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The Analysis of Performance Solar Panel Placement on the Deck House Fishing Vessel (30 GT) on Fishing Operation

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Abstract**—** The adoption of renewable energy technologies in fishing vessels has attracted increasing attention as a strategy to improve operational sustainability and reduce dependence on conventional fuel-based energy systems. However, the installation of photovoltaic systems on deckhouse structures may alter vessel weight distribution and potentially affect safety-related performance. This study aims to evaluate the influence of deckhouse-mounted solar panels on the stability characteristics and operational performance of a 30 GT fishing vessel. The investigation was conducted using secondary vessel data and numerical simulations in Maxsurf software. Stability performance was assessed using the A.N. Krylov method and verified against the International Maritime Organization (IMO) Intact Stability Criteria, while seakeeping characteristics were analyzed using strip theory and the JONSWAP wave spectrum under various loading conditions and wave environments. The results show that solar panel installation produces only minor increases in the vessel's vertical center of gravity and causes slight reductions in metacentric height and righting arm values. Nevertheless, all investigated loading conditions satisfy the IMO Intact Stability Criteria and Severe Wind and Rolling Criterion. Seakeeping analysis indicates that vessel motion responses are governed primarily by wave height and wave encounter angle rather than by the solar panel installation itself. The vessel maintains acceptable operational performance under most operating conditions, with beam seas and head seas representing the most critical scenarios. These findings demonstrate that deckhouse-mounted photovoltaic systems can be integrated into a 30 GT fishing vessel without significantly compromising stability performance or seakeeping characteristics, thereby supporting the development of safer and more sustainable fishing vessel operations.

Keywords—Fishing Vessel, Solar Panel, Stability, Ship Motion

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I. INTRODUCTION

The sustainability and productivity of coastal fisheries are closely linked to the performance of fishing vessels, which serve as the primary means for harvesting marine resources and supporting fishing-dependent communities. Beyond fulfilling operational functions, these vessels are required to maintain adequate levels of safety, reliability, and efficiency while operating in highly variable marine environments. Consequently, vessel design must account for factors such as loading conditions, structural configuration, and stability performance to ensure safe and effective operations throughout different stages of a fishing mission [1], [2].

Safety considerations are particularly critical within the fishing sector, which continues to be recognized as one of the most dangerous maritime occupations. Exposure to harsh weather, rough sea states, and extended offshore operations increases the likelihood of accidents and operational failures. Reports documenting casualty rates among fishing crews indicate that fatalities remain significantly higher than those observed in many other industries, highlighting the necessity of improving vessel seaworthiness and operational resilience [5], [6]. For this reason, compliance with established safety standards, especially those governing stability and vessel motion behavior, represents a fundamental requirement in fishing vessel design.

Parallel to these safety concerns, increasing environmental awareness and the global commitment to reducing greenhouse gas emissions have stimulated interest in renewable energy technologies for maritime applications. Efforts aimed at decreasing fuel consumption and mitigating environmental impacts have encouraged the exploration of alternative onboard energy sources, including photovoltaic systems, wind-assisted technologies, hybrid propulsion arrangements, and battery-based solutions. Among these options, solar energy has emerged as one of the most practical alternatives due to its accessibility, relatively low maintenance demands, and capability to supplement onboard power requirements [17].

Technological advancements in photovoltaic systems have facilitated their integration into a wide range of marine platforms, including ferries, passenger vessels, recreational craft, and fishing vessels [2], [4]. Existing investigations have demonstrated that solar energy can effectively contribute to onboard electrical supply while reducing reliance on conventional fuel-based power generation. Studies conducted by Sudjasta et al. [2] and Sunaryo et al. [4] confirmed the technical feasibility of solar panel implementation in fishing-related

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applications, whereas Salem and Seddiek [17] emphasized the environmental and economic advantages associated with renewable energy utilization in marine transportation systems. Although these studies provide valuable insights regarding energy performance, their analyses predominantly focus on power generation efficiency and economic benefits, leaving vessel safety considerations largely unexplored.

From a naval architecture perspective, the incorporation of photovoltaic systems introduces additional loads that may alter both hydrostatic and hydrodynamic characteristics. To maximize solar radiation exposure, panels are commonly positioned on deckhouses, wheelhouses, or elevated supporting structures. Such arrangements increase the concentration of weight above the main deck and may result in a higher vertical center of gravity. As a consequence, modifications in weight distribution can influence stability properties, righting capability, and wave-induced motion responses. These effects become increasingly significant in small and medium-sized fishing vessels, where relatively modest additions of topside weight may produce measurable changes in operational behavior [10].

The evaluation of vessel safety generally relies on two interrelated performance indicators: stability and seakeeping. Stability describes the capacity of a vessel to recover its equilibrium following external disturbances, whereas seakeeping concerns the vessel's dynamic behavior when subjected to wave excitation, including motions such as heave, pitch, and roll [11], [18]. Adequate performance in both aspects is essential for maintaining safe operations, protecting crew members, and preserving fishing efficiency. Excessive vessel motions can adversely affect crew performance, increase fatigue levels, disrupt fishing activities, and elevate the likelihood of accidents or equipment failures.

Previous investigations have extensively examined stability performance in fishing vessels. Research by Lapa [10] highlighted the importance of reliable stability assessment under varying loading arrangements, while the IMO Intact Stability Code [18] continues to serve as the principal international framework for evaluating compliance with vessel stability requirements. Additional studies have demonstrated that alterations in loading configuration, operational conditions, and fishing gear arrangements can significantly affect righting characteristics and overall safety margins.

Likewise, substantial attention has been devoted to seakeeping analysis. Tello et al. [11] emphasized the necessity of evaluating vessel motion responses during the design phase, while Im and Lee [24] showed that environmental conditions and hull form characteristics strongly influence the seakeeping performance of small fishing vessels. Numerical investigations conducted by Sariöz and Narli [25] further reinforced the importance of motion analysis as a tool for enhancing operational safety and vessel performance. Collectively, these studies underscore the critical role of hydrodynamic response assessment in fishing vessel design.

Despite the considerable volume of research devoted to renewable energy technologies, vessel stability, and seakeeping performance, these topics have generally been investigated as separate disciplines. Studies concerning photovoltaic systems largely emphasize energy-related outcomes such as fuel savings, electrical performance, and environmental benefits [2], [4], [17]. In contrast, stability research predominantly addresses regulatory compliance and loading effects [10], [18], while seakeeping investigations focus on vessel responses under wave excitation [11], [24], [25]. Consequently, limited attention has been directed toward understanding the combined influence of solar panel installations on both stability and seakeeping characteristics.

This knowledge gap is particularly relevant for fishing vessels, where changes in topside weight distribution may directly affect safety and operational capability. Although renewable energy technologies are increasingly promoted within the maritime sector, insufficient evidence is currently available regarding the extent to which photovoltaic installations influence compliance with IMO stability requirements and accepted seakeeping standards. Therefore, an integrated evaluation that simultaneously considers renewable energy implementation and naval architectural performance remains necessary.

To address this issue, the present study investigates the effects of deckhouse-mounted solar panels on a 30 GT fishing vessel. Vessel stability is assessed using the A.N. Krylov method and subsequently evaluated against IMO Intact Stability Criteria. In parallel, seakeeping characteristics are analyzed through strip theory in conjunction with the JONSWAP wave spectrum under multiple loading scenarios and wave conditions.

The principal contribution of this research is the development of a unified assessment framework that examines renewable energy integration alongside vessel stability and seakeeping performance. In contrast to earlier studies that considered these aspects independently, the present work quantitatively evaluates the influence of deckhouse-installed photovoltaic systems on both the hydrostatic and hydrodynamic behavior of a 30 GT fishing vessel. The resulting findings provide practical guidance for the implementation of solar energy technologies while supporting the design of fishing vessels that are sustainable, energy efficient, and compliant with safety requirements.

II. Method

2.1 Method of data collecting

This study focuses on a purse seine fishing vessel with a gross tonnage (GT) of 30. The data used in this research were obtained through a secondary data collection method, primarily sourced from the Ministry of Marine Affairs and Fisheries (KKP). Key vessel dimensions and information on consumables were derived from this source and are presented in Table 1.

This method enables the use of existing data published by reputable institutions, thereby supporting the credibility and precision of the analysis [2]. By relying on this secondary information, the study can systematically assess different aspects of the multipurpose fishing vessel, such as its principal dimensions and consumable requirements, allowing for a thorough evaluation of its features and operational performance. consumable resources, facilitating a comprehensive examination of its characteristics and capabilities [3].

Table 1 serves as a valuable resource, presenting essential parameters that will underpin our subsequent analyses and investigations. Through meticulous scrutiny and interpretation of these data points, we aim to gain deeper insights into the operational dynamics and performance potential of the Multipurpose Fishing Vessel within the context of our research objectives.

TABLE 1.
SHIP PARTICULAR

No	Dimension	Unit	Size
1	Loa	M	21
2	B	M	4.3
3	H	M	2
4	T	M	1.35
5	Fb	M	0.65
6	Cb	-	0.55
7	B/T	-	3.18
8	Fb/B	-	0.15
9	Crew	Person	12
10	Speed	Knot	8

TABLE 2.
CONSUMABLE NEEDS OF FISHING VESSELS 30 GT

No	Item	Quantity	Unit Weight (Kg)	Total Weight (Kg)
1	Fresh Water	2	750	1500
2	Fuel Oil	2	1750	3500
3	Provisions	12	15	180
4	Crew	12	75	900
5	Fish & Ice	2	6000	12000

The principal dimensions of the vessel together with the previously established consumable capacity data constitute the basis for the subsequent stage of this study, namely the development of a detailed lines plan. As a fundamental representation of the ship's geometry, this technical drawing provides the essential platform for evaluating both stability characteristics and maneuvering performance [13]. In preparing the lines plan, all relevant geometric features of the vessel are accurately represented, including key parameters such as length, beam, draft, and freeboard. In addition, the arrangement of operational consumables fuel tanks, freshwater storage, and other onboard compartments is incorporated to ensure a complete depiction of the vessel's configuration [14].

Following completion of the lines plan, a comprehensive investigation of the ship's dynamic behavior will be undertaken. Numerical simulations combined with hydrodynamic modeling will be employed to examine the vessel's response under a range of environmental influences and operating conditions [15]. This evaluation is intended to characterize the ship's overall performance by assessing its ability to maintain stability, withstand external disturbances, and execute maneuvering actions effectively in demanding marine environments. Key indicators, including metacentric height, turning radius, and rudder responsiveness, will be analyzed to reveal the governing factors that influence operational performance and handling qualities [16].

The outcomes derived from these analyses are expected to provide a thorough assessment of the vessel's capabilities while supporting subsequent improvements in both design and operation. Such refinements are directed toward strengthening navigational safety, improving operational efficiency, and enhancing overall performance throughout the vessel's service life at sea [17].

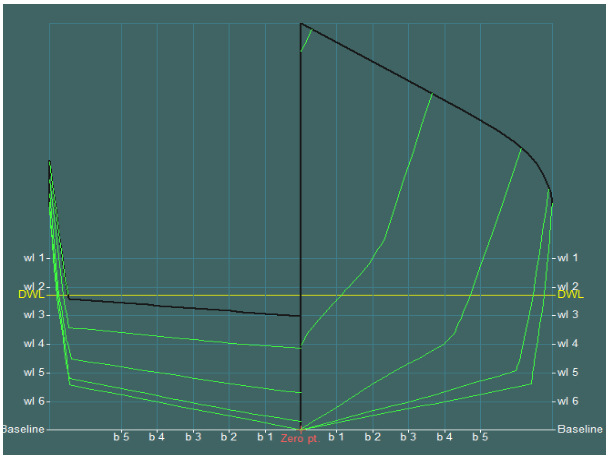


Figure 1. Fishing Vessel Lines Plan 30 GT

2.2 Stability Calculation

Ship-related data were analyzed using Maxsurf software, while stability calculations were performed based on the A.N. Krylov approach.

$F_B = g\Delta = \rho g \nabla$

The initial metacentric height equals the difference between the metacentric radii and the distance between the centre of buoyancy (B) and gravity G.$GM_0 = BM_0 - GB$ (2)

The transverse metacentre radius at each inclination is also called the metacentre difference.

$r_\varphi = B_\varphi M_\varphi = \frac{dI_{WL}}{d\nabla}$

The transverse metacentric radius for the upright position is:

$r_0 = BM_0 = \frac{I_{WL}}{\nabla}$

Where: Iwl = moment of inertia of the waterplane.

The relationship between the two equations is:

$r_\varphi = r_0 + \nabla \frac{dr_0}{d\nabla}$ (5)

The static stability arm can be calculated using the following equation:

$GZ = y_{B\varphi} \cos\varphi + (z_{B\varphi} - Z_B) \sin\varphi - GB \sin\varphi$

Where : $y_{B\varphi}, z_{B\varphi}$ are the coordinates of the centre of buoyancy.

The equation $BN = y_{B\varphi} \cos\varphi + (z_{B\varphi} - Z_B) \sin\varphi$ is called the righting arm of form, and BC = BG sinφ is called the righting arm of weight. The formula can also calculate GZ:

$GZ = y_{B\varphi} \cos\varphi + Z_{B\varphi} - KG \sin\varphi$ (7)

For small angles of heel, the righting arm (GZ) is considered to vary linearly with the angle of inclination. Under this assumption, the restoring moment may be determined using:

$M_R = g\Delta\, GM_0 \varphi$ (1)

Equation (8) is commonly referred to as the metacentric stability formulation. When the vessel experiences larger inclinations, the restoring moment is no longer represented solely by the metacentric height and must instead be evaluated directly from the righting arm, expressed as:

$M_R = g\Delta\, GZ$

The righting arm curve is required to exhibit (3) characteristics that correspond to the vessel's inclination behavior. Accordingly, GZ values associated with specific heel angles, such as GZ20^0, GZ30^0, GZ40^0, GZ (4) ^{0}m must be assessed in relation to their respective angles of inclination. The relationship between the righting arm and heel angle is represented by the generalized metacentric height.

$h_\varphi = \frac{d(GZ)}{d\varphi} = B_\varphi M - y_{B\varphi} \sin\varphi + Z_{B\varphi} \cos\varphi - KG \cos$ (10) (6)

Geometrically, this is equal to the distance between the metacentre M and the projection of G in the direction of the buoyant force, Z

$E_R = \int_0^\varphi M_R \, d\varphi = g\Delta \int_0^\varphi GZ \, d\varphi$

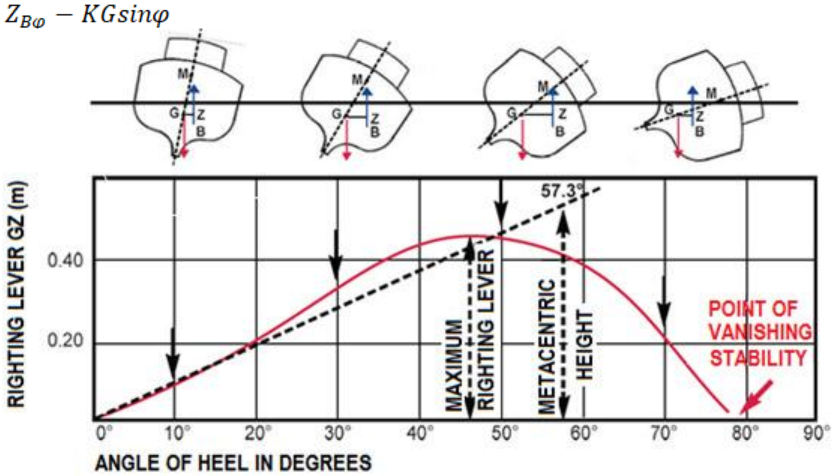


Figure 2. Stability Arm

Evaluation of the vessel's righting capability was carried out by applying the stability requirements prescribed by the International Maritime Organization (IMO). The assessment framework follows the provisions of the International Code on Intact Stability (IMO, 2008), which establishes mandatory stability criteria for fishing vessels operating under a broad range of marine environments [18]. Compliance with these provisions provides the basis for determining whether a vessel possesses adequate stability characteristics to support safe navigation and operational reliability.

The prescribed standards require examination of several key stability indicators, including metacentric height, heel angle behavior, and the characteristics of the righting arm (GZ) curve. These parameters are utilized to verify the vessel's ability to withstand external disturbances and maintain a satisfactory level of safety when exposed to unfavorable sea and weather conditions. Adherence to the IMO requirements is therefore a critical component of risk reduction and crew protection during maritime operations.

The area under the GZ curve must not be less than:

a. 0.055-meter radians up to 30°
b. 0.09-meter radians up to 40°
c. 0.03-meter radians between 30° - 40°.

1. More than 0.2 meters at 30°.
2. The metacentric height must not be less than 0.35 meters.

2.3 Weather Criterion

Environmental conditions encountered during vessel operations constitute an important factor affecting ship stability. Wind action acting on the vessel can generate heeling moments, causing variations in the angle of heel while the ship is underway or operating within a particular sea area. The assessment of these weather-induced effects is governed by the IMO 2008 Intact Stability Code, Part A, Chapter 2.3, Severe Wind and Rolling Criterion (Weather Criterion).

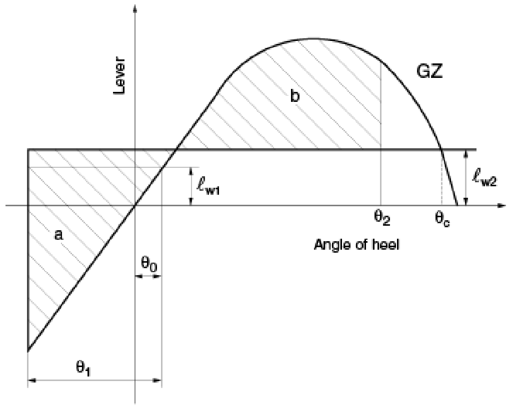


Figure 3. Severe Wind and Rolling

2.2 Seakeeping Calculation

Within hydrodynamic motion analysis, strip theory is categorized as a frequency-domain approach because the governing formulation is expressed with frequency as the primary variable. The method represents the vessel as a sequence of transverse cross-sections distributed along its length. Hydrodynamic properties are first determined for each individual section and subsequently combined through integration over the hull geometry to obtain the overall motion coefficients that characterize the ship's dynamic response.

For the purposes of this study, only the relevant mathematical expressions are presented, while their derivation is omitted. A more comprehensive discussion of the theoretical principles underlying this method can be found in Newman [19]. The analysis employs two distinct coordinate frameworks.:

1. The ship-fixed system x, y, z, in which the axes are defined from the vessel's center toward the bow, starboard side, and downward direction, respectively. Within this reference frame, the position of the center of gravity remains unchanged.
2. The inertial system ξ, η, ζ. This reference system translates together with the vessel at a forward velocity (V) and represents the time-averaged motion relative to the ship-fixed coordinate system..

Forces and moments acting on the ship are similarly combined into the six-component vector F.u, with F being a harmonic function of oscillation with encounter frequency We.

$$\vec{F} = R_e\left(\vec{F}e^{iw_e t}\right)\vec{u} = R_e\left(\vec{u}e^{iw_e t}\right) \quad (12)$$

The basic equation of motion is derived from F = M.u:

$$[-w^2{}_e(M + A) + iw_e N + S]\vec{u} = \vec{F_e} \quad (13)$$

Here M, N, A and S are real values of the 6 x 6 matrix. For a symmetrical mass distribution with respect to y = 0, the mass of the matrix M is:

$$M = \begin{bmatrix} m & 0 & 0 & 0 & mz_g & 0 \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & 0 & -mx_g & 0 \\ 0 & -mz_g & 0 & \theta_{xx} & 0 & -\theta_{xz} \\ mz_g & 0 & -mx_g & 0 & \theta_{yy} & 0 \\ 0 & mx_g & 0 & -\theta_{xz} & 0 & -\theta_{zz} \end{bmatrix} \quad (14)$$

The mass moment of inertia θ is related to the origin of the ship-fixed system coordinates:

$$\theta_{xx} = \int (y^2 + z^2)\, dm;\ \theta_{xz} = \int xz\ dm \quad (15)$$

If we ignore the contribution of the dry tansom stren and other hydrodynamic forces due to the ship's forward speed, the restoring force matrix S is:

$$M = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho g A_w & 0 & -\rho g A_w x_w & 0 \\ 0 & 0 & 0 & gm\overline{GM} & 0 & 0 \\ 0 & 0 & -\rho g A_w x_w & 0 & gm\overline{GM_l} & 0 \\ 0 & 0 & 0 & 0 & 0 & \theta_{zz} w^2{}_g \end{bmatrix} \quad (16)$$

$$M = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho g A_w & 0 & -\rho g A_w x_w & 0 \\ 0 & 0 & 0 & gm\overline{GM} & 0 & 0 \\ 0 & 0 & -\rho g A_w x_w & 0 & gm\overline{GM_l} & 0 \\ 0 & 0 & 0 & 0 & 0 & \theta_{zz} w^2{}_g \end{bmatrix} \quad (17)$$

Characterization of ocean wave energy across the frequency domain is commonly performed using the JONSWAP (Joint North Sea Wave Project) spectrum, an empirically derived spectral model developed to represent realistic sea conditions. Although its formulation originates from the Pierson–Moskowitz spectrum, the JONSWAP approach reflects a different stage of wave growth. Rather than describing a fully developed sea state, it represents wave systems that continue to evolve as energy redistribution occurs through nonlinear interactions among wave components over time and fetch.

A defining feature of this spectrum is the continued amplification of wave energy during propagation, a process represented through the α (alpha) parameter. The model also accounts for the pronounced concentration of energy around the dominant frequency, which is characterized by the γ (gamma) parameter. According to Hasselmann [20], incorporation of this parameter improves the representation of nonlinear wave interaction mechanisms, thereby providing a more realistic description of wave evolution. The mathematical formulation of the JONSWAP spectrum is founded upon a principal governing equation that serves as the basis for its spectral representation.

$$S(\omega) = \frac{\alpha g^2}{\omega^5}\, exp\left[-\beta \frac{\omega_p^4}{\omega^4}\right]\gamma^{\alpha} \quad (18)$$

Where :

$$a = \exp\left[-\frac{(\omega-\omega_p)^2}{2\omega_p^2\sigma^2}\right] \quad (19)$$

$$\sigma = \begin{cases} 0.07 & if\ \omega \le \omega_p \\ 0.09 & if\ \omega > \omega_p \end{cases} \quad (20)$$

$$\beta = \frac{5}{4} \quad (21)$$

Criteria for ship maneuvers using seakeeping [30]

TABLE 3.
SEAKEEPING CRITERIA

No.	Criteria	Value
1.	*Roll*	6 deg
2.	*Pitch*	3 deg
3.	*Lateral acceleration (at working deck AP & FP)*	0,1 g
4.	*Vertical acceleration (at working deck AP & FP)*	0,2 g

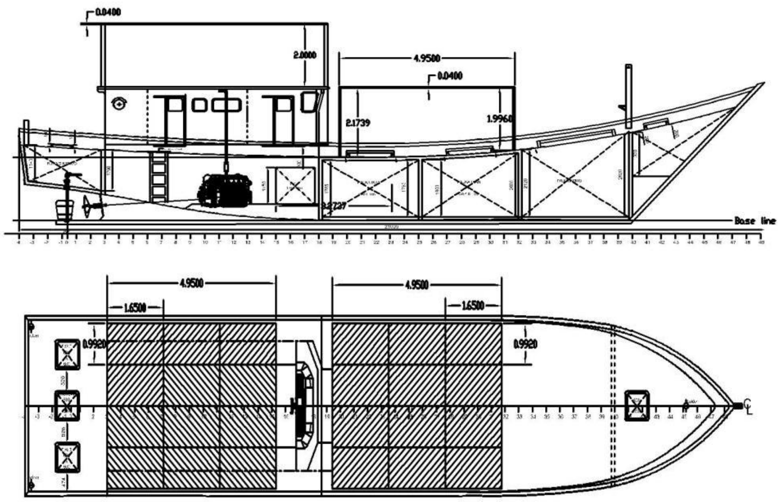


Figure 4. General Arrangement

III. RESULTS AND DISCUSSION

3.1 Stability Analysis

The vessel load cases were developed in accordance with the guidelines and assumptions established by the International Maritime Organization to address the specific operational requirements and challenges associated with fishing vessels. The operational conditions were systematically defined to represent the complete range of scenarios that may occur during maritime operations. In this study, the vessel was assumed to operate under a full-load condition, where all compartments were loaded to 100% of their maximum capacity. This loading condition enables a comprehensive assessment of the vessel's performance under demanding operational circumstances, providing valuable insights into its stability, maneuverability, and overall operational efficiency when fully loaded with equipment, supplies, and provisions.

The second scenario evaluates the vessel under a partial loading condition in which consumables, including fuel and freshwater, are maintained at 50% capacity, while the remaining compartments are left empty. This condition represents a common operational state where the vessel is not fully loaded but continues to carry essential supplies required for maritime operations. The analysis of this scenario provides a more comprehensive understanding of vessel performance under partially loaded conditions, particularly in terms of fuel efficiency, endurance, and operational capability.

In addition, the presence of solar panels onboard is taken into consideration, as their installation may influence the vessel's weight distribution, stability characteristics, and overall energy efficiency. This detailed assessment ensures that the evaluation accurately represents the vessel's actual configuration and operational performance. Consequently, the study enables the identification of potential areas for design improvement and operational optimization. Through this systematic approach to load case development, the vessel's performance can be comprehensively assessed under realistic operating conditions, thereby supporting informed decision-making to enhance safety, efficiency, and effectiveness within the maritime industry

TABLE 4.
LOADCASE CONDITION OF FISHING VESSEL

Item Name	Loadcase 1 tonne	Vert. Arm 1 m	Loadcase 2 tonne	Vert. Arm 2 m	Loadcase 3 tonne	Vert. Arm 3 m	Loadcase 4 tonne	Vert. Arm 4 m
'LWT								
Lightship	15.800	1.330	15.800	1.330	15.800	1.330	15.800	1.330
Solar Panel 1	0.000	6.000	0.168	6.000	0.168	6.000	0.000	6.000
Solar Panel 2	0.000	4.000	0.168	4.000	0.168	4.000	0.000	4.000
Total LWT	15.800	1.330	15.968	1.330	15.968	1.330	15.800	1.330
'DWT								
Food	0.105	2.800	0.105	2.800	0.105	2.800	0.105	2.800
Crew	0.900	2.300	0.900	2.300	0.900	2.300	0.900	2.300
CF 1	0.000	1.050	0.000	1.050	6.000	1.050	6.000	1.050
CF 2	0.000	1.000	0.000	1.000	6.000	1.000	6.000	1.000
FOT (S)	1.750	0.996	1.750	0.997	1.750	0.997	1.750	0.997
FWT (P)	0.753	1.483	0.753	1.484	0.753	1.484	0.753	1.484
FWT (S)	0.753	1.483	0.753	1.484	0.753	1.484	0.753	1.484
FOT (P)	1.750	0.996	1.750	0.997	1.757	0.997	1.757	0.997
Total DWT	6.007	1.478	6.007	1.478	18.007	1.478	18.007	1.478
Total Loadcase	21.807	1.334	21.975	1.362	33.975	1.243	33.807	1.224
FS correction		0.000		0.000		0.000		0.000
VCG fluid		1.334		1.362		1.243		1.224

Loadcase 1 examines the operational characteristics of the fishing vessel under an unloaded condition, with an empty cargo hold and without the installation of solar panels. This condition serves as the baseline configuration for evaluating the vessel's performance under conventional operating circumstances.

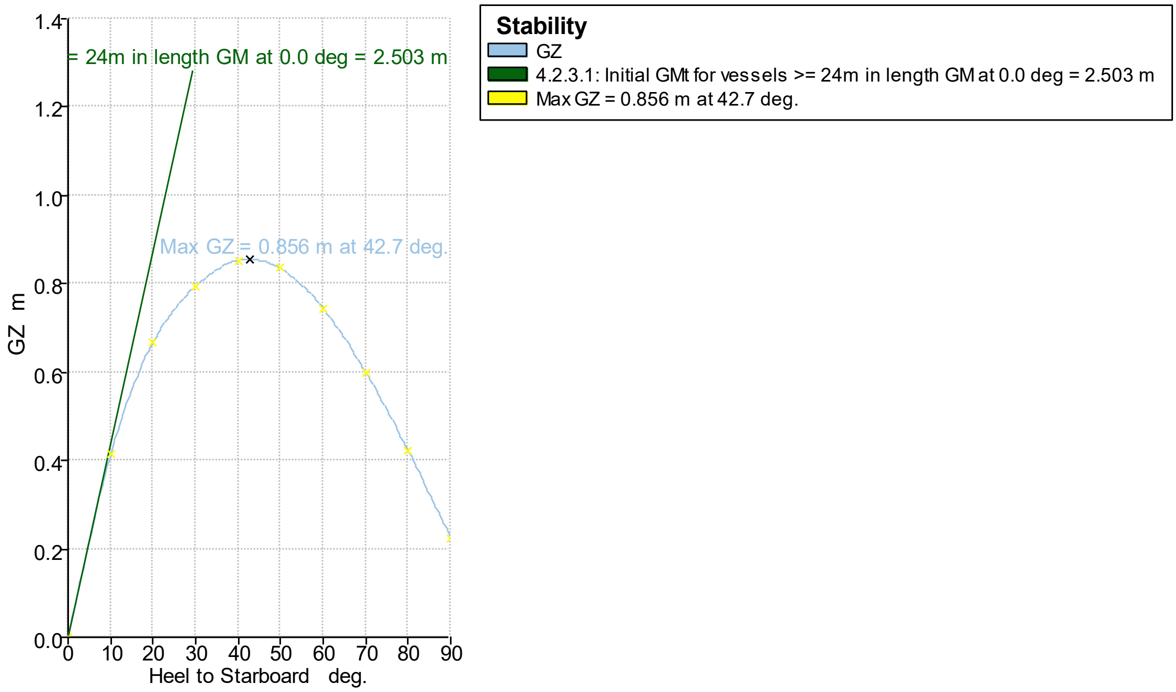
Loadcase 2 considers the vessel in the same unloaded condition; however, solar panels are integrated to supply the onboard energy demand. This configuration highlights the potential application of renewable energy systems in maritime operations and demonstrates the feasibility of utilizing solar power to support vessel functionality and energy sustainability.

Loadcase 3 further investigates the vessel's operational performance under fully loaded conditions while incorporating solar panel installations. This scenario reflects a more realistic operational environment by combining maximum cargo capacity with renewable energy utilization. The analysis emphasizes the relationship between payload capacity and the implementation of sustainable energy solutions in enhancing vessel efficiency and operational effectiveness. Conversely,

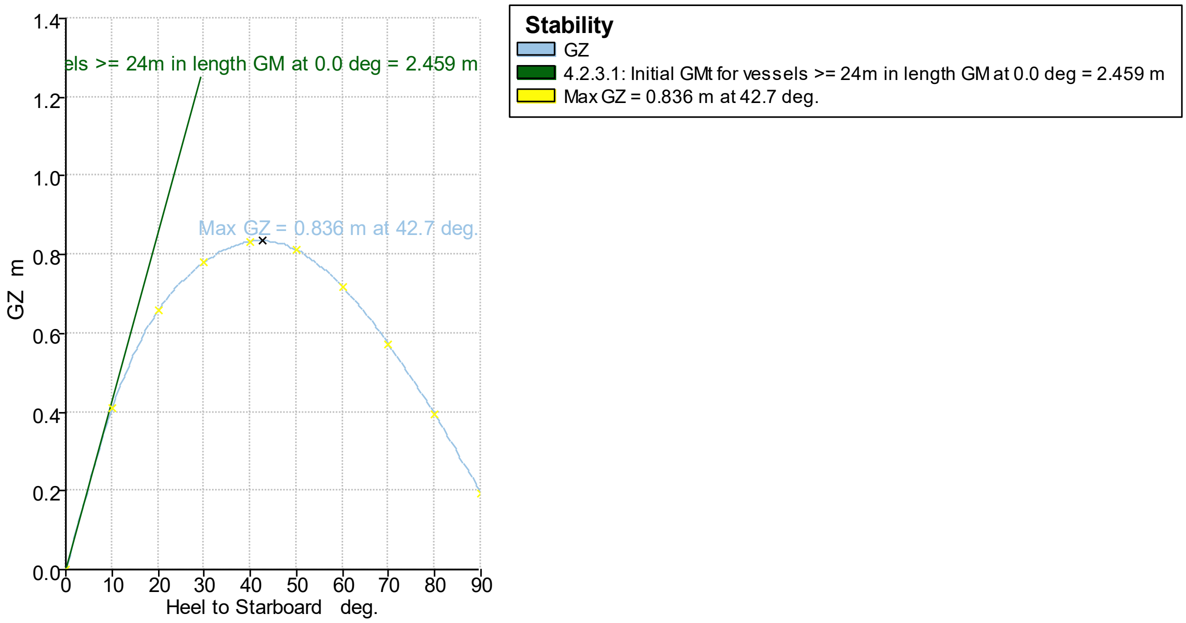
Loadcase 4 evaluates the vessel in a fully loaded condition without the use of solar panels. This case represents the vessel's performance under traditional operating conditions and provides a reference for assessing the advantages and impacts of solar energy integration. In all loadcases, a detailed evaluation of each component's weight is conducted to determine the longitudinal and transverse positions of the vessel's center of gravity, thereby ensuring an accurate assessment of stability and overall vessel performance. Specifically, the center of gravity shifts from 1.334 meters in Loadcase 1 to 1.362 meters in Loadcase 2, then down to 1.243 meters in Loadcase 3, and further to 1.224 meters in Loadcase 4. The calculations indicate that the centre of gravity experiences a consistent and predictable shift across all four load cases, with the installation of solar panels exerting a substantial influence on the vessel's weight distribution and stability characteristics. This finding emphasizes the necessity of carefully determining the placement of solar panels to ensure the maintenance of optimal vessel stability and operational safety.

The righting arm (GZ) values for heel angles ranging from 0° to 90° were determined using the A.N. Krylov method implemented in Maxsurf software [21]. The analysis provides a comprehensive evaluation of the vessel's stability performance under varying inclination conditions, which is essential for safe operation in dynamic marine environments. Furthermore, the resulting GZ curve, presented in the figure below, offers a clear visual representation of the vessel's stability behaviour and its ability to withstand external disturbances during operation. This study contributes to the optimization of vessel design and operational parameters in order to improve safety, efficiency, and overall performance in fishing activities.

The loading calculations indicate that the installation of solar panels produces only a limited increase in vessel displacement and vertical center of gravity. Under the unloaded condition, the VCG increases from 1.334 m to 1.362 m after solar panel installation, whereas under the fully loaded condition it changes from 1.224 m to 1.243 m. These variations demonstrate that the additional weight associated with the photovoltaic system remains relatively small compared with the overall displacement of the vessel. Consequently, although the solar panels are positioned above the deckhouse, their contribution to the overall weight distribution is insufficient to generate a substantial change in the vessel's stability characteristics.



(a)



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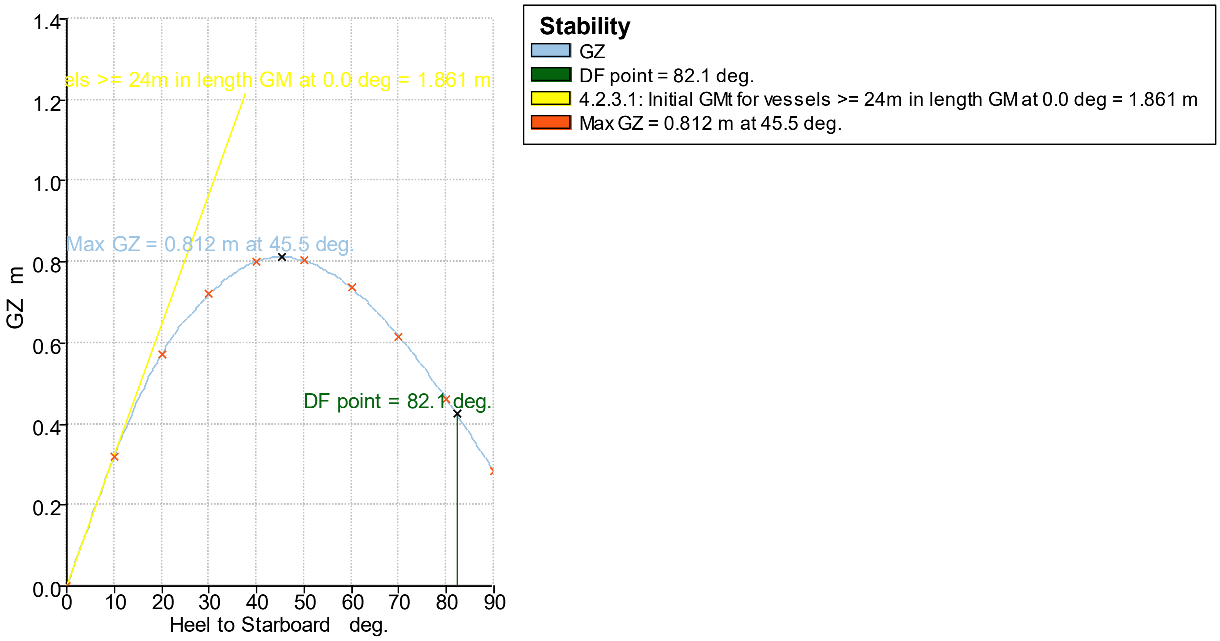

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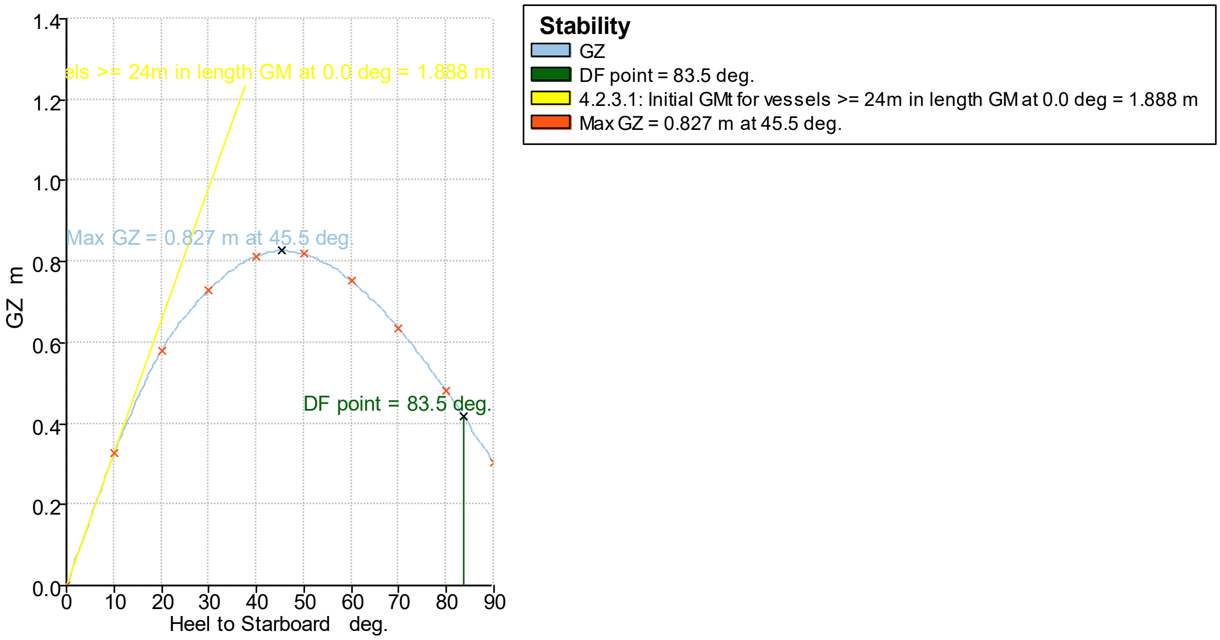

(d)

Figure 5. Stability Arm and Wind Criteria (a) Loadcase 1 (b) Loadcase 2 (c) Loadcase 3 (d) Loadcase 4

The observations derived from the diagram reveal that the GZ curves for Loadcases 1 through 4 exhibit highly similar characteristics. This consistency indicates that the vessel maintains a relatively stable righting arm performance under the evaluated loading conditions. Nevertheless, careful adjustments and optimization remain necessary to ensure full compliance with the stability criteria established by the International Maritime Organization. Adherence to these standards is essential to guarantee that the vessel satisfies the required safety margins and operational stability requirements for maritime activities.

The proposed corrections, as presented in the accompanying table, are intended to refine the GZ curves for Loadcases 1 to 4 in order to optimize the vessel's stability characteristics. This adjustment process contributes to improving the vessel's seaworthiness while simultaneously reducing the potential risks associated with unstable operating conditions at sea.

Furthermore, the implementation of these corrective measures is expected to ensure compliance with applicable stability regulations and safety standards established by the International Maritime Organization. Consequently, these efforts reflect a commitment to maintaining operational safety, protecting crew welfare, and supporting the reliability and integrity of maritime operations.

Figure 5 shows that the righting arm characteristics remain generally consistent across all loading conditions. The maximum GZ decreases slightly from 0.856 m in Loadcase 1 to 0.836 m in Loadcase 2 following solar panel installation. A similar trend is observed under fully loaded conditions, where the maximum GZ changes from 0.827 m to 0.812 m. Although a reduction in righting capability is evident, the magnitude of the change is relatively small and does not indicate a substantial deterioration in vessel stability.

The observed reduction in GZ can be attributed to the slight increase in the vessel's vertical center of gravity resulting from the deckhouse-mounted solar panels. From a hydrostatic perspective, an increase in the vertical position of the center of gravity generally reduces the restoring moment available during heeling. However, the present results demonstrate that the additional photovoltaic weight remains insufficient to significantly alter the vessel's overall righting characteristics.

TABLE 5.
CORRECTION RESULT

Code	Criteria	Value	Units	Load case1	Load case2	Load case 3	Load case 4	Status
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.1: Area 0 to 30	0.0550	m.deg	15.1313	14.8707	12.7289	12.8970	Compliant
	3.1.2.1: Area 0 to 40	0.0300	m.deg	24.4230	22.9909	20.3913	20.6712	Compliant
	3.1.2.1: Area 30 to 40	0.0900	m.deg	8.2917	8.1202	7.6625	7.7742	Compliant
	3.1.2.2: Max GZ at 30 or greater	0.200	m	0.856	0.836	0.812	0.827	Compliant
	3.1.2.3: Angle of maximum GZ	25.0	deg	42.7	42.7	45.5	45.5	Compliant
4.2 Fishing vessel	4.2.3.1: Initial GMt for vessels >= 24m in length	0.350	m	2.503	2.459	1.861	1.888	Compliant

The analysis indicates that the vessel complies with the severe wind and rolling criterion, which evaluates the balance between wind heeling moments and the vessel's righting ability under adverse environmental conditions. This confirms that the vessel has adequate dynamic stability and resistance to capsizing in extreme wind and wave conditions, in accordance with IMO regulations [18] & [22]. The results presented in Table 5 confirm that all loading conditions satisfy the IMO Intact Stability Criteria as well as the Severe Wind and Rolling Criterion. The calculated areas under the GZ curve, maximum righting arm values, angles of maximum GZ, and initial metacentric heights remain well above the minimum acceptance limits. These findings indicate that the vessel maintains adequate static and dynamic stability despite variations in loading condition and solar panel installation. This approach aligns with modern intact stability assessment practices, which emphasize multi-condition verification to ensure operational safety and regulatory compliance [23].

An important observation is that the integration of solar panels does not result in failure of any stability requirement. Although minor reductions in GM and GZ values are observed, these changes are not sufficient to compromise the vessel's restoring capability or overall safety performance. This outcome suggests that the additional topside weight introduced by the photovoltaic system remains within a tolerable range for the 30 GT fishing vessel.

The findings provide quantitative evidence that renewable energy systems can be incorporated into fishing vessels without significantly affecting compliance with internationally recognized stability regulations. Unlike previous studies that primarily focused on energy generation and fuel savings, the present study demonstrates that deckhouse-mounted photovoltaic installations can be implemented while maintaining acceptable hydrostatic safety characteristics. This represents an important contribution toward the development of sustainable fishing vessels that simultaneously address energy efficiency and operational safety.

Furthermore, the results confirm the adequacy and reliability of the vessel's stability performance across various operational scenarios. Compliance with both the IMO Stability Criteria and the Severe Wind and Rolling Criteria suggests that the vessel possesses sufficient capability to maintain stability under adverse environmental conditions, including severe sea states and wind effects.

Overall, this evaluation verifies the vessel's operational feasibility and structural stability, thereby providing confidence in its safety and seaworthiness for maritime operations. The successful fulfilment of the established criteria also emphasizes the vessel's conformity with internationally recognized maritime safety standards

3.2 Vessel motion to Safety of Catching Operations

Safety and the fulfillment of fishing objectives depend on the seaworthiness of the vessel before it sets sail. In order to accurately assess the vessel's seaworthiness, simulations are carried out with the vessel in a fully loaded condition, mirroring the conditions used in stability calculations.

This analysis incorporates the JONSWAP wave spectrum formulation, which provides a reliable representation of realistic sea state conditions and wave behavior. In addition, the study accounts for the wave encounter angle relative to the vessel, which is a key parameter influencing hydrodynamic response. For analytical purposes, wave headings are categorized into three principal conditions, namely following seas, beam seas, and head seas, each representing distinct vessel–wave interaction characteristics that affect ship motions and stability performance.

The accompanying figure illustrates these wave encounter orientations and highlights their relevance in operational maritime conditions. In practice, wave incidence may be further represented through multiple discrete heading angles, typically five in number, each associated with different levels of dynamic loading and varying implications for vessel stability and maneuverability under irregular sea states.

It should be noted that the vessel is designed to operate at a maximum service speed of 9 knots during transit, while encountering wave conditions with significant wave heights ranging from 0.5 m to 3 m. This variation in wave elevation reflects the inherently dynamic characteristics of the marine environment, thereby necessitating a comprehensive assessment of the vessel's performance envelope and operational limits across differing sea states.

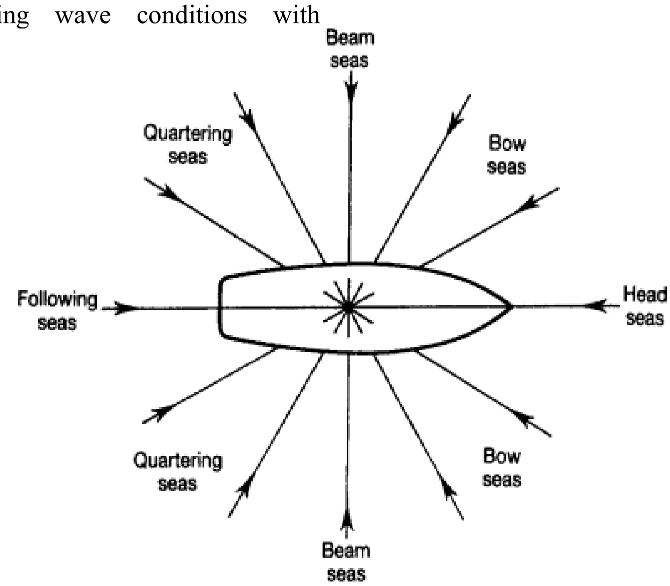

Figure 6. Wave Entry Angle in General

Motion conditions, with and without the installation of solar panels, are standardized to account for minor variations in water content. These adjustments are applied to ensure consistency across different scenarios, enabling a fair evaluation of the vessel's performance under varying conditions. The analysis considers both fully loaded and ballast (unloaded) conditions. By examining these two operational states, a comprehensive assessment can be obtained regarding the influence of solar panel installation on the vessel's motion characteristics. This systematic approach facilitates an accurate evaluation of the effects of solar panels on vessel stability and maneuverability, thereby supporting more informed decision-making in maritime operations and design.

TABLE 6.
FOLLOWING SEAS FULL LOAD

Wave Height (m)	RMS of Vertical Acceleration (at Working Deck AP & FP)	RMS of Lateral Acceleration (at Working Deck Ap & FP)	RMS of Pitch	RMS of Roll	Status
0,5	0,032 & 0,036	0	0,55	0	Acceptable
1	0,064 & 0,072	0	1,10	0	Acceptable
1,5	0,096 & 0,109	0	1,65	0	Acceptable
2	0,128 & 0,145	0	2,19	0	Acceptable
2,5	0,160 & 0,181	0	2,74	0	Acceptable
3	0,193 & 0,217	0	3,29	0	Exceeds Operational Limits

TABLE 7.
BEAM SEAS FULL LOAD

Wave Height (m)	RMS of Vertical Acceleration (at Working Deck AP & FP)	RMS of Lateral Acceleration (at Working Deck Ap & FP)	RMS of Pitch	RMS of Roll	Status
0,5	0,135 & 0,088	0,244 & 0,137	0,24	1,64	Acceptable
1	0,269 & 0,176	0,489 & 0,274	0,48	3,28	Acceptable
1,5	0,404 & 0,264	0,733 & 0,412	0,72	4,92	Acceptable
2	0,539 & 0,351	0,977 & 0,549	0,96	6,56	Exceeds Operational Limits
2,5	0,673 & 0,439	1,221 & 0,686	1,21	8,20	Exceeds Operational Limits
3	0,808 & 0,527	1,466 & 0,823	1,45	9,84	Exceeds Operational Limits

TABLE 8.
HEAD SEAS FULL LOAD

Wave Height (m)	RMS of Vertical Acceleration (at Working Deck AP & FP)	RMS of Lateral Acceleration (at Working Deck Ap & FP)	RMS of Pitch	RMS of Roll	Status
0,5	0,207 & 0,377	0	0,50	0	Acceptable
1	0,414 & 0,754	0	1,01	0	Acceptable
1,5	0,621 & 1,131	0	1,51	0	Acceptable
2	0,828 & 1,508	0	2,02	0	Acceptable
2,5	1,035 & 1,886	0	2,52	0	Acceptable
3	1,242 & 2,263	0	3,03	0	Exceeds Operational Limits

TABLE 9.
FOLLOWING SEAS EMPTY

Wave Height (m)	RMS of Vertical Acceleration (at Working Deck AP & FP)	RMS of Lateral Acceleration (at Working Deck Ap & FP)	RMS of Pitch	RMS of Roll	Status
0,5	0,033 & 0,039	0	0,58	0	Acceptable
1	0,067 & 0,078	0	1,17	0	Acceptable
1,5	0,100 & 0,116	0	1,75	0	Acceptable
2	0,134 & 0,155	0	2,33	0	Acceptable
2,5	0,167 & 0,194	0	2,91	0	Acceptable
3	0,200 & 0,233	0	3,50	0	Exceeds Operational Limits

TABLE 10.
BEAM SEAS EMPTY

Wave Height (m)	RMS of Vertical Acceleration (at Working Deck AP & FP)	RMS of Lateral Acceleration (at Working Deck Ap & FP)	RMS of Pitch	RMS of Roll	Status
0,5	0,134 & 0,088	0,294 & 0,165	0,25	1,66	Acceptable
1	0,269 & 0,175	0,588 & 0,330	0,50	3,31	Acceptable
1,5	0,403 & 0,263	0,881 & 0,495	0,74	4,97	Acceptable
2	0,537 & 0,351	1,175 & 0,660	0,99	6,63	Exceeds Operational Limits
2,5	0,672 & 0,438	1,469 & 0,825	1,24	8,29	Exceeds Operational Limits
3	0,806 & 0,526	1,763 & 0,990	1,49	9,94	Exceeds Operational Limits

TABLE 11.
HEAD SEAS EMPTY

Wave Height (m)	RMS of Vertical Acceleration (at Working Deck AP & FP)	RMS of Lateral Acceleration (at Working Deck Ap & FP)	RMS of Pitch	RMS of Roll	Status
0,5	0,193 & 0,366	0	0,48	0	Acceptable
1	0,386 & 0,731	0	0,95	0	Acceptable
1,5	0,579 & 1,097	0	1,43	0	Acceptable
2	0,771 & 1,462	0	1,91	0	Acceptable
2,5	0,964 & 1,828	0	2,38	0	Acceptable
3	1,157 & 2,914	0	2,86	0	Exceeds Operational Limits

Results from six wave conditions indicate that vessel seakeeping performance is strongly influenced by increasing significant wave height. The vessel maintains acceptable performance at wave heights below 2.5 m; however, beyond this threshold, the RMS pitch increases sharply and exceeds the defined operability limits. This trend aligns with Tello et al., who reported that ship motion responses in irregular waves increase non-linearly with wave height, with pitch being one of the most sensitive parameters in seakeeping analysis [11]. Similarly, Im and Lee found that RMS ship motions represent the spectral energy of vessel responses, which rises with increasing wave intensity [24]. Once the RMS pitch surpasses the allowable limit, the vessel no longer satisfies the operational criteria. Sariöz and Narli emphasized that seakeeping performance is governed by motion limiting criteria, where exceeding these thresholds indicates operational failure [25]. Additionally, MDPI studies note that such limits are vessel-specific and depend on the adopted operational standards [26].

Assessment under beam sea conditions indicates that vessel performance no longer satisfies the Tello criterion when wave heights exceed 1.5 m. According to this requirement, roll motion must remain below 6°, whereas the predicted roll response surpasses this threshold under the specified sea state. As a result, acceptable operational performance is achieved only when the vessel is exposed to waves lower than 2 m. From a safety perspective, operational reliability can therefore be maintained when the encountered wave height does not exceed 1.5 m.

A similar limitation is observed in the vertical acceleration response. The calculated RMS values become greater than the maximum level permitted by the Tello standard once wave heights exceed 2 m. This finding highlights a reduction in the vessel's capability to operate safely in head sea conditions beyond that wave limit and emphasizes the need for strict compliance with operational safety requirements. Furthermore, earlier investigations reported that installing solar panels on a vessel's deck does not adversely influence stability or motion performance, provided that the ship's center of gravity remains unchanged, the additional panel weight is kept within reasonable limits, and fishing operations are not obstructed by the installation arrangement [27].

The results demonstrate that environmental conditions, particularly wave height and wave encounter angle, exert a substantially greater influence on vessel motion characteristics than the installation of the photovoltaic system. Across all investigated scenarios, increasing wave height consistently resulted in larger motion responses, including pitch, roll, and vertical acceleration. This behavior is consistent with hydrodynamic theory, where greater wave energy generates stronger excitation forces acting on the vessel hull, leading to amplified motion responses.

A comparison between the evaluated loading conditions indicates that the installation of solar panels does not introduce a significant deterioration in seakeeping performance. Although the photovoltaic modules contribute additional weight above the deckhouse, the resulting change in displacement and center of gravity remains relatively small when compared with the overall mass of the vessel. Consequently, the dominant factors governing vessel motion continue to be hull geometry, displacement characteristics, and external wave conditions rather than the solar panel installation itself.

An important observation is that vessel operability is primarily restricted by roll motion under beam sea conditions and by vertical acceleration under severe head sea conditions. Under beam seas, the roll response exceeds the Tello criterion when wave heights become greater than 1.5 m, indicating that transverse wave excitation represents the most critical operating condition for the investigated vessel. In contrast, following seas generally produce lower motion responses and therefore allow a wider operational envelope. These findings highlight the importance of considering wave direction in operational planning and fishing activities.

The present study extends previous investigations on renewable energy implementation in fishing vessels by examining not only energy-related benefits but also the associated hydrodynamic consequences. Earlier studies predominantly focused on power generation capability, fuel savings, and environmental advantages of photovoltaic systems [2], [4], [17], [27], whereas the influence of solar panel installation on vessel motion performance received limited attention. The results obtained in this study provide quantitative evidence that deckhouse-mounted solar panels can be integrated into a 30 GT fishing vessel without causing substantial degradation of seakeeping characteristics.

The novelty of this research lies in the combined evaluation of renewable energy integration, stability performance, and seakeeping behavior within a unified assessment framework. The findings demonstrate that sustainable energy technologies may be adopted without compromising operational safety, provided that the additional topside weight remains within acceptable limits and vessel loading conditions are properly managed. This integrated approach provides a practical basis for future fishing vessel design and retrofit projects involving photovoltaic systems.

IV. CONCLUSION

This study evaluated the influence of deckhouse-mounted solar panel installation on the stability and operational performance of a 30 GT fishing vessel through stability and seakeeping analyses under various loading and wave conditions.

The stability assessment demonstrated that the additional weight introduced by the photovoltaic system produced only minor changes in the vessel's weight distribution and vertical center of gravity. Although slight reductions in metacentric height and righting arm values were observed, all investigated loading conditions remained fully compliant with the IMO Intact Stability Criteria and Severe Wind and Rolling Criterion. These results indicate that the installation of solar panels does not significantly compromise the vessel's hydrostatic safety characteristics.

The seakeeping analysis revealed that vessel motion responses are predominantly governed by wave height and wave encounter angle rather than by the presence of the solar panel system. The vessel maintained acceptable operational performance under most investigated conditions, while beam sea and head sea conditions generated the most critical responses. Based on the adopted operability criteria, safe fishing operations can be conducted at wave heights up to approximately 1.5–2.0 m, beyond which roll motion and vertical acceleration exceed the prescribed limits.

The principal finding of this study is that deckhouse-mounted photovoltaic systems can be integrated into a 30 GT fishing vessel without causing significant deterioration in either stability performance or seakeeping characteristics. This study therefore provides quantitative evidence that renewable energy implementation can be achieved while maintaining compliance with established safety and operability requirements. The results contribute to the development of sustainable fishing vessel designs by demonstrating that energy-efficiency improvements and vessel safety objectives can be addressed simultaneously within a unified evaluation framework.

Future research should investigate alternative photovoltaic arrangements, larger solar power capacities, and different fishing vessel configurations to further evaluate the interaction between renewable energy systems and vessel performance under broader operational conditions.

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