Determining the Optimal Inclination and Orientation Angles of Solar Panels Installed on Ship

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Abstract- Retrofitting photovoltaic (PV) systems to ships can help reduce their emissions and cost of operation. One of the most determining aspects in PV systems efficiency is the combination of the inclination and orientation angles of the panels, because it will affect the global solar radiation received by the panels. This study aims to determine the monthly optimal combination of those angles. The ship location and direction during the cruise, time, and local weather conditions were the factors considered for the analysis. Six shipping lines in the territory of Japan were considered as case studies and Artificial Neural Network (ANN) analyses were employed to calculate the general solar radiation received by the panels based on the input factors. Comparisons between the outputs of the panels arranged to the optimal angles and those at flat position are presented in one-year calculation. The results show that for the long route ships, low or constantly zero inclination angles are favorable, while monthly adjusted angles can draw higher solar energy for short route ships.

Keywords Artificial neural network, global solar radiation, orientation angle, photovoltaic on ship, tilt angle.

Nomenclature

γ	Orientation/azimuth angle
β	Inclination/tilt angle
θ_z	Zenith angle
θ	Incidence angle
δ	Solar declination angle
n	Number of the day
ω	Solar hour angle
t_{lsn}	Time of local solar noon
t_s	Time of observation
P	Solar panel output power
η	Solar panel efficiency
A	Sectional area of the panel
G_T	Global solar radiation on tilted surface
G_{Tb}	Direct solar radiation on tilted surface
G_{Td}	Diffuse solar radiation on tilted surface
G_{Tr}	Ground-reflected solar radiation on tilted surface
G_b	Direct solar radiation on horizontal surface
G_d	Diffuse solar radiation on horizontal surface
R	Direct radiation ratio
ρ	Longitude position
φ	Latitude position

1. Introduction

Increasing fuel prices and International Maritime Organization (IMO) regulations on gas emissions (chiefly through the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI) [1] have increased the interest in solar-powered ships and boats. While completely solar-powered systems may not always be feasible, hybrid PV-diesel power supply systems can reduce the operational cost and the exhaust gases produced by a ship [2-4], in fulfilment of IMO regulations.

In general, space for PV panels is limited to the roof of the structure [5]. Consequently, an efficient design and operation of the systems is required. The increase of the efficiency of PV systems on ships considering optimal sizing of the panels or batteries [6, 7], energy conversion [8, 9], and energy management [10-14] has been the subject of intense research. However, discussions regarding the optimal angle of the panels can hardly be found [15].

Currently, solar panels are mostly installed on the rooftop of the ship at 0 degree of inclination, in parallel or perpendicular with the ship direction. Nonetheless, the panels may receive higher solar radiation, thus, generating higher energy, if the panels are arranged in certain inclination and orientation angles, depending on the shipping line. While a mechanical tracker can ensure that panels directly face the sun, it is not suitable to be used in marine applications due to its high cost and significant risk of getting damaged due to the ocean climates [16].

Numerous studies have proposed methods to determine either the optimal inclination angle or the combination of inclination and orientation angles for PV systems on fixed coordinates. The optimum inclination angles can be obtained by calculating the global solar radiation on an inclined surface for a range of angles [17–20]. Another method to find the optimal inclination angle is by calculate the derivation of mathematical equation [21]. Artificial intelligence approaches, in the form of ANN [22] and the harmony search (HS) algorithm [23], are also utilized to estimate the optimal angle. The correlation between the optimal angles and several factors such as the effect of dust has also been investigated [24]. While the afore-mentioned methods are reliable and accurate, an adjustment is required to determine the optimal angles in ship applications.

Determining the optimal angle for PV panels on ships is particularly difficult due to several factors. First, the amount of solar radiation received by the panels is affected by the coordinate position of the panels. In ship applications, the coordinate position is dynamic due to the ship movement. Furthermore, solar radiation data are hardly available in sea locations. Second, the heading of the ship is also dynamic, which leads to the dynamic change of the panel orientation. Finally, the ship motions due to sea waves may alter the true inclination angle of the panel.

By using two steps of ANN, this paper proposes a method to determine the optimal combination of inclination and orientation angles for PV panels installed on ships. The first ANN is used to estimate the available amount of global solar radiation on horizontal plane at each coordinate position of the ship. The second ANN serves as the estimator of the global solar radiation received by the panels arranged in a varying combination of angles and utilizing the automatic identification system (AIS) of the ship to determine the ship position and direction. The training data are obtained by calculating the solar radiation received by the panels [20, 25] combined with the prediction from NASA database. This calculation is conducted for five locations across Japan where the actual data of direct, diffuse, and global solar radiation are available. The proposed method offers a new approach for the ship engineers to arrange the PV panels installed on the ships, based on their shipping lines.

2. Model for Calculating Global Solar Irradiance on Tilted Surfaces

2.1. Solar-related Angles

The angles related with the sun and the solar panel is defined on Fig. 1. The orientation or azimuth angle (γ) is the horizontal direction angle of the panel. For a panel located in the northern hemisphere, the azimuth angle is 0^0 for south-

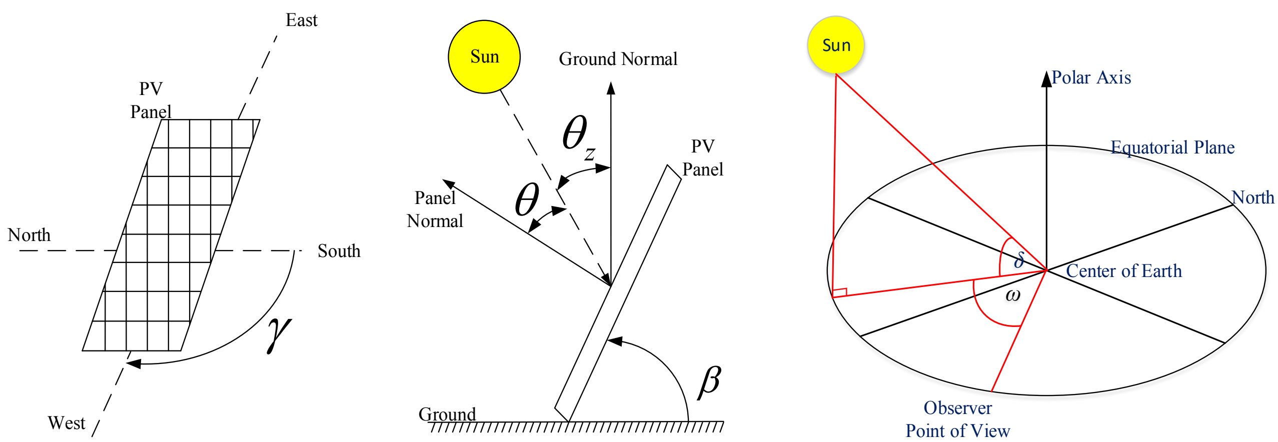

Fig. 1. Solar-related angles.

facing, positive for west-facing, and negative for east-facing panel [25]. The inclination or tilt angle (β) is the angle between the panel and the ground. The angle is 0^0 when the panel is laid flat on the ground [20].

The zenith angle (θ_z) is the angle between the vertical axis and the direction of direct solar radiation. The zenith angle is 0^0 when the sun is right above the panel and culminates at 90^0 during sunrise and sunset. The incidence angle (θ) is defined as the angle between the normal of the panel and the direction of direct solar radiation. The incidence angle will be equal to the zenith angle when the panel is flat on the ground [20].

One of the parameters needed to calculate the incidence angle is the solar declination angle (δ), which is the angle between the direct solar radiation and the equator. The value of this angle depends on the number of the day and can be determined by using the following equation [20]:

$$\delta = 23.45 \sin\left[2\pi\left(284 + n\right)/365\right] \quad (1)$$

where n is the number of the day, counted from the 1st of January. The declination angle is maximum at $+23.45^0$ during summer solstice in June and minimum at $-23.45\ ^0$ during winter solstice in December.

Another factor needed to calculate the incidence angle is the solar hour angle (ω). This angle is defined as the angle between the solar radiation and the longitude of the location of the solar panel. Its value is zero during local solar noon (t_{lsn}), negative before noon, and positive after noon. The solar hour angle at any given time (t_s) can be calculated as follows [26]:

$$\omega = 360(t_{lsn} - t_s)/24 \quad (2)$$

$$t_{sn} = 12 + 60\left[\left(82.5 - \rho\right)/15\right] \quad (3)$$

2.2. Mathematical Model

In general, the electric power generated by a solar panel depends on the specification of the panel itself, including its sectional area and efficiency, and the amount of global solar radiation received by the panel. The formula to calculate the output power is as follows:

$$P = \eta A G_T \quad (4)$$

When the panel is at a flat position, the value of G_T is equal to the available global solar radiation (G). To maximize the output power, the maximum G_T value needs to be achieved by finding the optimum inclination and orientation angles. Global solar radiation on tilted surfaces consists of 3 components, direct or beam (G_{Tb}), diffuse (G_{Td}), and reflected radiation on tilted surface (G_{Tr}):

$$G_T = G_{Tb} + G_{Td} + G_{Tr} \quad (5)$$

Direct solar radiation is a radiation received by the panel in a straight line from the sun. Direct solar radiation on a tilted surface can be estimated using the following equations [25]:

$$G_{Tb} = G_b R \quad (6)$$

$$R = \cos\theta / \cos\theta_z \quad (7)$$

$$\begin{aligned} \cos\theta = &\sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma \\ &+ \cos\delta\cos\varphi\cos\beta\cos\omega \\ &+ \cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega \\ &+ \cos\delta\sin\beta\sin\gamma\sin\omega \end{aligned} \quad (8)$$

$$\cos\theta_z = \sin\varphi\sin\delta\cos\varphi\cos\delta\cos\omega \quad (9)$$

Sky objects such as clouds and aerosols scatter part of the solar radiation. This scattered radiation is called diffuse solar radiation [18]. The diffuse solar radiation on tilted surface, compared with the available diffuse solar radiation on horizontal surface (G_d), can be calculated as [19]:

$$G_{Td} = G_d\left[\left(1 + \cos\beta\right)/2\right] \quad (10)$$

The ground and other surfaces around the panel also reflect the solar radiation to the panel. This reflected radiation is given by the following equation [25]:

$$G_{Tr} = r_g G\left(1 - \cos\beta\right)/2 \quad (11)$$

3. Estimation of Optimum Angles Using ANN

3.1. Obtaining Training Data

In this study, the training data for the ANN were obtained from the combination of the data from NASA prediction database and the calculation results from eq. (1)-(11). The values of G, G_b, and G_d were taken from the data provided by the Japan Meteorological Agency in five locations, namely Sapporo, Tateno, Fukuoka, Ishigakijima, and Minamitorishima. Sampling was performed one day each month, from 5 AM to 8 PM. The inclination angle varied between 0^0 and $+60^0$ while the orientation angle varied within the range from -90^0 to $+90^0$. In both cases, intervals of 5^0 were applied.

Based on the calculation results, the training data were concluded with G, G_b, G_d, n, ts, ρ, φ, γ, and β as inputs, whereas G_{Tb}, G_{Td}, and G_{Tr}, and consequently G_T, were the outputs. The configuration of the calculation process is shown in Fig. 2.

3.2. Proposed Method

The configuration model of the method to estimate the G_T at any given time and location is shown in Fig. 3. The amount of solar radiation during the voyage is estimated using ANN-1 [27], while ANN-2 acts as the main program to estimate the value of G_T based on the given inputs. The structure of the ANN-2 is presented in Fig. 4. The number of hidden neuron is determined by comparing the mean square error from various number of hidden neuron candidates during training process.

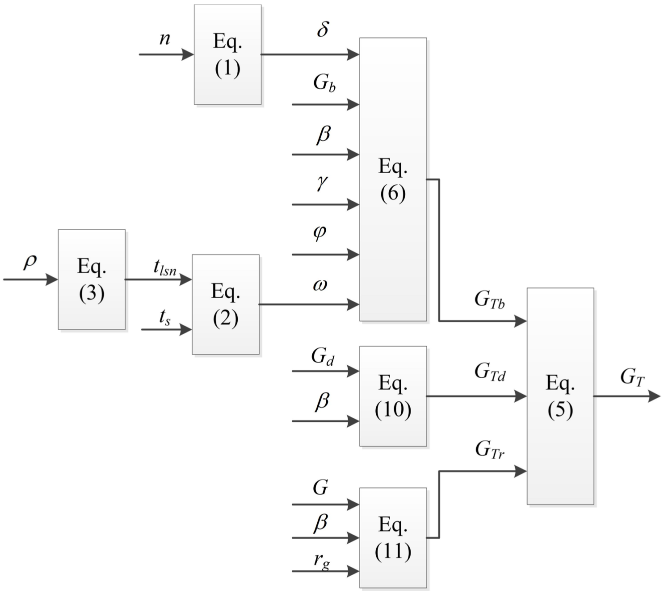

Fig. 2. Configuration of the calculation used to obtain training data.

The ship location and the direction angle (λ) were obtained from automatic identification system (AIS) data of Marine Traffic. The value of r_g was set at 0.06 and represents the reflectivity of water [28]. During the journey, the orientation of the panel may change from its initial position. Hence, the actual orientation angle (γ_{act}) is used as the input of ANN-2 instead of γ that was initially set, before the ship sailed. The correlation between the initial and actual panel orientation and ship direction angle is shown in Fig. 5. For each actual direction angle (λ_{act}), γ_{act} can be calculated as follows:

$$\gamma_{act} = (\gamma - \lambda) + \lambda_{act} \tag{12}$$

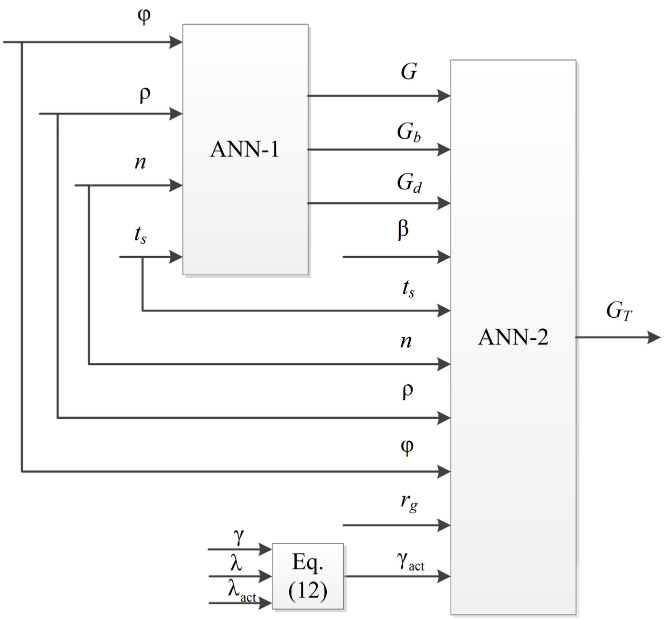

Fig. 3. Configuration model to estimate global solar radiation on inclined surface.

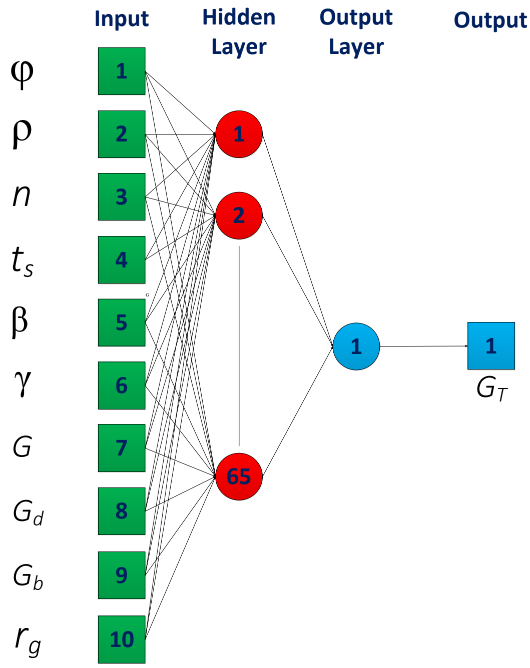

Fig. 4. Structure of ANN to estimate global solar radiation on inclined surface.

The configuration model was built and executed using the MATLAB software to estimate the G_T at any given inputs. For the long routes, the calculations were performed for one round trip, whereas the calculations for one day were performed for short routes. The angles γ and β were varied using the same values, within the range mentioned in section 3.1. Finally, the best combination of angles was determined based on the maximum value of G_T.

4. Case Studies

Six local shipping routes around Japan were used to investigate the optimum angles of solar panels on the ship. The selection of the shipping lines considered the variants in journey direction and distance. Among them, two are considered as long routes, in which one round trip takes more than one day. The remaining four are considered as short and medium routes in which several round trips are carried out in one day. The complete shipping routes are listed in Table 1.

All selected routes are spread around Japan. Among the destination ports, the northeast part of Japan is represented by Otaru, the southeast is represented by Chichijima, and the southwest is represented by the lines of the Rainbow Kamome and Ferry Koshiki ships, while the others are located around the center of Japan. The distribution of ship routes is shown in Fig. 6.

5. Results and Discussion

5.1. Training Accuracy

As mentioned in the introduction, discussions about the best angle of PV panels installed on ships can hardly be found. As a consequence, a comparison study to validate the accuracy of the proposed method cannot be done. Instead,

Table 1. Ship routes for the case studies.

No.	Ship name	Route	Direction	Journey duration	Route category
(1)	Ogasawaramaru	Tokyo - Chichijima	North West – South East	1 round trip in 3 days	Long Route
(2)	Akashia	Otaru - Maizuru	North East – South West	1 round trip in 2 days	Long Route
(3)	Kirikushi	Etajima – Hiroshima	North - South	11 round trips in 1 day	Short Route
(4)	Rainbow Kamome	Kumamoto – Shimabara	East – West	5 round trips in 1 day	Short Route
(5)	Tokiwamaru	Ryoutsu - Niigata	East-West	2.5 round trips in 1 day	Medium Route
(6)	Ferry Koshiki	Nagahama – Kushikino – Sato	Triangle	2 round trips in 1 day	Medium Route

the training performance of the ANN-2 is included. The regression plot between actual and predicted values of G_T is shown in Fig. 7. The statistical results show that the Mean Square Error (MSE) of the training, validation, and testing processes are 6.99×10^{-3} or less. Furthermore, the regression value (R) for each process is higher than 0.98, with an R value of 1 meaning that the estimations are 100% accurate.

5.2. Optimal Combination of Angles

In this study, the monthly, seasonal, and annual optimal combination of angles of the solar panel are predicted for six case studies. The hypothesis is that the more often the combination of angles is adjusted, the higher is the solar radiation that can be absorbed by the panel. However, adjusting the angles hourly, or even daily, is impractical [19]. Therefore, the shortest period chosen in this study to adjust the panel angles is once every month. While seasonal and annual adjustments may result in less solar radiation being absorbed by the panel, it is important to investigate the difference between these procedures in order to determine whether the monthly adjustment is worth doing. The optimal combination of angles for monthly, seasonal, and annual periods is shown in Table 2, Table 3, and Table 4, respectively.

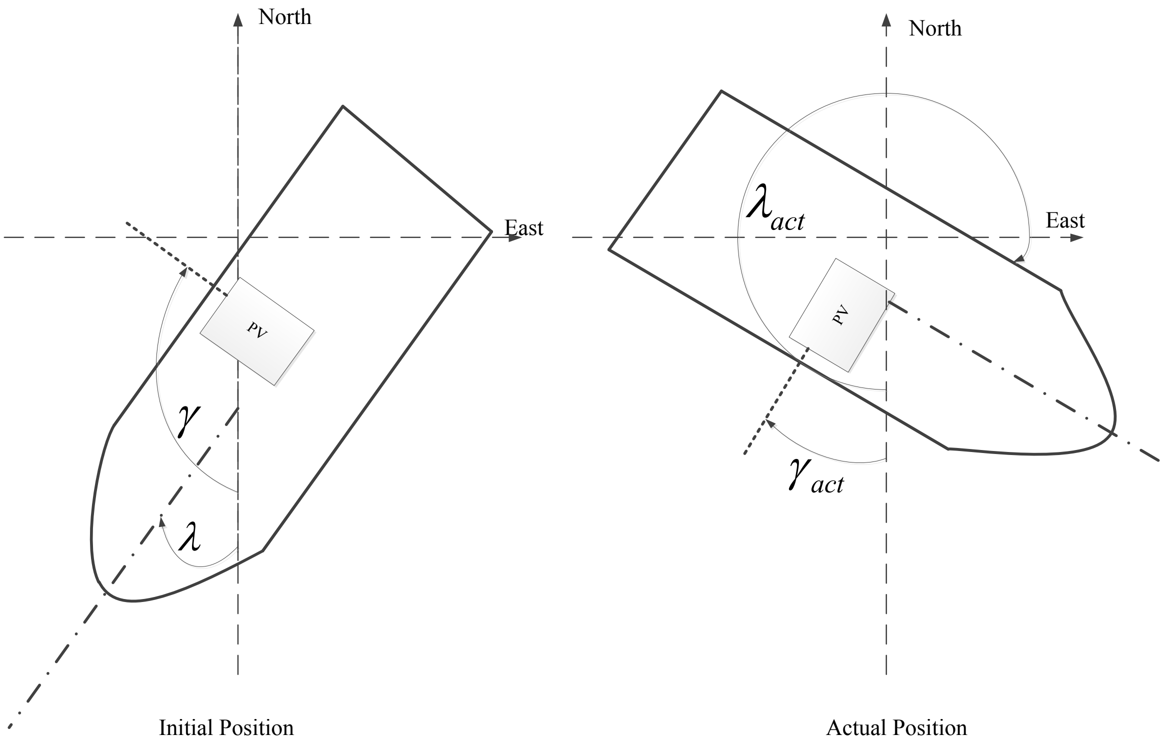

Fig. 5. Panel orientation and ship direction angle.

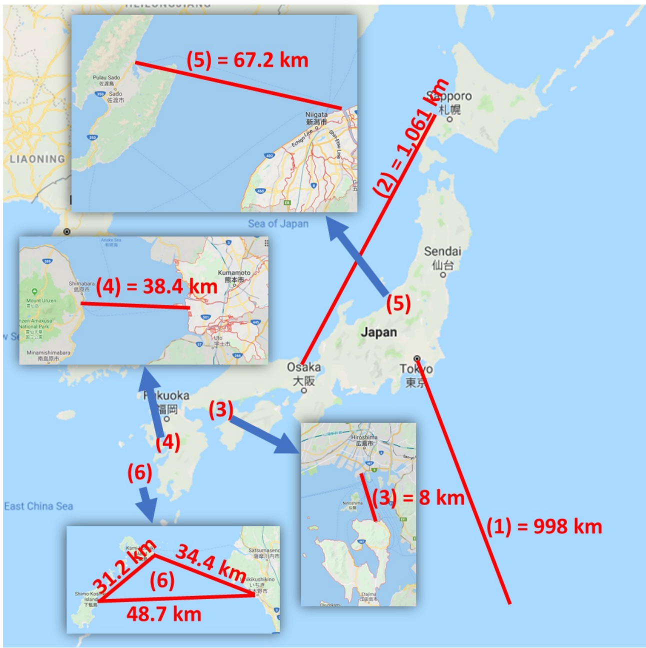

Fig. 6. Ship routes used for the case studies.

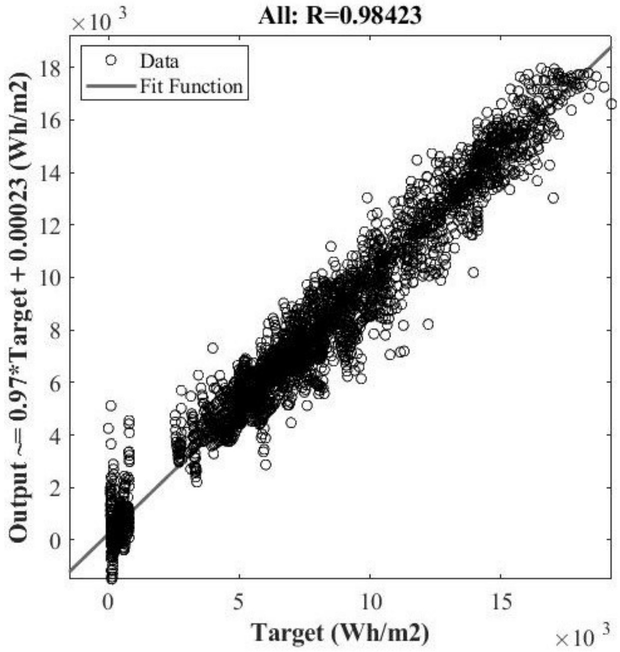

Fig. 7. ANN training regression.

The results show that there is a significant difference between long and short routes regarding the inclination angle (Table 2). For long routes, the inclination angle tends to be lower and less than 20º in any given month. Meanwhile, for the short and medium routes, the inclination angle tends to be higher during winter, getting lower during summer. This tendency has similarities with the optimal inclination angle on fixed coordinates [17, 19, 23].

The tendencies of the optimal initial orientation angle, on the other hand, are more difficult to be deduced, as they vary between each route and month. For the North-South route (Ogasaramaru, Akashia, and Kirikushi), the optimal orientation angles tend to be around north and south, while for the East-West route (Rainbow Kamome and Tokiwamaru), the optimal angles are mostly between east and south. For Ferry Koshiki, which has a triangular route, the optimal orientation angles scatter in almost every direction for different months.

The optimal combination of angles calculated for seasonal periods is close to the combination of angles calculated for each month. For example, the optimal inclination angles for December, January, and February are all 10º (Table 2), which is the same value of the optimal inclination angle for the winter season (Table 3). The optimal orientation angle for winter, which is 225º, is also close to the optimal orientation angles for December, January, and February, which are 230º, 225º, and 210º respectively.

The optimal fixed inclination angle for short and medium routes is between 20 and 35º (Table 4). These angles are closer to the optimal angle for summer than to the one for winter due to the higher availability of solar radiation in summer.

The optimal inclination angles for short routes are relatively low. This is due to the similar time and duration of the sunlight exposure between the outward and return legs of the journey. For example, the Akashia ship departs from Maizuru at 23:50 of the first day and arrives at Otaru at 20:45 of the second day. Then, the ship departs at 23:30 on the same day and arrives at Maizuru at 21:15 of the third day. Hence, the solar panel on the ship will get the solar radiation from the sunrise until the sunset on the second day, in the direction to Otaru. It will also get radiation for the same period on the third day, in the direction of Maizuru. When the panel inclination angle is high, it will receive high solar radiation for one direction of the journey and low solar radiation for the reverse direction. Conversely, at low or flat angles, the solar radiation received for both directions are similar and generates a resultant that is higher than the high angle.

The case is different for the short routes. Even though the duration of both legs of the journey is similar, the exposure time is different. Take the schedule of Kirikushi as an example. This ship departs from Etajima at 6:40 the earliest and arrives at Hiroshima at 7:05. It then returns to the direction of Hiroshima at 7:10, arriving at 7:35. The journey duration is 25 minutes, but the intensity of the solar radiation between 6:40 and 7:05 and between 7:10 and 7:35 may be different. As a result, when a flat angle is applied, the solar radiation received by the panel in each of the two directions may not be equal. On the other hand, an advantage of applying higher inclination angles is that it results in much higher solar radiation being received for one of the two directions. Even when the amount of solar radiation received during the reverse direction is low, the resultant is still higher when compared with the flat angle case.

Table 4. Monthly optimal combination of angles for six case studies. Angles are shown in degrees (º).

Months	Ship											
	Long Route				Short Route				Medium Route			
	Ogasawara-maru		Akashia		Kirikushi		Rainbow Kamome		Tokiwamaru		Ferry Koshiki	
	β	γ	β	γ	β	γ	β	γ	β	γ	β	γ
January	10	225	15	340	60	225	60	285	55	355	25	215
February	10	225	10	5	55	355	60	25	55	350	25	235
March	5	190	5	330	45	20	55	10	30	255	25	150
April	5	190	5	245	35	15	45	5	25	260	20	150
May	5	190	0	Any	30	10	20	5	25	270	15	135
June	5	210	0	Any	25	355	5	340	20	280	15	125
July	5	210	0	Any	25	0	5	335	20	275	15	105
August	5	210	0	Any	30	15	20	320	20	270	15	80
September	10	165	0	Any	40	15	50	15	25	255	25	80
October	10	165	5	275	40	340	55	335	35	250	25	65
November	10	165	5	350	60	15	60	305	55	350	25	30
December	10	225	15	345	60	185	60	285	60	350	35	195

Table 3. Seasonal optimal combination of angles for six case studies. Angles are shown in degrees (º).

Seasons	Ship											
	Long Route				Short Route				Medium Route			
	Ogasawara-maru		Akashia		Kirikushi		Rainbow Kamome		Tokiwamaru		Ferry Koshiki	
	β	γ	β	γ	β	γ	β	γ	β	γ	β	γ
Winter (Dec-Feb)	10	225	5	220	60	175	60	285	60	350	35	180
Spring (Mar-May)	5	190	0	Any	50	335	50	10	25	265	15	145
Summer (Jun-Aug)	5	210	0	Any	25	355	5	335	20	280	15	75
Autumn (Sep-Nov)	10	165	0	Any	35	5	60	15	30	265	25	50

Table 2. Annual optimal combination of angles for six case studies. Angles are shown in degrees (º).

Fixed Angle	Ship											
	Long Route				Short Route				Medium Route			
	Ogasawara-maru		Akashia		Kirikushi		Rainbow Kamome		Tokiwamaru		Ferry Koshiki	
	β	γ	β	γ	β	γ	β	γ	β	γ	β	γ
	10	210	0	Any	20	340	30	10	25	265	25	150

5.3. Comparison of Global Solar Radiation Received

The G_T received by the panel using the proposed method with monthly, seasonal, and annual adjustments were compared. The G_T of the panel at an inclination angle of 0º was also taken into consideration. The comparison of one-year estimation values of G_T for each method on each ship is presented in Fig. 8.

The result shows that the solar radiation received by the panel on long route ships varies only slightly according to

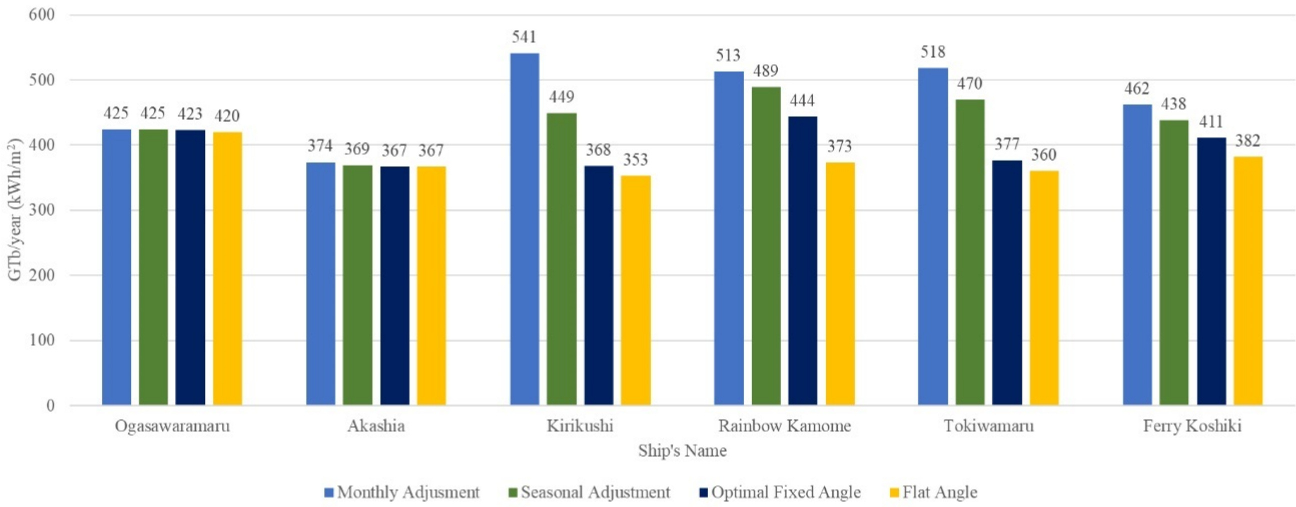

Fig. 8. One-year estimation values of the G_T received by the solar panels on each ship.

the panel adjustment method used. In the Ogasawaramaru case, the difference between the highest and lowest G_T values is only around 6 kWh/m^2, while this difference is about 10 kWh/m^2 in the Akashia case. On the other hand, the differences between the highest and lowest G_T values for short routes are more significant, reaching more than 100 kWh/m^2, except for the Ferry Koshiki case. The monthly adjustment methods also produce at least 24 kWh/m^2 more energy than the seasonal ones.

6. Conclusions

Adjusting the inclination and orientation angles of PV panels to the optimal position is important to draw the highest possible amount of energy. In this paper, a new method using ANN to determine the optimal combination of inclination and orientation angles of PV panels installed on ships was presented. The accuracy of the ANN built in this study is relatively high, with regression values of 0.98 or higher. The optimal monthly, seasonal, and annual fixed angles of 6 ship routes were estimated by the ANN. The results showed that the optimal inclination angles for long routes are relatively low throughout the year, with 15º as the highest. On the other hand, the optimal inclination angles for short routes are higher in the winter and get lower toward summer, which is similar to the behavior of the optimal inclination angle on fixed coordinates, investigated by previous researchers. In each case, the optimal orientation angles were varied monthly. The comparison of the solar radiation received using monthly, seasonal and annual adjustments, as well as using a flat angle, shows small differences for long routes but significant discrepancies for short ones. In short and medium routes cases, the radiation received by the panels are at least 21% higher when monthly adjustment is applied, compared to the flat angles. On the best case, the solar radiation reception can increase up to 53%. Therefore, the flat angle position is more recommended for PV panels installed on ships that travel routes longer than a day. Nevertheless, the monthly adjustment of the panel to the optimal inclination and orientation angles is highly recommended for ships with one or more round trips per day in order to improve the efficiency of the PV system.

An important outlook for this study is to propose a methodology for determining optimal angles of the PV panels installed on ships based on directions and schedules. By applying our proposed method to determine the monthly optimal position of the PV panels installed on short routes ships, the energy produced by the PV system will increase compared with the conventional flat angle. The accuracy of the proposed method could be increased in the future by taking the ship motions into consideration.

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