LEVERAGING AN INSTALLED STANDALONE PHOTOVOLTAIC SYSTEM FOR ECO-FRIENDLY SHIPPING

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ARTICLE INFO:

***Article history*:**
Received: 20.07.2023.
Received in revised form: 17.04.2024.
Accepted: 21.03.2024.

Keywords:
Decarbonisation
Energy harvesting and utilisation
Green shipping
Renewable energy systems
Stand-alone photovoltaic system

DOI: https://doi.org/10.30765/er.2318

Abstract:

This paper proposes an effective strategy to make an installed standalone photovoltaic energy system multifunctional by using stored energy in the batteries during different operational profiles of a ship. The authors had proposed a PV system for a typical vessel with an electrical load demand of 11,888 kW that can power the non-essential sailing loads during preferential tripping. To offset the challenges faced by the installation of the standalone PV system to some extent, it is made multifunctional by delivering power to specific loads and its feasibility is also explored. By using stored PV energy to power non-essential harbour loads and continuous harbour loads, the total load demand on harbour generators can be reduced by 30.56% and 44.61%, respectively. The percentage of loads to be supplied from PV energy can be decided based on the efficiency curve of the generator. Furthermore, the installed PV system can also be utilised to extend the backup period of the emergency generator to 1.17 hours. By utilising the installed PV energy system in various ways, the consumption of fuel by ship generators and the emission of carbon dioxide can be reduced. As a result, the payback period of the PV installation can be shortened. Additionally, this approach guarantees maximum comfort for both the crew and passengers on luxurious ships. Thus, this approach encourages an eco-friendly way of utilising renewable energy resources in the shipping industry.

1 Introduction

The International Maritime Organization (IMO) has imposed restrictions to gradually reduce greenhouse gas [GHG] emissions in marine transportation, leading to the adoption of various renewable energy resources (RES). The use of solar energy has become significant in regulating ship emissions, with large and small-scale photovoltaic installations successfully launched in boats, yachts, and cruises [1]. For instance, the ship ‘Planet Solar’ solely used PV energy to travel worldwide [2]. PV systems have also been installed in vehicles such as the Auriga Leader, with 6.9% of its lighting needs met by a 40 kW PV power output [3]. The Blue Star Delos, a Roll-on/Roll-off passenger ship, has a low voltage PV system for supplying its DC loads [4]. The vehicle carrier Emerald Ace has also utilised PV energy for its mooring applications [5]. Meanwhile, operations of the Pure Car and Truck Carrier (PCTC) COSCO TENGFEI are met by solar energy, both on and off-grid. Research on the installation of PV systems in different types of marine vessels has yielded useful information on the benefits and drawbacks of the system, as well as the necessary requirements and potential concerns related to PV installation. Solar energy has been used for lighting and cooling in a ferry Ro-Ro ship 500 gross tonnage (GT) [7] and marine water pumping applications in [8]. The system performance has been enhanced, and fuel consumption has been reduced for an emergency helicopter landing system onboard by integrating PV energy into the existing ship's electrical system [9]. PV energy system with 573 kW and other renewable energy

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resources could drive the luxurious 'Expedition Super-Yacht' [10]. The propulsion and electric loads of a Dubai ferry boat have been supplied by a hybrid PV/Fuel cell/Diesel [11]. A hybrid PV-Diesel system with a 202 kW PV capacity can be used for power generation instead of the diesel engine in 'KMP Port link III' [12]. Additionally, the study calculated the installation cost and the projected payback period. Ship hybrid system optimization in terms of accessible area for installing the solar panels, size of batteries, the purpose of the vessel, navigation route of the ship, installation cost, efficiency of the solar system, etc., are carried out in several vessels [13]-[20]. An optimal energy dispatch plan is proposed in [21] for an integrated energy system (IES) comprising combined heating and power device (CHPD), PV, and energy storage system (ESS). Currently, there is limited research on reducing the cost of PV systems in marine vehicles, as most studies have focused on land applications.

This is because land-based systems have a more consistent load energy and are not as affected by the weight of the system [22]. Determining the optimal size of the PV generation system and ESS in a stand-alone ship PV power system is also required for minimizing the investment cost, fuel cost and the CO_2 emissions [23]. An optimization procedure has been proposed for determining the PV system size (i.e., the number of PV modules and batteries) with minimum cost for an existing solar-powered boat [24]. The integration of PV system to a ship's main grid can cause several power quality issues. An integration of solar PV arrays with the ship's primary distribution grid to facilitate battery charging along with the power quality improvement has been proposed in [25]. These studies take into account various factors such as available space for PV system installation, solar output power calculation, energy storage system size, ship type, shipping route, and installation costs. Building a ship power system model integrated with PV energy system is also challenging as each ship is different in many aspects. A comprehensive simulation model for an integrated solar power system on a ship using PSCAD software is developed in [26]. The dynamic partial shading caused by the uncertainty of navigational environment and ship's geographical position also shading have adverse impacts on PV system performance. A novel structure of PV array configuration has been proposed in [27] and with the application of the structure, the ship can make full use of solar resources. The impact of ambient conditions on the performance of the solar PV system was studied in this work [28]. When PV is incorporated into ship electrical system using the power electronic converters, it can lead to the introduction of harmful harmonics which can cause damage to equipment connected to the network, as well as reduce their efficiency and lifespan [29]. Extensive research has been conducted on the features of solar-generated power, which include inconsistency, unpredictability, and non-simultaneous energy production [30]. In standalone PV system design, it can be difficult to balance power supply and demand. Often, an energy storage device with a capacity several times bigger than the PV modules is necessary, posing a technical challenge [31]. A ship's energy storage battery can age faster when the ship encounters a constant rocking motion [32]. The movements of the vessels can affect the output of PV systems and the quality of the ship's power during different operating scenarios [33].

The fault identification of marine PV systems is extremely difficult due to the long-term exposure to the marine environment and an aerial image recognition fault identification system is designed in [34]. The article [35] outlines the key factors that impact ship stability when loading and unloading heavy cargo. It is important to consider the weight of the PV system as it can affect the ship's stability when additional weight is added during loading. An efficient energy management strategy (EMS) is required for a ship hybrid energy system to augment the marine electric power system reliability, efficiency, and sustainability. The energy management strategy proposed in [36] succeeded in meeting the requirements of the Energy Efficiency Operating Index (EEOI) for ships. A proposal of a scheme for the incorporation of PV panels in a typical luxury cruise vessel's electrical power system for maintaining supply for several non-essential loads such as air conditioning, ventilation, and other comfort equipment at the instant of preferential tripping has been detailed and designed by the authors in [37]. A standalone solar PV system that meets the electrical demands of non-essential loads had been designed for a typical ship with a speed of 26 knot, having an overall length of 141 m and a breadth of 41 m, gross tonnage (GRT) of 8129 tons and deadweight (DWT) of 2651 tons**.** Supplying the non-essential loads of 1312 kW during the period of preferential tripping required the installation of 266 solar panels, each rated 540 watts, and battery bank having a total capacity of 2300Ah. It has been established that the solar panels occupy 685 m^2, about 13.35 % of the total useful deck area the ship can accommodate. It has been found that the weight of the total solar panels installed for preserving the non-essential loads is 7.315 tons which is about 0.27% of the deadweight of the ship. Battery bank occupies 224.92% of the total useful deck area the ship can accommodate .Also, the weight of the battery packs for the designed PV system comes nearly 11.11

tons which is about 0.38% of the ship's deadweight. Therefore, when the ship is in seagoing condition, the proposed PV energy system installed onboard could supply the non-essential loads of 1312 kW to protect the main generator against overload, without shedding the non-essential loads during preferential tripping.

1.1 Need for making an installed PV system multifunctional

After reviewing the literature, it has become apparent that the cost of implementing a solar PV system and ensuring the stability of the ship are the two foremost concerns when designing PV-installed ships. Additionally, since each ship has unique characteristics such as its purpose, structural arrangement, available space, primary voltage, and dead weight, the designed standalone PV system can only be employed for a specific vessel. Therefore, every vessel requires individual design based on its different features and this means that designing solar PV installations on ships is more challenging than on land. However, if the installed PV system can efficiently meet the ship's electrical energy needs based on the ship's operational profile, a standalone PV system can be a more practical option. The possibility of using RES located at the harbour to power ships while they are docked has been discussed in [38]. The RES system, which includes both solar panels and wind turbines, can recharge the depleted battery energy storage system (BESS) and provide power to cold ironing loads [39]. Setting up the equipment for alternate marine power (AMP)/cold ironing at harbours requires a significant investment and some ships may not be compatible with the AMP process.

The cold ironing technique has been made better by incorporating a properly designed and sized PV plant for a commercial vessel [40]. By making the installed standalone PV system multifunctional, the electric load demand on cold ironing process can also be reduced to some extent. Therefore, this paper addresses the potential of transforming the installed standalone photovoltaic energy system into a multifunctional one by utilising the battery-stored energy for different ship operational profiles. Additionally, the feasibility of this approach is also analyzed. This paper is organized into 4 sections. Section 2 describes the methods and calculations used in this research work and recalls the design of PV system onboard in a typical vessel. The proposed strategy for the maximum utilisation of standalone PV system and loads powered by ship generators and PV during different operational profiles of the ship are described in this section. Section 3 describes the results and discussion. Section 4 draws conclusions with this work's contributions and future scope.

2 Methods and calculations

The publication [37] offers a precise explanation of the PV utilisation process for non-essential loads in a typical ship electrical distribution system. The authors also presented a functional block diagram and demonstrated the feasibility of incorporating a PV system into the ship's power system using Electrical Transient Analysis Program (ETAP) software. The standalone PV system includes all conventional components. The battery incorporated into the aforementioned standalone PV system had a capacity of 2300 ampere-hours. The design of the solar PV system and battery is outlined below to facilitate better understanding of the proposed strategy.

2.1 Design of solar PV system

A standalone solar PV system is proposed to meet the non-essential loads of 1312 kW in a typical ship and the details of chosen ship are given in the section 1. The useful length 'L*use*' and useful width 'W*use*' of the ship concerning installation of solar panels are taken as 135m and 38m respectively [41]. Therefore, the useful area 'A*use*' for panels to be installed is estimated as 5130 m^2 using Eq.1.

$$A\_use = L\_use \times W\_use \tag{1}$$

Load requirements: Considering the chosen ship, the non-essential loads that need to be powered by solar energy during preferential tripping amount to 1312kW. For the purpose of designing the standalone PV system, this value is rounded to 1400kW.

AC voltage: 440V, Power factor: 0.8

Design of PV system is done using the following steps.

Step1: Inverter sizing

Solar PV energy is stored in the battery and converted into AC so that the non-essential loads are fed from the inverters provided. Ship's non-essential loads consists of several motors, compressors and pumps which require more starting current and therefore a 30% excess power is considered for the design.
Therefore, required inverter output power in KW = 1400 × 1.3
=1820kW

A standard 500kW inverter, whose specifications are detailed in the Table 1 is selected [42]. Four units of 3 phase inverters, each rated 500kW can be connected in parallel to meet the non-essential loads.

Table 1. Inverter details.

Parameter	**Value**
DC input	rated voltage 700V, 600-900V
AC output	rated power 500kW, 440V
Efficiency	98.5

Considering the efficiency of inverter, input power requirement of inverter is calculated using Eq.2.

$$\text{Input power requirement of inverter in kW} = \frac{\text{Inverter output power in kW}}{\text{efficiency of inverter}} \tag{2}$$

= 1820/0.985
=1847.7157 kW
~1850 kW

Step2: Battery bank capacity calculation
Required battery output power = Inverter input power
= 1850 kW

Considering a standard Lithium Iron Phosphate ($LiFePO_4$) prismatic cell 230Ah, 1C with the following specifications given in the Table 2, energy requirement for one hour is calculated and therefore,
Battery capacity requirement in kWh = 1850kW × 1 hour
= 1850kWh

Table 2. 230Ah battery details.

Specification	**Value**
Manufacturer	EVE
Nominal Voltage	3.20V
Max charge voltage	3.65V
Min discharge voltage	2.50V
Minimum Capacity	230Ah
Cell Grade	A (First Life)
Chemistry	LiFePO4
Max cont. discharge current	1C (230A)
Nominal charge current	0.5C (115A)
Cycle Life	>4000 Cycles @ 80%DOD with 80% capacity retention
Dimensions (max)	174.2mm x 53.8mm x 207.3mm
Weight	~4.2kg
Specification	EVE

Choosing a battery bank voltage of 750V, which aligns closely with the DC input range of the selected inverter, requires connecting 234.375 cells in series, each with a nominal voltage of 3.2V.
Taking into account a typical battery unit with a rating of 48V and 230Ah, with each unit comprising 15 cells in series;

The number of batteries needed to be connected in series to achieve 750V is 15.625 (750/48). This figure can be rounded to 16 batteries.
Hence, the total number of cells in series equals (16 × 15) = 240 cells.
The minimum battery voltage during discharge is calculated as 240 × 2.5 = 600V.
Similarly, the maximum battery voltage during discharge is determined as 240 × 3.65 = 876V.
This meets the required inverter input DC voltage range [600V- 900V].
Battery bank voltage can be calculated using the Eq.3.

$$\text{Battery bank voltage} = \text{Number of batteries in series} \times \text{Voltage of each battery.} \tag{3}$$

Substituting the values in Eq.3, total battery bank voltage = 16 × 48V
= 768V
To supply 1850 kWh, battery capacity required is calculated using the Eq.4.

$$\text{Total battery bank capacity required in ampere hour} = \frac{\text{Total energy capacity}}{\text{Battery bank voltage}} \tag{4}$$

Substituting the values in Eq.4,
Total battery bank capacity required in Ah =1850000Wh/768V
=2.4kAh
To meet this capacity, number of batteries that has to be connected in parallel is calculated using Eq.5.

$$\text{Number of batteries connected in parallel} = \frac{\text{Total battery bank capacity in Ah}}{\text{Ah capacity of one battery}} \tag{5}$$

Substituting the values in Eq.5,
Number of batteries that has to be connected in parallel = (2.4 × 1000)/ 230
= 10.47 batteries
~ 10 batteries
Therefore, 10 batteries should be connected in parallel and the actual Ah capacity of battery bank = 2.3kAh.
Thus, sixteen batteries, each rated at 48V and 230Ah, are arranged in a series to create a string. Ten such strings are connected in parallel to form a battery bank with 768V and 2300Ah.
Therefore, total number of battery units installed= 16 × 10 = 160 batteries

Step 3: PV system

The necessary duration for the non-essential loads to be powered by solar energy during the preferential tripping period amounts to a maximum of 15 minutes daily. Since the maximum continuous discharge current of battery is 1C it is capable of delivering 230A for one hour. Then the PV system is also designed for powering non-essential loads for one hour per day. Therefore, the losses in the inverter, battery, MPPT controller, as well as panel efficiency are neglected.
Selecting a standard PV panel rated 540 watt, 24V, Monoperc (Waree) [43], the number of panels required to power 1400kW non-essential loads for one hour during the ship's operation at sea is calculated using Eq.6, assuming a peak of 10 solar hours.

$$\text{Number of panels required} = \text{Daily kWh} \,/\, (\text{peak solar hours} \times \text{solar panel rating}) \tag{6}$$

By substituting the values mentioned earlier, the calculation yields the number of panels required as 259.25, which is rounded to a total of 260 panels. Taking PV array voltage as 900V, substituting the values in Eq.7, the number of panels that has to be connected in series to form a string is obtained as 38 panels.

$$\text{Number of panels connected in series to form a string} = \frac{\text{PV array voltage}}{\text{PV panel voltage}} \tag{7}$$

= 900V/24V
= 37.5
~ 38 panels

Then the number of parallel strings required is calculated using Eq.8.

$$\text{Number of parallel strings required} = \frac{\text{Total number of panels}}{\text{Number of PV panels in a string}} \tag{8}$$

= 260/ 38
= 6.84
~ 7 parallel strings

Therefore, a total of 266 panels (38×7) are installed. Thus, a robust solar PV system has been meticulously designed to power non-essential loads of 1400kW at 440V AC.

2.1.1 Potential variations and uncertainties associated with battery performance

$LiFePO_4$ batteries currently represent the most suitable technology to meet the technical performance, size constraint, and reliability requirements for the maritime industry [44]-[46]. However, the behavior of lithium-ion batteries on marine vessels can be significantly influenced by factors such as charging and discharging rate capabilities, depth of discharge (DoD), storable energy, temperature, cell aging and lifetime energy throughput during various operational profiles of the ship.

- *Temperature Sensitivity:* Even with marine-grade lithium-ion phosphorous batteries, high temperatures can accelerate battery degradation, leading to reduced efficiency and lifespan. Conversely, cold temperatures can increase internal resistance, limiting the battery's ability to deliver power effectively. Extreme temperatures increase the risk of thermal runaway, a phenomenon where the battery experiences uncontrolled heat generation, potentially leading to fire or explosion.
- *Charging and discharging rates*: Frequent deep discharges may lead to a shorter battery life. Environmental Impact: Exposure to seawater and extreme temperatures can corrode components, affecting performance and lifespan.
- *Monitoring Challenges*: High charging rates require careful monitoring to prevent overcharging or overheating, crucial for safety and longevity.
- *Pressure Vulnerability*: Underwater pressure stresses battery casings, risking leakage or structural damage if not designed appropriately and cause uncertainties in battery performance.
- *Cell variation uncertainty:* Differences in cell performance introduce uncertainty, impacting overall system behavior and lifespan.
- *Self-Discharge risks*: Unbalanced cells may discharge unevenly, reducing overall capacity and performance over time.

A lithium battery can be discharged almost completely without significant adverse effects, but it's crucial to prevent individual cells from over-discharging, a task managed by the Battery Management System (BMS) [47], [48]. The BMS ensures safety and reliability by monitoring, evaluating, and protecting cells against overcurrent, under/over voltage, and under/over temperature conditions. Additionally, it balances the pack during charging to prevent overcharging and ensure all cells receive a full charge. Failure to balance cells can lead to significant variance over time, impacting battery performance.

2.2 Proposed strategy for the maximum utilisation of standalone PV system

The installed PV system can be leveraged by utilising the stored PV energy in the battery for various operational conditions of the ship. The ship's electrical load demand varies depending on its various operational profiles. To analyze energy usage during different operating conditions, necessary data has been collected from the ship's electrical load analysis sheet. Table 3 provides overall information of the ship's generators and loads powered by them during different operational profiles of the ship. The ship's main electrical load comprises essential loads, non-essential loads, emergency loads etc. These electrical loads operate either continuously or intermittently, depending on the ship's operational profiles. Essential services are those required for the safety of personnel and for the safe navigation and propulsion of the ship. The non-essential loads are that type of loads, whose momentary stoppage does not affect the safe operation of the ship. These non-essential loads can again be restarted once the additional power is available. A continuous load is a load that operates for long periods of time and consumes a constant amount of power. Conversely, intermittent loads operates for short periods of time and then turns off. For simplicity, the proposed PV system's multifunctionality is explored in three distinct operational profiles of the ship: 'at sea', 'at harbour', and 'during an emergency'. Each operational scenario is examined both without PV energy and with PV energy. Table 4 enumerates the various loads that must be supplied by ship's generators during these different scenarios.

The duration for which these different connected loads can be supplied by battery for each operational scenario can be calculated using Eq.9 [49]. The round-trip energy efficiency of a $LiFePO_4$ battery is generally 95-98% [50]. Battery efficiency is taken as 0.95 for calculation purposes. The calculation is based on the assumption that the initial SOC in the batteries is 30% in order to compare the different modes of operational profiles with PV utilisation and without PV utilisation under same available SOC. Consequently, the installed bank capacity is multiplied by a factor of 0.3 to yield more realistic values, particularly in adverse conditions. It's noteworthy that battery operating time can be calculated for any SOC value within the range of 0% to 100%. For example, the duration for which these different connected loads that can be supplied by the battery increases for the fully charged battery (SOC =100%). Moreover, the BMS can provide real-time information about the varying SOC of the battery.

$$\text{Battery operating time in hours(t)} = \frac{(\text{Battery bank capacity in Ah} \times \text{Battery bank voltage} \times \text{Battery efficiency})}{\text{Load in watts}} \tag{9}$$

Table 3. Ship electrical load details.

Number and Capacity of working generator (kW)	Operating Condition	Total load on generator (kW)	Generator load percentage (%)
4 × 4000 (Main generators)	At sea	13,200	82.5
	At sea after preferential tripping (excluding non-essential loads)	11,888	74.3
1 × 1300 (Harbour generator)	At harbour	1070	82.3
	At harbour after preferential tripping (excluding non-essential loads)	544	50.84
	At harbour (intermittent loads)	490	37.69
1 × 600 (Emergency generator)	At an emergency	430	71.6

Table 4. Load ratings of different operational profile.

Type of load	Name of load	Load (kW)
Non-essential sailing loads	Galley, Laundry, Pantry	70
	Boiler plant	12
	Chilled circulating pumps	210
	Sewage treatment plant pumps	120
	Reefer plug	60
	Air condition units	840
	Total non-essential sailing loads	**1312**
Non-essential harbour loads	Ballast Water Treatment Plant (BWTP)	11
	Hydrophore pumps	12
	Hot water calorifier	5
	Specific pumps of boiler plant	2
	Chilled water plant and circulating pumps	200
	Air handling units	100
	Packaged air conditioning unit for wheelhouses	2
	Reefer plug	170
	Galley, Laundry and Pantry	15
	Sewage treatment plant	2
	RO plant	6
	Impressed Current Cathodic Protection (ICCP) plant	1
	Total non-essential harbour loads	**526**
Continuous harbour loads	Generator fuel supply pump	2.0
	Main sea water cooling pump	20
	Auxiliary sea water cooling pump	37
	Hot water circulating pump	1.0
	Chilled water plant and circulating pumps	180
	Air condition unit	100
	Ventilating fans	50
	Reefer plug	170
	UPS for drive control system	11
	Fire detection alarm system	1.0
	Watertight sliding doors control system	0.3
	Integrated alarm monitoring and control system (IAMCS)	3.0
	Impressed current cathodic protection (ICCP) remote control panel	0.5
	Closed circuit television (CCTV)	0.5
	Marine growth prevention system (MGPS)	0.5
	CO_2 system, sprinkler system	1.0
	Differential global positioning system (DGPS)	0.01
	Weather facsimile receiver and voyage data recorder	0.25
	Navigation light and communication light	0.5
	Local area network (LAN)	1.0
	Total continuous harbour loads	**580**
Emergency loads	Steering gear	44
	Generator engine supply pump,	5
	Main generator engine LO priming pump	3
	Harbour generator engine lubricating oil priming pump	3
	Starting and service air compressor	14
	Bilge/ballast pump	42
	Fire and deck wash pumps	35
	Sprinkler sea water pump	63
	Water mist system	12
	Jockey pump for fire main pressure tank	7
	Hydraulically operated sliding doors	10
	Ventilating fans for various rooms	120
	Lighting, navigation, control, and monitoring equipment	25
	Emergency lighting systems	45
	Fire dampers	2
	Total emergency loads	**430**

2.2.1 Load sharing during the operational profile- 'At sea'

The operational profile is considered as 'Mode A', when the ship is at 'at sea', with its four main generators, each with a rating of 4MW, supply power to both essential and non-essential sailing loads. In this mode, the main generators are loaded with a total load of 13,200kW, approximately 82.5% of their capacity. When the main generator encounters an overload condition, inorder to alleviate it, preferential tripping occurs. As a result, non-essential sailing loads are disconnected from the main generator and stored PV energy is used to supply these loads. At the same time, remaining essential sailing loads totaling 11,888kW, are supplied by the ship's four main generators and the generator load percentage has come down to 74.3%. This operational profile is considered as 'Mode A1'.The installed standalone PV system had been designed onboard for this mode providing power to the non-essential sailing loads at the instant of preferential tripping. The comparison between mode A without PV utilisation and mode A1 with PV utilisation is depicted in Fig.1. Available battery bank capacity is taken as 30% of installed capacity for the calculation purposes. The battery backup time 't_1' which can supply power to non-essential loads from the PV system is calculated using Eq.8 resulting in a duration of 23 minutes as obtained below.

$$t_1 = \frac{(2300Ah \times 0.3) \times 768V \times 0.95}{1312000W}$$

= 0.38 hours (23 minutes)

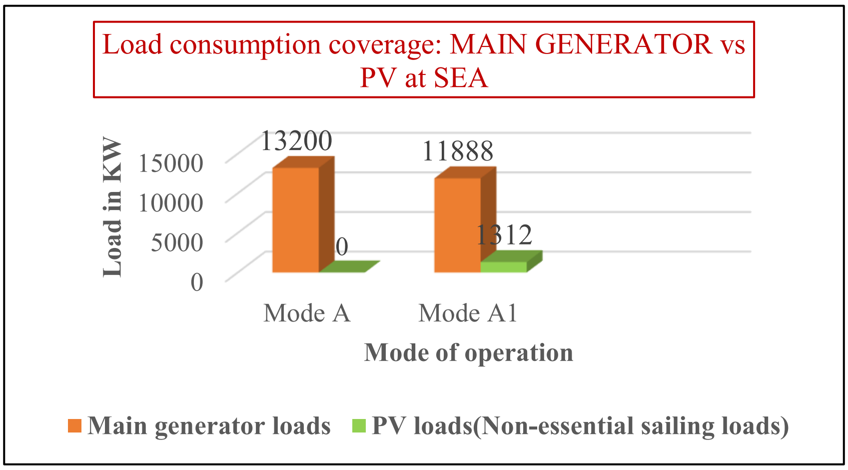

Figure 1. Loads supplied by main generator and PV in mode A and mode A1.

2.2.2 Loads powered by Harbour Generator and PV - 'At Harbour'

The operational profile is considered as 'Mode B', when the ship is at 'at harbour', with harbour generator rated 1300 kW, supply power to both essential and non-essential harbour loads. In this mode, the harbour generator is loaded with 1070kW, approximately 82.3% of its capacity. When the harbour generator encounters an overload condition, inorder to alleviate it, preferential tripping occurs. As a result, non-essential harbour loads are disconnected from the generator and stored PV energy is used to supply these loads totaling 526kW. At the same time, remaining essential harbour loads totaling 544kW are supplied by the harbour generator and the generator load percentage has come down to 41.84%. This operational profile is considered as 'Mode B1'. The battery backup time 't_2' which can supply power to these 526kW loads from the PV system is calculated using Eq.9 resulting in a duration of 57.4 minutes as obtained below.

$$t_2 = \frac{(2300Ah \times 0.3) \times 768V \times 0.95}{526000W}$$

= 0.95 hours(57.4 minutes)

There are different types of loads operating when the ship is at harbour - some require continuous operation, while others only need to be used intermittently. To make the PV energy system more versatile, the installed PV energy system can be used to power continuous harbour loads, when the ship is docked and this operational profile is considered as 'Mode B2'. During this mode, the PV energy stored in the batteries is used to power continuous harbour loads of 580 kW, while the harbour generator is used for intermittent loads. This can bring down the generator load percentage to 37.69%. The comparison between mode B without PV utilisation and mode B1 as well as B2 with PV utilisation is depicted in Figure 2. The battery backup time 't_3' which can supply power to these 580 kW continuous harbour loads from the PV system is calculated using Eq.9 resulting in a duration of 52.07 minutes as obtained below.

$$t_3 = \frac{2300Ah \times 0.3 \times 768V \times 0.95}{580000W}$$

= 0.867 hours (52.07 minutes)

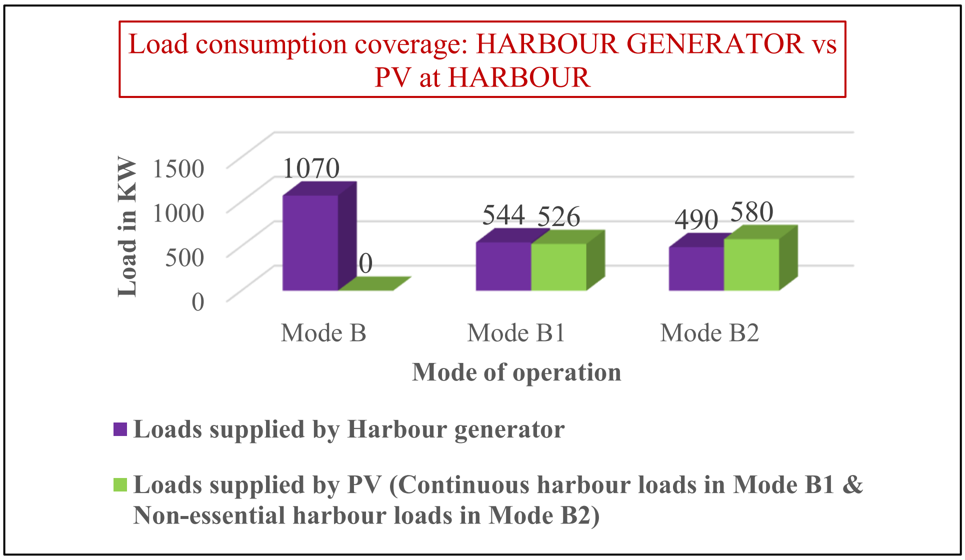

Figure 2. Load supplied by harbour generator and PV in Mode B, Mode B1 AND Mode B2.

2.2.3 Loads sharing during the operational profile- 'At emergency'

The operational profile is considered as 'Mode C', when the ship is in an emergency situation, the emergency generator rated 600 kW, supply power to the whole emergency loads. In this mode, the emergency generator is loaded with 430 kW, approximately 71.6% of its capacity. Generally, the emergency generator is designed to serve emergency loads for 36 hours for passenger ships. If the generator becomes depleted / overloaded or runs low on power, alarms will sound instead of tripping them. To extend the emergency generator's operation beyond 36 hours, the PV energy stored in the batteries can be utilised and this mode of operation is termed as 'Mode C1'. The comparison between mode C without PV utilisation and mode C1 with PV utilisation is depicted in Figure 3. The battery backup time 't_4' which can supply power to these 430 kW emergency loads from the PV system is calculated using Eq.9 resulting in a duration of 70.24 minutes as obtained below.

$$t_3 = \frac{2300Ah \times 0.3 \times 768V \times 0.95}{430W}$$

= 1.17 hours (70.24 minutes)

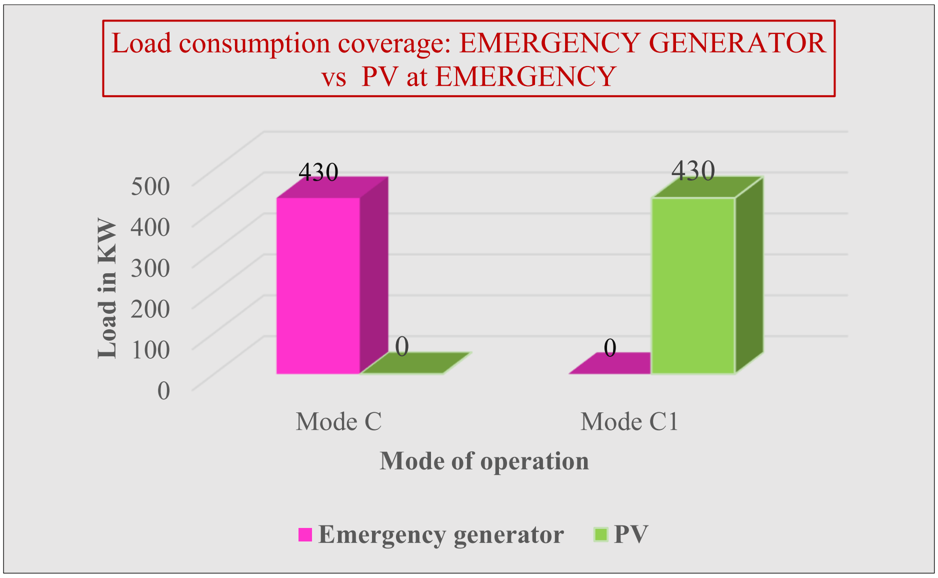

Figure. 1 Load supplied by the emergency generator and PV in mode C and mode C1.

3 Results and discussion

To alleviate the overload of the ship's generator, the ship uses preferential tripping mechanism, which disconnects non-essential loads that may cause discomfort or luxury-related issues. However, with an installed PV energy system, the generator's overload can be reduced without interfering with non-essential loads. The potential of transforming the installed standalone photovoltaic energy system into a multifunctional one by utilising the battery-stored energy for different ship operational profiles has been explored. The installed PV energy can be employed to reduce the total harbour generator load from 81.6% to 50.84% without shedding the non-essential loads while the ship is at the harbour. Therefore, supplying the non-essential harbour loads from the stored PV energy reduces the total harbour generator load by 30.76%. In addition, continuous harbour loads can be fed from the stored PV energy in the batteries, reducing the harbour generator load percentage from 82.3% to 37.69%. Furthermore, the installed PV system can be utilised to supply the emergency loads when the emergency generator is fatigued/overloaded and can thereby extend the backup period of the emergency generator. According to the results obtained, the PV energy system that was installed can provide power to non-essential sailing loads for 23 minutes, non-essential harbour loads for 57.4 minutes, continuous harbour loads for 52.07 minutes and emergency loads for 70.24 minutes when the available capacity of the battery bank is 30% of the rated capacity.

The proposed strategy aims to increase the amount of energy harvested from renewable solar resources. This will improve the comfort of both crews and passengers on luxury vessels. Implementing this strategy is an important step towards decarbonisation of shipping industry and in line with IMO regulations. Installing a multifunctional standalone PV energy system can minimize the fuel consumption of the ship's generators and carbon dioxide emissions, thereby making the ship more environmentally friendly. To transfer electrical loads from one power source to stored PV energy, various switchgear components such as Automatic Bus Transfer (ABT) switches, sensors, relays, and microcontrollers can be used. However, this process requires skilled expertise and proper coordination of BMS and power management system (PMS). The amount of load that can be handled by PV during different operational profiles and battery backup time for the connected loads is summarized in Table 5.

Table 5. PV energy utilisation details during different modes of operation .

Power source	**Mode of operation**	**Generator load percentage (%)**	**Percentage of generator load supplied by PV (%)**	**PV Battery backup time for the connected loads (minutes)**
Main generator	Mode A	82.5	0	-
	Mode A1	74.3	8.2	23
Harbour generator	Mode B	82.3	0	-
	Mode B1	50.84	31.46	57.4
	Mode B2	37.69	44.84	52.07
Emergency generator	Mode C	71.6	0	-
	Mode C1	0	71.6	70.24

The efficiency of a generator is the ratio of output power to input power. The relationship between the generator loading (expressed as a percentage of its maximum capacity) and energy efficiency (expressed as a percentage) is usually shown as the efficiency curve of diesel generators. The illustration of an efficiency curve of a typical diesel generator in Fig.4 elucidates how altering the percentage of load connected to the generator influences its efficiency. Various factors like the specific design of the generator, its operating conditions, and any external factors manipulating its functionality can change the exact shape of the curve. The efficiency curve of a generator can be acquired either by conducting load test or obtaining it directly from the generator manufacturer. Diesel generators often run less effectively at lower loads because of factors including incomplete combustion, higher heat losses, and decreased engine efficiency.

The generator's efficiency generally increases as the load approaches its rated capacity, reaching an optimal point at which it operates most effectively. However, pushing the generator beyond its optimal load can lead to inefficiencies due to overloading. This is because running the generator at excessively high loads can stress its components, increase wear and tear can lead to reduced efficiency and possibly higher fuel consumption [51]. Conversely, operating the generator at loads significantly lower than its rated capacity can also reduce efficiency, as diesel engines are designed to operate efficiently within a certain load range. In summary, the energy efficiency and fuel consumption of diesel generators are directly affected by the loading level. Operating within the optimal load range ensures the best balance between efficiency and performance, while deviations from this range can lead to decreased efficiency and increased fuel consumption. Operating marine diesel generators as close to their nominal capacities as possible will contribute to the decrease of emissions and reduce fuel consumption [52,53]. The percentage of loads that can be switched to solar bus from the ship's main bus can be decided in such a way that the ship's generators can operate at or near the rated output of the machine inspecting the efficiency curve of each generator.

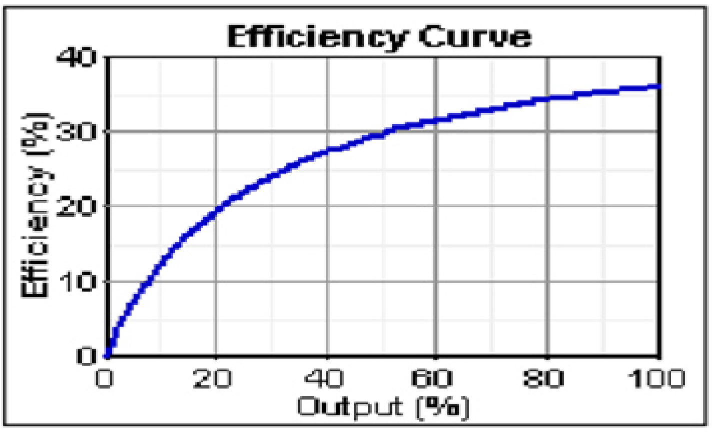

Figure 2. Efficiency curve of a typical generator.

4 Conclusion

This paper discusses the growing significance of PV energy systems within shipping transportation. It aims to establish the possible benefits of PV energy application through an extensive examination of various operational profiles of the ship. These benefits include the lowering greenhouse gas emissions and improvement of energy efficiency which contributes to the decarbonisation and environmental sustainability of the maritime sector.To address the challenges of installed standalone PV system onboard associated with cost and ship stability, the paper explores its multifunctionality in delivering power to specific loads, throughout vaious operational profiles of the ship thereby exploring its feasibility. It has been found that utilising stored PV energy for non-essential sailing loads can significantly decrease the overall load demand on main generators. Similarly, utilising stored PV energy for non-essential and continuous harbour loads can considerably reduce the total load demand on harbour generators. Additionally, incorporating the PV system extends the backup period of emergency generators, leading to decreased fuel consumption, carbon dioxide emissions, and reduced payback periods for PV installations.

The utilisation of solar PV energy has become significant for regulating GHG emissions in marine industry. Since shipboard power systems are tailor-made designs, it's important to analyze how loads should be divided between generators and PV sources on different vessels, considering their individual load profiles. To offset the concerns related to the implementation of PV in marine vessels, a strategy for the maximum utilisation of the installed standalone PV energy system onboard has been proposed in this paper, with the following conclusions.

1) The installed PV energy system can supply the ship’s loads during its various operational profile, thus preventing overloading of concerned generators. Furthermore, the installed PV system can be exploited to extend the backup period of the emergency generator. The percentage of loads that can be supplied from the solar bus can be decided by examining the efficiency curve of the ship's generators. The time for which the PV system can supply different categories of loads can be calculated.
2) By making the PV system multifunctional, the consumption of fuel by ship’s generators and carbon dioxide emissions can be reduced, and the payback period of the PV installation can be shortened.
3) Moreover, this strategy effectively ensures the utmost comfort for the crew and passengers aboard opulent vessels.
4) It's a crucial stride towards promoting eco-friendliness and complying with IMO mandates, which is of utmost importance.
5) Careful coordination of the BMS and PMS is crucial for the system's reliability. One potential area for future research is the use of artificial neural network (ANN) controllers for controlling the ABT switches effectively. These techniques can also assist in modelling and predicting weather data, determining the optimal size for PV systems, and calculating solar irradiance.

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