Adaptability of solar energy conversion systems on ships

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Abstract. International trade of goods largely uses maritime/transoceanic ships driven by engines using fossil fuels. This two centuries tradition is technologically mature but significantly adds to the CO₂ emissions; therefore, recent trends focus on on-board implementation of systems converting the solar energy into power (photovoltaic systems) or heat (solar-thermal systems). These systems are carbon-emissions free but are still under research and plenty of effort is devoted to fast reach maturity and feasibility. Unlike the systems implemented in a specific continental location, the design of solar energy conversion systems installed on shipboard has to face the problem generated by the system base motion along with the ship travelling on routes at different latitudes: the navigation direction and sense and roll-pitch combined motion with reduced amplitude, but with relatively high frequency. These raise highly interesting challenges in the design and development of mechanical systems that support the maximal output in terms of electricity or heat. The paper addresses the modelling of the relative position of a solar energy conversion surface installed on a ship according to the current position of the sun; the model is based on the navigation trajectory/route, ship motion generated by waves and the relative sun-earth motion. The model describes the incidence angle of the sunray on the conversion surface through five characteristic angles: three used to define the ship orientation and two for the solar angles; based on, their influence on the efficiency in solar energy collection is analyzed by numerical simulations and appropriate recommendations are formulated for increasing the solar energy conversion systems adaptability on ships.

1. Introduction

International shipping provides about 80% of world trade by volume and 70% in value [1] based mainly on fossil fuels (diesel or fuel oil) and hence responsible for a significant amount of greenhouse gases emissions (exhaust gases) resulted from the fuel combustion in the main and auxiliary engines, as well as in auxiliary equipment. These are mixtures of carbon dioxide (CO₂), carbon monoxide (CO), sulfur oxides (SOₓ), nitrogen oxides (NOₓ), methane (CH₄), carbon black (BC), organic carbon (OC), have both climatic effects and a significant impact on the environment at local and regional level [2]. According to recent studies, shipping is responsible for 3.1% of the global CO₂, 15% of NOₓ emissions and 13% of SOₓ emissions [3].

Reducing climate changes asks all major greenhouse gases emitters to find viable solutions; therefore, the shipping industry faces the need to increase the efficient use of energy and to replace the traditional energy sources with renewables. Typically, additional sails, kites, wind turbines, photovoltaic modules and hydrogen fuel cells are proposed as green energy systems for power
generation on-board [4]. Despite their extended inland applications, the use of solar energy converters in modern marine technology is still limited, mainly as power suppliers to small lighthouses, buoys, and to charge batteries of small sailing yachts [5]. Feasibility of installing photovoltaic modules on vessels is considering a payback time between 10 and 27 years, depending on solar radiation and fuel cost [6]. The largest reported applications reported are PlanetSolar (with a 537 m² active photovoltaic area) and Nichioh Maru with 281 photovoltaic modules. Common to both applications is the horizontal mounting of the photovoltaic array; despite the safety, this solution has the obvious disadvantage of a significantly reduced collection degree of the solar radiation, [7].

Solar thermal systems are even more seldom mentioned in the literature [4] and, to the best of our knowledge, are not implemented on merchant vessels.

The optimal orientation of solar energy conversion systems integrated with the ship deck, comparing with systems mounted inland in a fixed location, is facing the additional issue of the conversion system base mobility (translation and rotation) during navigation, (figure 1). The main challenges in predicting the amount of collected solar energy are due to:

a) significant changes to the ship location (latitude, longitude) in a relatively short time, e.g. the ship position can be changed by at least 1° latitude / longitude in one day and hence different weather features and parameters such as atmospheric turbidity factor can occur;

b) the ship azimuth during navigation can be changed in the range 0..360° (angle \( \phi_z \), figure 1), with direct impact on the amount of solar radiation collected by a fixed tilt convertor surface mounted on-board). The pathway direction of long-haul ships is typically maintained over a relatively long period of time;

c) two additional pitch and roll motions (with angular displacements defined by the \( \phi_x \) and \( \phi_y \) angles, figure 1) can occur during ship navigation, characterized by relatively low oscillation amplitude (usually not exceeding 5° for pitching motion and 15° for rolling motion) and small oscillation period, of tens of seconds.

Despite to the inland applications where a fixed tilt solar convertor has fixed orientation in the local coordinate system, the ship angular displacements allow changes in the orientation of the solar convertor active surface (i.e., the orientation of the unit normal vector \( \hat{n} \), figure 1) and thus in the incidence angle of sunrays on the converter surface, with significant consequences on the collecting efficiency of the direct solar radiation.

The paper investigates the influence of yaw-pitch-roll motion of a ship on the efficiency and the amount of direct solar energy collected by a fixed tilt converting area mounted on-board. The results for a set of locations in the northern hemisphere and several representative days are used to formulate general recommendations on the adaptability of solar energy conversion systems on ships. Thus, the first part of the paper gives a general model describing the incidence angle of the direct solar radiation on the conversion surface. Based on, the direct solar radiation collecting efficiency is further numerically simulated considering the yaw angle, the pitch-roll motion, and the tilt angle of the convertor. Recommendations are further on formulated for implementing flat solar energy convertors on ships.

2. Modelling the influence of ship motion on the incidence angle

A solar converter flat surface with unit normal vector \( \hat{n} \), is considered, mounted with a fixed tilt angle \( \chi \) on the deck of a ship with yaw-pitch-roll general motion (figure 1). In the location \( O \) are defined two coordinate systems: a fixed reference system \( x_0y_0z_0 \), where \( x_0y_0z_0 \) is the horizontal plane with \( x_0 \) axis toward Est and \( y_0 \) toward North, and local moving system \( xyz \) attached to the ship. The orientation of the vector \( \hat{n} \) in the reference system is modelled considering the following sequence of the ship rotational motions:

a) yaw motion, characterized by the angle \( \phi_z \) around the \( Oz_0 \) axis (figure 2a);

b) pitch motion, as rotation around the \( Ox_1 \) axis with angle \( \phi_x \) (figure 2b);

c) roll motion, with angle \( \phi_y \) around the \( Oy_2 \) axis (figure 2c).
Figure 1. The motion parameterization of a ship with solar convertors on-board.

Figure 2. The ship rotational motions: (a) yaw, (b) pitch, (c) roll.
Figure 3. The equivalent kinematic chain for the ship general rotational motion.

The tilt angle $\chi$ is modelled by a rotation around the $x$-axis of the ship local coordinate system (figure 3). As a result, the vector $\vec{n}$ orientation is determined by rel. (1)

$$[\vec{n}] = R_{x_0}(\varphi_z) \cdot R_{y_0}(\varphi_x) \cdot R_{y_2}(\varphi_y) \cdot R_x(\chi) \cdot [0 \ 0 \ 1]^T$$

where: $R_{x,y,z}$ is the rotation matrix around $x$, $y$, $z$ axes.

The orientation of the unit vector $\vec{b}$ associated to the sunray (figure 3) is typically described in the fixed reference coordinate system $x_0y_0z_0$ by using the solar angles $(\psi, \alpha)$, where $\psi$ is the azimuth angle and $\alpha$ the altitude angle [8]:

$$[\vec{b}] = [\cos \alpha \sin \psi \ - \cos \alpha \cos \psi \ \sin \alpha]^T$$

The angles $\psi$ and $\alpha$ are time variables with specific variations according to the selected day and location latitude.

The incidence angle $\nu$ of the sunray on the solar convertor surface is given by rel. (3)

$$\cos \nu = [\vec{b}]^T \cdot [\vec{n}] = \sin \psi \cos \alpha (\sin \varphi_z \cos \varphi_x \sin \chi + \cos \varphi_z \sin \varphi_x \cos \chi + \sin \varphi_z \sin \varphi_x \cos \varphi_z \cos \chi) +$$

$$+ \cos \psi \cos \alpha (\cos \varphi_z \cos \varphi_x \sin \chi - \sin \varphi_z \sin \varphi_x \cos \chi + \cos \varphi_z \sin \varphi_x \cos \varphi_y \cos \chi) +$$

$$+ \sin \alpha \cos \varphi_z \cos \varphi_y \cos \chi - \sin \alpha \sin \varphi_z \sin \chi$$

The rel. (3) represents the instantaneous efficiency in collecting the direct solar radiation:
where: \( B_n \) and \( B_b \) [W/m²] are the direct solar radiation measured on a plane perpendicular to the direction \( \vec{n} \), and respectively \( \vec{b} \).

The average daily efficiency of the collected direct solar radiation is given by the ratio between the collected direct solar energy \( E(B_n) \) and the maximum available energy \( E(B_b) \) during the day, calculated based on the \( B_n \) and \( B_b \) values integrated over the entire day-time interval [8]:

\[
\eta_{b_d} = \frac{E(B_n)}{E(B_b)}
\]

The Meliss model of direct solar radiation in clear sky assumption [9] gives:

\[
B_b = I_0 e^{-\frac{TR}{0.99 \sin^4 \alpha}} \quad I_0 = 1367(1 + 0.0334 \cos(0.9856' \cdot N - 2.72')) \tag{5}
\]

where: \( N \) is the day number (\( N = 1 \) for 1 January), and \( TR \) – the turbidity Linke factor of the location.

Further on, based on numerical simulations, the influence of the ship motion and the tilt angle on the energy behaviour of a solar energy converter mounted on-board is addressed and the relevant results are presented.

3. The influence of the yaw angle

The pathway direction of a ship is defined by its azimuth (yaw) angle (the angle between the \( y \)-axis of the ship and \( y_0 \) axis on the North direction), figure 1. Usually, the ship direction is maintained unchanged for a long time and thus the angle \( \phi_z \) becomes a constant parameter for longer periods of time, e.g. one day. The yaw angle \( \phi_z \) directly affects the amount of direct solar radiation collected by a fixed tilt surface, thus larger deviation of the ship direction from North lead to higher decrease of the collecting efficiency.

As example, a ship navigating at latitude 45°N on a calm sea (without pitching and rolling motions) and holding a solar converter mounted at 45° tilt angle is considered. The yaw angle influence is analyzed for three representative days: winter solstice (\( N = 355, T_R = 2.25 \)), the spring equinox (\( N = 80, T_R = 2.5 \)) and the summer solstice (\( N = 172, T_R = 3.4 \)), (www.soda-is.com). The results in figure 4 outline that the yaw angle has a significant impact on the amount of solar radiation that reaches the convertors’ surface, particularly in winter and during adjacent seasons when the collecting efficiency decreases down to zero for large yaw angle values (in this case, higher than 140°). Although it has a less influence in summer, there are registered significant losses (approximately 18%) at higher values of the yaw angle, with a slight improvement in the daily efficiency for \( \phi_z \) lower values, figure 4. Obviously, the angle \( \phi_z \) has a major influence in collecting direct solar radiation, unless the tilt angle is zero, and in most cases the maximum collecting efficiency is obtained for null values of the yaw angle; therefore, the South-face orientation of tilted converting surfaces is recommended.

4. Influence of the pitch and roll motions

Pitching and rolling of the ship are oscillatory motion of sinusoidal type characterized by relative short oscillation periods (tens of seconds) and usually low angular amplitudes of less than 15°. During a ship oscillation cycle, the unit vector \( \vec{n} \) of the fixed tilt solar converter at \( \chi = 45° \) is changing its relative orientation to the solar ray and thus the incidence angle \( \nu \) is continuously modified.

Due to the short oscillation period, the unit vector \( \vec{b} \) associated to the sunray and the direct solar radiation \( B_b \) are assumed to remain unchanged during one oscillation.
**Figure 4.** Variation of the daily collected direct solar energy with the yaw angle $\varphi_z$, at 45°N latitude, 45° tilt angle and without pitch-roll motion, during: (a) winter solstice, (b) spring equinox, (c) summer solstice.
Thus, the average efficiency $\eta_{Bosc}$ in collecting the direct solar radiation during one oscillation period $T$ can be calculated with rel. (6)

$$
\eta_{Bosc} = \frac{E_T(B_n)}{E_T(B_0)} = \frac{1}{T} \int \frac{B_n}{B_b} = \frac{1}{T} \int \cos \varphi = \langle \cos \varphi \rangle_{\text{average}} = \langle \eta \rangle_{\text{average}}
$$

(6)

As example, a ship navigates at spring equinox ($N = 80$) to the North ($\varphi_z = 0$) with a pitching amplitude of $5^\circ$ and roll amplitude of $15^\circ$, both sinusoidal motions have the same oscillation period $T = 20$ seconds, figure 5a. The case of the ship without oscillations ($\varphi_x = \varphi_y = 0$) is considered as reference in this comparative approach; the collected solar radiation in this reference case is shown in figure 5b. The time variation of the collecting efficiency at noon (solar time $t_s = 12$ h) in figure 6 highlights a lower impact of the pitch motion (curve $\varphi_x = \text{var}, \varphi_y = 0$) comparing with the roll motion. Even in the worse-case scenario of combined pitch-roll motions (curve $\varphi_x = \text{var}, \varphi_y = \text{var}$) a low variation of the collecting efficiency is observed and hence a low deviation of the average efficiency during one oscillation cycle in relation to the reference efficiency occurs (less than 1%, figure 6b).

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**Figure 5.** Time variation of: (a) pitch and roll angles, during one oscillation period, (b) direct solar radiation at spring equinox in the absence of pitch and roll motions (reference).
Figure 6. Time variation of the collecting efficiency: (a) instantaneous efficiency over one oscillation period, (b) average efficiency on an oscillation cycle compared with the reference efficiency (red line).

Figure 7. Daily efficiency loss from the reference efficiency, due to the pitch-roll motions.
Figure 8. Time variation of the direct solar radiation collected by a fixed converting surface mounted with different tilt angles: (a) winter solstice, (b) spring equinox, (c) summer solstice.
Figure 9. Variation of the daily collecting efficiency in relation with the tilt angle, for three representative days at latitude 45°N.

Figure 10. Variation of the daily collecting efficiency in relation with latitude, for zero tilt angle and spring equinox.

Figure 11. Maximum daily collecting efficiency obtained for optimal fixed tilt angle.
The parameter of daily efficiency loss is introduced as difference between collecting daily efficiencies in the reference case and considering pitch-roll motions, to measure the impact of the ship oscillations on the collected solar energy. Based on the results in figure 6b, daily efficiency losses are calculated for the three representative days and the results in figure 7 show the limited influence of the pitch-roll motion on the amount of direct solar radiation collected by the convertor (lower than 0.65% for the worst case of spring equinox). Following these results, one may conclude that the pitch and roll motions can be neglected in the process of optimizing the solar converter orientation.

5. Influence of the tilt angle

Solar converters are currently installed horizontally on ships and thus the loss of the collecting efficiency by changing the navigation azimuth angle is avoided. However, this approach has the drawback of a non-optimal collection of solar radiation over one year and strongly depends on the ship location latitude.

Considering the case study of the ship that navigates at latitude 45°N towards North without pitch-roll motions, the results in figure 8 show that the zero tilt angle (horizontally mounted convertor) represents an advantageous solution during summer (figure 8c), with significant disadvantages in other seasons, figure 8a,b and figure 9; in this case study, the optimum tilt angle is \( \chi_{\text{opt}} = 45^\circ \) during the spring season, and \( \chi_{\text{opt}} = 72^\circ \) during winter months. The results show that the 0° tilt angle represents a solution for locations in the equatorial zone and is not recommended for latitudes higher than 30°, figure 10.

Consequently, the collection of direct solar radiation with high efficiency requires adjustment of the tilt angle according to latitude and season.

6. Influence of solar tracking

The optimal fixed tilt solar converters ensure a better collection of the solar radiation, but limited to different collection efficiency thresholds depending on the season [10]. For example, an optimal fixed tilt solar convertor at latitude 45°N can achieve the daily collecting efficiency of 88% during the winter season, 73% in the spring season and only 69% at summer solstice, figure 11. By using single-axis and especially dual-axis solar tracking systems an increase up to 100% of the collecting efficiency can be reached [11, 12] and consequently a significant increase in the amount of solar radiation collected in summer and transitory seasons.

7. Conclusions

The implementation of the solar energy conversion systems on ships represents a quite recent solution to decrease the fossil fuel consumption on-board; however, it raises additional problems generated by the ship mobility that changes in time both the location and spatial orientation of a tilt solar converter fixed on deck. From the numerical analysis presented in the paper the following recommendations on adapting solar energy conversion systems on ships can be formulated:

- the ship yaw angle has a significant impact on the direct solar radiation collected by a fixed tilt solar converter. Therefore, a single-axis orienting system able to orient the active surface of the convertor towards South is required, unless the solar converters are mounted horizontally;
- the pitch-roll motions can be neglected in the design process and when implementing the solar convertors on ships, as the efficiency loss directly related to these motions is less than 1%;
- the adjustment of the tilt angle depending on location and season is an option that can provide a significant increase in the amount of the collected solar radiation;
- the collection of up to 100% of available solar energy and thus maximizing the output (electric or thermal) of the solar energy conversion system can be ensured by integrating tracking systems.

8. References

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