International Journal of Advanced Technology and Engineering Exploration, Vol 9(92)
ISSN (Print): 2394-5443 ISSN (Online): 2394-7454
http://dx.doi.org/10.19101/IJATEE.2021.875537

Research Article

Harnessing solar energy during preferential tripping to supply non-essential loads in luxury vessels

Midhu Paulson[1*] and Mariamma Chacko[2]
Research Scholar, Department of Ship Technology, Cochin University of Science & Technology, Kerala, India[1]
Professor, Department of Ship Technology, Cochin University of Science & Technology, Kerala, India[2]

Received: 12-February-2022; Revised: 17-July-2022; Accepted: 21-July-2022

Abstract
This paper presents a ship electrical power system architecture that integrates solar photovoltaic (PV) energy for supplying the non-essential loads at the instant of preferential tripping. The shipping industry has to create and apply innovative measures for making the ship 'greener' to comply with the increasing standards and regulations made by an international maritime organisation (IMO). A popular green shipping strategy is using renewable energy resources (RER) and solar energy plays an important role in making ships more eco-friendly. Despite this, the expectations of comfort and luxury are high for the passengers when they board a cruise ship or a luxury vessel. Therefore, maintaining indoor air quality and cabin comfort is very imperative. Hence continuous electrical supply for different non-essential loads such as air conditioning, several other entertainment and comfort equipment is significant in these vessels. Even though numerous projects that utilized solar energy that meet different energy needs of the ship are available, utilizing solar energy at the instant of preferential tripping of non-essential loads has not been done yet. A standalone solar PV system that meets the electrical demands of non-essential loads has been designed. A typical ship has been chosen with 5130-meter square (m^2) of useful area for installing solar panels. For supplying the non-essential loads of 1312 kW during the period of preferential tripping requires installation of 196 solar panels occupying 372.4 m^2 which are only 7.2% of total useful area that the ship can accommodate. It is also found that the weight of the total solar panels installed for preserving the non-essential loads is about 5.8 tons which are only 0.21% of the deadweight of the ship. Also, the weight of the associated 1295 battery packs for the designed PV system comes nearly 132 tons, which is about 6.46% of the ship's deadweight. The simulation results validate the proposed approach and are found to be feasible and satisfactory. The functioning of the proposed system can be integrated into the power management systems onboard. This paper also tackles some research possibilities and requirements in the area of onboard PV vessels.

Keywords
Green shipping, Preferential tripping, Non-essential loads, Renewable energy systems, Ship photovoltaic power system, Stand-alone photovoltaic system.

1.Introduction
The naval industry is being imposed by international maritime organisation (IMO) [1] to gradually reduce its greenhouse gas emission. Different types of pollutant gases are produced by the marine fuels [2] consumed by bulk carriers, cargo ships, passenger vessels, etc., which is harmful to both humans and the environment. Therefore maritime sector is diverging from fossil fuels and moving toward new energy resources like batteries, fuel cells, photovoltaic (PV) cells, wind energy, biofuels, hydrogen, liquefied natural gas (LNG), liquefied petroleum gas (LPG), etc. for becoming zero emission vessel (ZEV) [3−9].

The usage of ammonia in decarbonising maritime sector is discussed in [10]. Different alternative fuels that can be utilized for the maritime sector required for reducing the carbonization is excellently detailed in [11]. The capabilities and needs of each vessel vary based on the purpose of the vessel, and therefore a solution that satisfies the energy needs of all different types of ships is practically impossible. The aforementioned technologies, when pooled with the benefits of digitalization and computerization, can further reduce emissions.

The proposed work is motivated by the following facts. Firstly, different renewable energy resources are adopted in marine transportation in a great

*Author for correspondence

manner due to the restrictions by IMO. The exploitation of solar energy for various ship's needs has become significant for limiting the emissions from ships [12]. Secondly, maintaining supply for several non-essential loads such as air conditioning, ventilation and other comfort equipment, is a bothering factor in luxury cruise vessels. Literature review reveals that utilizing solar energy for supplying the non-essential loads during the preferential tripping onboard ships has not been done yet. This necessitates the proposal of a scheme for the incorporation of PV panels in the ship electrical power system.

The first objective of this paper is to propose a ship electrical power system architecture that utilizes a standalone solar PV energy for supplying the non-essential loads at the instant of preferential tripping. The second objective is to analyse the feasibility of installing the PV panels for feeding the non-essential loads during preferential tripping. Designing the required PV panel and battery system to meet the above requirements for a typical ship is the third objective.

This paper contributes to utilize solar energy for supplying the non-essential loads during the time of preferential tripping. Some ships prefer steadiness of supply to some non-essential loads and this could be accomplished by the proposed ship PV system architecture. The proposed architecture helps to provide a continuous supply for the non-essential loads. A standalone PV system has been designed for the non-essential loads and the system is tested using electrical transient analysis program (ETAP) software. Utilization of clean solar energy for supplying the non-essential loads also helps the ships to reduce pollutants, thus helping the vessels to achieve the goal of 'green ship' concept. Feasibility analysis in installing the PV panels in terms of ship's weight and area are also contributed in this paper.

This paper comprises of six sections. Section 1 presents the introduction explaining the background, motivation, objectives and contributions of this research work. The literature work is discussed in section 2. In section 3, the methodology of the research work is presented with the help of block diagrams. In section 4, two different simulation cases have been considered and also discussed the different aspects of the proposed standalone PV systems. The benefits of the proposed approach, key findings, interpretations, a few recommendations are covered in section 5. The limitations of the research work along with the overall analysis of the results obtained are also covered in section 5. Finally, conclusions and future scope are presented in section 6.

2.Literature review

Installation of PV systems in marine vessels has attracted the interest of many scholars due to the low fuel consumption and pollutant. The ship named 'Planet Solar' with a peak solar power of 93.5 kW could revolve around the globe utilizing PV energy alone [13]. PV panels occupy around 512 square feet, which could charge the 8.5 tons of lithium-ion batteries in the ship. The 'Auriga Leader' a vehicle carrier ship with 328 panels having a maximum power output of 40 kW could meet 6.9% of its lighting requirements [14]. 'Blue Star Delos' a Roll-on/Roll off (Ro-Ro) passenger ship utilized a low voltage PV system for direct current (DC) loads with 16 numbers of panels each rated at 145 watts [15]. The performance of the marine PV system is checked and analyzed for two days of ship trails. Another vehicle carrier 'Emerald Ace' installed with 768 PV panels utilized PV energy for mooring applications [16]. Solar energy is used for both off-grid and on-grid operations in pure car and truck carrier (PCTC) 'COSCO TENGFEI' [17]. The deck area is installed with 540 PV panels having maximum output power of 143.1 kW and occupies 1300 m^2 providing light emitting diode (LED) lighting. Several boats, yachts, and cruises installed with solar panels have been designed and manufactured for different types of applications in the vessels. The lighting and cooling applications of a ferry Ro-Ro ship 500 GT is met by solar energy in [18]. Solar PV energy has been used for marine water pumping applications in [19]. The speed of the motor is controlled by an eleven-level inverter which is fed from PV energy. PV arrays are added to the ship hybrid electric power system for enhancing the system performance and reducing the fuel consumption for an emergency aircraft landing system [20]. The 'Expedition Super-Yacht' is driven by a combination of many sustainable energy resources along with the PV energy which could produce 573 kW [21]. In [22], a hybrid PV/Fuel cell/Diesel is designed to meet the main and electric loads of a Dubai ferry boat. In [23], a hybrid PV-Diesel engine can replace a diesel engine in 'KMP Portlink III' for power generation with 577 PV panels each rated 350 watts. The installation cost and the payback period is also calculated. Optimization of ship hybrid system, taking different considerations like available area for installing the PV system, size of energy storage systems (ESS), type of ship, route of the ship, installation cost, etc. are carried out by many researchers in [24−27]. Both large-scale and small-scale PV installations that operate in off-grid mode and on-grid mode have been successfully installed onboard ships [28]. In [29], the possibility of increasing the efficiency of PV integrated ship power system using the PV cooling system has been analysed. Installation site of PV in a cruise ship is thoroughly examined in [30]. It is found that 48% of harvestable PV energy is reduced due to the problem of shading and current PV configuration technology. A model establishment for the utilization of combined PV and hydrogen fuel cell in a ship has been conducted in [31]. An optimal energy dispatch scheme is proposed and integrated for an integrated energy system (IES) ship comprising combined heating and power device (CHPD), PV and ESS [32].

PV energy has been used in several marine vessels for different applications of the ship. Some solar projects utilized solar energy for the auxiliary energy requirements and a few boats make use of PV for propulsion. Various research outputs that could enhance the efficiency of PV panels are also available. However, harnessing solar energy during preferential tripping to supply non-essential loads has not been done yet. In this paper, a solar PV system that meets the electrical demands of non-essential loads during the preferential tripping has been designed. A new configuration of ship power system incorporating PV panels is proposed which could help for greener shipping.

3.Methodology

3.1Preferential tripping

This section describes the theory of preferential tripping in ship electrical power system network. To protect the main generator of the ship against the overload condition, an overload relay is associated with each generator. When such a condition arises, it leads to tripping of non-essential loads and this tripping can be done for individual loads or group of loads by a microprocessor-controlled system with a multiplicity of inputs and outputs. This decreases the generator load so that the main generator may continue to supply to the essential loads of the ship. Generally, the preferential trip relays get activated when the generator load reaches above 110% of full load. When the main generator load reaches above 110% of full load, a preference trip relay gets activated and the non-essential loads are disconnected in a definite order at definite time intervals until the load falls below 110%. Depending upon the ship type the order of tripping can also differ. The preference overload trip resets after the adequate non-essential load has been disconnected, and no further load is disconnected. If the overload condition is not resolved even after the non-essential loads are shed, the overcurrent relay begins to time out which activates the master trip relay of the generator and the main generator generally trips.

3.2Working mechanism of the proposed standalone PV system for the non-essential loads during the preferential tripping

The complete working mechanism of the PV utilization of non-essential loads can be explained with the help of a functional block diagram shown in the *Figure 1.* The proposed standalone PV system comprises of all the components of the conventional standalone PV system. PV power generated by the PV array charges the battery through a charge controller. The charge controller regulates the battery charging and discharging. The DC power produced by the solar panels is converted into alternating current (AC) using an inverter. The ship main generator is connected to the main bus of the main switchboard (MSB). The ship’s MSB comprises ship’s main generator circuit breakers, different protective relays such as overload relays, reverse power relays, overcurrent relays and preferential relays. Under normal working conditions, the non-essential loads are fed from the main bus and the switch position will be at ‘N’. When an overload condition arises, the overload relay sends a signal to the microcontroller for activating the preferential trip relays for protecting the main generator from the overload condition. The preferential trip relay disconnects the non-essential loads in different predefined time sets and thereby attempting to reduce the connected loads on the main generator. Whenever the preferential trip relay activates, power management system (PMS) of the ship connects the non-essential load to the inverter immediately by transferring the switch position from ‘N’ to ‘PT’ where ‘N’ denotes the position of the switch during the normal condition and ‘PT’ denotes the position of the switch after the preferential trip. If the ‘state of charge’ (SoC) of battery for feeding the non-essential loads is sufficient, PMS send the signals to change the switch positions from ‘N’ to ‘PT’. Thus, these non-essential loads are fed from the inverter through the automatic bus transfer (ABT) switches in the case of preferential tripping events. The preference trip relay resets after the overload condition is resolved. If the overload condition still persists, the overcurrent relay begins to time out which activates the master trip relay of the generator and the main generator generally trips.

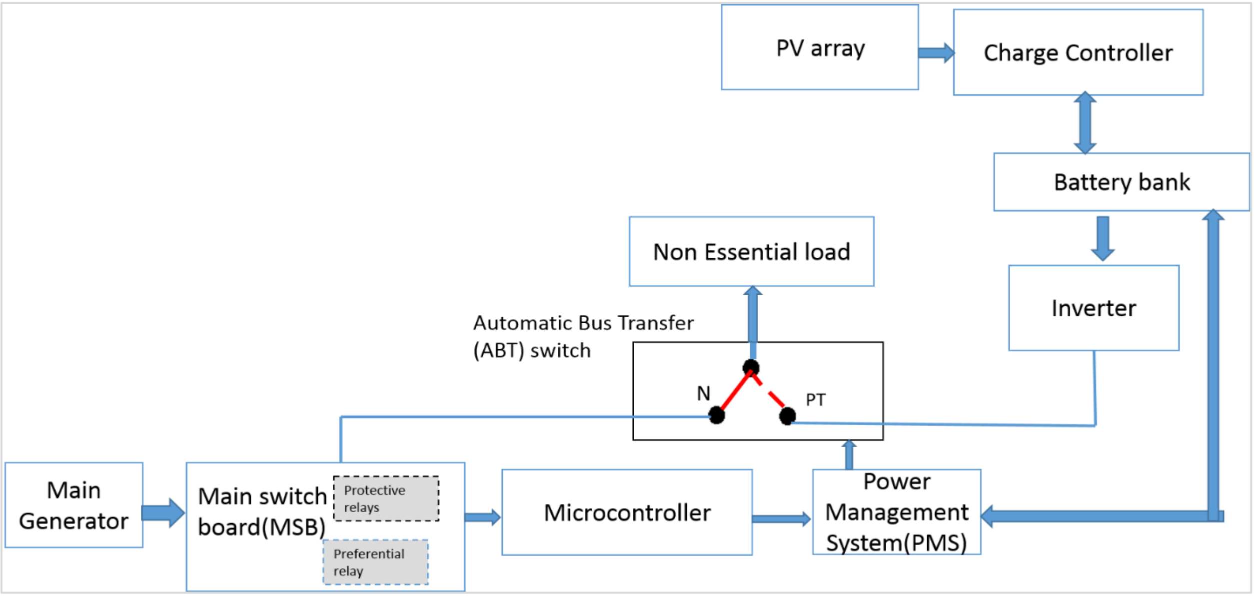

Figure 1 Functional block diagram of the proposed standalone PV system for supplying non-essential loads during preferential tripping

The schematic diagram of PV incorporated ship power system for supplying the non-essential loads is shown in *Figure 2*. The ship's power system is an autonomous micro-grid and its marine main generators have to tolerate the total loads irrespective of the addition of the PV system. Four diesel generators provide a 6.6 kV AC supply to the ship AC main distribution system and directly feed large AC motor loads and propulsion motor. Other low voltage AC loads are fed through a step-down transformer. Non-essential loads are fed from the main bus through a non-essential bus under normal working conditions. In the present work, the preferential tripping is performed for three groups of non-essential loads with different time delay period. Non-essential loads are grouped under three different groups named as 'load category1', 'load category2' and 'load category3' based on the priority of shedding the different loads. The first group 'load category1' includes the galley, laundry, pantry, and boiler plant. The second group 'load category2' consists of chilled circulated pumps, sewage treatment plant pumps, air circulating pump trips, and the third group 'load category3' includes deck equipment. When the main generator load reaches above 110% of full load, a preference trip relay gets activated and the 'load category1' trips with a delay of 5 seconds. As soon as the 'load category1' is disconnected from the main bus as a result of preferential tripping, the ABT switch will transfer those 'load category 1' from a position 'N' to position 'PT'. Now the 'load category1' is fed from the solar inverter through the ABT switch. If the overload condition is resolved, no further groups of non-essential loads are disconnected. Otherwise 'load category2' get also disconnected with 10 seconds of time delay. As soon as the 'load category2' is disconnected from the main bus as a result of preferential tripping, the ABT switch will transfer those loads from position 'N' to position 'PT'. If the overload condition still persists, 'load category3' will also get disconnected with a delay of 15 seconds and the ABT switch will transfer those loads to position from 'N' to 'PT'.

3.3 Solar PV system design and calculations

A solar PV system is proposed to meet the non-essential loads in a typical ship. In the present research, a PV panel with an area of 1.9 m^2 weighing 26.9 kg is considered. The technical specifications of the PV panel are given in the *Table 1*. A typical ship has been chosen for the PV array application. The overall length of the ship is 141 m and the breadth of the vessel is 41m. The gross tonnage (GRT) and dead weight (DWT) of the vessel are 8129 ton and 2651 ton respectively. The technical details of the ship are given in the *Table 2* [33]. The useful length (L) and useful width (W) of the ship concerning installation of solar panels are taken as 135 m and 38 m respectively [34]. Therefore, the useful area (A) for panels to be installed is 5130 m^2 using Equation 1.

$$A = L \times W = 5130m^2 \quad (1)$$

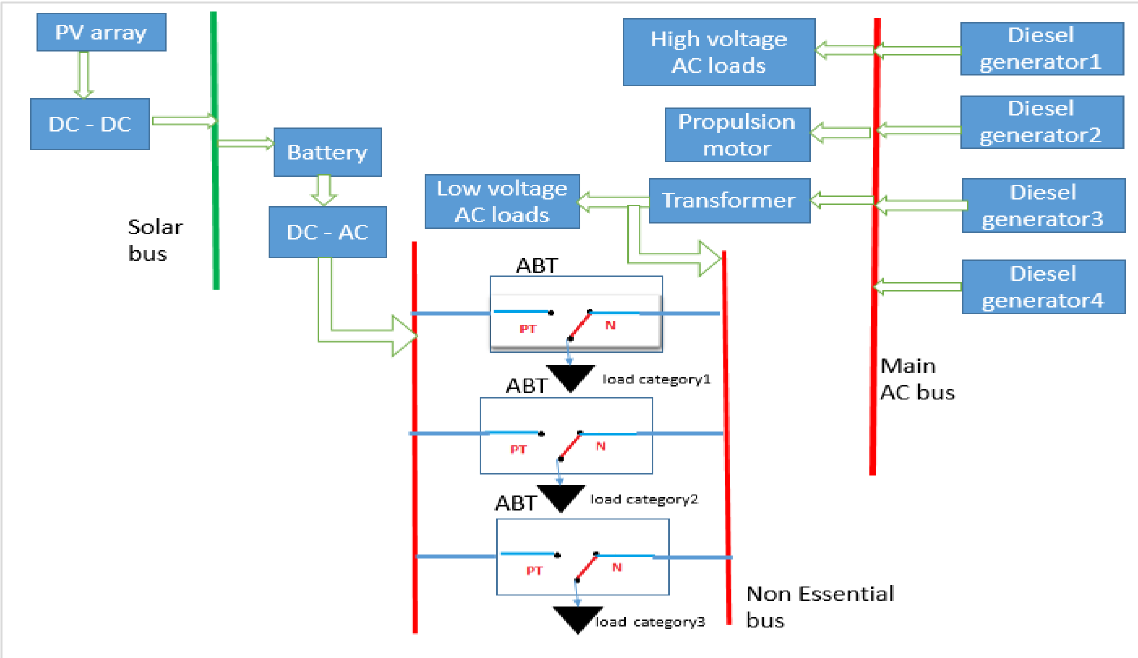

Figure 2 Schematic diagram of PV incorporated ship Power system for supplying the non-essential loads

Theoretically, the ship could accommodate 2700 solar panels, each occupying 1.9 m^2. Assuming non-essential loads are fed by PV energy for a maximum of 15 minutes per day. The number of sunshine hours is assumed to be 6 hours per day. A solar panel with specifications in *Table 1* can be installed to meet the above demands. The total non-essential loads are taken as 1312 kW and assumed to be fed by PV energy for a maximum of 15 minutes per day. Therefore, the total kilowatt-hours per day needed from the PV modules is 328 kWh. The total kilowatt peak rating '*S*' needed for PV modules for operating the loads is obtained by dividing the total kilowatt-hours per day '*P*' needed from the PV modules by the average sunshine hours per day '*h*' using Equation 2.

$$S = \frac{P}{h} = \frac{328\ \text{kWh}}{6} = 54.666\ \text{kWp} \qquad (2)$$

The number of panels 'N' can be obtained by dividing the result by rated output watt peak '*R* 'of PV panel using Equation 3.

$$N = \frac{S}{R} = \frac{54666}{280} = 196 \qquad (3)$$

Considering that each panel occupies an area of 1.9 m^2 a total area of 372.4 m^2 is required for placing 196 panels. Placing solar panels horizontally on the vessels has been stated as the most efficient power generation.

Table 1 280 W PV panel specifications

Parameter	Value
Rated peak output (W_p)	280
Maximum power point voltage (V_{mp})	36.55
Open circuit voltage (V_{oc})	43.92
Maximum power point current (I_{mp})	7.73
Short circuit current (I_{sc})	8.4
Area of the panel(m^2)	1.9
Weight of the panel (kg)	26.9

Table 2 Typical ship details

Parameter	Value	
Length	141m	
Breadth	41 m	
Gross Tonnage(GRT)	8129	
Deadweight (DWT)	2651	
Service speed	26	knot

3.4Design and role of batteries in PV incorporated ships

Owing to the varying nature of the output power from the PV system an ESS has to be employed. A battery management system (BMS) is necessary to monitor the state of the battery. The battery SoC estimation required for BMS is depicted in [35]. Battery bank capacity 'C' required for the connected non-essential loads during the time of preferential tripping can be calculated using Equation 4 [36, 37].

$$C = \frac{(N \times Wt)}{(DOD \times B \times V)} \qquad (4)$$

Where, N = Days of autonomy,
W = Total connected load,
t = Number of hours,
DOD = Depth of discharge,
B = Battery loss factor,
V = Nominal battery voltage.

Days of autonomy are defined as the number of days that the battery can supply the site's loads without any support from generation sources. Taking depth of discharge (DOD) as .8, battery loss factor as .85 and nominal battery voltage as 12 V, number of operating hours per day as .25, battery bank capacity 'C1' required for supplying the first and second load category having a total connected load of 572 kW can be calculated using the above equation.

$$\mathrm{C1} = \frac{(1\times572000\times.25)}{(.8\times.85\times12)} = 11.315\ \mathrm{kAh}$$

Therefore 12 kAh battery bank can be taken for supplying the first and second load category during the time of preferential tripping. Similarly, for the third load category having a total load of 740 kW, the required battery bank sizing 'C2' can be calculated as

$$\mathrm{C2} = \frac{(1\times740000\times.25)}{(.8\times.85\times12)} = 22.671\ \mathrm{kAh}$$

Therefore 23 kAh battery bank can be taken for supplying the third load category during the time of preferential tripping. A string of 37 lithium ion marine battery packs each rated 12 V, 1000 Ah can be connected in series to provide the required voltage level of connected loads. And 12 such strings are connected in parallel to feed the NE_group1 and NE_group2 loads. Similarly 23 such strings are connected in parallel to feed the NE_group3 loads. Each battery pack weight can be taken as 120 kg. Therefore, it would require almost 1295 battery packs for the proposed stand- alone PV system in the ship.

Different batteries suitable for marine renewable energy applications are available in the market [38]. UB-50-12 valve regulated lead acid (VRLA) battery (capacity 50 Ah, nominal voltage 12 V and weighing 22 kg), FCP-1000 (1000 Ah, 12 V, weighing 500 kg) FC 38-12 which is suitable for small marine solar power applications are some of them. Lithium-ion batteries are available these days with advanced features like 95% efficiency, pollution-free, lightweight, less space requirement, silent operation with more than 13 years of the life cycle, shorter charging time, and therefore can be used onboard safely. Besides preserving the non-essential loads for a short period, installing and maintaining expensive batteries is becoming a very exciting alternative to traditional fuels for shipping. As both the size and average battery cost of batteries decreased, several electric ship projects with a big battery capacity have been implemented. German cruise line AIDA Cruises, the first regular cruise vessel has a battery on board with a 10,000kWh lithium-ion battery system and another pure electric ferry 'Ellen" has a 4300kWh battery system [39]. The world's first electric container ship, 70m-long and 14m-wide tanker launched by Chinese company Guangzhou Shipyard in 2017 have a battery system made up of more than 1,000 lithium-ion batteries and supercapacitors [40, 41]. By the coordination of PMS and energy management system (EMS), these batteries could also contribute to a percentage of propulsive power needed for the ship. Therefore the batteries required for installing the PV system are not a burden for the onboard vessels and the application of batteries could be extended to other services for the vessels.

4.Results

To validate the feasibility of the proposed PV incorporated ship power system, a typical ship electrical distribution system is simulated using ETAP software as depicted in *Figure 3*. The operational profile of the ship at seagoing condition is simulated and the connected load is taken as the sailing load. Four generators rated at 4 MW each operate at 6.6 kV, 60 Hz, each having rated full load current of 411.7 ampere supplies the propulsion load and other ship service loads. Two propulsion motors are each rated at 6.5 MW. The main electrical load is distributed into essential and non-essential loads. Essential services include equipment that requires for the safety of personnel, propulsion of the ship and safe navigation. Some of those include navigational gadgets, communication systems, machinery, control stations, steering gear, etc. The main switchboard supplies the essential loads through section boards or distribution boards. An emergency generator is provided to supply the power for the essential loads if the main power failure occurs. The first group of non-essential loads 'load category1' is shown as 'NE_group1', 'load category2' is shown as 'NE_group2' and 'load category 3' is shown as 'NE_group3' in the simulation diagram as depicted in *Figure 3*. 'NE_SW1', 'NE_SW2' and 'NE_SW3' are taken as the ABT switches for the 'NE_group1', 'NE_group2' and 'NE_group3' respectively. The switch position 'N' is marked as 'A' and position 'PT' is marked as 'B'. Under overload condition of generator, each switch transfers the corresponding non-essential loads from position 'A' to position 'B' in different time sets as discussed in section 3.2 thus feeding the disconnected non-essential loads from the solar energy during preferential tripping.

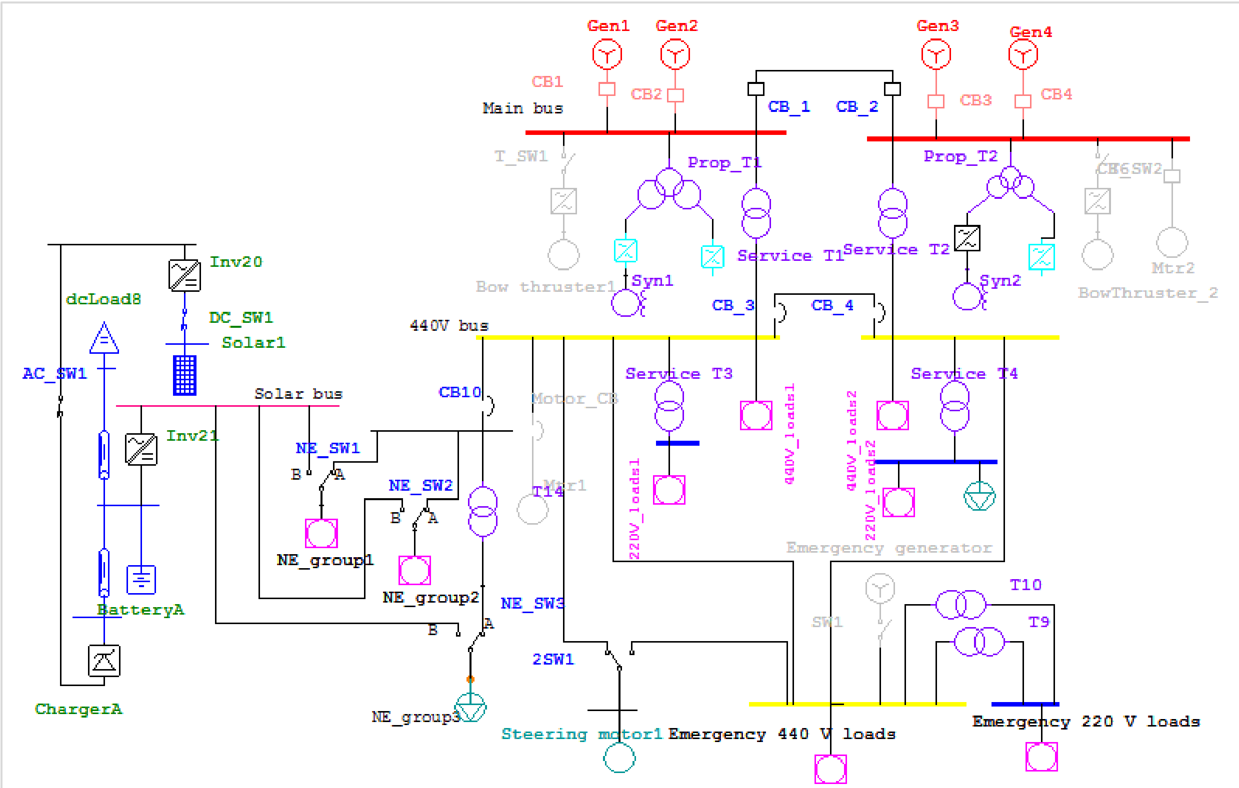

Figure 3 Simulation of PV incorporated ship power system under normal operating condition in ETAP

Case 1: An overload condition of the generator is initiated by a large load step. Bow thruster 1, Bow thruster 2, and 1500 HP motor 'Mtr1' are switched into operation as shown in *Figure 4*. The generator is then overloaded with 117.29% of the full load. After a delay period of 5 seconds, some non-essential loads are tripped to bring down the generator load below 110% of the full load. 'NE_group1' has been disconnected from the main bus and the main generator load has been reduced to 116.92% of the generator full load as shown in *Figure 5*. When 'NE_group1' has been disconnected from the main bus, switch 'NE_SW1' will transfer the loads from the position 'A' to 'B' and solar energy stored in the batteries feeds the non-essential loads 'NE_group1'. After a delay time of 10 seconds 'NE_group2' has been disconnected from the main bus and the generator load has been reduced to 114.01% as shown in *Figure 6*. When 'NE_group2' has been disconnected from the main bus, switch 'NE_SW2' will transfer the loads from the position 'A' to 'B' and solar energy stored in the batteries feeds the non-essential loads 'NE_group2'. After a delay period of 15 seconds 'NE_group3' has been disconnected from the main bus and the generator load has been reduced 109.52% as shown in *Figure 7*. When 'NE_group2' has been disconnected from the main bus, switch 'NE_SW2' will transfer the loads from the position 'A' to 'B' and solar energy stored in the batteries feeds the non-essential loads 'NE_group3'.

Case 2: An overload condition of the generator is initiated by switching both motor load 'Mtr1'rated 1500 HP motor and 'Mtr2' rated 2500 kW, 6.6 kV into operation as shown in the *Figure 8*. The generator is then overloaded with 110% of the full load. After a delay period of 5 seconds, 'NE_group1' and 'NE_group2' non-essential loads are disconnected from the main bus to bring down the generator load to 107.3% of the full load and solar bus feeds the same loads as shown in the *Figure 9*. Since the overload condition of main generator is prevented by transferring the two groups of non essential loads to the solar bus, no further load is disconnected. The results of the research work are summarized in the *Table 3*.

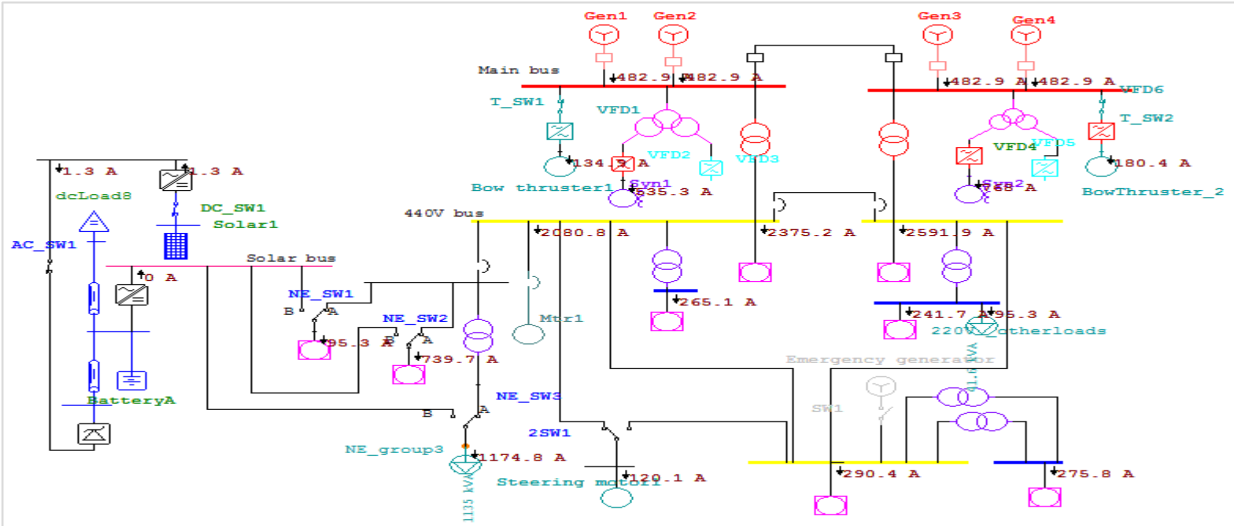

Figure 4 Bow thruster 1, Bow thruster 2, and 1500 hp motor 'Mtr1' switched into operation

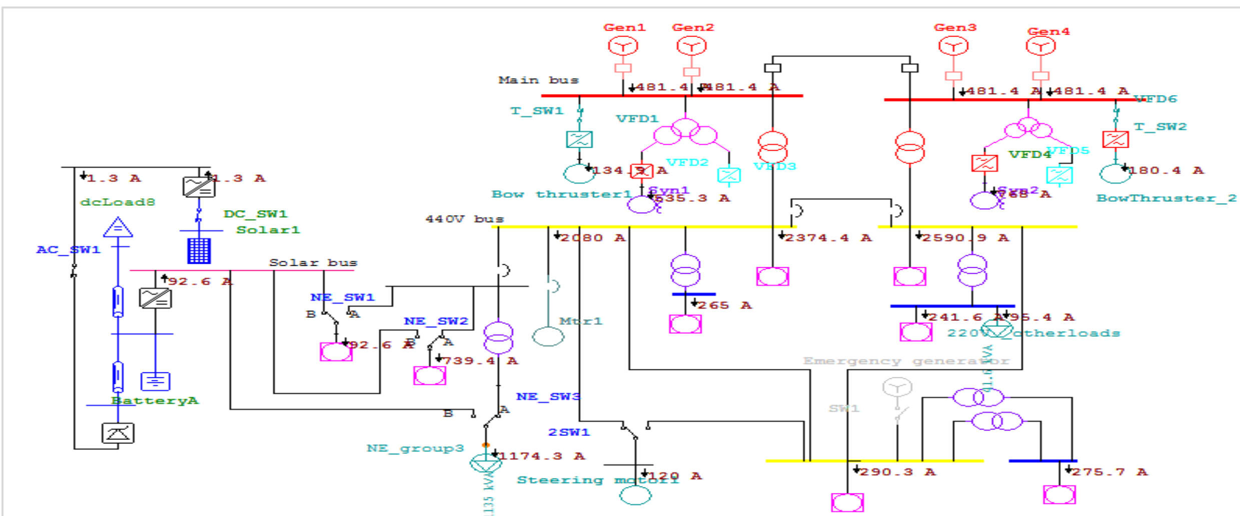

Figure 5 NE_group1' is being supplied from solar bus when it is disconnected from the main bus

4.1Different aspects of installed solar PV system

The proposed standalone PV system is analogous to the land based conventional standalone PV system and therefore the reliability of solar PV system, chances of failure of standalone PV system, PV module failures, the distribution of temperature on the PV panels, and the cooling methods of panels all are same to some extent. Generally, the energy conversion efficiency of PV module can be considered as the energy factor of the PV module and it can be known from the manufacturer's datasheet. Solar panel efficiency is a measurement of a solar panel's ability to convert sunlight into usable electricity. Apart from that, some peculiarities that have to be considered while designing standalone PV systems for the marine vessels are the following.

Reliability: As compared to the land-based PV systems, marine solar PV panel system requires more attention in its construction to be more reliable [42]. The reliability of solar PV system refers to the ability of these systems to produce power over a long and predictable service life time. Marine PV panels should be tolerant to harsh sea conditions like high humidity, salt, bird droppings, extreme winds, ice fall, etc. Moisture penetration into the PV panels, debris accumulation, strong winds, etc., can damage the mechanical parts of the whole PV system. Using light weight, vibration tolerant and space saving designed batteries make the complete installed PV system more reliable. Limited open spaces in the ship for installing PV panels can cause partial shading effects which decrease the panel efficiency. The weight of the standalone PV system onboard should not seriously affect the stability of the ship. The reliability of solar PV system installed in marine vessels also depends upon the navigation route and navigation time of the vessel. The uncertainties in the climatic conditions along the complete journey of the ship can cause variations in the PV output power. In [43], the high uncertainties of onboard PV power output are forecasted using machine learning algorithms and hybrid optimization techniques. Many companies like 'F-WAVE Company limited' have developed shatter proof and flexible PV technology for shipping and maritime applications [44]. The 'Furukuwa' battery company of Japan and the 'Eco marine power' are some other companies that are able to supply a wide range of marine graded batteries [24].

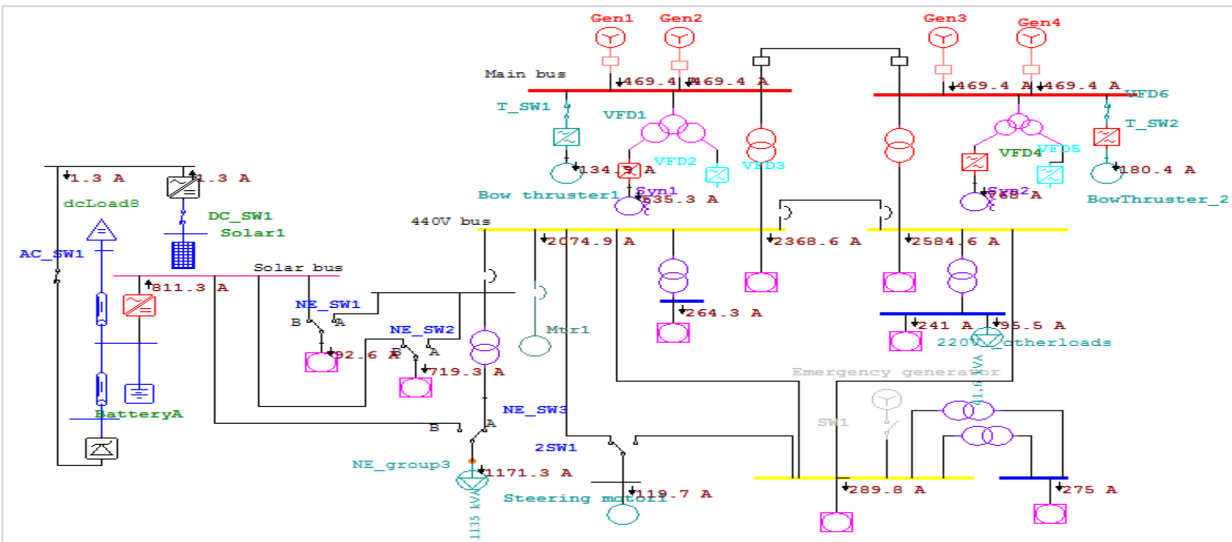

Figure 6 'Both NE_group1 and NE_group2' is being supplied from solar bus when they are disconnected from the main bus

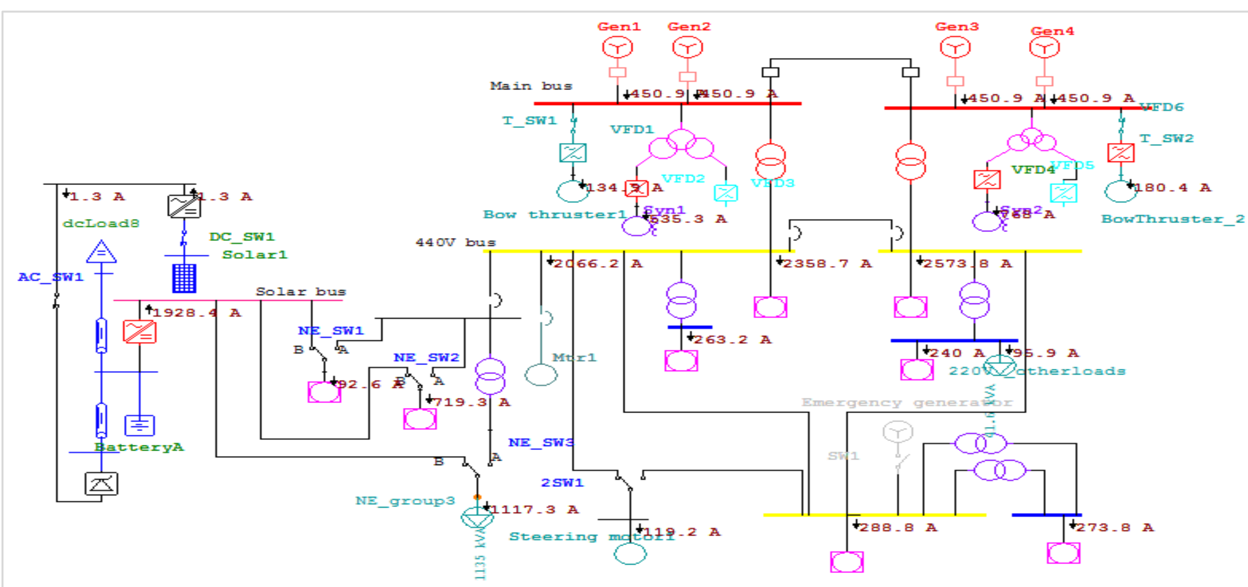

Figure 7 'NE_group1, NE_group2 and 'NE_group3' is being supplied from the solar bus when it is disconnected from the main bus

Table 3 Results

Details of installed PV system	**Connected load (kW)**	**Battery capacity (kAh)**	**Number of battery packs**	**Total weight of batteries**	**Total number of panels**	**Total weight of panels (ton)**	**Total area occupied by the panels (m^2)**
First and second load category	572	11.395	444	132 ton	196	5.8	372.4
Third load category	740	22	851				

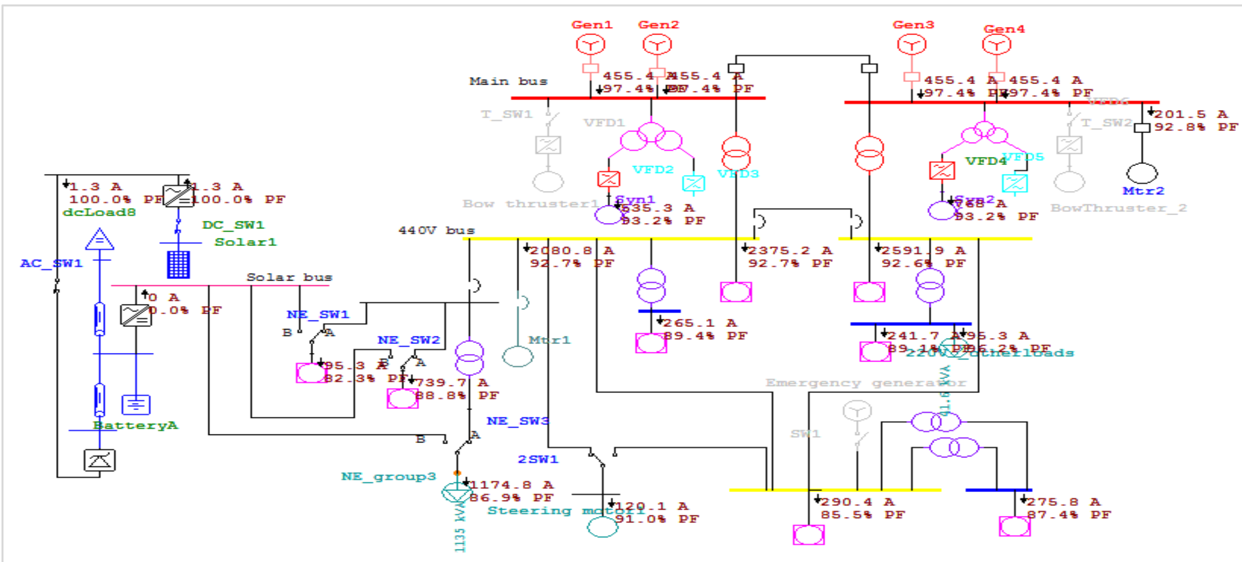

Figure 8 Both 1500 hp motor 'Mtr1' and 2500 hp motor 'Mtr2' switched into operation

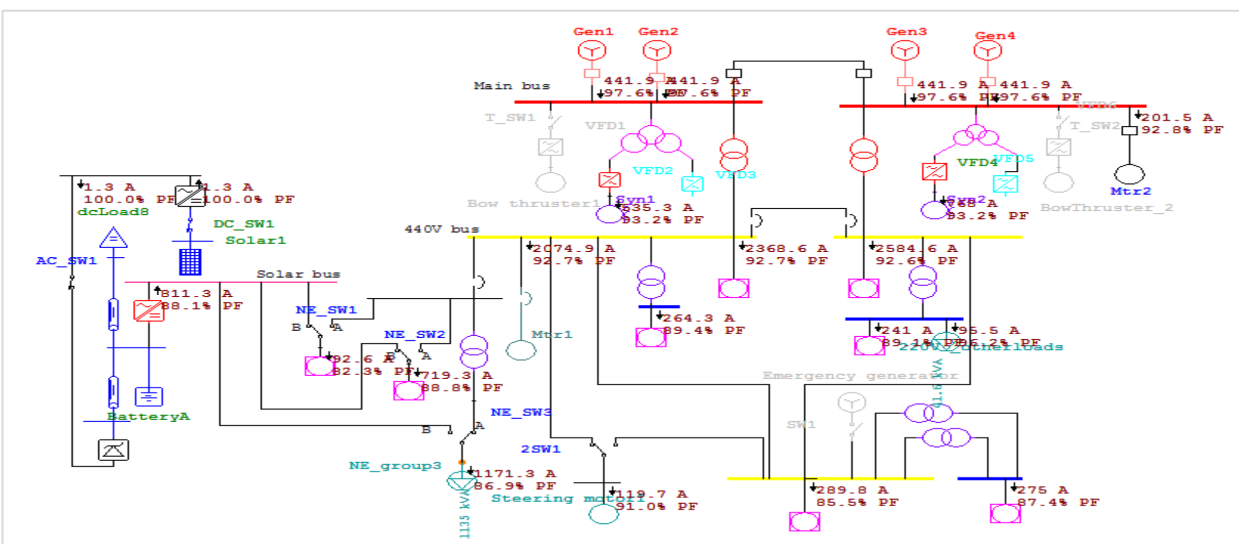

Figure 9 Both NE_group1 and NE_group2 are disconnected due to the preferential tripping and being supplied from the solar bus

***Failure modes*:** As in the case of conventional standalone PV system, the harsh environment, insulation problems, improper installation, less lifetime span, etc., causes the inverter to fail. Mounting systems can become weak due to the continuous movement of the ship. Lack of maintenance can cause battery acid leakage, corrosion and cracks. Extinguishing fire outbreaks onboard a ship is more difficult and complicated than the terrestrial based systems. Therefore, the risk of failure of the standalone PV systems caused by fire is more pronounced in marine PV systems.

PV module failure**:** Chances of sea water penetration into the PV panels, high humidity and temperature conditions, continuously varying climatic conditions throughout the navigation route of the ship, frequent crashing of sea water onto the PV panels, etc., can accelerate the common PV module failures such as encapsulant discolouration, delamination, discolouration, corrosion, cracks, breakage of PV panels, potential induced degradation (PID), etc. Various cleaning methodologies for reducing the soiling effect of PV panels is described in [45].

Temperature distribution and control: The performance of the PV panels worsens due to increasing its operating temperature. In order to avoid the excessive temperature rise of the panels, the cooling methods adopted for land based PV panels such as active cooling, passive cooling, cooling by phase change type materials and spray jet cooling can be utilized. In addition to that, cooling of PV panels by means of overboard water can also be adopted.

Voltage rise issue: The energy produced by the installed PV system is stored in the batteries. A charge controller can prevent the battery from overcharging and only when the non-essential loads are preferentially tripped the battery gets discharged, thereby feeding energy to the non-essential loads. Therefore the ship's main AC bus system need not have to face voltage rise issues caused by excess PV power.

5.Discussion

In this section, the overall analysis of the results has been discussed in detail along with the benefits of the proposed approach. The benefits of the current research is that the proposed standalone PV system helps the marine vessels to realize the 'green ship' concept by using clean solar energy without any byproducts. Every ship can adopt the proposed approach as a first step stone for following the policies by IMO. It also helps to preserve the non-essential loads in a luxury vessel without using additional backup generators. Besides, it is easy to expand the installed standalone PV system by using multiple panels and batteries for meeting many other electrical demands of the ship during the different operating modes of the ship. With the proposed approach, disconnecting non-essential loads from the main bus during an overload condition of main generator is achieved.

From the simulation results, it is perceived that the proposed PV system is feasible for the installation in the ships. Solar energy stored in the batteries can feed the non-essential loads at the time of preferential tripping and thus it provides a continuity of supply to them. It can be found that for a typical ship, a standalone PV system can be designed if the ship dimensional details and electric load sheet is available. It has been observed that the batteries required for the proposed standalone PV system can contribute a percentage of other power needs of ship and therefore the application of batteries is not a liability for the vessels.

The following interpretations can be made from the research results. The installation of 196 solar panels for supplying the non-essential loads occupies 372.4 m^2 which is only 7.2% of total useful area that the ship can accommodate the solar panels. It is also found that the weight of the total solar panels installed for preserving the non-essential loads is about 5.8 tons which are only 0.21% of the deadweight of the ship. Also, the weight of the battery packs comes nearly 132 tons, which is about 6.46% of the ship's deadweight.

Large scale deployment of standalone PV system onboard can cause stability issues and therefore requires careful stability analysis study. Several factors like trim, buoyancy and stability of the ship have to be analyzed according to the statutory regulations of IMO before installing the battery packs onboard vessel. The position of the battery packs without affecting the stability and safety of the ship has also to be analyzed and determined. The cost analysis of installed standalone PV system can be performed to give a clear insight for the ship owners to adopt the proposed method.

A comparative study analysis can be done by calculating the ship's energy efficiency design index (EEDI) [46] before and after installing the proposed standalone PV system onboard.

5.1Limitations

In this work, a clear sky scenario is taken for the PV system design. But the output power generated varies according to the climatic conditions and navigation route of the vessel. Another limitation is that each vessel requires individual PV system design based on each shipload profile, as each ship is different in many aspects like the purpose, structure, available free space, main voltage, dead weight, etc. Non-essential loads are also not the same in all marine vessels. Another constraint is that the aesthetics of luxury vessels can be affected by the installation of PV panels. Several challenges and future research requirements in marine photovoltaic have been detailed by authors in [47] also. Further research work which could enhance the PV installation onboard for non-essential loads are recommended below:

- Coordinating PV installation in PMS.
- Incorporating artificial intelligence (AI) for the better performance of standalone PV systems.
- Coordinating other energy resources along with the installed PV for increasing the sustainability and efficiency of the marine vessels.
- Retrofitting existing marine vessels with PV systems and designing of PV-based newly constructed vessels also comes under this area.
- Enhancing power harvesting from the installed PV system by different optimization techniques.

A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion

This paper proposed an architecture for ship electrical system which could accommodate PV energy for supplying the non-essential loads which help to make the ships greener thus protecting the environment from pollutants. A PV ship power system that meets the electrical requirements of non-essential loads has been designed. The above proposed system is simulated using ETAP and the simulation results show that the proposed application of solar PV energy could be an efficient solution for becoming the ships greener. The proposed architecture utilized clean solar energy for preventing the unnecessary tripping of the main generator circuit breaker thereby preserving non-essential loads.

All the results attained in this research work are inspiring and the work can be further extended by optimizing the utilization of the installation of standalone PV system for meeting the other different electrical energy needs of the ship. The structure, size, purpose and navigation route of a ship differs from one ship to another and therefore design and installation of a PV system for each type of marine vessel requires more detailed research.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

Midhu Paulson: Data collection, conceptualization, investigation, writing-original manuscript and editing, design, calculation and simulation, analysis and interpretation of results. **Mariamma Chacko:** Conceptualization, supervision, review and editing, analysis and interpretation of results.

References

[1] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx. Accessed 20 January 2020.

[2] https://www.chevronmarineproducts.com/content/dam/chevron-marine/Brochures/Chevron_EverythingYouNeedToKnowAboutFuels_v3_1a_DESKTOP.pdf. Accessed 02 June 2022.

[3] Xing H, Stuart C, Spence S, Chen H. Fuel cell power systems for maritime applications: progress and perspectives. Sustainability. 2021; 13(3):1-34.

[4] Atilhan S, Park S, El-halwagi MM, Atilhan M, Moore M, Nielsen RB. Green hydrogen as an alternative fuel for the shipping industry. Current Opinion in Chemical Engineering. 2021.

[5] Tan EC, Hawkins TR, Lee U, Tao L, Meyer PA, Wang M, et al. Biofuel options for marine applications: technoeconomic and life-cycle analyses. Environmental Science & Technology. 2021; 55(11):7561-70.

[6] Xing H, Stuart C, Spence S, Chen H. Alternative fuel options for low carbon maritime transportation: pathways to 2050. Journal of Cleaner Production. 2021.

[7] Bach H, Mäkitie T, Hansen T, Steen M. Blending new and old in sustainability transitions: technological alignment between fossil fuels and biofuels in Norwegian coastal shipping. Energy Research & Social Science. 2021.

[8] Cassar MP, Dalaklis D, Ballini F, Vakili S. Liquefied natural gas as ship fuel: a maltese regulatory gap analysis. Transactions on Maritime Science. 2021; 10(1):247-59.

[9] Balcombe P, Staffell I, Kerdan IG, Speirs JF, Brandon NP, Hawkes AD. How can LNG-fuelled ships meet decarbonisation targets? an environmental and economic analysis. Energy. 2021.

[10] Ayvali T, Tsang SE, Van VT. The position of ammonia in decarbonising maritime industry: an overview and perspectives: part ii: costs, safety and environmental performance and the future prospects for ammonia in shipping. Johnson Matthey Technology Review. 2021; 65(2).

[11] Mallouppas G, Yfantis EA. Decarbonization in shipping industry: a review of research, technology development, and innovation proposals. Journal of Marine Science and Engineering. 2021; 9(4):1-40.

[12] Zhang R, Liang H. Application of solar energy in ship power field. In Asia-pacific conference on image processing, electronics and computers 2022 (pp. 1588-90). IEEE.
[13] http://www.theverge.com/2013/6/22/4454980/ms-turanor-planetsolar-solar-powered-boat-photo-essay. Accessed 05 June 2020.
[14] https://www.marineinsight.com/types-of-ships/auriga-leader-the-worlds-first-partiallypropelled-cargo-ship/. Accessed 05 June 2020.
[15] Atkinson GM. Analysis of marine solar power trials on blue star delos. Journal of Marine Engineering & Technology. 2016; 15(3):115-23.
[16] https://www.mol.co.jp/en/pr/2012/12035.html. Accessed 20 October 2020.
[17] Tang R, Wu Z, Fang Y. Configuration of marine photovoltaic system and its MPPT using model predictive control. Solar Energy. 2017; 158:995-1005.
[18] Faturachman D, Yandri E, Pujiastuti ET, Anne O, Setyobudi RH, Yani Y, et al. Techno-Economic analysis of photovoltaic utilization for lighting and cooling system of ferry Ro/Ro ship 500 GT. In E3S web of conferences 2021. EDP Sciences.
[19] Stonier AA, Murugesan S, Samikannu R, Krishnamoorthy V, Subburaj SK, Chinnaraj G, et al. Fuzzy logic control for solar PV fed modular multilevel inverter towards marine water pumping applications. IEEE Access. 2021; 9:88524-34.
[20] Gaber M, El-banna SH, Hamad MS, Eldabah M. Performance enhancement of ship hybrid power system using photovoltaic arrays. In PES/IAS power Africa 2020 (pp. 1-5). IEEE.
[21] Eastlack E, Faiss E, Sauter R, Klingenberg S, Witt M, Szymanski S, et al. Zero emission super-yacht. In fourteenth international conference on ecological vehicles and renewable energies 2019 (pp. 1-8). IEEE.
[22] Ghenai C, Al-ani I, Khalifeh F, Alamaari T, Hamid AK. Design of solar PV/fuel cell/diesel generator energy system for Dubai ferry. In advances in science and engineering technology international conferences 2019 (pp. 1-5). IEEE.
[23] Khresna R. Installation of hybrid power system in ro-ro passenger vessel. In international conference on innovative research and development 2019 (pp. 1-3). IEEE.
[24] Margaritou MD, Tzannatos E. A multi-criteria optimization approach for solar energy and wind power technologies in shipping. FME Transactions. 2018; 46(3):374-80.
[25] Tang R, Li X, Lai J. A novel optimal energy-management strategy for a maritime hybrid energy system based on large-scale global optimization. Applied Energy. 2018; 228:254-64.
[26] Tang R, Wu Z, Li X. Optimal power flow dispatching of maritime hybrid energy system using model predictive control. Energy Procedia. 2019; 158:6183-8.
[27] Tang R, Wu Z, Li X. Optimal operation of photovoltaic/battery/diesel/cold-ironing hybrid energy system for maritime application. Energy. 2018; 162:697-714.
[28] Ghenai C, Bettayeb M, Brdjanin B, Hamid AK. Hybrid solar PV/PEM fuel cell/diesel generator power system for cruise ship: a case study in Stockholm, Sweden. Case Studies in Thermal Engineering. 2019.
[29] Zapałowicz Z, Zeńczak W. The possibilities to improve ship's energy efficiency through the application of PV installation including cooled modules. Renewable and Sustainable Energy Reviews. 2021.
[30] Schwager P, Gehrke K, Vehse M. Applicability of standard photovoltaic modules for an increased share of renewable energies on board cruise ships. In sixteenth international conference on ecological vehicles and renewable energies 2021 (pp. 1-5). IEEE.
[31] Wei L, Wang Q, Wang Z, Zhou Z. Research on hydrogen-light ship power system. In Asia-pacific conference on image processing, electronics and computers 2021 (pp. 836-40). IEEE.
[32] Igder MA, Rafiei M, Boudjadar J, Khooban MH. Reliability and safety improvement of emission-free ships: systemic reliability-centered maintenance. IEEE Transactions on Transportation Electrification. 2020; 7(1):256-66.
[33] https://www.marinetraffic.com/en/ais/details/ships/shipid:212537/mmsi:240389000/imo:9208679/vessel:BLUE_STAR_MYCONOS. Accessed 20 October 2017.
[34] Koumentakos AG. Developments in electric and green marine ships. Applied System Innovation. 2019; 2(4):1-21.
[35] Roselyn JP, Ravi A, Devaraj D, Venkatesan R. Optimal SoC estimation considering hysteresis effect for effective battery management in shipboard batteries. IEEE Journal of Emerging and Selected Topics in Power Electronics. 2020; 9(5):5533-41.
[36] https://www.leonics.com/support/article2_12j/articles2_12j_en.php. Accessed 15 June 2020.
[37] Photovoltaics DG, Storage E. IEEE guide for array and battery sizing in stand-alone photovoltaic (PV) systems. IEEE. 2008.
[38] https://www.ecomarinepower.com/en/aquarius-marine-solar-power/8-products-services-and-consulting/110-energy-storage-and-batteries. Accessed 26 September 2021.
[39] https://www.ship-technology.com/features/electric-ships-the-world-top-five-projects-by-battery-capacity/ Accessed 26 September 2021.
[40] https://spectrum.ieee.org/first-battery-powered-tanker-coming-to-tokyo. Accessed 30 September 2021.
[41] Verma J, Kumar D. Recent developments in energy storage systems for marine environment. Materials Advances. 2021.
[42] Kobougias I, Tatakis E, Prousalidis J. PV systems installed in marine vessels: technologies and specifications. Advances in Power Electronics. 2013.
[43] Wen S, Zhang C, Lan H, Xu Y, Tang Y, Huang Y. A hybrid ensemble model for interval prediction of solar power output in ship onboard power systems. IEEE

Transactions on Sustainable Energy. 2019; 12(1):14-24.
[44] https://www.fwave.co.jp/en. Accessed 16 June 2022.
[45] Sivagami P, Jamunarani D, Abirami P, Harikrishnan R, Pushpavalli M, Geetha V. Review on soiling implications and cleaning methodology for photovoltaic panels. In international conference on innovative computing, intelligent communication and smart electrical systems (ICSES) 2021 (pp. 1-10). IEEE.
[46] Zakaria NG, Rahman S. Energy efficiency design index (EEDI) for inland vessels in Bangladesh. Procedia Engineering. 2017; 194:362-9.
[47] Paulson M, Chacko M. Marine photovoltaics: a review of research and developments challenges and future trends. International Journal of Scientific and Technology Research. 2019; 8:1479-88.

Midhu Paulson was born in 1986 at Ernakulam, India. She received her Bachelor's degree in Electrical Engineering from Mahatma Gandhi University, Kerala in 2008, Master's degree in Power systems from Saintgits College of Engineering, Kottayam in 2011. From 2011 to 2016 she has been working in various fields, as an Assistant system engineer at Tata consultancy service limited and as a faculty in the Department of Electrical Engineering at various engineering colleges in India. Since 2016 she has been working as a research scholar in the Department of Ship Technology at Cochin University of Science and Technology. Her research interests include Renewable Energy, Application of Power System Simulation Software and Power Quality in Marine Power Systems.
Email: midhumt@gmail.com

Dr. Mariamma Chacko was born in 1961 at Changanacherry, India. She received her Bachelor's degree in Electrical Engineering from the University of Kerala in 1985, Master's degree in Electronics from Cochin University of Science and Technology in 1987 and Ph.D. in Computer Science from Cochin University of Science and Technology in 2012. She joined Department of Ship Technology, as lecturer in 1990 and currently working as Professor there. From 1987 to 1990 she was associated with the Department of Electronics, Cochin University of Science and Technology, as a Research Associate. She has more than 25 research publications to her credit and her research interests include Validation and Optimization of Embedded Software, Motor Control, Big Data and Power Quality in the Ship's Electrical System.
Email: mariamma@cusat.ac.in

Appendix I

S. No.	Abbreviation	Description
1	ABT	Automatic Bus Transfer
2	AES	All Electric Ship
3	AC	Alternating Current
4	AI	Artificial Intelligence
5	BMS	Battery Management System
6	CHPD	Combined Heating and Power Device
7	DOD	Depth of Discharge
8	DWT	Dead Weight
9	DC	Direct Current
10	EEDI	Energy Efficiency Design Index
11	EMS	Energy Management System
12	ESS	Energy Storage System
13	ETAP	Electrical Transient Analysis Program
14	GRT	Gross Tonnage
15	IES	Integrated Energy System
16	IMO	International Maritime Organisation
17	LED	Light Emitting Diode
18	LNG	Liquefied Natural Gas
19	LPG	Liquefied Petroleum Gas
20	MSB	Main Switch Board
21	MW	Mega Watt
22	PCTC	Pure Car and Truck Carrier
23	PMS	Power Management System
24	PV	Photovoltaic
25	Ro-Ro	Roll-on/Roll off
26	RER	Renewable Energy Resources
27	SoC	State of Charge
28	VRLA	Valve Regulated Lead Acid
29	ZEV	Zero Emission Vessel