

# A design and experimental investigation of a large-scale solar energy/diesel generator powered hybrid ship

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**Abstract:** Due to the increasing demand for energy conservation and the reduction of emissions, renewable energy applications for ships have attracted a great deal of attention. In this paper, a 5000-vehicle space pure car and truck carrier (PCTC) is selected as the research object. Then, on the basis of the existing power system, a unified grid-tied/stand-alone solar system is designed with a built-in battery energy storage system. The system includes a solar energy generation unit, a battery storage system, a diesel generating set, grid-tied/stand-alone controlled inverters, a battery management system (BMS) and an energy management system. According to an analysis of the experimental data, it can be concluded that the use of solar energy hybrid power can reduce fuel consumption by 4.02% and carbon dioxide (CO<sub>2</sub>) emissions by 8.55% a year. Thus, the proposed solar-powered hybrid system can reduce both oil consumption and CO<sub>2</sub> emissions significantly.

**Keywords:** Solar Energy; Hybrid Powered Ship; Grid-tied/stand-alone; Energy Conservation and Emission Reduction

## 1. Introduction

Energy shortages, environmental pollution, and global warming are common challenges

23 faced by the global energy community today. The fossil fuel energy systems established in  
24 the 20th century are unsuitable for the efficiency, economic, and safety demands of today's  
25 society. According to a forecast of the International Energy Agency, the annual global  
26 energy demand will increase from 12 billion tons of oil equivalent in 2009, to 17-18  
27 billion tons of oil equivalent in 2035. Moreover, if the current emissions policy is  
28 maintained, emissions will increase from 29 billion tons in 2009 to 43 billion tons in 2035;  
29 furthermore, even taking into account the new regulations, emissions will rise to 36 billion  
30 tons [1].

31 Whilst it is an important part of intercontinental communication and economic activity,  
32 the shipping industry causes a much higher emission of pollutants than the aviation  
33 industry. Additionally, the energy consumption of ships is quite significant and problems  
34 such as the exhausting of resources and oil leakages are also severely threatening the  
35 environment. Accordingly, the emission requirements for coastal ships, or those sailing on  
36 inland lakes, are more stringent [2]. The results of the Greenhouse Gas (GHG) study  
37 completed by the International Maritime Organization (IMO) in 2009 showed that in 2007,  
38 the global shipping industry's CO<sub>2</sub> emissions were approximately 1.046 billion tons,  
39 accounting for 3.3% of the total global carbon dioxide emissions. Moreover, if no  
40 restrictions were imposed, by 2050, the CO<sub>2</sub> emissions from the shipping industry would  
41 increase by 150% to 250%, accounting for between 12% and 18% of the global allowable  
42 carbon dioxide emissions [3]. The latest report of the International Energy Agency in  
43 October 2017 stated that the current total global carbon dioxide emissions are 800 million

44 tons and, according to the IMO, this number will double by 2060. In order to deal with the  
45 stringent demands of the regulations relating to ships' emissions, all major shipping  
46 nations in the world have adopted "green ships", as these are seen as the future of the  
47 shipping industry [4].

48       Against this background, all countries in the world, including China, are faced with  
49 the problem of the structural reform of energy. The development and utilization of clean  
50 energy, such as solar energy, wind energy, hydropower, hydrogen energy and liquefied  
51 natural gas (LNG), is an effective way of conserving energy and reducing the emissions of  
52 ships [5-7]. These clean energy sources, which do not pollute the environment, are  
53 increasingly becoming more widely appreciated. Inexhaustible solar energy is a good  
54 example of a renewable energy source and in the post-fossil fuel era, it will become one of  
55 the most important natural energy sources [8]. To date, solar energy has been widely used  
56 on land [9-12]; however, research and development regarding its use as a power source for  
57 transport, particularly in water transportation, has been slower to progress. If solar power  
58 can be used to provide electricity for ships, or as a propulsion system to replace traditional  
59 diesel power, it can greatly reduce both a ship's energy consumption and emissions [13].

60       However, due to the limitations of solar energy conversion efficiency for ships that  
61 have relatively large power requirements and a limited installation area for solar panels,  
62 solar energy often needs to be combined with a diesel engine or other energy sources to  
63 act as a hybrid power system [14-15]. In recent years, researchers around the world have  
64 conducted a large number of studies on the design of solar photovoltaic (PV) systems. For

65 example, literature [16] proposed a method of using solar energy and ocean thermal  
66 energy as a means of propulsion for ships, and provided a detailed design proposal.  
67 Moreover, Zhu Y et al. [17] studied the factors affecting the power generation of solar PV  
68 systems for newly constructed ships, and concluded that ships using solar energy as an  
69 auxiliary power, at a latitude of 31.9 degrees north, can achieve a reduction in fuel  
70 consumption and emissions that meets the requirements of the energy efficiency design  
71 index (EEDI). Atodiresei D et al. [18] analyzed the economics of using solar PV systems  
72 in commercial ships on the northwest route of the Black Sea Basin. Their results show that  
73 at different latitudes and climatic conditions, more energy can be generated by adjusting  
74 the optimal angle of the solar panel. Liu H [19] proposed a marine hybrid power system  
75 consisting of a diesel generator, solar energy, a battery, and a super capacitor, and  
76 established a mathematical model of solar power generation under ocean conditions.  
77 Accordingly, the fluctuation characteristics of the solar output power and the optimal  
78 capacity of the supercapacitor were analyzed. Although the ship used as the research  
79 object was large with a displacement of 5878.8t, the capacity for installing a solar energy  
80 system was very small, with only a PV panel area of 1.25m<sup>2</sup>. Salem A A et al. [20]  
81 proposed a scheme for the installation of marine grid-connected solar power systems, and  
82 analyzed their economical and emission characteristics. The authors then used a case study,  
83 where the object boat was 43.1m in length and the power of the solar energy system was  
84 260 watts, to prove that the proposed power system solution could achieve the dual goal of  
85 energy conservation and the reduction of emissions. Atkinson G M [21] used a high-speed

passenger ship with a deadweight of 2775 t as the research object and designed a solar energy PV system with a peak power of 2.32 kWp and a battery energy storage system with a capacity of 5.4 kWh. Their test results showed that there was a 28% loss in the performance ratio of the system and further testing and evaluation were required. Wen S and Lan H et al [22-23] proposed a PV/diesel/energy storage system (ESS) ship's power system, which used an interval optimization algorithm and particle swarm optimization algorithm to ascertain the optimal size of a hybrid power system. Japan's Kokusho T [24] proposed a Sailing Solar-Cell Raft Project, which was supposed to develop a large wind-sailing solar cell raft that could produce 8 kwh/m<sup>2</sup>/day of solar energy when the weather was good. Finally, Kyoung-Jun Lee et al. [25] designed a solar PV system using the stand-alone mode and used a cruise ship, whose displacement was 1.154 t, as the research object. The maximum peak power of the solar energy was calculated to be 3.2 kW.

Most of the above-mentioned hybrid systems were based on boats, while designs and applications that are based on large scale vessels are rare. Even in a small number of cases when there were designs for large ships, the related solar and battery capacities were relatively small. In addition, the results relating to energy conservation and the reduction of emissions were only based on theoretical analysis and simulation, and any experimental verification was usually lacking.

Against this background, in 2013, the Wuhan University of Technology undertook a high-tech marine scientific research project on behalf of the Ministry of Industry and Information Technology. A unified grid-tied/stand-alone integrated solar PV system, with

107 a peak power of 143 kW, was designed, which had a built-in 652.8 kWh lithium ion  
108 battery storage system. In March 2014, it was installed in an actual 5000-vehicle space  
109 PCTC, the "COSCO Tengfei", and put into operation. This ship was the world's first large-  
110 scale cargo ship to use solar energy, and it also has the world's largest solar installation  
111 area. Although the "COSCO Tengfei" has been in operation since March 2014, the PV  
112 system and energy storage system on board are still in a good condition and to date, no  
113 failures have occurred.

114 The main contribution of this paper is the design of a hybrid power system consisting of  
115 solar energy, diesel generators, batteries, inverters, a battery management system (BMS),  
116 and energy management system (EMS), based on the existing power system of the  
117 "COSCO Tengfei". The energy saving and emission reduction effect of the solar PV  
118 system is verified through an experimental test on the actual ship. The proposed hybrid  
119 system will hopefully provide guidance for the future design of solar ships. It also will  
120 lead to the conservation of energy and environmental protection. In addition, the solar  
121 hybrid power system design scheme in this paper has broad application prospects for  
122 various types of energy storage power plants, small and medium-sized PV grid-connected  
123 power stations and microgrids.

124 The paper is organized as follows. Section 2 introduces the parameters of the research  
125 object, and discusses the configuration and operation modes of the solar hybrid system.  
126 Section 3 discusses the experimental results of tests conducted on the solar ship. Section 4

analyzes the energy-saving and emission reduction effects of the solar energy system.

Conclusions are drawn in Section 5.

## 2. A design for the solar/diesel hybrid power system

The "COSCO Tengfei" is a ship belonging to COSCO Shipping Co., Ltd. It is an ocean-going ship built in 2011, which has parking spaces for 5000 vehicles. The ship is classified in the China Ships Classification Society and flies the flag of Panama, as shown in Figure 1.

The ship has a total length of 182.80 m, a profile width of 32.20 m, a depth of 14.95 m, a design draught of 8.40 m, a structural draught of 9.40 m, a design speed of 20.20 kn, and a cruising range of 20,000 nautical miles. The technical parameters of the ship are listed in Table 1.



Figure 1 The "COSCO Tengfei"

Table 1 The basic parameters of the "COSCO Tengfei"

|              |         |                |                            |
|--------------|---------|----------------|----------------------------|
| Type length  | 182.80m | Parking spaces | 5000                       |
| Type width   | 32.20m  | Main machine   | 1set, 14520kW              |
| Depth        | 14.95m  | Generator      | 1020kW×2 sets, 960kW×1sets |
| Design draft | 8.40m   | Total weight   | 14759.06t                  |
| Speed        | 20.20kn | Cruising range | 20000 nautical miles       |
| Displacement | 29150t  |                |                            |

Based on the parameters of the "COSCO Tengfei" and the original power configuration, a hybrid solar energy system was designed, as shown in Figure 2. The system consists of solar panels, PV controllers, on/off-grid inverters, lithium-ion battery packs, a BMS, diesel generator sets, transformers, and power distribution cabinets. The parameters of the system's main components are shown in Table 2. The system's operation mode can be set by the user to four different modes using a manual selection switch. These modes are now outlined.

1. The off-grid operation mode. PV modules charge the battery through the PV controller. The off-grid mode directly converts the PV and battery's direct current (DC) voltage to a 450V alternating current (AC) voltage. Then the AC voltage is stepped down using a three-phase transformer, and directly supplied to the lights.

2. The grid-connected operation mode. Under the grid-connected mode, the energy stored in the battery is delivered back to the grid. To prevent a current reverse impact on the ship's synchronous generator, a set of anti-backflow devices is situated at the busbar.

3. The ship's grid powering mode under an insufficient output of solar energy. When the PV system experiences a steep drop in output power and the battery energy is insufficient to support the load, the bypass backup power is activated, and the ship's original electrical power is used to provide energy to the lighting load.

4. The ship's grid powering mode under a PV system's fault condition. Under this condition, a single pole double throw switch is switched to the original ship's power grid, which provides energy to the lighting load.



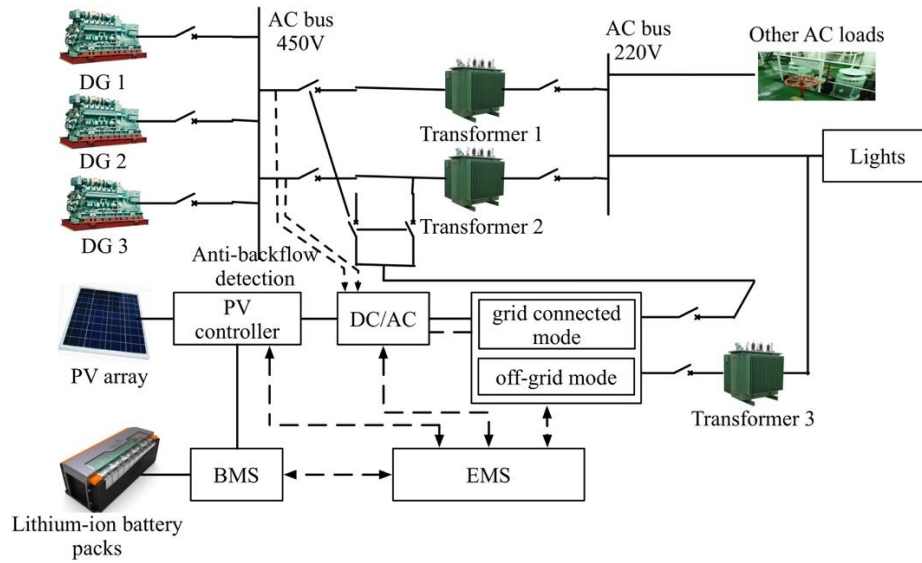


Figure 2 A block diagram of the solar hybrid system

Table 2 The main component parameters of the hybrid power system

| Solar system                    |                        |                                       |                                 |                       |                        |                       |
|---------------------------------|------------------------|---------------------------------------|---------------------------------|-----------------------|------------------------|-----------------------|
| String relationship             | Total Power            | Solar cell number                     | Series open circuit             | Short circuit current | Series peak voltage    | Parallel peak current |
| 18 in series<br>30 in parallel  | 143kW                  | 540 pieces                            | 702V                            | 267.9A                | 558V                   | 256.5A                |
| Battery system                  |                        |                                       |                                 |                       |                        |                       |
| String relationship             | Rated output voltage   | Overcharge protection                 | Over discharge recovery voltage | Maximum capacity      | Rated working capacity |                       |
| 120 in series<br>17 in parallel | 384V                   | 438V                                  | 300V                            | 734.4kWh              | 652.8kWh               |                       |
| On/off inverter                 |                        |                                       |                                 |                       |                        |                       |
| Off-grid mode                   | Maximum DC input power | Maximum DC input open circuit voltage | Input voltage range             | Rated AC output power | Power factor           | Maximum efficiency    |
|                                 | 160kWp                 | 900Vdc                                | 300Vdc-780Vdc                   | 50kW                  | >0.99（at rated power）  | 95%                   |
| Grid-connected mode             | Maximum DC input power | Maximum DC input open circuit voltage | Input voltage range             | Rated AC output power | Power factor           | Maximum efficiency    |
|                                 | 160kWp                 | 900Vdc                                | 300Vdc-780Vdc                   | 150kW                 | >0.99（at rated power）  | 95%                   |
| Diesel generator                |                        |                                       |                                 |                       |                        |                       |
| Model                           | Calibration power      | Calibration speed                     | Fuel grade                      | Generator model       |                        | Generator power       |
| 6N21AL-GV                       | 1020 kW                | 900 r/min                             | 380cst                          | HTCT506-84R/2         |                        | 960kW                 |

## 2.1 The solar PV system

The "COSCO Tengfei" has a total of 14 decks, of which the 1st-3rd floors are used for the ship's equipment, such as cabins, ballast water and anchor chains. The 3rd-12th floors

are the ship's warehouses, which are mainly used to carry vehicles. The 13th-14th floors are crew living areas and the ship's control area. According to the ship's actual measurements, the uncovered area of the "COSCO Tengfei's" upper deck is not more than 1700 m<sup>2</sup> and can be divided into 7 sections (as shown in Figures 3-4). The 1# zone is the front of the ship's bridge, with an area of 180 m<sup>2</sup>; the 2# zone is the top deck of the ship's bridge, with an area of 90 m<sup>2</sup>; the 3# zone is the U-shaped zone of the bridge's deck with an area of 436 m<sup>2</sup>; and the 4# zone is the emergency generator room and the top of the CO<sub>2</sub> room in the middle of the ship (number 4#). It is approximately 100 m<sup>2</sup>, and a back-up area of approximately 80 m<sup>2</sup> is set beside the basketball court next to this area. The 5# zone is the rear area of the helicopter landing platform in the ship's middle section, with an area of 140 m<sup>2</sup>; the 6# zone is the ship's tail area which is 240 m<sup>2</sup>, with 60 m<sup>2</sup> of spare space set near it; and the 7# zone consists of a 300 m<sup>2</sup> back-up area on the walkways on both sides of the ship. Taking into account the driving specifications and safety requirements, as well as the arrangement of the channels between the solar arrays, the actual area available for the installation of solar panels is approximately 1300 m<sup>2</sup>.

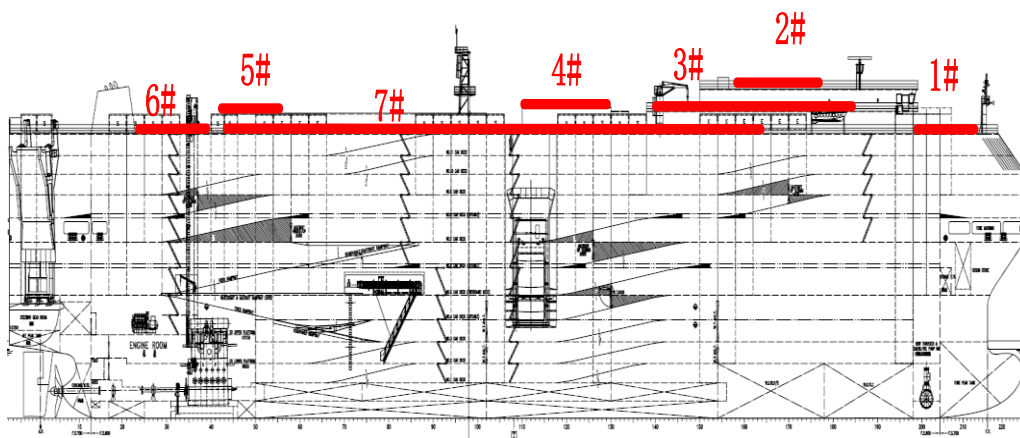


Figure 3 The vertical section of the area that can be used to arrange the PV panels

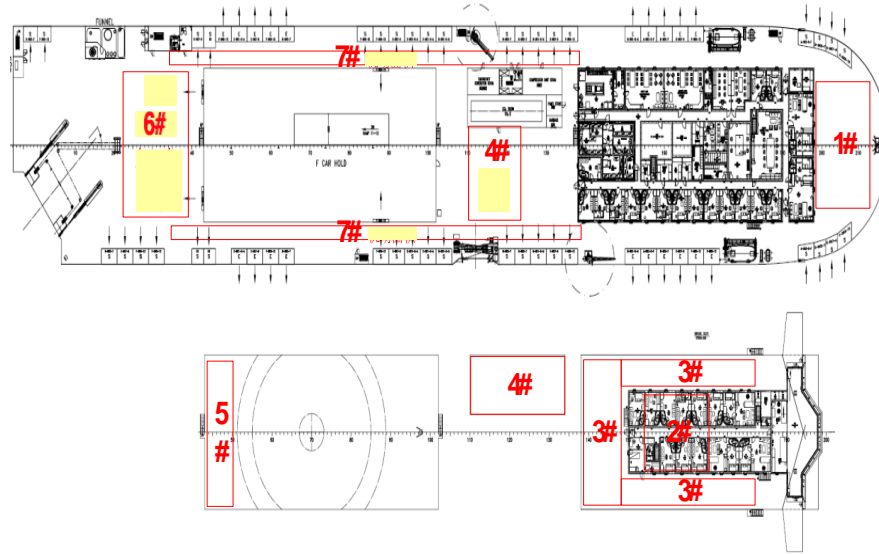


Figure 4 The top view of the main deck of the solar PV panel area

The solar PV system uses a PANDA 60 Cell 40 mm series monocrystalline silicon solar panel produced by Yingli Green Energy Holdings Co., Ltd., whose model number is YL265C-30b. The peak power under standard test conditions is 265 W, and its size is 1650 mm×990 mm× 40mm, with a weight of 19.1 kg.

Based on the 140kW total capacity design and standard irradiation conditions (1000 W/m<sup>2</sup>, panel temperature 20°C), by using 18 solar panels in series for a string and 30 strings in parallel, a total number of 540 solar panels are required. After considering the set-up of the maintenance aisle, the total installation area is approximately 1050 m<sup>2</sup>. The solar module mounting bracket is customized according to the ocean ship's anti-corrosion protection grade. A galvanized steel material bracket is used and covered with high quality anti-corrosion paint. Riveting is used to secure the ship's hook, and the riveted components are also covered with anti-corrosion paint.

The grid-tied/stand-alone inverter is designed independently and has two operational modes. 1. The off-grid mode. Through a three-phase inverter, the DC voltage of the battery is converted into a high-frequency three-phase AC voltage. The three-phase transformer is used to isolate and boost the AC voltage to supply the load, and there is a bypass access (generator) output. 2. The grid-tied mode. Through the three-phase inverter, the DC voltage of the solar string and battery pack is converted to a high-frequency three-phase AC voltage, which is isolated and boosted by a three-phase transformer and then connected to the power grid. The main feature is that in the stand-alone mode, the closed-loop control of the inverter current is controllable and adjustable. While in the grid-connected mode, the grid injected current is closed-loop controlled, controllable and adjustable. In addition, it is equipped with frequency-disturbed detection technology, which can achieve anti-islanding control. An overview of the solar PV system installation is shown in Figure 5.



Figure 5 A photo of the solar PV system installation on the actual ship

## 2.2 The battery energy storage system

The solar PV energy storage system uses a total of 2040 3.2V/100Ah lithium-ion batteries. This battery is produced by China Shipbuilding Heavy Industry (Beijing) Technology Co., Ltd. and has a weight of 20 kg. The 120 battery cells are connected in series as a string and 17 strings are connected in parallel to formulate a battery energy storage system with a total capacity of 652.8 kWh. The PACK unit of the energy storage system is designed according to the power requirements of the actual ship, while the heat dissipation and protection under high temperatures are fully taken into consideration. The BMS is used to manage the battery pack. The actual installation photo of the battery system is shown in Figure 6.



Figure 6 The battery system installation on the actual ship

### 2.3 The diesel generators and loads

There are three diesel generators installed on the "COSCO Tengfei", which are produced by YANMAR. Two of them are 1020kW 6N21AL-GV diesel engines, while the other is a 960 kW 6N21AL-UV diesel engine. Figure 7 shows a 1020 kW 3# diesel generator.



Figure 7 A 3# diesel generator

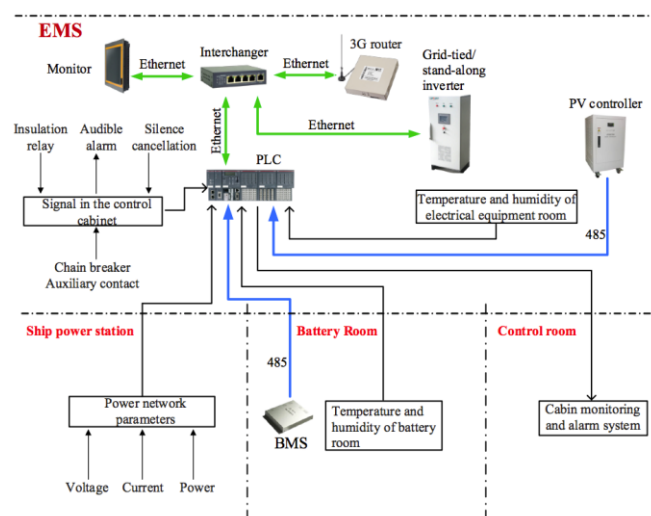
The solar PV system has stand-alone and grid-connected operational modes. In the stand-alone mode, solar energy is mainly used to power the lighting loads of the 3rd-12th floors. The lighting is provided by 1220 18W LED lamps and 376 40W ordinary fluorescent lamps. The cargo deck is lit for 24 hours and the total power consumption is 888kWh. In the grid-connected mode, the solar energy will be injected into the ship's power grid system to produce its maximum power level, with an output power of up to 143 kW.

## 2.4 The EMS

The EMS consists of four modules: data input and process, display, output and control which are shown in figure 8. The EMS reads the PV voltage and current of the solar system and the voltage, current, frequency, power and efficiency of the inverter from the solar charging controller, the BMS, the inverter and the ship power station monitoring system through a RS485 communication interface. The voltage, current, radiation intensity, panel ambient temperature and cabin temperature of the N sets of solar panels are read through an analog input module. The connection state of the inverter output side contactor is read via the



digital input module. The received data is processed by a data processing unit, and then displayed on a monitor. The system controls the output of each power source according to the load variation, the instantaneous power generation of solar energy, and the state of charge (SOC) of the battery pack through a pre-designed EMS. Since the solar controller, inverter, BMS and ship's power station monitoring system all have self-protection functions, they will automatically take protective measures when encountering any faults. The safety monitoring device can receive the fault data through a RS485 communication interface and issue an alarm accordingly. In the meantime, it controls the contactor located at the output of the grid-connected inverter, which can be disconnected from the entire system. To facilitate historical data acquisition and failure analysis, all the collected data can be stored in the host computer and the system can also realize remote data transmissions through a 3G network. In order to avoid the communication signal from being interfered with distance, various metals and electronic equipment inside the cabin, the industrial computer and the 3G wireless router are placed inside the cabin on the side of the ship. The communication antenna extends out of the box to the outside of the cabin, and is attached to the iron wall through its bottom magnet.



### 3. The experimental result of the tests conducted on the solar-powered hybrid ship

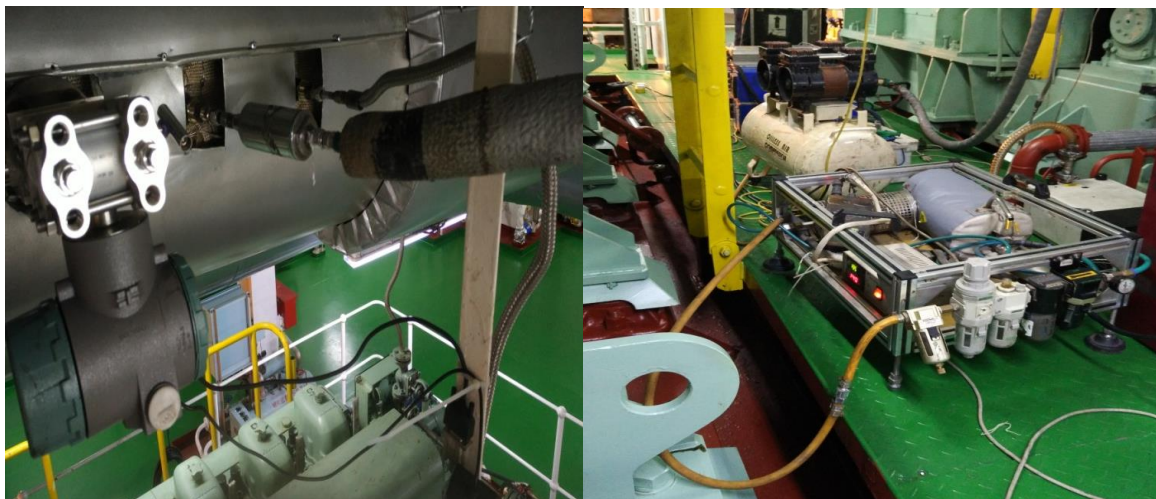
When ships arrive or depart from a harbor (including the time they are docked), due to the frequent switching of electrical equipment, the ship's load may change between 250 kW and 600kW, while the engine is generally not allowed to use more than 75% of the rated power. Therefore, to ensure the safety of the ship during its arrival or departure, two auxiliary generators work simultaneously. The total load of the ship during normal sailing is around 600kW, and only one auxiliary generator is in operation.

After completing the installation and debugging of the solar PV system and the battery energy storage system, the research team conducted a test on the operation parameters of the actual ship's hybrid power system. In which, tests for CO<sub>2</sub> and some other gases adopted the SEMTECH-DS exhaust gas analysis system (as shown in Figure 9). The SEMTECH-DS mainly performs CO<sub>2</sub> detection by a non-dispersive infrared analysis method with an accuracy of  $\pm 0.1\%$ . The system sampling probe is installed at the end of the diesel engine with at least a distance of 10 exhaust pipe diameters, but at the same time at least 0.5m or 3 times the exhaust pipe diameter (whichever is greater) above the outlet of the exhaust system (see figure 9(a)). During the measurement process, the power system data can be directly obtained by the EMS. Each measurement point is assessed after the diesel engine reaches a stable operation mode, and the measurement time is 10 min. At each measurement point, after the system is stable for 5 minutes,



samples are continuously taken from the diesel engine exhaust gas. Then, the measurement data is stored in the data acquisition system. The sampling rate of the SEMTECH-DS exhaust gas analysis system is set to three times per minute. The average value of the CO<sub>2</sub> concentration during this acquisition period is taken as the effective value of the CO<sub>2</sub> emission at the measurement point.

The test took place on March 29, 2016 from 11:05 am to 19:20 pm. The power generation data acquisition experiments were performed in the grid-connected mode under both the arrival/departure and normal sailing conditions.



(a) The sampling probe installation position

(b) The data acquisition box

Figure 9 The SEMTECH-DS exhaust gas analysis system

Figure 10 shows the power curve of the solar and diesel generators and loads during arrival/departure. It can be seen from Figure 10 that the load switches frequently between 250 kW and 600 kW, due to the frequent operations and the switching of electrical equipment when arriving or leaving the port. The output power of the solar energy also fluctuates during this period. This is because the direction of the ship changes when it

arrives or departs from a port, leading to an intense change in the solar radiation levels of the solar panels. Figure 11 shows the power curve of the solar and diesel generators and loads under normal sailing conditions. When the ship is sailing normally, the ship's load only changes within a small range of about 600 kW, and the output power of the solar energy changes slowly with the change of the sunlight's intensity.

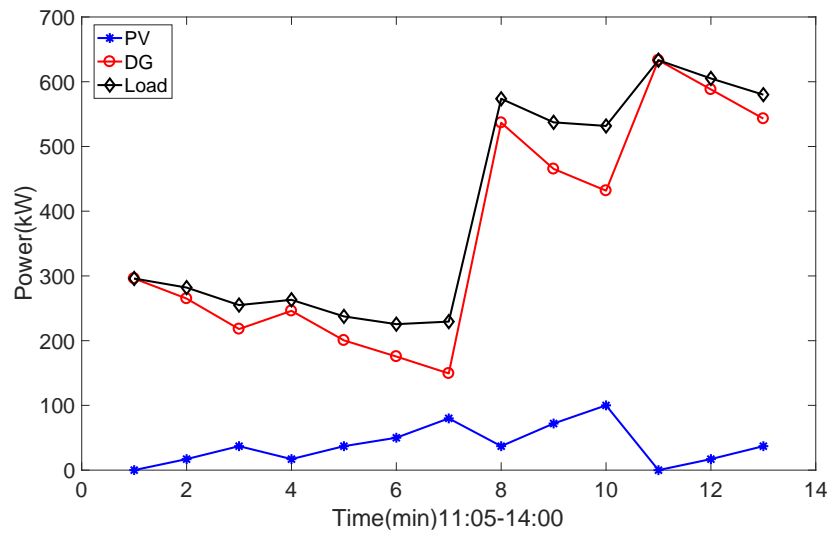


Figure 10 The experimental data during arrival/departure

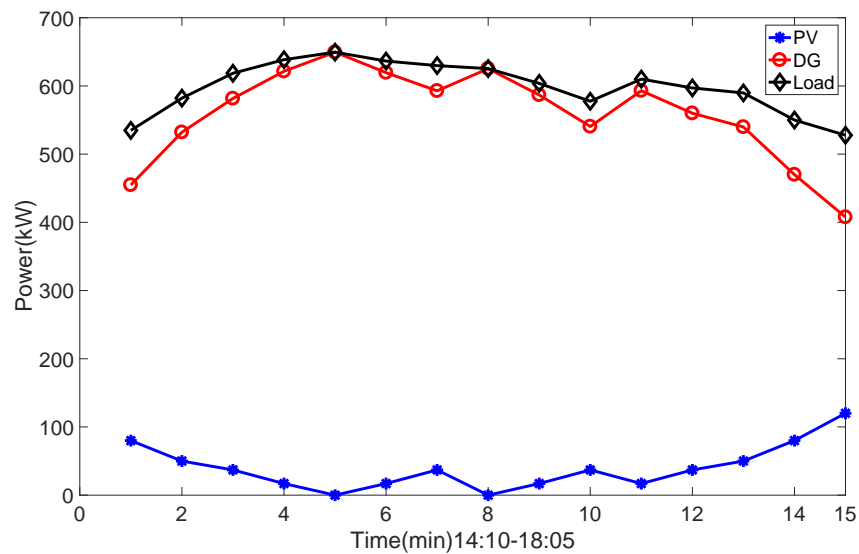


Figure 11 The experimental data during normal sailing

310 The corresponding fuel consumption of the diesel generator was also collected while  
311 the operating parameters of the hybrid power system under various operating conditions  
312 were being obtained. Figure 12 shows the relationship between fuel consumption, solar  
313 power and load power during arrival/departure. It can be clearly seen from figure 12 that  
314 when the ship's load power is low and the solar PV system power generation is between  
315 50-80 kW, the ship's fuel consumption is low. As the demand for the ship's load increases,  
316 so does its fuel consumption. However, when the ship's load is constant, its fuel  
317 consumption first decreases with the increasing solar power and then increases slightly.  
318 To illustrate the problem more clearly, the defined PV penetration is the ratio of the solar  
319 power integrated with the grid power and the ship's load. Figures 13 and 14 show the  
320 relationship between diesel fuel consumption and PV penetration during the  
321 arrival/departure process when the load is 300 kW and 600 kW respectively. When the  
322 load demand is 300kW, the PV penetration is below 20%, and the fuel consumption  
323 decreases with the increase of the PV penetration. When the PV penetration is between  
324 20-30%, that is, when the power is between 60-90 kW, the ship's fuel consumption is the  
325 lowest. When the proportion of solar energy is greater than 30%, the ship's fuel  
326 consumption will increase slowly. Similarly, when the load demand is 600 kW, the PV  
327 penetration is below 12%, and the fuel consumption is reduced with the increase of the  
328 PV penetration. When the PV penetration is between 12-15%, that is, when the power is  
329 between 72-90 kW, the ship's fuel consumption is the lowest. The reason for this is that  
330 the maximum fuel efficiency of the diesel engine occurs between 60% and 100% of the

load. During arrival/departure, the two diesel engines provide electricity to the ship, and the diesel engines are all under a low load. Figure 15 shows the relationship between specific fuel consumption and the power of the diesel engine. It can be seen that under low load conditions, the specific fuel consumption of the diesel engine will increase rapidly with the decrease of the load, resulting in the phenomenon that the fuel consumption of the diesel engine increases while the power is reduced.

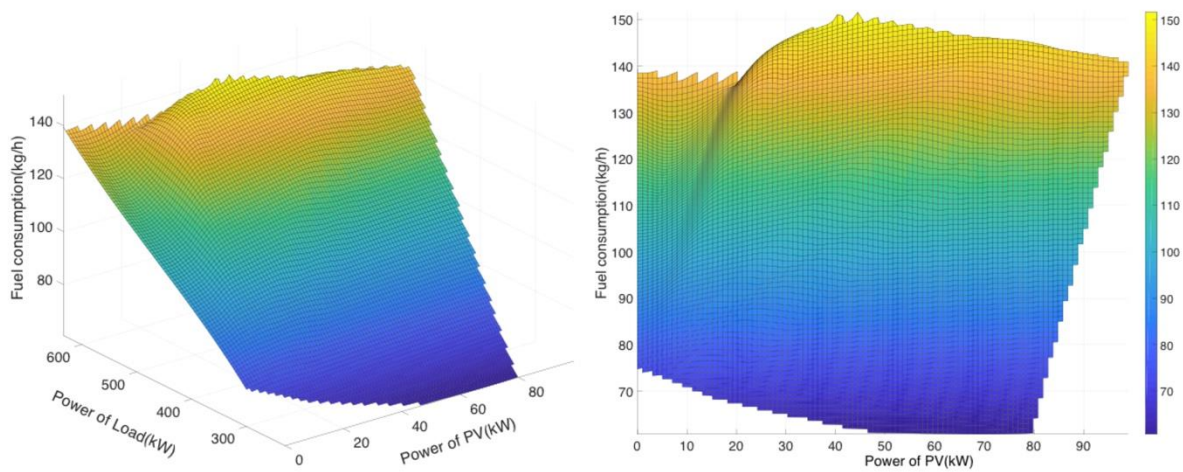


Figure 12 The fuel consumption vs. the PV and load power changes during arrival/departure

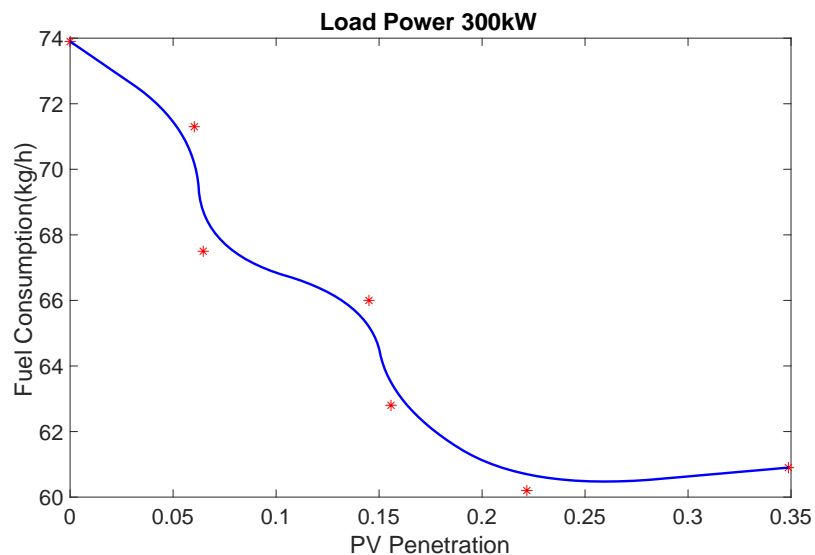


Figure 13 The relationship between fuel consumption and PV penetration during arrival/departure (load = 300kW)

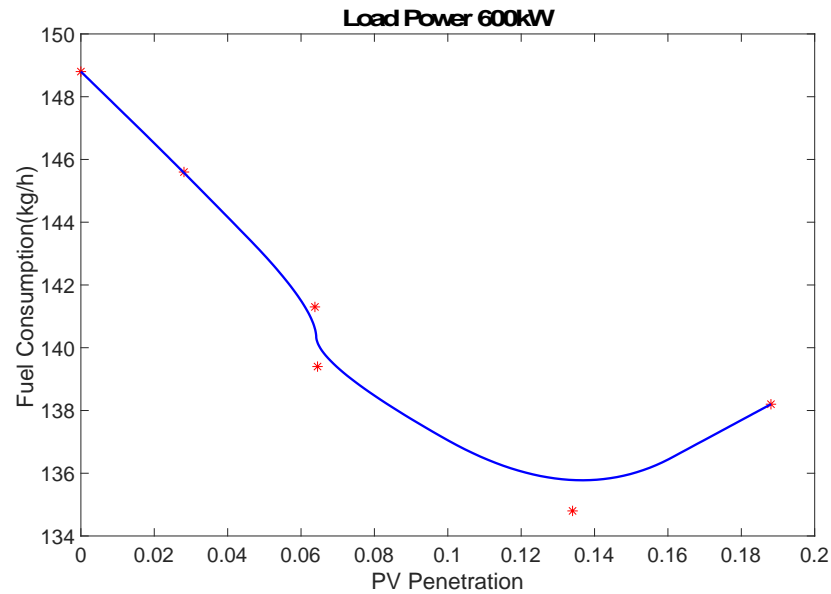


Figure 14 The relationship between fuel consumption and PV penetration during arrival/departure (load = 600kW)

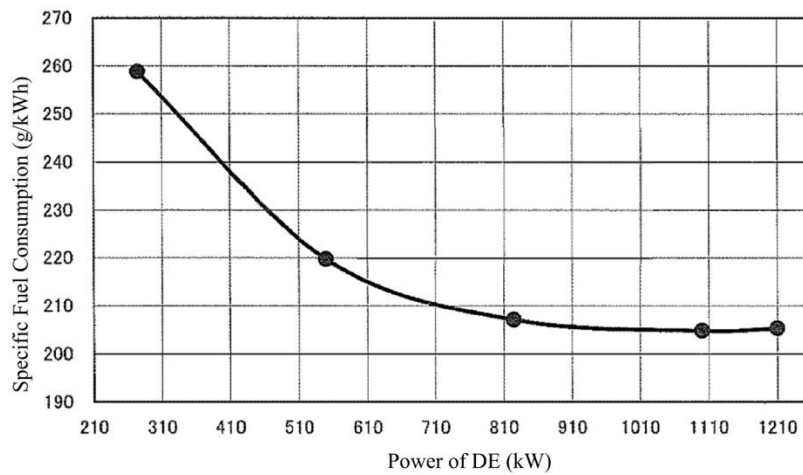


Figure 15 The relationship between specific fuel consumption and the power of the diesel engine

Figure 16 shows the relationship between the fuel consumption when solar power is generated and the load demand during normal navigation conditions. As can be seen,

when the ship's load demand is low and the PV system power is 120 kW, the fuel consumption is minimal. As the demand for the ship's load increases, so does the fuel consumption. When the ship's load is constant, the ship's fuel consumption decreases as the solar power increases. Figure 17 displays the curve of the change between the fuel consumption and the PV penetration when the ship's load demand is 600 kW during normal sailing conditions. It can be seen that the ship's fuel consumption gradually decreases as the PV penetration increases. This is because when the ship is sailing normally, its load is basically around 600 kW. A diesel generator provides electrical energy for the ship and basically operates within an economic scope. Therefore, the fuel consumption varies little with the load (see figure 15); thus when the power is reduced the fuel consumption will also reduce.

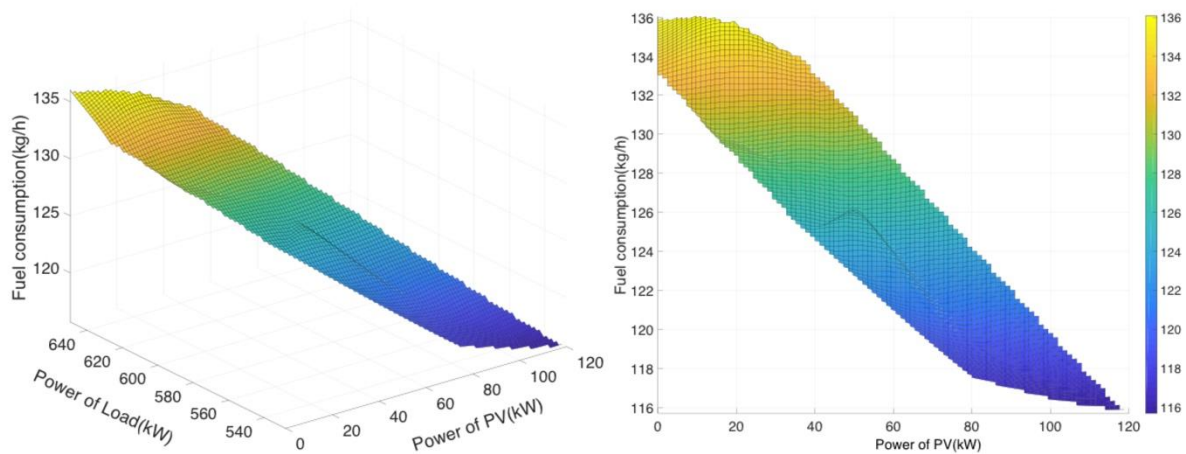


Figure 16 The fuel consumption under a function of PV and load power during normal sailing

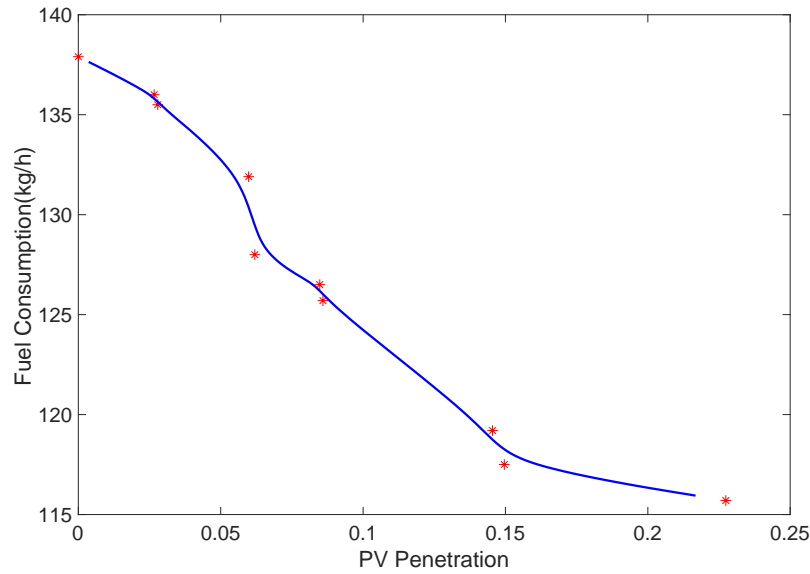


Figure 17 The relationship between fuel consumption and PV penetration during normal sailing (load = 600 kW)

#### 4. An analysis of the energy saving and emission reduction of solar hybrid ships

The "COSCO Tengfei" operates for an average of 365 days per year. Its routes are mainly: China (Tianjin, Shanghai, Guangzhou) - Brazil (Victoria) - Nigeria - Germany (Hamburg) - Belgium - Netherlands (Rotterdam) - Suez Canal - India - Singapore - China; about 11 ports, a total of 55 days in harbor and 310 days of normal sailing. Through a statistical analysis of the weather information on the route, the solar PV system can work for 292 days per year, which is 80% of the total operation time. More specifically, the operation of the solar system in a harbor is about 44 days, while the operation of the solar system during normal sailing is about 248 days. According to the time period in port or during normal sailing, an average electricity load of 600 kW and 6 h of sunshine per day are assumed in order to calculate the effects of energy saving and emission reductions for

one year. For the solar hybrid system proposed in this paper, since the diesel generator only uses diesel as a fuel, the emitted CO<sub>2</sub> is only generated by the diesel generator. During one year of arrival/departure and normal navigation, the fuel consumption and CO<sub>2</sub> emissions of a ship are:

(1) Arrival/departure period

● Fuel Consumption

$$\begin{aligned} Q_{\text{fuel}} &= \frac{24 \times 44 \times q_0}{10^3} & \text{when } PV_{\text{Penetration}} = 0 \\ Q_{\text{fuel}} &= \frac{18 \times 44 \times q_0}{10^3} + \frac{6 \times 44 \times q}{10^3} & \text{when } PV_{\text{Penetration}} > 0 \end{aligned} \quad (1)$$

● CO<sub>2</sub> emissions

$$\begin{aligned} Q_{\text{CO}_2} &= \frac{3600 \times 24 \times 44 \times g_0}{10^6} & \text{when } PV_{\text{Penetration}} = 0 \\ Q_{\text{CO}_2} &= \frac{3600 \times 18 \times 44 \times g_0}{10^6} + \frac{3600 \times 6 \times 44 \times g}{10^6} & \text{when } PV_{\text{Penetration}} > 0 \end{aligned} \quad (2)$$

(2) Normal Navigation period

● Fuel Consumption

$$\begin{aligned} Q_{\text{fuel}} &= \frac{24 \times 248 \times q_0}{10^3} & \text{when } PV_{\text{Penetration}} = 0 \\ Q_{\text{fuel}} &= \frac{18 \times 248 \times q_0}{10^3} + \frac{6 \times 248 \times q}{10^3} & \text{when } PV_{\text{Penetration}} > 0 \end{aligned} \quad (3)$$

● CO<sub>2</sub> emissions

$$\begin{aligned} Q_{\text{CO}_2} &= \frac{3600 \times 24 \times 248 \times g_0}{10^6} & \text{when } PV_{\text{Penetration}} = 0 \\ Q_{\text{CO}_2} &= \frac{3600 \times 18 \times 248 \times g_0}{10^6} + \frac{3600 \times 6 \times 248 \times g}{10^6} & \text{when } PV_{\text{Penetration}} > 0 \end{aligned} \quad (4)$$

In equations (1)-(4):  $Q_{\text{fuel}}$  is the fuel consumption per year;  $q_0$  is the fuel consumption per unit time when the PV penetration is 0, kg/h;  $q$  is the fuel consumption per unit time when the PV penetration is greater than 0, kg/h;  $Q_{\text{CO}_2}$  is the CO<sub>2</sub> emission per year, t;  $g_0$  is the CO<sub>2</sub> emission per unit time when the PV penetration is 0, g/s; and  $g$  is the CO<sub>2</sub> emission per unit time when PV penetration is greater than 0, g/s. According to the actual ship experiments, the



value of  $q_0$ ,  $q$ ,  $g_0$  and  $g$  during the arrival/departure and normal navigation periods are shown in Table 3.

Table 3 Fuel consumption and CO<sub>2</sub> emissions under different PV penetrations

| Departure/Arrival |                                    |  | Normal Navigation |                                    |  |
|-------------------|------------------------------------|--|-------------------|------------------------------------|--|
| PV penetration    | Fuel Consumption ( $q_0/q$ , kg/h) | CO <sub>2</sub> emission rate ( $g_0/g$ , g/s) | PV penetration    | Fuel Consumption ( $q_0/q$ , kg/h) | CO <sub>2</sub> emission rate ( $g_0/g$ , g/s) |
| 0%                | 148.8                              | 116.38   | 0%                | 137.9                              | 114.8  |
| 6.4%              | 139.4                              | 112.38   | 8.4%              | 126.5                              | 87.52  |
| 13.4%             | 134.8                              | 98.48  | 14.5%             | 119.2                              | 80.52  |
| 18.8%             | 138.2                              | 93.64  | 22.7%             | 115.7                              | 75.54  |

According to the test data and equations (1)-(4), the ship's fuel consumption and CO<sub>2</sub> emissions under different PV penetrations during the year, whilst the ship is in port, are shown in Figure 18.

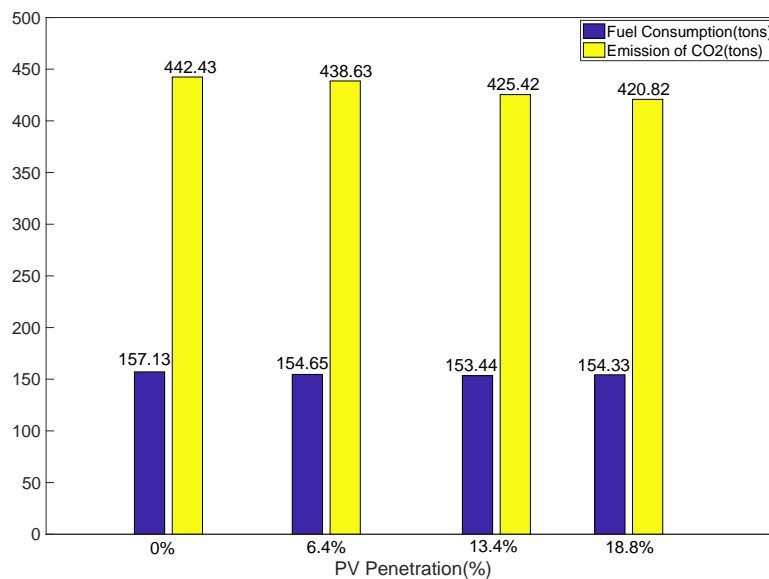


Figure 18 The CO<sub>2</sub> emissions and fuel consumption with different PV penetrations in a year during arrival/departure

Based on the calculations, the energy saving and emission reduction effects of different PV penetrations during the time of arrival/departure are shown in Table 4. When the proportion of solar energy is 6.4%, 13.4% and 18.8%, the ship can save 2.48 t, 3.70 t

and 2.80 t of fuel respectively, and reduce the CO<sub>2</sub> emissions by 13.80 t, 17.01 t and 21.61 t. Compared with the pure diesel generator system, the reduction of fuel consumption will be 1.58%, 2.35% and 1.78% and the reduction of CO<sub>2</sub> emissions is 0.86%, 3.85% and 4.88% respectively.

Table 4 The energy saving and emission reduction results of different PV penetrations during arrival/departure

| PV penetration | Fuel consumption per year (t) | CO <sub>2</sub> emission per year (t) | Fuel saving(t) | Emission reduction(t) | Fuel saving ratio% | Emission reduction ratio% |
|----------------|-------------------------------|---------------------------------------|----------------|-----------------------|--------------------|---------------------------|
| 0%             | 157.13                        | 442.43                                | 0.00           | 0.00                  | 0.00%              | 0.00%                     |
| 6.4%           | 154.65                        | 438.63                                | 9.93           | 3.80                  | 1.58%              | 0.86%                     |
| 13.4%          | 153.44                        | 425.42                                | 14.78          | 17.01                 | 2.35%              | 3.85%                     |
| 18.8%          | 154.33                        | 420.82                                | 11.19          | 21.61                 | 1.78%              | 4.88%                     |

The annual fuel consumption and CO<sub>2</sub> emissions of ships with different proportions of solar energy during normal navigation are shown in Figure 19. Based on the calculations, the energy saving and emission reductions under different PV penetrations during the ship's normal navigation period are shown in Table 5. When the PV penetration is 8.157%, 14.5% and 22.7%, the ship can save 16.96 t, 27.83 t and 33.03 t of fuel respectively, while reducing the CO<sub>2</sub> emissions by 146.13 t, 183.63 t and 210.31 t. Compared with the pure diesel generator, the reduction in fuel consumption is 2.07%, 3.39% and 4.02%, while the CO<sub>2</sub> emissions are cut by 5.94%, 7.47% and 8.55% respectively.

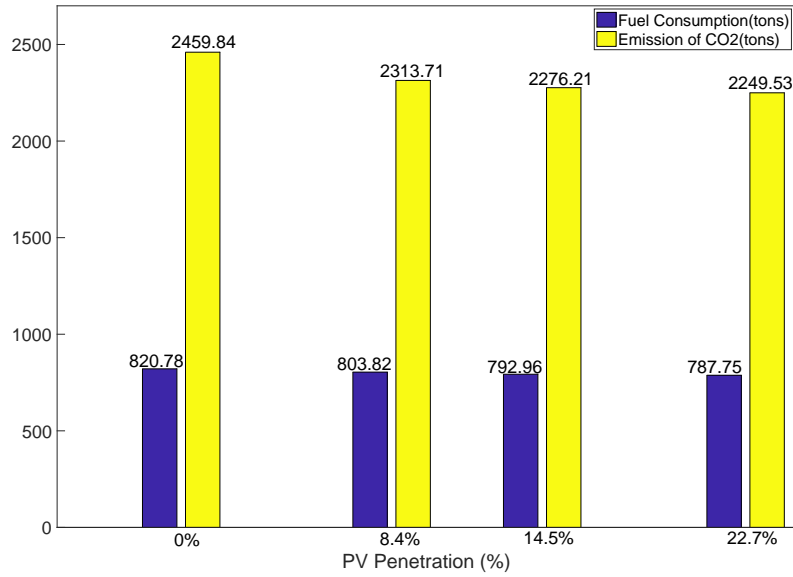


Figure 19 The CO<sub>2</sub> emissions and fuel consumption under different PV penetrations in a year during normal sailing periods

Table 5 The energy saving and emission reduction results under different PV penetrations during normal sailing periods

| PV penetration | Fuel consumption per year (t) | CO <sub>2</sub> emission per year (t) | Fuel saving(t) | Emission reduction(t) | Fuel saving ratio % | Emission reduction ratio % |
|----------------|-------------------------------|---------------------------------------|----------------|-----------------------|---------------------|----------------------------|
| 0%             | 820.78                        | 2459.84                               | 0              | 0                     | 0.00%               | 0.00%                      |
| 8.4%           | 803.82                        | 2313.71                               | 16.96          | 146.13                | 2.07%               | 5.94%                      |
| 14.5%          | 792.96                        | 2276.21                               | 27.83          | 183.63                | 3.39%               | 7.47%                      |
| 22.7%          | 787.75                        | 2249.53                               | 33.03          | 210.31                | 4.02%               | 8.55%                      |

In recent years, the prices of international crude oil have fluctuated greatly. Therefore, in order to ensure the representativeness of the calculation results, the historical average price of marine diesel oil (MDO) from 2014 to 2017 [26] is selected for analysis when conducting an assessment of the economic benefits. The light fuel price is calculated to be about \$837.96/ton. In an ideal case, the economic savings of fuel during one year for a ship would be:

440 
$$(14.78 + 33.03) \times 837.96 \approx 40062.87\$$$

## 441 5. Conclusions

442 In this paper, a 5000-vehicle space PCTC named the "COSCO Tengfei" was  
443 redesigned using a large-scale (peak power 143 kW) solar PV system with a grid-  
444 tied/stand-alone control and built-in battery energy storage element. Through the analysis  
445 of the actual ship's experimental data under the conditions of arrival/departure and normal  
446 sailing, the following conclusions can be drawn.

447 1. In the case of arrival/departure, when the ship's load is low, the solar output power  
448 should preferably be 60-90 kW. When the ship's load is high, the solar output power  
449 should be between 72-90 kW. If the entire ship remains in the power range recommended  
450 above, its fuel economy will be optimal.

451 2. Under normal sailing conditions, the greater the output power of solar energy, the  
452 better the energy saving and emission reductions at peak power.

453 3. When ships are sailing using a solar energy hybrid power system, they can reduce  
454 fuel consumption by a maximum of 4.02% and CO<sub>2</sub> emissions by a maximum of 8.55%  
455 in a year.

456 4. The solar hybrid energy system design scheme in this paper can be applied to and  
457 provide significant guidance for the same type of ships, distributed power stations and  
458 microgrid systems.

## 459 6. Acknowledgments

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