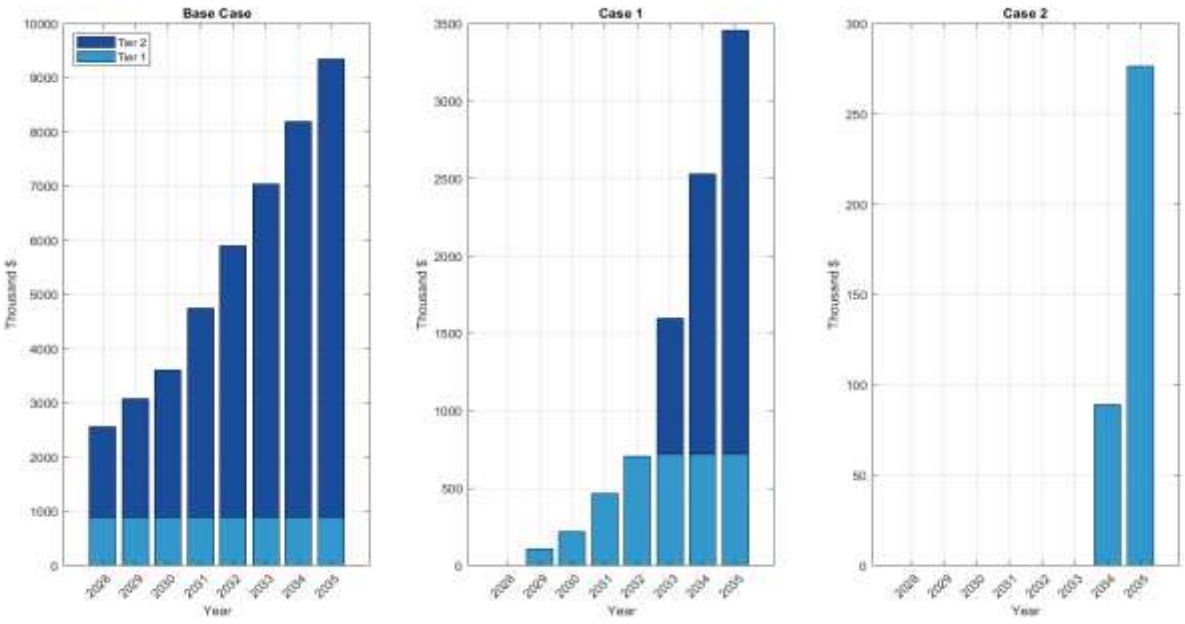


Figure 2. Penalty costs under GFI regulation for base case and WAPS scenarios.

4. CONCLUSION

The tightening of environmental regulations in maritime transportation has accelerated the search for alternative methods to reduce GHG emissions from ships. While numerous studies have examined WAPS, their implications under the recently introduced GFI regulation remain largely unexplored. This study addresses this gap by analyzing three different sizes of WAPS installed on a case Ro-Ro vessel.

The results demonstrate that larger WAPS installations deliver the most significant benefits, fully avoiding GFI-related penalties until 2035. Medium-sized systems remain compliant until 2034, while smaller systems provide compliance only until 2029. Nevertheless, even the smallest WAPS configuration achieves notable cost reductions, approximately $35.4 million in avoided penalties over eight years compared with the base case, excluding fuel savings. The medium- and large-scale systems achieve savings of $44.1 million and $44.5 million, respectively. The narrow cost difference between medium and large systems reflects the fact that regulation targets are currently defined only until 2035. However, stricter future targets would likely extend the advantage of large-scale WAPS, creating a more substantial cost gap. Based on present projections, the medium-sized WAPS appears to be the most cost-efficient option.

Although this analysis focused on a Ro-Ro vessel, outcomes may differ across ship types, underscoring the need for replication in other vessel categories. Moreover, the performance of WAPS depends on various operational and environmental factors, suggesting that results may vary under different conditions. Future research should therefore explore ship-type-specific applications, optimize WAPS design and operation, and evaluate their role in long-term compliance with evolving GHG regulations.

REFERENCES

Čalić, A., Jurić, Z., Kalinić, M. (2024). Impact of Wind-Assisted Propulsion on Fuel Savings and Propeller Efficiency: A Case Study. Journal of Marine Science and Engineering, 12(11), 2100. https://doi.org/10.3390/jmse12112100

Chou, T., Kosmas, V., Acciaro, M., Renken, K. (2021). A Comeback of Wind Power in Shipping: An Economic and Operational Review on the Wind-Assisted Ship Propulsion Technology. Sustainability, 13(4), 1880. https://doi.org/10.3390/su13041880

Det Norske Veritas (DNV). (2025a). Energy Transition Outlook 2025: Maritime Forecast to 2050.

Det Norske Veritas (DNV). (2025b). Wind-Assisted Propulsion Systems (WAPS): How WAPS can help to comply with GHG regulations.

European Maritime Safety Agency (EMSA). (2023). Potential of Wind-Assisted Propulsion for Shipping.

International Maritime Organization (IMO). (2024). Resolution MEPC.391(81). 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels (2024 LCA Guidelines).

International Maritime Organization (IMO). (2025). Draft Amendments to MARPOL Annex VI: Regulations for the Prevention of Air Pollution from Ships.

Kolodziejski, M., Sosnowski, M. (2025). Review of Wind-Assisted Propulsion Systems in Maritime Transport. Energies, 18(4), 897. https://doi.org/10.3390/en18040897

Lloyd's Register (LR). (2024). Energy Efficiency Retrofit Report: Applying Wind-Assisted Propulsion to ships.

Lu, R., Ringsberg, J. W. (2019). Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the Flettner rotor technology. Ships and Offshore Structures, 15(3), 249–258. https://doi.org/10.1080/17445302.2019.1612544

United Nations Conference on Trade and Development (UNCTAD). (2024). Review of maritime transport: Navigating maritime chokepoints.

Zincir, B. A. (2025). Transitioning to sustainable shipping: A multidimensional analysis of maritime emission strategies. Ocean & Coastal Management, 269, 107823. https://doi.org/10.1016/j.ocecoaman.2025.107823