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Photovoltaic Generating System on Ships to Reduce Fossil Fuel Dependence*

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Abstract

The release of polluting gases such as NOx or SOx to the atmosphere from ships is causing increasing concern. To reduce destruction to the marine environment, the value of the utilization of photovoltaic energy is highly appreciated since photovoltaic energy is an alternate clean energy source to fossil fuels.

The use of a photovoltaic generating system to supplement diesel engine driven electric power system on ships has been studied. The design of the photovoltaic generating system based on a photovoltaic array is presented in this paper. The amount of NOx and SOx emission is found to be significantly reduced for a small vessel operated within a harbour after a photovoltaic generating system is installed to supplement the diesel engine generator system.

1. Introduction

Among various alternate energy sources to fossil fuels, great advances has been achieved in the use of photovoltaic generating systems to convert solar energy to electric power. 3kW_p of electric power can be extracted from house roof top installations, while the capacities of similar installations in school or light industrial facilities is in the range of 30-300kW_p. At the high end of the spectrum, a 1MW_p power station has been built by New Sunshine Project of Japan to verify the technology for large scale power generation. Another similar facility in Carrissa Plane of the United States develops 7MW_p[1].

Since NOx and SOx emission from marine diesel engine is source of concern from environmental considerations, various strategies are proposed to reduce it[2].

One basic and effective way to reduce NOx and SOx emission is to reduce the reliance of electric power requirement on fossil fuel. Electric power from photovoltaic generating system can supply in part or even all the electric power requirements of the ship, thus making it possible to reduce the capacity of the diesel engine generator system or even to eliminate it altogether, resulting in reduction of NOx and SOx emission.

The use of photovoltaic generating systems on ships is largely restricted to pleasure boats, or in the propulsion of solar boats used in races[3) 4)]. As of yet, there are hardly any commercial systems used to supply electric power on commercial vessels. The obvious reason for this is that a large area of photovoltaic array is required to supply all electric power requirement on ships. However, the photovoltaic generating system is still recommendable as a supplementary electric power system if the possibility of scaling down the diesel engine generator system is considered.

For this purpose, electric power energy of a commuter boat was investigated. The area available for putting photovoltaic array was estimated. Based on weather statistics, photovoltaic energy was estimated. Battery and inverter capacities were decided accordingly and the design of a photovoltaic generating system was proposed. In this paper, the design of the photovoltaic generating system supplemented electric power system is presented. The system is found to be practical, and its environmental merits are discussed based on a comparison of the present NOx and SOx emission with that of the system proposed.

2. Ship Environment

2. 1 Commuter Boat

Not all ships are suitable targets for the introduction of photovoltaic generating system. For example there would be very little deck space for putting up photovoltaic array on the deck of tankers, where there are lot of pipelines. The following conditions are essential for choosing a suitable target ship.

* There is sufficient deck space. In addition there should not be much operations on the deck so as to secure safe and sufficient area for putting up photovoltaic array.

A commuter boat, Kinki, was chosen as an actual platform for our studies. The boat is being used mainly to transport inspectors within Osaka Bay for Kinki District Bureau of the Ministry of Transport. The operation area of the boat is within the Osaka Bay. The mooring point of the boat is the Osaka Harbour.

Details of the boat is shown in Table 1.

The layout of the electric power system of Kinki is shown in Fig. 1. A diesel engine generator system(AC 220V, 16kW) provides the electric power. Electric

Table 1 Details of the commuter boat

Ship	
Length (including added structure)	17.30 m
Registered length	16.60 m
Beam	4.00 m
Draft at full load	0.70 m
Gross tonnage	19.0 t
Displacement at full load	21.438 t
Main engine	
Diesel engine	2 sets
Power output	654 kW
Speed	1800 rpm
Generator diesel engine	
Diesel engine	1
Power output	20.2 kW
Speed	1800 rpm
Generator	
3 phase AC generator	1
Capacity	16 kW
Voltage	220 V
Speed	1800 rpm

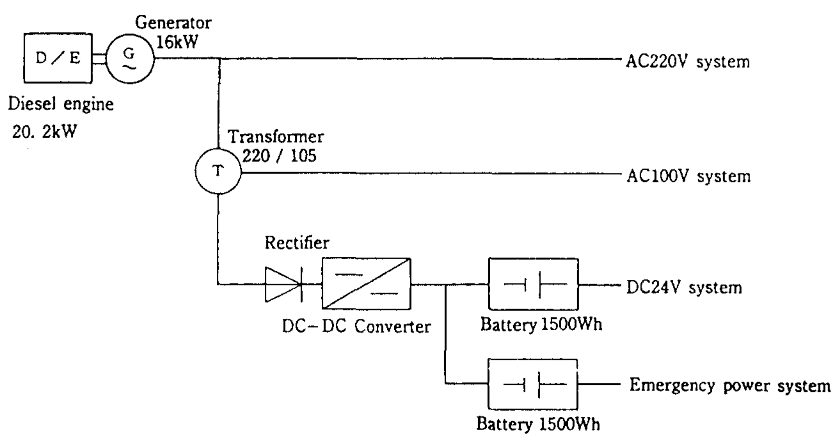

Fig. 1 Present electric power system

power system has the steering gear(2.6kW), bilge pump(1.8kW), engine room fan (1.8kW), air conditioning system 1(6.1kW) and air conditioning system 2(2.9kW) in the AC 220V system. There are also the lighting system on the bridge(60W), interphone(90W), engine room lighting(120W), oily water separator(50W), fresh water pump(300W), monitor camera equipment(100W), etc. on the AC 100V system. The third DC 24V system drives the capstan(750W), turning windows(140W), toilet pump(180W), navigation lights(140W) and searching lights(150W), through the secondary battery.

2.2 Electric Energy Consumption of Commuter Boat

Electric power was measured and recorded during a navigation in July, when maximum electric power is expected. The maximum electric power was found to be 4.35kW.

The monthly average of electric energy consumption was then estimated. According to deck log, navigation time is on average 6 hours, every other day. The main consumer of electric power is the air conditioning system. It was then assumed that heating is used from December to February and cooler is used from June to August, with the system idle during the rest of the year. With measured data of electric energy consumption, the average daily consumption was found to be 9.08kWh during March - May and September - November, and 26.09kWh during the rest of the year.

The present estimate is based on measured data of the maximum electric energy consumption. Time series data of power system will be taken in due course so as to build a detailed model of electric energy consumption in the future.

3. Photovoltaic Generating System Supplemented Electric Power System

3.1 Photovoltaic Energy

In order to maximaize the area available for putting up a photovoltaic array, a flat top structure is proposed to be added to the aft deck of the boat as shown in Fig. 2. Together with the area in front of the deck house the total area of a photovoltaic array that could be installed is 33.5m^2.

Next, the electric energy from the photovoltaic array has to be calculated. For that purpose the flux of solar radiation has to be estimated. Accordingly, the monthly data of the daily average of the duration of flux of global solar radiation in Osaka from 1974 - 1990 is used[5].

As for the solar modules, 3 types of commercial solar modules are available: single-crystal silicon type, poly-crystalline silicon type and amorphous silicon type, which have conversion efficiency of 12.5%, 11.9% and 4.1% respectively. Each type was evaluated.

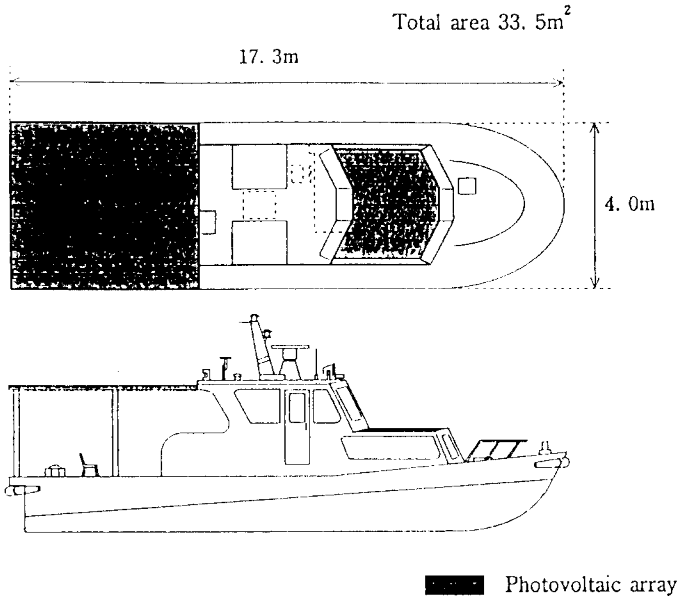

Fig. 2 Commuter boat and area available for photovoltaic array

The electric energy from photovoltaic array is given by the following equation[6)]

$P_{dc} = K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot Q_m \cdot W_N$ [kWh/day] (1)

where

P_{dc} is photovoltaic energy [kWh/day]

Q_m is average flux of incline solar radiation [kWh/m^2/day]

Since the photovoltaic array is not tilted, the flux of horizontal solar radiation is used.

W_N is the photovoltaic array power at standard [kW_p]

K_1 is a coefficient for compensating temperature effect.

Let T be temperature of solar module [℃], and 25℃ be the reference temperature. Then K_1 is given by the following equation.

$K_1 = 1 - \mathbf{a} \cdot (T - 25)$ (2)

Since temperature of the solar module has not been measured, various methods were reviewed for the estimation of this temperature. The following equation is adopted[7)] for the calculation of the temperature of solar modules. In this equation air temperature, similar to data of the duration of flux of global solar radiation, is adopted from Rika Nenpyo (Chronogical Scientific Tables, National Astronomical Observatory, Maruzen).

$T = T_a + 0.3 \cdot E$ [℃] (3)

where

T_a is air temperature [℃]

E is intensity of solar radiation on photovoltaic array [mW/cm²]

Also, the values of **a** in equation (2) is 0.03 and 0.05 respectively for amorphous silicon and crystal silicon type.

K_2 is the coefficient to account for the stain and wear which worsens with the passage of time on the solar modules. In this investigation, its value is 0.9 for sea environment.

K_3 is the coefficient to account for dc losses, including those of the protective diode against reverse current. Usual value is 0.95

K_4 is the coefficient of the photovoltaic array when it is not generating at the maximum output point, including the losses when a number of solar modules are connected. Its usual value is 0.95

Photovoltaic energy as derived from equation (1) is shown in Fig. 3. Electric energy consumption is also shown in Fig. 3. Their ratio is plotted in Fig. 4. It is shown that on average 60.7%, 55.7% and 19.7% of the electric energy consumption could be provided by the photovoltaic array if single-crystal silicon type, poly-crystalline silicon type and amorphous silicon type are used respectively. Since the boat operates every other day, energy generated on 2 days' time is used for the operation of 1 day. In that case sufficient energy is generated for the major part of the load, except in the middle of winter and summer, for photovoltaic arrays other than the amorphous silicon type.

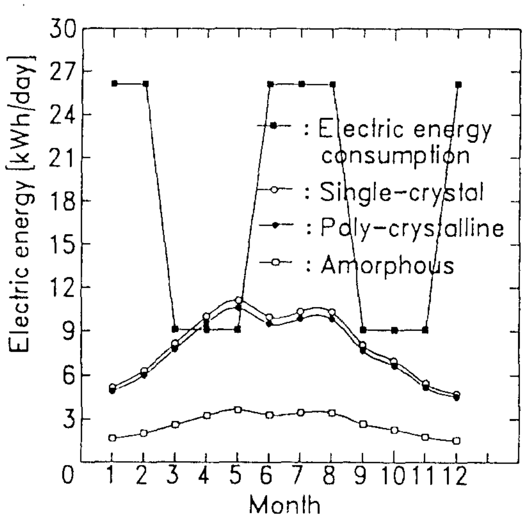

Fig. 3 Photovoltaic energy

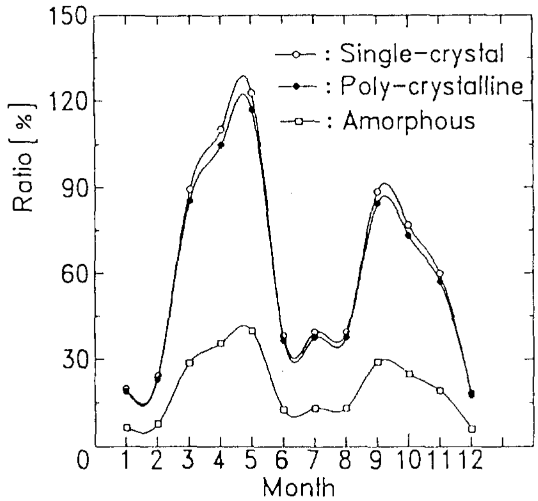

Fig. 4 Ratio for photovoltaic energy to electric energy consumption

3.2 Photovoltaic Generating System Supplemented Electric Power System

The design of the overall electric power system should reflect the aim of maximizing the usage of photovoltaic energy. Major components of the photovoltaic generating system is the secondary batteries and inverters. On the other hand since photovoltaic energy may not be able to fulfill all electric energy needs of the boat, a scaled down diesel engine generator is still needed. Emergency backup battery of capacity the same as the present system is retained. Lead storage battery are chosen for the secondary batteries. Its capacity should be large enough to sustain 6 hours of navigation even when no photovoltaic energy is available at all.

Capacity of the battery is calculated from following equation.

$$C = D \cdot F \cdot P/(L \cdot U \cdot K) \quad [kWh] \qquad (4)$$

where

C is the capacity of the battery [kWh]

D is the maximum number of days per month of no-sunshine [days]

F is the coefficient the battery discharges. Usual value is 1.05

L is the battery condition correcting factor. Usual value is 0.8

U is the capacity of the battery available for use. Value depends on the level of discharge. Usual value of 0.5 is adopted.

K is efficiency of the circuit, taking into consideration inverters losses, etc. Usual value is 0.7

P is the average load per day [kWh/day]

The capacity of the inverter is given by the following equation[8].

$$P_{IN} = P_{MAX} \cdot F_{RC}/(F_M \cdot R_{IN}) + (P_{LAX} - P_{MAX}) \cdot F_{PL}/F_N \quad [kVA] \qquad (5)$$

where

P_{IN} is inverter capacity [kVA]
P_{MAX} is the maximum load of ac motors [kW]
F_{RC} is the ratio of inrush current = 7
F_M is the power factor of motors = 0.8
R_{IN} is the design margin of inverter = 2
P_{LAX} is the maximum ac load [kW]
F_{PL} is the maximum load fluctuation = 1.8
F_N is the usual power factor = 0.9

The capacity of the diesel engine is given by the following equation[9].

$$P_n = 1.36 \cdot P_g / (\eta_g \cdot \eta_t) \quad [kW] \tag{6}$$

where

P_n is the diesel engine capacity [kW]
P_g is the normal capacity of the generator [kW]
η_g is the generator efficiency, which is usually 0.91
η_t is the transmission efficiency between the engine and the generator, which is usually 1.0

Layout of the overall system is shown in Fig. 5. It is shown that when a secondary battery of capacity of 9.84kW and 2 inverters of capacity of 22.3kW and 1.9kW respectively are installed, the capacity of the diesel generator could be reduced by 3.3kW from 16kW. As a result the capacity of the diesel engine is reduced by 4.4kW, or around 20% of its original capacity of 20.2kW.

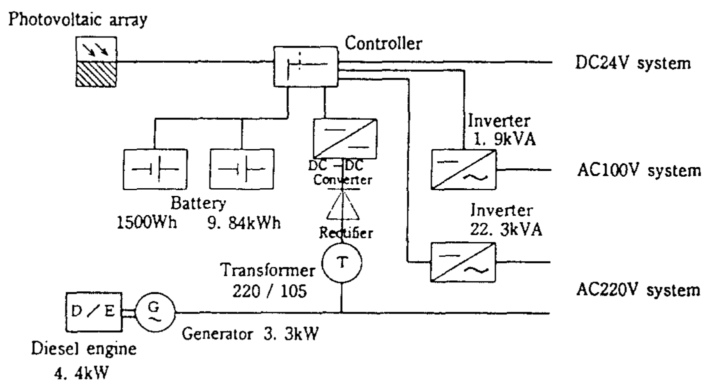

Fig. 5 Photovoltaic generating system supplemented electric power system

4. Reduction in NOx and SOx Emission

With the introduction of the photovoltaic generating system supplemented electric power system, the capacity of the diesel engine could be reduced by 20%. As a result NOx and SOx emissions are expected to be reduced.

Here NOx and SOx emissions from the present system are compared to that of the photovoltaic generating system supplemented electric power system.

NOx and SOx emission is estimated by a method proposed by one of the authors[10].

Fuel oil is assumed to be light oil.

NOx emission is calculated in the form of equivalent NO_2 emission by equation (7).

$$E_{nt} = \{2.11-1.92\cdot(1-Z)\}\cdot P^{1.14}\cdot 10^{-3}\cdot 46/22.4 \quad [kg/h] \qquad (7)$$

where

E_{nt} is NOx emission [kg/h]

Z is the load factor of the diesel engine

P is the capacity of the diesel engine [kW]

SOx emission is calculated from the sulphur content of the fuel oil.

$$E_{st} = 0.28\cdot Cs\cdot P^{0.95} \quad [kg/h] \qquad (8)$$

where

E_{st} is SOx emission [kg/h]

C is sulphur content

P is the capacity of the diesel engine [kW]

When NOx and SOx emission is estimated using equation (7) and (8) for both the present system and the photovoltaic generating system supplemented electric power system, results as shown in Table 2 and Table 3 are obtained.

It is concluded that when the photovoltaic generating system is included, NOx and SOx emissions are reduced by 25% and 17% respectively.

Table 2 Comparison of NOx emission

Load factor	1	0.8	0.6	0.4	0.2
NOx emission [kg/h] of present system	0.136	0.109	0.085	0.061	0.036
NOx emission [kg/h] of PV system supplemented system	0.023	0.019	0.015	0.011	0.006

Table 3 Comparison of SOx emission

Sulphur content	0.19	0.29	0.30	0.33	0.36
SOx emission [kg/h] of present system	0.926	1.413	1.462	1.608	1.754
SOx emission [kg/h] of PV system supplemented system	0.217	0.332	0.343	0.377	0.412

5. Conclusion

In this paper the design of marine electric power system which is supplemented by a photovoltaic generating system has been presented. The theories that are relevant are reviewed, and the environmental merits are justified. In summary,

(1) it is shown that electric energy consumption of a commuter boat can be 100% met by photovoltaic generating system. For vessel such as a harbour commuter, whose load is relatively small, it is shown that in principle, the use of photovoltaic generating system is practical.

(2) it is found that by the active use of photovoltaic generating system techniques available, the capacity of the diesel engine of the generating unit can be reduced by 20%. As a result NOx and SOx emissions are reduced by 25% and 17% respectively. The environmental impact is positive.

Up to now there have been hardly any studies on the use of photovoltaic generating systems onboard ships. In this study the basis of the methodology for the use of photovoltaic generating system in ships is worked out. Furthermore, ground work has been laid so that marine environmental problems could be tackled from a completely different starting point; that is, by reducing the reliance on fossil fuel by using photovoltaic energy. The design of the electric power system which make full use of a photovoltaic generating system is, in general, applicable to other ship types also.

In the near future, hopefully experiments could be carried out to verify the effectiveness of the system on the field.

Acknowledgement

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