Decarbonization Potential by Combining Slow Steaming and Wind-Assisted Propulsion Systems: A Case Study of a 6,500 DWT Tanker Operating in Indonesian Waters

Potencijal za dekarbonizaciju kombiniranjem spore plovidbe i pogonskih sustava s pomoću vjetra: Studij slučaja tankera od 6.500 bruto nosivosti u indonezijskim vodama

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Abstract

This study addresses the growing environmental concerns of climate change, which is exacerbated by rising greenhouse gas emissions, particularly in the transportation sector. Maritime shipping, responsible for approximately 2.89% of global CO_2 emissions, is a key contributor to this issue. The International Maritime Organization (IMO) has set ambitious targets to reduce CO_2 emissions from this sector by 40% by 2030 and 100% by 2050, relative to 2008 levels. In response, this study explores the potential of combining two decarbonization strategies, slow steaming and wind-assisted propulsion systems (WAPS), to reduce emissions from maritime transport. The analysis of a 6500-ton DWT tanker operating around Sumatra Island, Indonesia, from July 21, 2023, to July 20, 2024, shows that slow steaming, reducing speed by up to 1 knot, can lead to up to a 20.1% reduction in fuel consumption and carbon emissions, although this results in increased sailing time. The challenge lies in balancing environmental benefits with operational time efficiency. The integration of WAPS, featuring three 250 m² square wingsails, further reduces emissions by 10.3% by harnessing wind power to assist propulsion, without altering the ship's schedule. By combining both strategies, the tanker achieves a total emissions reduction of up to 29.7%, while maintaining operational efficiency. This combined approach offers a promising, sustainable solution for decarbonizing maritime transport and significantly reducing emissions without disrupting time-sensitive operations.

KEY WORDS

decarbonization
slow steaming
wind-assisted propulsion system
tanker ship

Sažetak

Ovaj rad bavi se rastućim ekološkim izazovima uzrokovanim klimatskim promjenama koje dodatno pogoršavaju emisije stakleničkih plinova, osobito u prometnom sektoru. Pomorski prijevoz, koji čini 2,89% globalnih emisija CO_2, značajno pridonosi tom problemu. Međunarodna pomorska organizacija (IMO) postavila je visoke ciljeve smanjenja emisija CO_2 u ovom sektoru – za 40% do 2030. i 100% do 2050. godine u odnosu na razine iz 2008. godine. U skladu s time rad istražuje mogućnost kombiniranja dviju strategija dekarbonizacije – spore plovidbe (slow steaming) i pogonskih sustava s pomoću vjetra (engl. WAPS) – u svrhu smanjenja emisija iz pomorskog prometa. Analiza tankera od 6.500 bruto nosivosti na pravcu oko otoka Sumatre (Indonezija) od 21. srpnja 2023. do 20. srpnja 2024. pokazuje da spora plovidba (smanjenje brzine do 1 čvora) može smanjiti potrošnju goriva i emisije ugljika do 20,1%, ali produljuje vrijeme putovanja. Izazov je uravnotežiti ekološke prednosti i operativnu učinkovitost. Integracija WAPS sustava, s trima krilnima jedrima od 250 m², dodatno smanjuje emisije za 10,3% koristeći se snagom vjetra za pogon, bez utjecaja na red plovidbe. Kombinacijom obiju strategija tanker postiže ukupno smanjenje emisija do 29,7%, uz očuvanje operativne učinkovitosti. Ovaj pristup nudi obećavajuće, održivo rješenje za dekarbonizaciju pomorskog prometa, bez narušavanja vremenski osjetljivih operacija.

KLJUČNE RIJEČI

dekarbonizacija
spora plovidba
pogonski sustav s pomoću vjetra
tanker

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1. INTRODUCTION / *Uvod*

Climate change has become an urgent global issue, with its impacts manifesting in extreme temperature fluctuations, rising sea levels, floods, droughts, storms, wildfires, landslides, and polar ice melting [1-3]. Recognizing the severity of the crisis, the United Nations (UN) established the Intergovernmental Panel on Climate Change (IPCC) in 1988 to conduct comprehensive research on climate-related phenomena [4]. This was followed by the creation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, which provided a platform for international negotiations on climate agreements. The first Conference of the Parties (COP-1) was held in Berlin, Germany, in 1995, marking the beginning of structured climate discussions. A major milestone was reached at COP-3 in 1997 in Kyoto, Japan, leading to the Kyoto Protocol, which set binding emission reduction targets for developed nations. Further progress was made at COP-21 in 2015 in Paris, France, where the Paris Agreement was adopted, establishing global commitments to limit temperature increases to well below 2°C, with efforts to cap it at 1.5°C relative to pre-industrial levels [5].

Among various sectors, transportation significantly contributes to greenhouse gas (GHG) emissions, accounting for approximately 16.2% of total emissions worldwide, with maritime transport responsible for around 1.7% [6]. Despite its lower proportion compared to other transport sectors, maritime shipping facilitates over 80% of global trade, leading to approximately 2.89% of total CO_2 emissions [7]. Without intervention, emissions from this sector are projected to increase by 50% to 250% by 2050 [8]. In response, the International Maritime Organization (IMO) has set progressive targets to reduce CO_2 emissions from maritime transport by 40% by 2030 and 100% by 2050, based on 2008 levels.

To align with these regulatory frameworks, multiple strategies have been explored to enhance ship energy efficiency and mitigate CO_2 emissions. Design-phase improvements, such as hull form selection [9-11] and hull optimization [12, 13]. For operational vessels, energy efficiency and decarbonization can be enhanced through various techniques, including microbubble injection around the hull [14], the application of antifouling coatings [15, 16], and slow steaming, which involves reducing vessel speed below its designated service speed [17], these conditions is applied to achieve fuel efficiency under low RPM conditions of the ship, where sailing at an optimal speed enhances fuel efficiency and reduces emissions [18]. Besides, there is renewed interest in alternative propulsion technologies, particularly wind energy. Wind-assisted ship propulsion (WASP) systems, utilized as either primary or auxiliary propulsion sources, offer a promising solution by reducing fuel consumption and associated emissions [19, 20].

Based on the solutions outlined above, this study proposes combining the slow steaming strategy in ship operations with the addition of sails as a wind-assisted propulsion system by assessing emissions over a year of operation, with a 6,500-ton DWT tanker operating in Indonesian waters as the case study.

2. METHODS / *Metode*

2.1. Decarbonization Calculations / *Izračuni dekarbonizacije*

Carbon emissions (E) are determined by multiplying fuel consumption (FC) by a carbon factor (C_F), a coefficient that represents the amount of carbon dioxide released per unit of fuel burned by main engine, considering the fuel type and its specific combustion properties [21].

$$E = FC \, . \, C_F \tag{1}$$

Meanwhile, for decarbonization by implementing slow steaming (ΔE_{SS}), wind assisted propulsion (ΔE_{WASP}), and combination of both stragies ($\Delta E_{SS+WASP}$) are calculated using equations (2) to equation (4),

$$\Delta E_{SS} = (FC - FC_{SS}) \, . \, C_F \tag{2}$$

$$\Delta E_{WASP} = (FC - FC_{WASP}) \, . \, C_F \tag{3}$$

$$\Delta E_{SS+WASP} = (FC - FC_{SS+WASP}) \, . \, C_F \tag{4}$$

where FC is fuel consumption under normal condition, FC_{SS} is fuel consumption under slow steaming condition, FC_{WASP} is fuel consumption with wind assisted propulsion system, and $FC_{SS+WASP}$ is fuel consumption with combination of slow steaming and wind assisted propulsion system. The fuel oil consumption of each conditions are presented in equation (5) to equation (8).

$$FC = \sum_{i=1}^{n} \left(\left(R_{Ti} \, . \, v_{si} / \eta_p \right) \, t_i \, . \, SFC \right) \tag{5}$$

where R_{Ti} represents the total resistance at segment-i route under normal operational conditions, v_{si} is ship speed at segment-i route under normal condition, t_i is ship sailing time duration at segment-i route under normal condition, η_p is the overall propulsion efficiency, and SFC is the specific fuel consumption of the main engine.

Under slow steaming condition, fuel consumption (FC_{SS}) is represented by equation (6), where R_{TSSi} represents the total resistance at segment-i route under slow steaming conditions, v_{ssi} is ship speed at segment-i route under slow steaming condition, and t_{ssi} is ship sailing time duration at segment-i route under slow steaming condition.

$$FC_{SS} = \sum_{i=1}^{n} \left(\left(R_{TSSi} \, . \, v_{SSi} / \eta_p \right) \, t_{ssi} \, . \, SFC \right) \tag{6}$$

While, fuel consumptions under normal condition with WAPS and under slow steaming condition with WASP are represented by equation (7) and (8) respectively.

$$FC_{WAPS} = \sum_{i=1}^{n} \left(\left((R_{Ti} - T_i) \, v_{si} / \eta_p \right) \, t_i \, . \, SFC \right) \tag{7}$$

$$FC_{SS+WAPS} = \sum_{i=1}^{n} \left(\left((R_{TSSi} - T_i) \, v_{SSi} / \eta_p \right) \, t_{ssi} \, . \, SFC \right) \tag{8}$$

where T_i is the sail thrust at segment-i route.

2.2. Sail Thrust Calculation / *Izračun potiska jedra*

The forces acting on the sail are illustrated in Figure 1. The thrust (T) generated by the sail is the component in ship direction of the resultant force (R) of lift (L) and drag (D). Additionally, the R also produces a side force (S).

L and D are generated by the sail at an angle α relative to the direction of the apparent wind with velocity v_a. The apparent wind velocity v_a is the resultant of the true wind velocity (v_w) and the ship's velocity (v_s). The angle between v_a and v_s is denoted as β, while the angle between v_w and v_s is represented as θ.

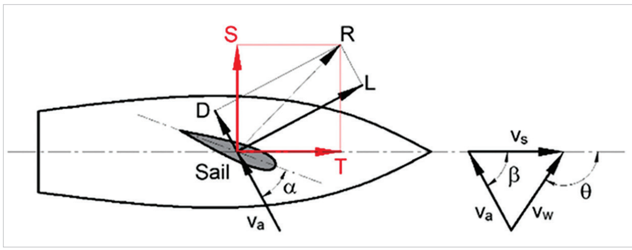


Figure 1 Sailing vessel forces

Slika 1. Sile koje djeluju na jedrilicu

T and *S* can be calculated by using equation (9) and equation (10).

$$T = L \,.\, \sin\beta - D \,.\, \cos\beta \tag{9}$$

$$S = L \,.\, \cos\beta + D \,.\, \sin\beta \tag{10}$$

where,

$$\beta = \cos^{-1}\left((v_w \,.\, \cos\theta + v_s)/v_a\right) \tag{11}$$

$$v_a = \sqrt{(v_w^2 + v_s^2 + 2 \,.\, v_w \,.\, v_s \cos\theta)} \tag{12}$$

$$L = 0.5 \,.\, \rho \,.\, v_a^2 \,.\, A_s \,.\, C_L \tag{13}$$

$$D = 0.5 \,.\, \rho \,.\, v_a^2 \,.\, A_s \,.\, (C_D + C_{Di}) \tag{14}$$

$$C_{Di} = C_L^2/(\pi \,.\, AR \,.\, e) \tag{15}$$

A_s is sail area, C_L represent the lift coefficient of wingsails, C_D is drag coefficients of wingsails, and C_{Di} refers to the induced drag considering the three-dimensional shape of the wingsail. *AR* is sail aspect ratio and *e* is efficiency factor.

2.3. Slow Steaming Operational Conditions Set-Up / *Postavljanje radnih uvjeta za sporu plovidbu*

In this study, the variation of slow steaming is applied to a ship operating at normal speed, with speed reductions of up to 1 knot, decreasing in increments of 0.2 knots.

2.4. Limitation / *Ograničenja*

In this study, several limitations are applied. For the carbon emission calculation, emissions are considered only from the main engine. The weight of the wind-assisted propulsion system is not taken into account in its effect on the ship's resistance. Similarly, the side force generated by the ship is not considered in its impact on resistance. Additionally, the influence of the sail's construction and the side force produced by the wingsail on the ship's stability is not addressed in this study.

3. RESULTS AND DISCUSSION / *Rezultati i rasprava*

3.1. Case Study / *Studija slučaja*

3.1.1. Ship Particulars / *Tehničke specifikacije broda*

This paper presents a case study of a 6,500-ton DWT tanker, with the details provided in Table 1 and Figure 2. Additionally, the ship's resistance data is presented to support decarbonization calculations, as illustrated in Figure 3.

Table 1 Ship Particulars

Tablica 1. Tehničke specifikacije broda

Ship Particulars	Value
Length Between Perpendiculars, LBP (m)	102
Breadth, B (m)	19.2
Height, H (m)	9.3
Draught, T (m)	8
Service Speed, v_s (knots)	12
Main Engine	Wartsila W6L32 3480 kW @ 750 rpm

Figure 2 A 6500-ton DWT tanker [22]

Slika 2. Tanker od 6.500 bruto nosivosti [22]

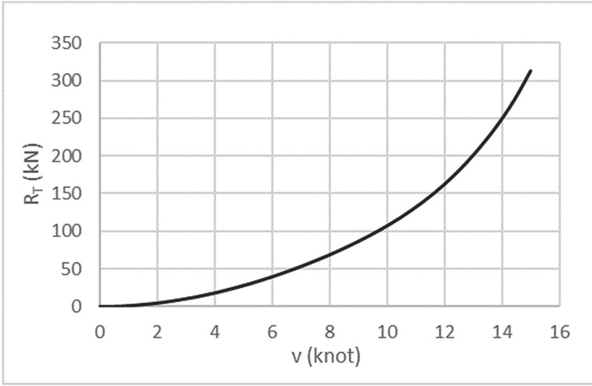


Figure 3 Total resistance (R_T) of 6500 DWT ton tanker with function of speed (v)

Slika 3. Ukupni otpor (RT) tankera od 6.500 bruto nosivosti u funkciji brzine (v)

3.1.2. Configuration of Wingsails as a Wind-Assisted Propulsion System / *Konfiguracija krilnih jedara kao pogonskog sustava s pomoću vjetra*

The wingsail configuration is derived from [23], featuring a three-wingsail design with a NACA-0012 airfoil cross-section and a rectangular shape. It has an aspect ratio (*AR*) of 2.5, and each wingsail covering an area (A_s) of 250 m^2 as presented in Figure 4.

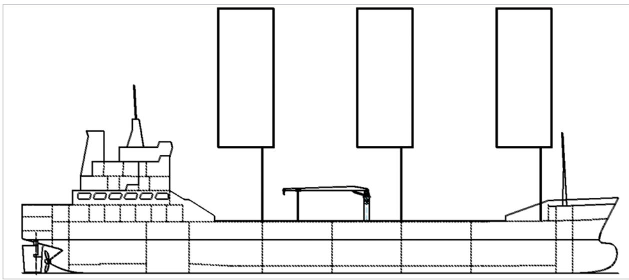
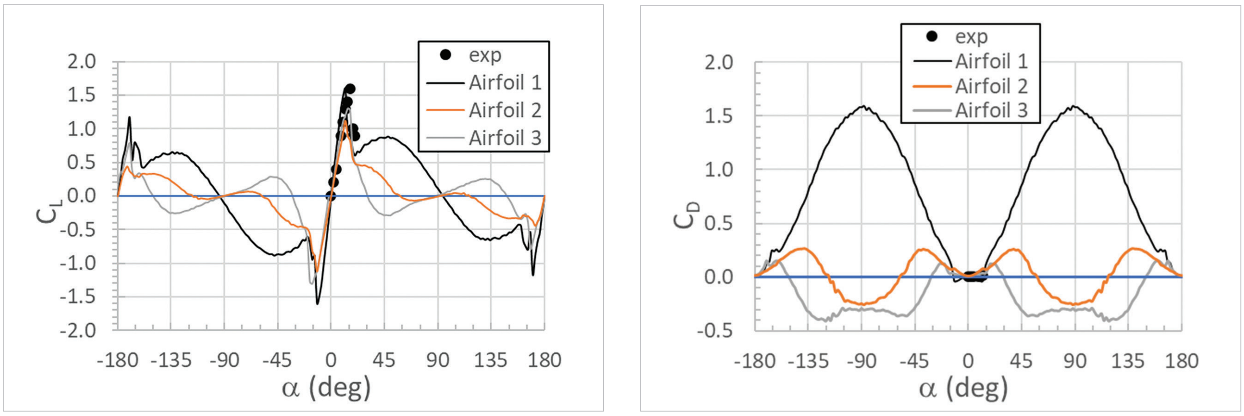


Figure 4 Wingsails configuration

Slika 4. Konfiguracija krilnih jedara

The lift and drag coefficient of that configuration (C_L and C_D) as presented in Figure 5. Figure 5(a) shows the variation of C_L of each two-dimension wingsail (airfoil) with respect to the wingsail angle relative to the apparent wind direction (α). C_L for Airfoil 1 (black line) is the lift coefficient for the wingsail located at the front near the ship's bow, C_L for Airfoil 2 (red line) is the lift coefficient for the wingsail located in the middle, and C_L for Airfoil 3 (blue line) is the lift coefficient for the wingsail at the rear, near the ship's accommodation area. While Figure 5(b) illustrates the variation of C_D.



(a) (b)

Figure 5 Lift and Drag Coefficient (a) C_L (b) C_D [22]

Slika 5. Koeficijenti uzgona i otpora: (a) CL (b) CD [22]

3.1.3. Ship Routes / *Pomorski pravci*

In this study, the ship is operating in Indonesian waters along a route around Sumatra Island over a one-year period, starting from July 21, 2023, to July 20, 2024. The ship's route are shown in Figure 6.

Figure 5 illustrates the route, which is divided into two paths: the southern route of Sumatra Island (red line) and the northern route (blue line). The southern route is taken by the ship from July 21, 2023, until approximately April 20, 2024, while the northern route is followed from around April 21, 2024 to July 20, 2024.

3.1.4. Voyage Data / *Podaci o plovidbi*

To quantify the contribution of slow steaming and application of wind assisted propulsion system to the decarbonization, it is essential to consider the ship's voyage data which covers ship speed and its direction and also wind speed and its direction. For this case, the data which are collected starts from July 21, 2023, to July 20, 2024 [24, 25].

Figure 7 illustrates the ship speed (solid blue circle) and wind speed (hollow orange triangle) over the course of one year, from July 21, 2023, to July 20, 2024. Generally, as shown in Figure 7, the ship's speed predominantly ranges from 10 knots to 12 knots, while the wind speed is mostly below 8 knots. In some data, it is observed that the ship's speed is 0 (zero), as is the wind speed. A ship speed of 0 (zero) indicates that the ship is either moored or at anchored.

Figure 8 shows the ship's direction (solid blue circle) and wind direction (hollow orange triangle) over the course of one year. Based on Figure 8, it can be observed that throughout the year, the ship primarily sails at angles between 300°-350° (heading northwest) and 100°-150° (heading southeast) for numerous round trips, both on the southern route of Sumatra Island (from July 21, 2023, to around April 20, 2024) and the northern route of Sumatra Island (from April 21 to July 21, 2024). Meanwhile, the wind direction is distributed across an angle range of 0° to 360°.

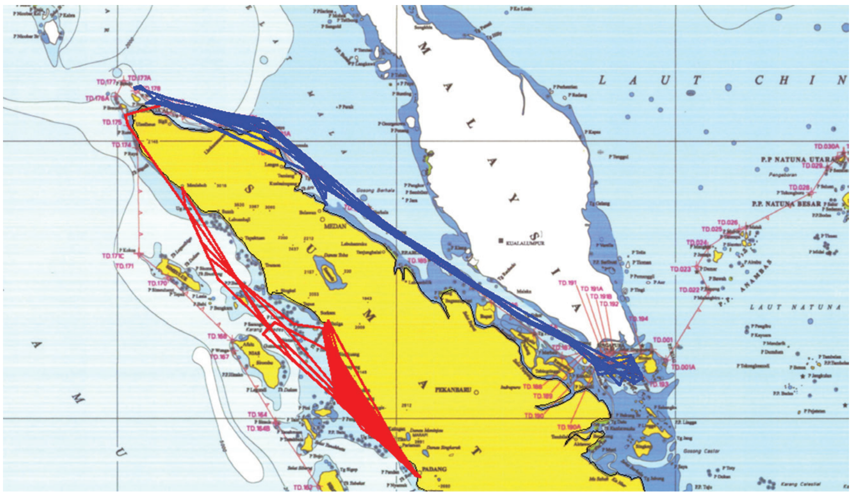


Figure 6 Ship's routes

Slika 6. Pomorski pravci

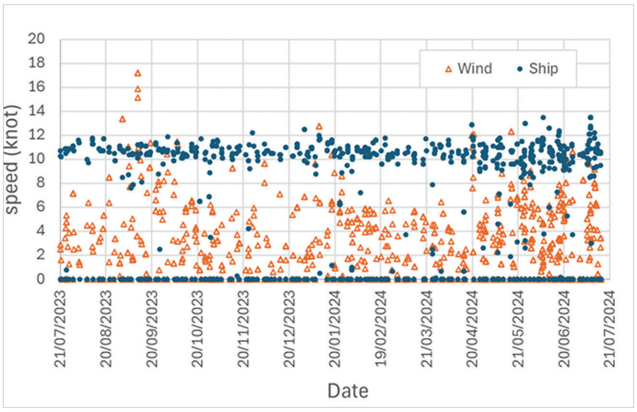


Figure 7 Ship and wind speed
Slika 7. Brzina broda i vjetra

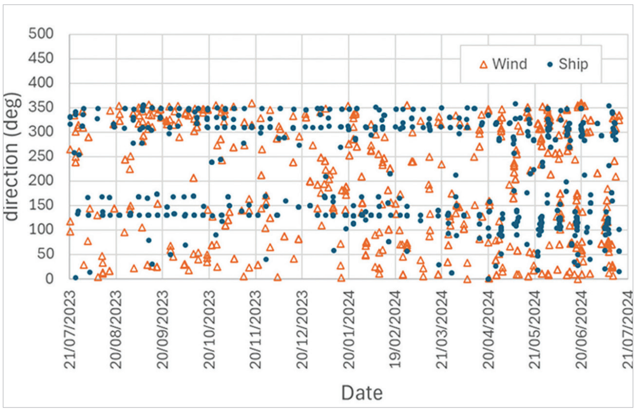
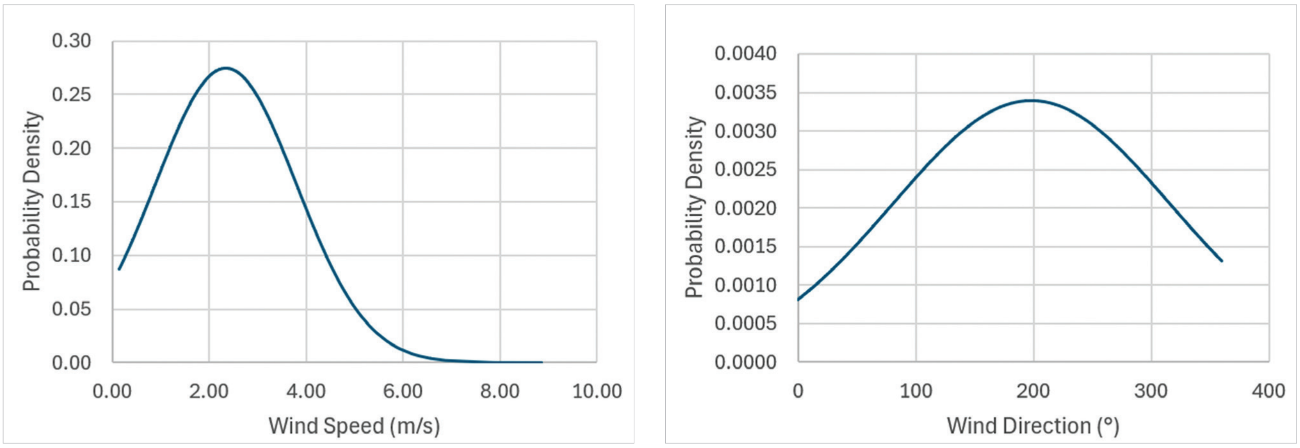


Figure 8 Ship and wind direction
Slika 8. Smjer broda i vjetra



(a) (b)

Figure 9 Normal distribution (a) wind speed (b) wind direction
Slika 9. Normalna distribucija: (a) brzina vjetra (b) smjer vjetra

Particularly for wind speed and direction, the statistical probability of their occurrence is presented in Figure 9. Figure 9(a) illustrates the normal distribution of wind speed events over the course of one year of navigation, where the x-axis represents wind speed and the y-axis denotes probability density. Meanwhile, Figure 9(b) shows the normal distribution of wind direction events over the same period, with the x-axis representing wind direction and the y-axis indicating probability density. From Figure 9(a), it can be observed that the average wind speed over one year is approximately 2.4 m/s. As for wind direction, the average is around 200°, as depicted in Figure 9(b).

3.2. Ship's Carbon Emission Under Normal Operational Condition / *Emisija ugljika pri uobičajenim radnim uvjetima*

Based on the voyage data and emission calculation formulas, the carbon emission under normal conditions can be determined. Figure 10 shows the trends of carbon emissions, fuel consumption, and sailing days for each month, where the x-axis represents the division of each month starting from July 21, 2023, to July 20, 2024. The left y-axis displays fuel consumption and carbon emissions for each month, while the right y-axis shows the sailing days for each month.

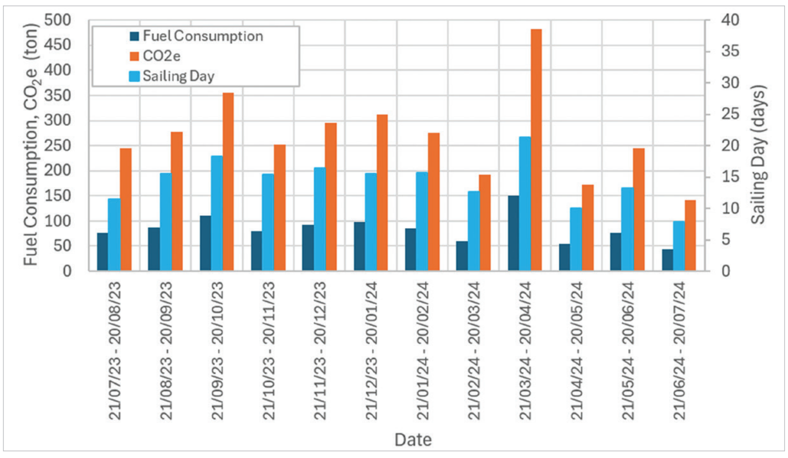


Figure 10 Monthly CO_2e, fuel consumption, and sailing day
Slika 10. Mjesečne vrijednosti CO_2e, potrošnja goriva i dan plovidbe

From Figure 10, it can be seen that carbon emissions fluctuate in line with fuel oil consumption, while fuel oil consumption follows the duration of the sailing days. The highest emissions occur during the period from March 21 to April 20, 2024, reaching approximately 480 tons of CO_2e, with a fuel consumption of about 150 tons and 21 sailing days. The lowest emissions are observed between June 21 and July 20, 2024, with emissions around 140 tons of CO_2e, fuel consumption of approximately 44 tons, and 8 sailing days. The accumulation of carbon emissions, fuel oil consumption, and sailing days for the period of one year, from July 21, 2023, to July 20, 2024, can be seen in Figure 11.

Figure 11 presents the accumulation of carbon emissions (represented by the orange line) and fuel consumption (represented by the blue line), which are shown on the left ordinate. Meanwhile, the sailing days (represented by the green line) are shown on the right ordinate. Based on Figure 11, it can be seen that at the end of the year, specifically on July 20, 2024, the total carbon emissions amount to approximately 3,244 tons, total fuel consumption is around 1,014 tons, and the total sailing days of the ship over the year is approximately 173 days. Additionally, it is observed that the accumulation lines for both carbon emissions and fuel consumption are not smooth (they fluctuate), which is due to the varying sailing days (fluctuating) for each ship movement, as well as changes in the ship's speed, causing it to not remain constant, as can be seen in the ship's speed data in Figure 7.

The fluctuations in the accumulation of carbon emissions and fuel consumption reflect the dynamic nature of ship operations. The variability in sailing days throughout the year indicates that the ship's operational patterns, such as the frequency and length of voyages, are not constant. This irregularity leads to inconsistent fuel usage and, consequently, fluctuating emissions. The ship's speed, which changes as seen in Figure 7, further impacts fuel efficiency, with higher speeds generally resulting in greater fuel consumption and higher emissions. These factors highlight the need for optimizing operational conditions, such as route planning and speed management, to reduce emissions and fuel consumption over time.

3.3. Decarbonization by Implementing Slow Steaming / *Dekarbonizacija primjenom spore plovidbe*

One of the strategies for reducing carbon emissions (decarbonization) is speed management, one of which involves reducing the ship's speed or implementing slow steaming. Figure 12 shows the annual carbon emissions (orange line), annual fuel consumption (blue line), and annual sailing days (green line). The x-axis represents the reduction in speed (slow steaming) down to 1 knot, with a 0.2 knot interval. The left y-axis indicates the annual carbon emissions and fuel consumption, while the right y-axis shows the annual sailing days.

Figure 12 indicates a clear trade-off between fuel consumption reduction, carbon emissions reduction, and the impact on sailing days as the speed is reduced. As the speed reduction increases, fuel consumption and carbon emissions decrease, but the time required to complete the journey increases.

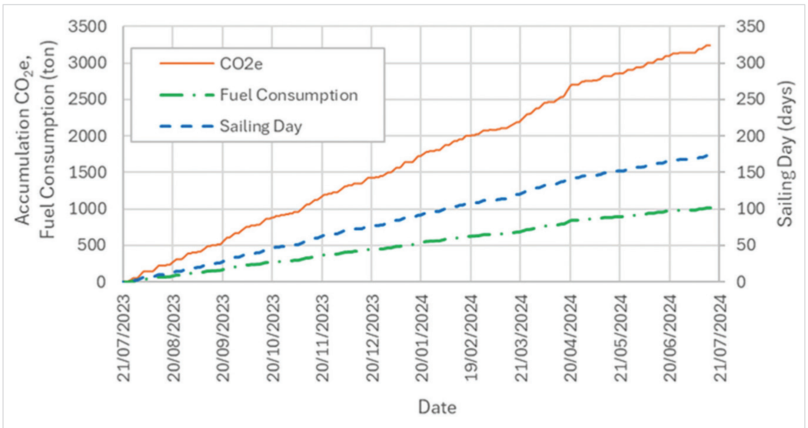


Figure 11 Accumulation of CO_2e, fuel consumption, and sailing days during a year operation
Slika 11. Akumulacija CO_2e, potrošnja goriva i dan plovidbe tijekom jednogodišnjeg rada

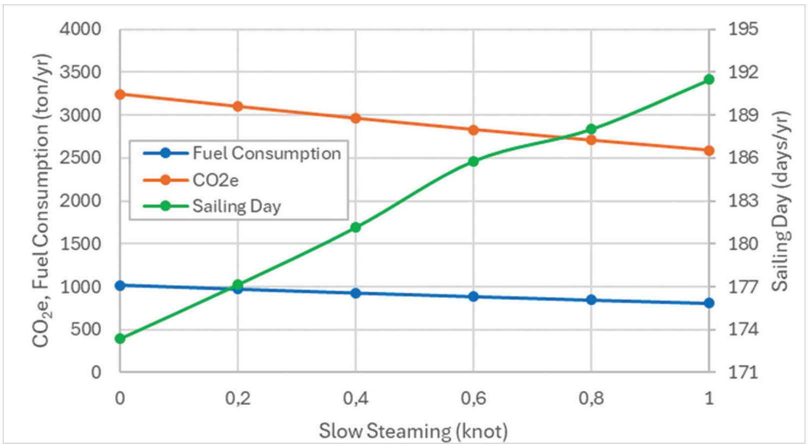


Figure 12 Annual CO_2e, fuel consumption, and sailing day by implementing slow steaming
Slika 12. Godišnje vrijednosti CO_2e, potrošnja goriva i dan plovidbe primjenom spore plovidbe

Table 2 Decarbonization by implementing slow steaming
Tablica 2. Dekarbonizacija primjenom spore plovidbe

Item	Speed Reduction (knot)					
	0	0,2	0,4	0,6	0,8	1,0
Annual Sailing Day (days)	173,4	177,1	181,2	185,8	188,0	191,5
Anuual FC (ton)	1013,8	968,7	925,7	884,8	846,1	809,6
Annual CO2e (ton)	3244,3	3099,8	2962,3	2831,4	2707,5	2590,6
Δ Annual Sailing Day (days)	0,0	3,8	7,8	12,4	14,7	18,1
Δ Annual FC (ton)	0,0	-45,1	-88,1	-129,0	-167,8	-204,3
Δ Annual Decarbonization (ton)	0,0	-144,5	-282,0	-412,9	-536,8	-653,7
Decarbonization (%)	0,0%	4,5%	8,7%	12,7%	16,5%	20,1%

As can be seen in Table 2, with a 0.2 knot speed reduction, fuel consumption is reduced by approximately 45.1 tons, leading to a 4.5% decrease in carbon emissions (144.5 tons). However, this reduction adds around 3.8 extra sailing days annually, demonstrating that while there are environmental benefits, the operational efficiency in terms of time is slightly compromised.

Increasing the speed reduction to 0.4 knots results in a more significant decrease in fuel consumption (88.1 tons) and a greater reduction in emissions (8.7% or 282 tons). However, this comes with an additional 7.8 sailing days, indicating that the benefits in terms of emissions reduction are achieved at the less operational efficient of travel times.

A 0.6 knot reduction brings a notable decrease in fuel consumption (129 tons) and emissions (12.7% or 412.9 tons), but it also adds 12.4 extra sailing days. As the speed reduction increases, the benefits in emission reductions become more substantial, but the operational efficiency in terms of time decreases further.

Reducing the speed by 0.8 knots results in a fuel consumption reduction of 167.8 tons and an emission decrease of 16.5% (536.8 tons). This more significant reduction in emissions, however, leads to an increase of 14.7 sailing days, further highlighting the time trade-off associated with greater decarbonization efforts.

Finally, a 1 knot speed reduction leads to the highest reduction in fuel consumption (204.3 tons) and carbon emissions (20.1% or 653.7 tons). However, this comes at the lowest efficient in terms of additional sailing days (18.1 days), demonstrating that while the environmental benefits are the greatest, the impact on operational time is most significant.

3.4. Decarbonization by Implementing Wind Assisted Propulsion System / *Dekarbonizacija primjenom pogonskog sustava s pomoću vjetra*

In addition to slow steaming, decarbonization efforts can also be achieved by incorporating a Wind Assisted Propulsion System (WAPS). While slow steaming involves internal factors that can be directly controlled by reducing the ship's speed, the addition of WAPS relies not only on internal factors, such as the ship's speed, but also heavily depends on external conditions, particularly the wind speed and direction along the ship's route. In this case, the accumulated carbon emission over one year resulting from the addition of WAPS under normal sailing condition compared to the ship without WAPS can be seen in Figure 13.

Figure 13 presents a comparison of the accumulated carbon emissions produced by the ship under normal operational conditions, both without WAPS (black line) and with WAPS (red line). As shown in Table 3, the accumulation of carbon emissions with WAPS is lower than without WAPS, where the carbon emissions without WAPS amount to 3244.3 tons, while with WAPS, the carbon emissions are 2909.8 tons. This indicates that the addition of WAPS results in a decarbonization of 334.5 tons, or a 10.3% reduction. It should be noted that the contribution of WAPS in this case is based on the assumption that, at certain points during the ship's journey, if the sails become ineffective or actually increase emissions, they will be deactivated. However, the technical details of deactivating the sails are not covered in this paper.

In addition, from Table 3, the 10.3% reduction in emissions (decarbonization) corresponds to a fuel reduction of 104.5 tons

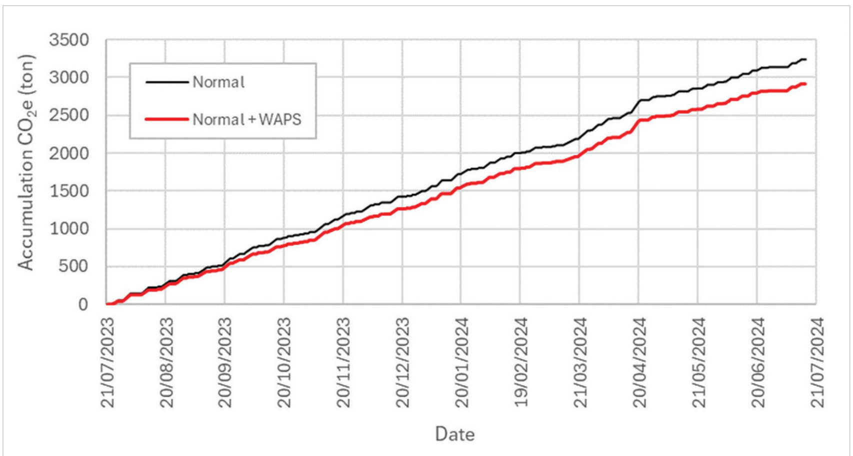


Figure 13 Accumulation CO2e with and without WAPS
Slika 13. Akumulacija CO_2e s WAPS-om i bez njega

while maintaining the ship's speed under normal operational conditions, resulting in no change in sailing days, which remains at 173.4 days per year.

Table 3 Decarbonization by implementing WAPS
Tablica 3. Dekarbonizacija primjenom WAPS-a

Item	Normal	Normal + WAP
Annual Sailing Day (days)	173,4	173,4
Anuual FC (ton)	1013,8	909,3
Annual CO2e (ton)	3244,3	2909,8
Δ Annual Sailing Day (days)	0,0	0,0
Δ Annual FC (ton)	0,0	-104,5
Δ Annual Decarbonization (ton)	0,0	-334,5
Decarbonization (%)	0,0%	-10,3%

From the above data reveals a clear benefit of incorporating Wind Assisted Propulsion System (WAPS) in terms of reducing carbon emissions. When compared to the ship operating under normal conditions without WAPS, the ship equipped with WAPS shows a significant reduction in accumulated carbon emissions. The decarbonization is achieved through the reduction in fuel consumption, while the ship's speed is maintained under normal operational conditions. A key advantage of this approach is that it results in no additional sailing days; the ship's operational efficiency remains unchanged. This suggests that the use of WAPS can provide significant environmental benefits without negatively impacting the time required for the ship's journey.

3.5. Decarbonization by Implementing Slow Steaming and WAPS / *Dekarbonizacija primjenom spore plovidbe i WAPS-a*

In this part, the combination of slow steaming and Wind Assisted Propulsion System (WAPS) is applied. Figure 14 presents a comparison between annual carbon emissions with the implementation of slow steaming only (orange line) and annual carbon emissions with the implementation of both slow steaming and WAPS (orange dashed line), annual fuel consumption with the implementation of slow steaming only (blue line) and annual fuel consumption with the implementation of both slow steaming and WAPS (blue dashed line), as well as sailing days (green line).

Without changing the sailing days, it can be observed that carbon emissions and fuel consumption can be further reduced with the installation of WAPS. The reduction in emissions (decarbonization) achieved ranges from 10.3% to 29.7% (Table 3).

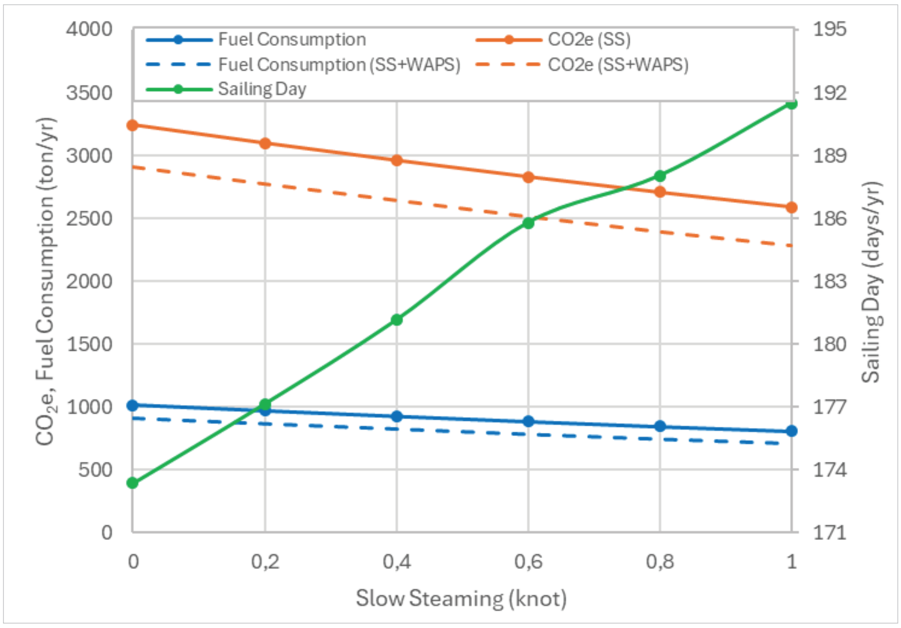


Figure 14 Annual CO_2e, fuel consumption, and sailing day by implementing SS and WAPS
Slika 14. Godišnje vrijednosti CO_2e, potrošnja goriva i dan plovidbe primjenom spore plovidbe (SS) i WAPS-a

Table 4 Decarbonization by implementing slow steaming and WAPS
Tablica 4. Dekarbonizacija primjenom spore plovidbe i WAPS-a

Item	Speed Reduction (knot) +WAPS					
	0	0,2	0,4	0,6	0,8	1,0
Annual Sailing Day (days)	173,4	177,1	181,2	185,8	188,0	191,5
Anuual FC (ton)	909,3	866,8	825,8	785,0	747,2	712,6
Annual CO2e (ton)	2909,8	2773,6	2642,7	2512,1	2391,1	2280,4
Δ Annual Sailing Day (days)	0,0	3,8	7,8	12,4	14,7	18,1
Δ Annual FC (ton)	-104,5	-147,1	-188,0	-228,8	-266,6	-301,2
Δ Annual Decarbonization (ton)	-334,5	-470,7	-601,6	-732,2	-853,2	-963,9
Decarbonization (%)	-10,3%	-14,5%	-18,5%	-22,6%	-26,3%	-29,7%

The combination of slow steaming and WAPS provides valuable insights into how the integration of WAPS enhances the benefits of slow steaming, particularly in reducing both carbon emissions and fuel consumption, without impacting the sailing days. Comparing the annual carbon emissions and fuel consumption in both scenarios (slow steaming alone and slow steaming combined with WAP) clearly demonstrates the positive effect of WAPS. By incorporating WAPS into the slow steaming strategy, both carbon emissions and fuel consumption are significantly lowered.

The particularly noteworthy is that, despite the reduction in carbon emissions and fuel consumption with WAPS, the sailing days remain unchanged. This indicates that the use of WAPS does not require additional time for the ship's journey, making it an efficient solution for decarbonization without affecting operational schedules.

4. CONCLUSIONS / *Zaključak*

In conclusion, the analysis of a 6500-ton DWT tanker operating around Sumatra Island, Indonesia, from July 21, 2023, to July 20, 2024, reveals that implementing slow steaming, with a speed reduction of up to 1 knot, leads to a significant decrease in both fuel consumption and carbon emissions, with reductions of up to 20.1%. However, this comes with the trade-off of increased sailing time. The challenge lies in balancing the environmental benefits of reduced emissions with the operational need for time efficiency. Identifying the optimal speed reduction is crucial to maximizing environmental benefits while maintaining operational schedules, which can be effectively achieved by combining it with weather routing.

The implementation of the Wind Assisted Propulsion System (WAPS), equipped with three square wingsails totaling 250 m^2 in surface area, significantly supports the ship's decarbonization efforts. By capturing and utilizing wind energy to provide additional thrust, WAPS reduces the demand on the main engine, leading to decreased fuel consumption. This assisted propulsion achieves an estimated 10.3% reduction in greenhouse gas emissions. Notably, WAPS operates without requiring changes to the vessel's schedule, ensuring that voyage timelines and operational efficiency remain unaffected. Its seamless integration into existing systems makes it an attractive solution for shipping companies seeking to lower their environmental impact while maintaining reliability and performance. Furthermore, WAPS offers a practical and scalable approach to emission reduction that aligns with international efforts to decarbonize the maritime industry. As environmental regulations grow stricter, the adoption of WAPS becomes increasingly valuable in promoting sustainable and responsible maritime operations.

The combination of WAPS and slow steaming presents a highly effective approach to reducing both carbon emissions and fuel consumption in the maritime sector, with potential savings of up to 29.7%. This integrated strategy enhances energy efficiency while preserving the operational reliability of shipping services. By utilizing wind power through WAPS and reducing vessel speed via slow steaming, fuel demand is significantly lowered without disrupting voyage schedules. As a result, this dual-method approach offers a practical and sustainable solution to environmental challenges in maritime transport. It supports industry efforts to meet stricter emissions regulations without sacrificing performance or punctuality, making it particularly suitable for time-sensitive operations. This synergy between technological innovation and operational adjustment represents a forward-looking pathway for greener shipping. Overall, the adoption of both WAPS and slow steaming contributes meaningfully to the decarbonization of marine transportation, promoting long-term sustainability and environmental stewardship across the industry.

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