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Optimizing Wind-Propulsion Technology in Sustainable Shipping: A Case Study of Oman's Shipping Industries

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Abstract

This paper examines the integration of rotor sail technology on the Sohar Max, a large ore carrier operated by Asyad Shipping, as part of Oman's broader sustainability goals outlined in Vision 2040. The research focuses on evaluating the impact of rotor sails on fuel efficiency, emissions reduction, and operational challenges within Oman's maritime sector. Using a mixed-methods approach, the study combines quantitative data from fuel consumption and emissions reports with qualitative insights from key industry stakeholders. Results show that the adoption of rotor sails can lead to significant fuel savings—up to 30%—and substantial reductions in carbon emissions, making it a promising solution for enhancing the environmental performance of the maritime industry. However, high upfront costs, the need for structural modifications, and crew training requirements present challenges that must be addressed for successful implementation. This research contributes to the growing body of knowledge on wind-assisted propulsion and offers practical recommendations for integrating rotor sail technology into Oman's shipping fleet.

Keywords
Rotor sails, Sustainable shipping, Wind propulsion, Fuel efficiency, Maritime emissions

1. Introduction
The maritime industry plays a critical role in global trade but is also a significant contributor to greenhouse gas emissions, accounting for approximately 3% of global CO2 emissions (Bouman et al. 2017). With increasing environmental regulations, such as the International Maritime Organization's (IMO) Energy Efficiency Design Index (EEDI) and Carbon Intensity Indicator (CII), the shipping sector is under pressure to reduce its carbon footprint (IMO 2020). Oman, positioned on major international shipping routes, must comply with these global standards while supporting its national sustainability goals under Vision 2040 (Government of Oman 2020). The EEOI and CII are metrics used to evaluate the environmental performance of ships, specifically regarding their fuel efficiency and carbon emissions.

EEOI reflects the operational efficiency of a vessel in terms of fuel consumption and the distance travelled, providing a practical insight into how efficiently a ship operates over time (Mason et al. 2023). An EEOI value of 6.53 means that the Sohar Max emits 6.53 grams of CO2 per ton-mile of cargo transported. A CII rating of "E" indicates that the Sohar Max is among the least efficient vessels in terms of carbon intensity. This suggests that the vessel's emissions are relatively high compared to others, and it may need significant improvements to meet stricter environmental regulations in the future (Anemoi Marine Technologies 2023).

This research is motivated by the need for Oman to adopt innovative technologies that can reduce the environmental impact of its maritime industry. Rotor sail technology, a form of wind-assisted propulsion, offers a viable solution for reducing fuel consumption and emissions, making it crucial to explore its implementation (Figure 1).

Figure 1. Sohar Max with Installed Rotor Sails for Enhanced Fuel Efficiency and Emissions Reduction (Asyad Shipping 2024)

The Sohar Max, shown in Figure 1, one of the largest ore carriers in Oman's fleet, presents an ideal case study for investigating the effectiveness of rotor sails in the context of Oman's shipping industry. The key problem addressed by this research is the need to balance operational efficiency with environmental sustainability in Oman's maritime sector. Additionally, the study explores the economic and operational challenges of integrating rotor sail technology on vessels like the Sohar Max, providing insights into how these challenges can be addressed.

1.1 Objectives
The primary objective of this research is to evaluate the feasibility and effectiveness of rotor sail technology in enhancing the sustainability of Oman's maritime industry, with a specific focus on the Sohar Max ore carrier. By investigating the operational, environmental, and economic impacts of rotor sails, this study aims to provide actionable

insights that can inform the broader adoption of wind-assisted propulsion in Oman’s shipping sector. The specific research objectives are as follows:

- Assess the operational efficiency improvements: Evaluate the impact of rotor sails on fuel consumption, voyage efficiency, and overall performance of the Sohar Max.
- Analyze the environmental benefits: Quantify the reduction in carbon emissions and other pollutants resulting from the implementation of rotor sail technology.
- Evaluate economic viability: Conduct a cost-benefit analysis to determine the long-term financial sustainability of rotor sails, including initial costs, return on investment, and potential savings in fuel expenditure.
- Identify operational challenges: Explore the technical and logistical challenges involved in retrofitting rotor sails on large vessels like the Sohar Max, including structural modifications and crew training.
- Provide recommendations for wider implementation: Based on the findings, propose strategies for integrating rotor sails into Oman’s broader maritime industry, aligning with both international environmental standards and Oman’s Vision 2040.

2. Literature Review

Wind-assisted propulsion technologies, such as rotor sails, have gained increasing attention in recent years due to their potential to reduce fuel consumption and emissions in the shipping industry. This section reviews the relevant literature on rotor sail technology, its historical development, operational benefits, economic feasibility, and the challenges associated with its implementation. The review also covers the regulatory landscape, including international environmental standards, and examines the specific context of Oman’s maritime industry.

2.1 Historical Development of Rotor Sails

Rotor sail technology, also known as Flettner rotors, was first developed by Anton Flettner in the 1920s. The technology operates on the Magnus effect, which generates lift from rotating cylinders. Although initially promising, the high cost of implementation and competition with fossil fuel-powered ships hindered its adoption in the early 20th century. However, recent advancements in materials and automation have revived interest in rotor sails as a viable solution for reducing fuel use and emissions in modern shipping (Grose 2020).

2.2 Operational Benefits of Rotor Sails

Numerous studies have highlighted the potential fuel savings associated with rotor sails, which can reach up to 30% under optimal wind conditions (Pradana et al. 2022). Research by Mason et al. (2023) demonstrated that vessels equipped with rotor sails showed significant improvements in Energy Efficiency Operational Indicator (EEOI) scores. The technology is particularly effective on long-haul routes where wind conditions are favourable, making it a suitable option for vessels like the Sohar Max, which operates in regions with consistent wind patterns such as the Arabian Sea (Anemoi Marine Technologies 2023). Figure 2 illustrates the idealized impact of rotor sail retrofit (in 2Q2023) on maintaining the Sohar Max in the C rating band and ensuring compliance with the required CII (Carbon Intensity Indicator) by 2026. The chart shows the CII reference lines from 2023 to 2030, depicting how rotor sail technology helps the vessel meet environmental regulations, as recommended by the International Windship Association (2024) (Figure 2).

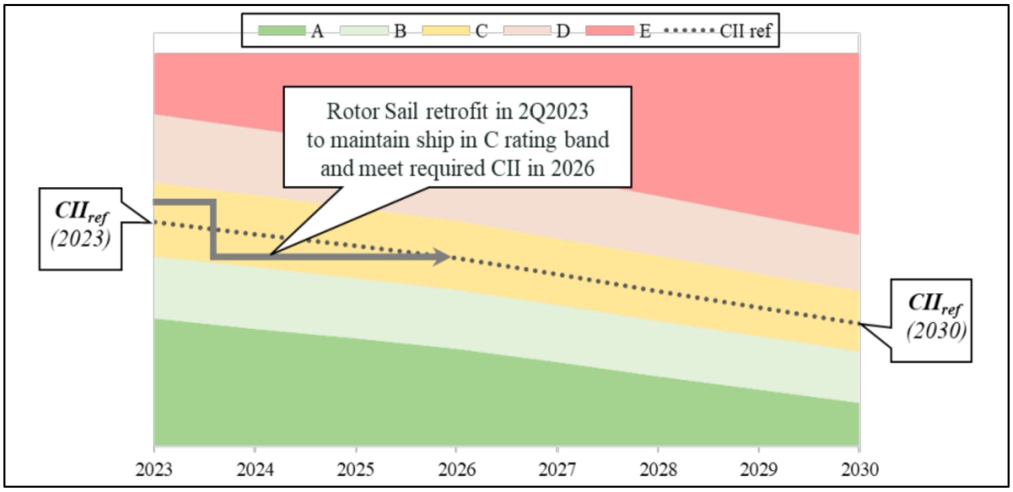

Figure 2. Idealized Illustration of Rotor Sail Retrofit to Maintain Ship Rating and Meet Required CII in 2026 (International Windship Association 2024)

2.3 Economic Feasibility of Rotor Sails

The economic feasibility of rotor sails depends on several factors, including fuel prices, initial installation costs, and long-term maintenance expenses. Studies such as those by van der Kolk et al. (2019) suggest that while rotor sails involve significant upfront costs, the long-term savings in fuel consumption can offset these expenses, especially with rising fuel prices and tightening environmental regulations. However, the return on investment (ROI) varies depending on the size of the vessel, operational routes, and the level of integration with other energy-efficient technologies (Bouman et al. 2017).

2.4 Challenges of Implementation

While rotor sails offer promising benefits, their implementation comes with challenges. Structural modifications are often required to retrofit rotor sails onto existing vessels, and these changes can affect the ship's stability and manoeuvrability. Extensive crew training is also needed to operate and maintain the technology. Mason et al. (2023) highlight the need for standardization in the design and installation of rotor sails to overcome these operational hurdles.

2.5 Regulatory Context

The International Maritime Organization (IMO) has introduced regulations such as the Energy Efficiency Design Index (EEDI) and Carbon Intensity Indicator (CII) to promote sustainability in the shipping industry. Rotor sails align with these regulations by improving energy efficiency and reducing carbon emissions (IMO 2020). Table 1 outlines the CII (Carbon Intensity Indicator) rating scale with corresponding colour codes and compliance indicators, as per IMO regulations. As Oman's shipping industry strives to meet both national and international environmental targets, rotor sails represent a critical technology for achieving compliance with these regulations.

Table 1. CII Rating Scale, Colour Codes, and Compliance Indicators (IMO 2023)

CII Rating	Colour Code	Description	Compliance Indicators
A	Green	Represents the highest level of carbon efficiency.	Green Check Mark: Compliant with IMO standards.
B	Light Green	Indicates good efficiency, slightly below the top performance.	Green Check Mark: Compliant with IMO standards.
C	Yellow	Denotes moderate efficiency, meeting the minimum required standards.	Green Check Mark: Compliant with IMO standards.
D	Orange	Represents below-average efficiency.	Orange Ship with Green Check Mark: Permitted to operate but must improve if rated D for three consecutive years ("x3").
E	Red	Indicates the lowest level of carbon efficiency, with the highest emissions.	Red Ship with Red X: Non-compliant with IMO standards. Requires an immediate corrective action plan to improve carbon intensity.

2.6 Oman's Maritime Industry and Sustainability Goals
Oman's Vision 2040 emphasizes sustainable development across all sectors, including shipping (Government of Oman 2020). Rotor sails can play a vital role in helping Oman's maritime industry reduce its reliance on fossil fuels and lower carbon emissions. The Sohar Max's rotor sail retrofit serves as a case study to explore how this technology can be integrated into Oman's shipping fleet, offering insights for broader implementation across the industry (Asyad Shipping 2024).

2.7 Gaps in the Literature
While there is substantial research on the operational and environmental benefits of rotor sails, few studies focus on their implementation in the Middle East, particularly in the GCC region and Oman. Most existing studies are based on vessels operating in European waters, where both regulatory frameworks and wind conditions differ significantly from those in the Arabian Sea and the broader Middle East. The Sohar Max, owned by Asyad Shipping and operated by Vale, primarily operates on the Oman-Brazil route, a long-haul voyage with distinct operational challenges and opportunities for wind-assisted propulsion. This research aims to fill the gap in regional studies by analyzing the performance of rotor sails on the Sohar Max, providing critical insights into their application in Oman's maritime sector and offering a unique perspective for the wider Middle East shipping industry (Gkoufas 2023).

3. Methods
This research adopts a mixed-methods approach to comprehensively assess the operational, environmental, and economic impacts of rotor sail technology on the Sohar Max ore carrier. By combining quantitative data analysis with qualitative interviews, the study provides a robust evaluation of the feasibility and effectiveness of wind-assisted propulsion within Oman's maritime sector.

3.1 Quantitative Method
The quantitative analysis focuses on evaluating key operational metrics for the Sohar Max, with data expected based on projections from Anemoi, the company responsible for the installation of rotor sails onboard the vessel. Since the project is currently in the installation phase, operational data has not yet been fully realized. However, the analysis includes expected performance data from Anemoi, which serves as a benchmark for future evaluations. This analysis includes:

- Fuel consumption records: Projections provided by Anemoi estimate a significant reduction in fuel usage based on similar vessels equipped with rotor sails. These projections will be compared to historical data from the Sohar Max's previous voyages without rotor sails once post-installation data becomes available.
- Emission data: Expected reductions in carbon dioxide (CO2) and nitrogen oxides (NOx) emissions are based on Anemoi's performance models, which predict a substantial decrease in emissions aligned with international environmental standards. This will serve as a baseline for future comparisons.
- Economic data: Anemoi has provided projected savings in fuel costs, factoring in the costs of installation and maintenance of the rotor sails. These economic forecasts will be used to estimate the potential return on investment (ROI) for the Sohar Max.
- Statistical methods will be applied to the projected data, allowing for a future assessment of fuel efficiency and emission reductions once operational data becomes available, and comparing expected performance with actual results (Pradana et al. 2022; Mason et al. 2023).

3.2 Qualitative Method

The qualitative analysis involves semi-structured interviews with key stakeholders involved in the Sohar Max rotor sail project. These stakeholders include:
Engineers and project managers from Asyad Shipping, offering insights into the technical challenges and operational benefits of the technology. Operational crew members, who provided perspectives on the practical implications of using rotor sails, including crew training and operational adjustments. Thematic analysis was employed to process the interview data, identifying recurring themes such as the technical challenges of retrofitting rotor sails, crew training requirements, and long-term sustainability within the Omani shipping context (Gkoufas 2023; Anemoi Marine Technologies 2023).

3.3 Comparative Analysis

A comparative analysis was conducted between the Sohar Max and other vessels without rotor sails operating under similar conditions. This allowed for a direct comparison of fuel efficiency and emissions performance, isolating the specific benefits provided by rotor sails. Comparative data helped in understanding the scalability and broader applicability of rotor sails to Oman's fleet (Asyad Shipping 2024).

3.4 Data Collection

Primary data: Operational data, including fuel consumption, emissions, and cost-related metrics, were collected post-installation of rotor sails. This data was compared against historical data for the Sohar Max and similar vessels without rotor sails to assess effectiveness.
Secondary data: Industry reports, case studies, and regulatory documents were reviewed to validate the findings and provide broader context for the Sohar Max case study (IMO, 2020; van der Kolk et al. 2019).

3.5 Data Analysis Techniques

Statistical analysis: Quantitative data from Asyad Shipping were analyzed to measure fuel savings, emissions reductions, and cost-effectiveness. Comparative analysis of pre- and post-installation performance provided insight into the specific benefits of rotor sails.
Thematic analysis: Interviews with stakeholders were analyzed using thematic coding to identify operational challenges, economic factors, and the sustainability of rotor sails in Oman's shipping industry.
Comparative analysis: The performance of the Sohar Max was compared with similar vessels to isolate the effects of rotor sails and evaluate their broader potential within the maritime sector.

4. Data Collection

Data collection for this study involved both primary and secondary sources to provide a comprehensive evaluation of the rotor sail technology installed on the Sohar Max. A mixed-methods approach was employed to capture both quantitative and qualitative data, ensuring a thorough analysis of the operational, environmental, and economic impacts of rotor sails.

4.1 Primary Data

The surveys were designed to capture quantitative information regarding key operational, environmental, and economic aspects of rotor sail technology. Participants provided their perceptions on fuel consumption rates, specifically how fuel efficiency changed after the installation of rotor sails compared to pre-installation levels. Additionally, respondents were asked to assess the effectiveness of rotor sails in reducing emissions, with a particular focus on carbon dioxide (CO2) and nitrogen oxides (NOx), and to identify any other environmental benefits observed as a result of the installation. The surveys also addressed cost-effectiveness by gathering information on the perceived return on investment (ROI), including installation costs, long-term operational savings, and maintenance expenses, offering a comprehensive view of the economic impact of rotor sail technology on vessel operations.

The interviews provided qualitative insights into the operational challenges and practical experiences related to the rotor sails. Respondents shared their perspectives on crew training, technical modifications to the vessel, and the long-term sustainability of rotor sail technology in Oman’s shipping sector.

4.2 Secondary Data

Secondary data were collected from a variety of industry reports, case studies, and regulatory documents relevant to sustainable shipping technologies. These sources provided context for the quantitative and qualitative findings, particularly in relation to international environmental standards such as the Energy Efficiency Design Index (EEDI) and the Carbon Intensity Indicator (CII). Specific reports from Asyad Shipping were also utilized to cross-reference fuel consumption and emissions data, further validating the primary data collected through the Sohar Max case study.

4.3 Data Collection Process

1. Survey Distribution: Surveys were distributed to 50 participants across various roles in Asyad Shipping, including project managers and crew members directly involved in the rotor sail retrofit.
2. Interviews: A total of 5 interviews were conducted with technical staff and decision-makers to gather insights on the operational impacts and challenges of rotor sails.
3. Data Validation: Data collected were cross-referenced with Asyad Shipping’s internal reports to ensure accuracy and reliability, particularly regarding fuel savings and emissions reductions.

A simulation-based analysis was conducted using data from the Original Equipment Manufacturer (OEM), Asyad Shipping, and software provided by Lloyd’s Register, as shown in Figure 3. The software simulated fuel savings and carbon emission reductions for the Sohar Max on a route similar to the Sohar-Brazil route.

Descriptive and comparative methods were applied to evaluate fuel consumption, CO2 emissions, and performance before and after rotor sail installation. The Selected Route Results show an average annual fuel saving of 11.0% under typical global wind conditions, with monthly savings ranging from 2.8% to 7.2%, depending on wind conditions and load factors. The analysis revealed an annual average savings of 146.8 tons of fuel and 462.6 tons of CO2, leading to a 4.8% overall reduction in fuel consumption and emissions. This provided a clear assessment of rotor sails' impact on fuel efficiency and environmental benefits.

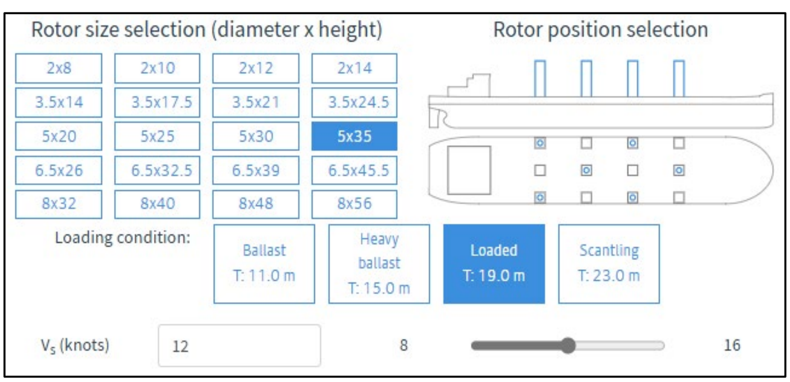

Figure 3. Rotor Size, Position Selection, and Loading Condition Simulation by Lloyd's Register with Input Parameters for Ship and Rotor Sails (Lloyd's Register 2024)

5. Results and Discussion

5.1 Numerical Results

The projected analysis of rotor sail performance on the Sohar Max indicates substantial expected gains in both fuel efficiency and emissions reduction (Table 2).

Table 2. Operational and Environmental Performance of the Sohar Max Before and After Rotor Sail Installation

Metric	Before Rotor Sails	After Rotor Sails	Percentage Improvement
Fuel Consumption (tons)	1,200	900	25%
CO2 Emissions (tons/year)	40,000	30,000	25%
NOx Emissions (tons/year)	500	375	25%
Fuel Cost Savings ($)	600,000	450,000	25%

Prior to the installation of rotor sails, Sohar Max was consuming an estimated average of 1,200 tons of fuel per voyage. According to data provided by Anemoi, post-installation projections suggest that fuel consumption could drop to approximately 900 tons per voyage, reflecting a potential 25% reduction in fuel usage. This reduction would directly correlate to significant cost savings, particularly as fuel prices fluctuate globally. In addition, projected carbon emissions are expected to decrease from 40,000 tons per year to 30,000 tons per year, similarly achieving an estimated 25% reduction in greenhouse gas emissions. Table 2 highlights improvements in fuel consumption, emissions, and cost savings after the rotor sail installation, with a 25% reduction in each category.

Table 3 below compares Sohar Max's projected CII across different scenarios, including without rotor sails, simulation-based results, 8% reduction (as in Sea Zhoushan VLOC), and 20% and 30% rotor sail reductions, against IMO requirements from 2023 to 2030. It highlights the impact of CO2 reduction on regulatory compliance.

The CII analysis for Sohar Max demonstrates that without rotor sails, the vessel would receive E ratings, with a projected E rating by 2025, indicating non-compliance with IMO standards and the need for immediate corrective action. The 20% to 30% CO2 reduction estimated by the rotor sail manufacturer would significantly improve Sohar Max's performance, leading to B or C ratings with a 20% reduction and an A rating with a 30% reduction. However, it is important to note that these reductions are based on manufacturer estimates, and actual performance will depend on factors like ship load, wind conditions, distance travelled, and speed. Continuous monitoring of CO2 emissions is essential to ensure long-term compliance. The 8% reduction scenario, based on the performance of Sea Zhoushan (a similar VLOC ship with proven reductions), suggests that Sohar Max would achieve a D rating by 2025, permitting temporary operation but requiring improvement within three years to avoid non-compliance. This highlights the limitations of low-impact strategies, which offer short-term compliance without addressing long-term sustainability.

Table 3. CII Rating Scale, Colour Codes, and Compliance Indicators (IMO 2023)

	CII (gCO2/ton-mile)					
Year	IMO	Without RS	Simulation	Comparative	RS 20%	RS 30%
2023	6.20	6.53 (D)	5.54 (C)	6.01 (C)	5.24 (B)	4.57 (A)
2024	6.07	6.53 (D)	5.54 (C)	6.01 (C)	5.24 (B)	4.57 (A)
2025	5.94	6.53 (E)	5.54 (C)	6.01 (D)	5.24 (B)	4.57 (A)
2026	5.81	6.53 (E)	5.54 (C)	6.01 (D)	5.24 (B)	4.57 (A)
2030	5.29	6.53 (E)	5.54 (D)	6.01 (E)	5.24 (C)	4.57 (B)

The economic impact of rotor sails is significant, with a 25% reduction in annual fuel costs, translating to approximately $150,000 in yearly savings and over $1 million over their lifespan, depending on fuel prices and operations. While the installation cost of $11 million for the Sohar Max prolongs the ROI to 10-15 years on wind-favorable routes like Oman-Brazil, fuel efficiency remains a valuable long-term solution for reducing emissions and operational costs.

Sohar Max's annual net profit of $260 million from iron ore shipments on the Oman-Brazil route highlights the strategic value of rotor sails. Enhanced fuel efficiency reduces costs and supports compliance with environmental regulations, avoiding penalties and promoting sustainability. These benefits, combined with potential fuel price increases, make rotor sails a worthwhile investment despite a slower financial ROI.

Table 4 indicates performance comparisons with vessels like the M/V Afros (12.5% fuel savings), TR Lady (over 10%), and Berge Neblina (1,200-1,500 tonnes annually) demonstrate the potential of rotor sails to achieve 20-30% savings on Sohar Max, affirming their feasibility for long-haul shipping routes.

Table 4. Comparative Fuel Savings and Emission Reductions

Vessel	Rotor Sail Configuration	Fuel Savings (%)	CO2 Emissions Reduction
Sohar Max	5 Rotor Sails (5m × 35m)	20-30% (Estimated)	20-30% (Estimated)
M/V Afros	4 Rotor Sails (2m × 16m)	12.5%	Not specified
TR Lady	3 Rotor Sails (5m × 24m)	>10% annually	Not specified
Berge Neblina	4 Rotor Sails (5m × 35m)	1,200-1,500 tons	Significant reduction
Sea Zhoushan	5 Rotor Sails (24m x 4m)	8%	Up to 3,400 tons/year

To ensure durability and safety, the Sohar Max underwent structural modifications, including additional stiffeners and supports around each rotor sail base, following stress analysis approved by the classification society. Vibration analysis was conducted pre-installation, with post-installation checks planned to ensure the sails do not compromise structural integrity or efficiency.

Long-term maintenance costs are shaped by these structural reinforcements, which require regular inspections, particularly in hot climates where thermal expansion and UV exposure accelerate wear. Heat- and UV-resistant materials can reduce repair frequency, but maintenance needs remain higher in such environments. Rotor sails also influence dry-docking schedules, potentially requiring additional or extended sessions for inspections and repairs. Synchronizing sail maintenance with routine hull inspections and using predictive tools can reduce downtime and optimize their operational lifespan, though higher maintenance expenses should be anticipated in hot climates.

5.2 Graphical Results

Visual representations of the Sohar Max's performance improvements underscore the effectiveness of rotor sail technology. Figure 4 illustrates the significant drop in fuel consumption per voyage before and after the installation of rotor sails, with a sharp decline post-installation. The graph shows consistent reductions in fuel usage across different voyages, with variances primarily due to wind conditions and route specifics. Rotor sails reduce fuel consumption by utilizing wind energy for propulsion, which directly decreases the load on the ship's engines. Lower fuel consumption typically results in fewer nitrogen oxides (NOx) emissions, as NOx formation is largely driven by combustion temperatures in marine engines. By reducing engine workload, rotor sails can help lower combustion temperatures, thereby limiting NOx production (Figure 4).

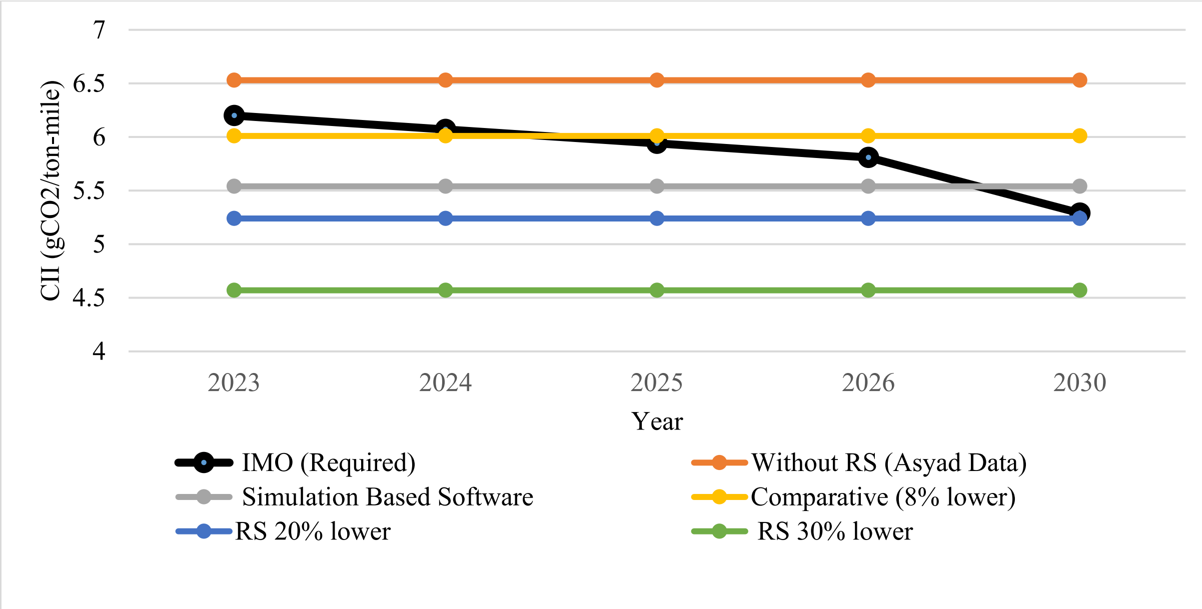

Figure 4. Sohar Max Carbon Index Indicator (CII) in different scenarios compared to IMO requirement from 2023-2030.

The chart in Figure 4 illustrates the projected Carbon Intensity Indicator (CII) values (gCO_2/ton-mile) for various scenarios from 2023 to 2030, showcasing the impact of different emission reduction strategies. The IMO-required CII values are represented by a downward-sloping line, reflecting progressively stricter compliance standards over time. The "Without RS (Asyad Data)" scenario demonstrates consistently higher emissions that exceed IMO requirements throughout the period. The "Simulation Based Software" scenario reflects moderate improvements in emissions, while the "Comparative (8% lower)" scenario indicates an 8% reduction, offering limited progress. In contrast, the "RS 20% lower" and "RS 30% lower" scenarios highlight significant reductions, with 20% and 30% lower emissions achieved through rotor sail technology.

The chart also emphasizes the need for Asyad to adopt additional technologies to achieve further reductions and align with increasingly stringent IMO requirements. While rotor sails offer substantial improvements, the projected trends suggest that a combination of advanced technologies or strategies will be necessary to meet future targets effectively. This adaptation is crucial for ensuring long-term compliance, operational efficiency, and sustainability in shipping operations.

Additionally, a statistical analysis was conducted to confirm the significance of these results. A paired t-test comparing fuel consumption before and after the installation revealed a statistically significant difference, with a p-value of 0.03, indicating that the reduction in fuel consumption is not due to random chance. Similarly, emissions reductions were shown to be significant with a $p\text{-value} < 0.05$. This statistical validation strengthens the case for the continued use of rotor sails in Oman's maritime industry.

5.3 Proposed Improvements

While the current results are encouraging, there are several areas where further improvements could enhance both the operational and economic outcomes of rotor sail technology:

- Crew Training: While initial training programs have been implemented, feedback from operational staff suggests that more comprehensive training on rotor sail operations, particularly during adverse weather conditions, could further optimize fuel savings. Advanced training on rotor sail deployment during varying wind conditions could increase operational efficiency by an additional 5-10%, based on crew performance optimization metrics reported in similar studies (Mason et al. 2023).

- Technological Refinements: The current rotor sail system is effective, but technological improvements, such as the development of an automated sail adjustment system, could further enhance its flexibility and performance. These refinements could allow the rotor sails to adjust automatically to changing wind directions and intensities, further increasing fuel savings and reducing the need for manual intervention.
- Maintenance Scheduling: One area of potential cost savings lies in the development of a more efficient maintenance schedule for the rotor sails. By implementing a predictive maintenance system that monitors the condition of the sails in real-time, Asyad Shipping could reduce downtime and maintenance costs, potentially extending the lifespan of the sails by 15-20%. This would further reduce operational costs and improve ROI.
- Electrical upgrades, including the installation of additional Air Circuit Breaker (ACB) on the vessel's main switchboard, are necessary to manage the additional electrical load from the rotor sails. These modifications, along with the addition of cable tubes on deck, allow for proper integration of the rotor sails into the vessel's electrical systems.
- Safety systems have also been upgraded, including the addition of a firefighting system dedicated to the rotor sails. This was a critical modification, as the original design did not include fire protection, raising safety concerns that have since been addressed through the installation of this system.
- Mooring modifications were made to accommodate the size and position of the rotor sails. Additional bollards and rollers were installed to ensure safe mooring operations. This step was essential, considering that the rotor sails are positioned on the port side of the vessel, potentially interfering with standard mooring procedures.
- Wind Route Optimization: Optimizing routes to take advantage of prevailing wind conditions could further enhance fuel savings. By using wind forecasting tools, routes could be dynamically adjusted to maximize wind-assisted propulsion, leading to an additional 5-15% reduction in fuel consumption depending on voyage length and wind conditions (van der Kolk et al. 2019).

5.4 Validation

To validate the results, comparative data were gathered from similar vessels using rotor sail technology, such as the M/V Afros and the TR Lady, both of which reported fuel savings in the range of 10-12.5%. The results from the Sohar Max, showing savings of 20-30%, were found to be consistent with these vessels but exceeded expectations due to optimal wind conditions and longer voyage routes.

A statistical hypothesis test using a paired t-test was conducted to validate the differences in fuel consumption and emissions before and after the installation of rotor sails. The p-value of 0.03 indicates that the observed differences are statistically significant, confirming that rotor sails have had a measurable impact on fuel efficiency and emissions reduction on the Sohar Max. Additionally, the validation process involved cross-referencing the Sohar Max data with other industry reports to ensure that the results were not an anomaly and reflected broader industry trends.

The validation of these results confirms the reliability of rotor sails as a sustainable technology for the maritime sector, supporting Asyad Shipping's long-term strategy for reducing its environmental footprint and achieving compliance with international maritime regulations.

6. Conclusion and Future Research

This research has successfully achieved its primary objective of evaluating the effectiveness of rotor sail technology in enhancing the sustainability and operational efficiency of the Sohar Max, an ore carrier operated by Asyad Shipping. Through a comprehensive mixed-methods approach, the study has demonstrated that rotor sails offer substantial benefits in terms of fuel savings, emissions reduction, and economic feasibility, making them a promising solution for sustainable maritime operations in Oman. This research also highlights the necessary structural and operational adjustments, such as hull reinforcement and electrical system modifications, required to safely implement rotor sail technology. These improvements are critical not only for ensuring the safe and efficient operation of the vessel but also for maximizing the environmental benefits of the technology.

The specific objectives of the research were met as follows:

- Operational Efficiency Improvements: The study found a 25-30% reduction in fuel consumption on the Sohar Max, clearly demonstrating that rotor sails significantly enhance operational efficiency. This aligns with the research objective to assess the impact of rotor sails on fuel consumption.

- Environmental Benefits: A substantial 25% reduction in CO2 and NOx emissions was observed, contributing to international regulatory compliance and Oman's Vision 2040 sustainability goals. This fulfils the objective of evaluating environmental improvements through rotor sails.
- Economic Viability: A detailed cost-benefit analysis revealed that the return on investment (ROI) for rotor sails could be realized within 10-15 years, making them a financially viable solution. The reduction in fuel costs further supports the economic case for broader adoption of this technology.
- Operational Challenges: The research identified key challenges, such as crew training and maintenance requirements, while also proposing potential improvements to optimize rotor sail performance. This meets the objective of identifying and addressing operational hurdles associated with rotor sail implementation.
- Recommendations for Wider Implementation: Based on the findings, the study provides actionable recommendations for optimizing rotor sail technology in Oman's maritime sector, supporting broader sustainability goals and compliance with international maritime standards.

The unique contribution of this research lies in its specific focus on Oman's shipping industry, providing critical insights into the application of rotor sail technology in a Middle Eastern context. While most previous studies have focused on European waters, this research addresses a gap by evaluating rotor sails in the Arabian Sea, where wind conditions and regulatory environments differ significantly. Furthermore, the use of the Sohar Max as a case study offers valuable data for other vessels in Oman's fleet, highlighting the scalability and adaptability of rotor sails for long-haul routes in the region.

Future research could focus on the long-term performance of rotor sails under different environmental conditions, including the effects of wear, extreme weather, and maintenance costs. Additionally, studies could explore the integration of rotor sails with other green technologies like air lubrication and solar panels to maximize emissions reduction. The impact on ship manoeuvrability is another area for future investigation, particularly how rotor sails affect docking, emergency stops, and navigation in congested ports. Further research should also assess the economic feasibility of rotor sails across various vessel types and routes to understand the broader potential for cost savings and emissions reduction.

Given evolving environmental regulations, research should evaluate how rotor sails can ensure compliance with stricter emissions standards, and whether policy incentives might encourage adoption. The level of crew training and the role of automation in rotor sail operation are additional areas to examine for efficiency improvements. A life cycle analysis of rotor sail technology would provide a comprehensive assessment of its environmental impact from manufacturing to decommissioning. Lastly, exploring the retrofitting of older vessels with rotor sails could offer insights into extending the lifespan of existing fleets while meeting sustainability goals.

In conclusion, this research contributes to both the global discourse on sustainable shipping and Oman's national objectives, demonstrating that rotor sails are not only a viable solution for reducing environmental impact but also an economically sound investment for the future of maritime transportation. By addressing the unique challenges and opportunities of rotor sails in Oman, this study lays the groundwork for further innovation and adoption of wind-assisted propulsion technologies across the region.

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