Influence of Solar Energy on Ship Energy Efficiency: Feeder Container Vessel as Example

A. Aijjou, L. Bahatti, and A. Raihani
SSDIA Laboratory, ENSET Mohammedia, Hassan II University of Casablanca, Morocco
Email: thalassa1310@yahoo.fr; lbahatti@gmail.com, abraihani@yahoo.fr

***Abstract*—The shipping industry is facing three major challenges: climate change, increasing bunker fuel price and tightening international rules on pollution and CO2 emissions. All these challenges can be met by reducing fuel consumption. The energy efficiency of shipping is already very good in comparison with other means of transportation but can still be and must be improved. There exist many technical and operational solutions to that extent. But assessing their true and final impact on fuel consumption is far from easy as ships are complex systems.**

The use of clean and renewable energies, such as solar energy for instance, is proposed as a method to improve the ship efficiency. Ships can get the benefits from solar energy since most of their upper decks are always exposed to the Sun, especially in tropical regions.

The article presents an example of practical application of energy saving by fitting the solar panels on container vessel. The paper discusses the effectiveness and challenges of installing solar panels for auxiliary power production on board a ship.

***Index Terms*—environment, energy efficiency, container vessel emissions, solar energy**

I. Introduction

Maritime transport emits around 1 billion tons of carbon dioxide annually and is responsible for about 2.5 per cent of global greenhouse gas emissions from fuel combustion [1]-[3]. By 2050, depending on future economic growth and energy developments, shipping emissions may increase by between 50 and 250 per cent [4].

Although the obvious CO2 efficiency of shipping in terms of grams of CO2 emitted per ton-km, it is recognized within the shipping industry that reductions in these totals must be made. Recent legislation is aimed at reducing these emissions through the introduction of emission control areas and requirements on newly built marine diesel engines [5], [6]. The maritime industry is very dependent on fuel price. Note also that the overwhelming majority ships use fossil fuel energy to navigate. This energy source is exhaustible, and its cost has become the first responsible in expenditures. This situation will not change favorably because the fuel prices have historically almost always increased [7].

So, the shipping sector must find ways to stabilize or reduce its emissions and provide the energy efficiency especially that the energy losses are important [8].

This is how in 2010, IMO introduced “Technical measures”, “Operational measures” and “Economic instruments” as instruments for reducing CO2 emissions, the use of renewable energy (wind, solar, etc.) was one of promising solution among others [8].

The main purpose of adopting renewable energy-based systems on board merchant marine vessels is to reduce consumption of fuel and several alternatives for obtaining this desiderate are sails, kites, receiving electricity in ports, use of biodiesel instead of classical diesel oil, wind turbines, photovoltaic panels and hydrogen fuel cells [9].

By considering the development of the technologies, we can imagine that future ships will produce less emission of pollutants into atmosphere. However, considering the large amount of energy used by a ship, it is obvious that only by design of hybrid systems based on alternative sources of energy there can be reduced environmental impact of shipping industry.

Nevertheless, the study on renewable energy infrastructures for shipboard is still in first step as such application still facing big challenges.

Solar energy is one of the renewable energy sources which can play a vital role in meeting the increasing energy demand and save the depleting fossil fuel resources.

This paper aims to study the feasibility and environment aspect of using solar energy as supplement power source on container ship trading in west Africa in order to reduce fuel oil consumption and GHG emissions.

II. Solar Energy Generation

The generation of electricity with the ever-depleting conventional sources has led to the development of photovoltaic systems (SPV). Photovoltaic is a technical term for generating electricity from light. In the present-day scenario of electricity generation, it is fast becoming an important industrial product [10]-[12].

A SPV generates electrical energy and provides power for different types of devices after storing the energy in a battery bank. The SPV panel is the fundamental component irrespective of any system configuration. Solar cells are the building blocks of the panel. A complete system includes different components which are

Manuscript received October, 2018; revised May 13, 2019.

doi: 10.18178/ijoee.7.1.21-25

selected taking into consideration individual needs, site location, climate and expectations.

The functional and operational requirements determine the components to be included in the PV system.

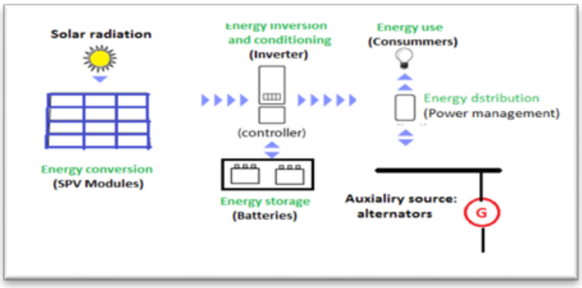

Figure 1. SPV system equipment.

The major components incorporated in PV system as shown in Figure 1 are: DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and sometimes the specified electrical loads.

- PV Module: It converts sunlight instantly into DC electric power.
- Inverter: It converts DC power into standard AC power for use.
- Battery: Battery stores energy when there is an excess coming in and distribute it back out when there is a demand. Solar PV panels continue to re-charge batteries each day to maintain battery charge.
- Auxiliary energy source: utility power is automatically provided at night and during the day
- when the demand exceeds the solar electric power production.
- Charge Controller – It prevents battery overcharging and prolongs the battery life of the PV system. In addition, an assortment of balance of system hardware; wiring, over-current surge protection and disconnect devices, and other power processing equipment.

Application of solar PV systems for ships depends on many factors mainly: (i) Solar radiation availability in ship's operation areas, (ii) Existence of sufficient and adequate deck area to accommodate the solar panels, and (iii) Techno-economic efficiency of solar panels system: energy efficiency, fuel oil rates and investment costs.

III. Ship Electric Power Layout

The typical electric power distribution for container vessel is illustrated on Figure 2, two set or more diesels generators are generally fitted on board, one has sufficient capacity for normal running of the vessel, others are in standby mode to take over in case of failure of running generator or to be used when additional intermittent power is required like during maneuvering, crane operation etc. [13]. In some configuration, one generator is driven by propulsion engine called "shaft generator".

The voltage is usually 440V, in some large installation it's higher as 6.6KV, Bus Bars for carriage and transfer of load and Transformers for lower voltage necessary for lighting, navigation equipment, domestic devices etc.

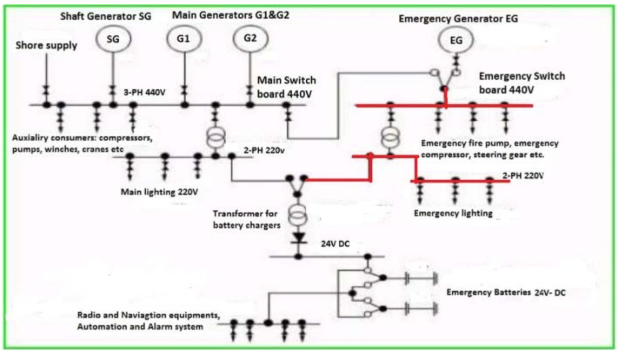

Figure 2. Ship electric power diagram.

IV. Case Stydy

As sample, we choose the container ship trading between north and west African ports in regular lines. Its' particulars are shown in Table 1.

TABLE I. Main Particulars of the Vessel

Type	Container vessel
Length /Beam	123 / 121 m
Gross Tonnage	6479
Propulsion Engine	5400 KW
Diesel generators	2 sets: 640 KW each
Shaft generator	990 KW
Emergency generator	340 KW

The ship is equipped with two diesel generator sets, one generator driven by main engine (shaft generator) and one diesel generator for emergency use. Table 2 collates extract from electric energy balance of this vessel at sea, in the port and in case of emergency.

From the table 2 we can deduct that 24 KW is the total power needed in worst case for supplying the essential consumers necessary for the safety of the vessel (emergency lighting, Navigation and radio equipment and alarms systems).

1) Solar radiation in Ship's route:

The amount of solar radiation is one of the keys for assessing the feasibility of using solar energy in one region. Our vessel is engaged in container transports trading in regular line between ports in North and West Africa. These two regions have a good PV potential [15].

From the map in figure 3 we can assume that minimum annual average of solar radiation is 2000 KW/m^2.

The global formula (1) to estimate the electricity generated in output of a photovoltaic system is:

$$E = A_{pv} \times \eta \times H_a \times P_r \quad (1)$$

where E is the Energy (kWh), A_{pv} denotes the total solar panel area (m^2) having an efficiency η (%). H_a is the annual average solar radiation on tilted panels (shadings not included) and P_r represents the performance ratio, coefficient for losses, it includes all losses (range between 0.5 and 0.9, default value = 0.75).

TABLE II. VESSEL ENERGY BALANCE

			Normal seagoing			Harbour			Emergency		
	Mode	Rated power	DF	CL	IL	DF	CL	IL	DF	CL	IL
Inner lighting	C	22.7	80	18.16	0	80	18.16	0			[redacted]
Outdoor lighting	C	18.8					15.0				[redacted]
Emergency lighting	C	10.3	80	8.24		99	10.3		99	10.2	[redacted]
Radio & navigation equipment	C	11	80		8.8	80			80	8.8	[redacted]
Battery charger	C	1.8	40		0.7	80		0.7	80	1.4	[redacted]
Navigation & signal light	C	2.8	80	2.2		80	2.2		80	2.2	[redacted]
Total loads				11.62	11.1		12.5	0.7		23.6	[redacted]
Diversity factor of intermittent loads			0.3			0.3			1.0		
Total necessary electric power (kW) for safety and emergency use			14.95			12.71			23.6		
ABBREVIATION: For Working Mode (WM): "C" Means Continous, "I" Means Intermittent, "L" Means Less Use; For each condition, "D.F." Means Demand Factor, "C.L." Means Continous Load, "I.L." Means Intermittent load											

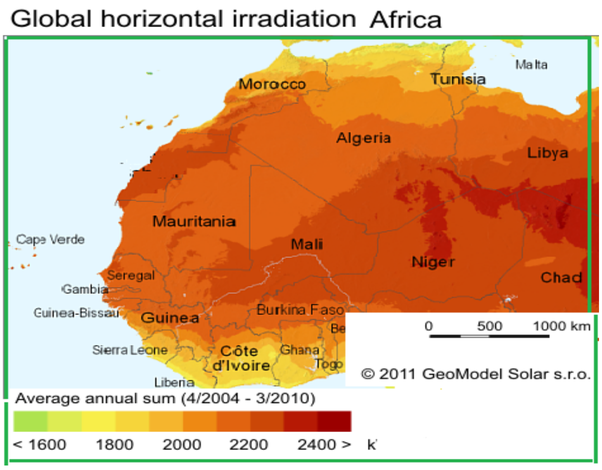

Figure 3. Solar radiation map (NW Africa).

2) Ship free deck area:

Figure 4 shows partly the deck area, the aft part covering superstructure and poop deck and fore area covering forecastle deck.

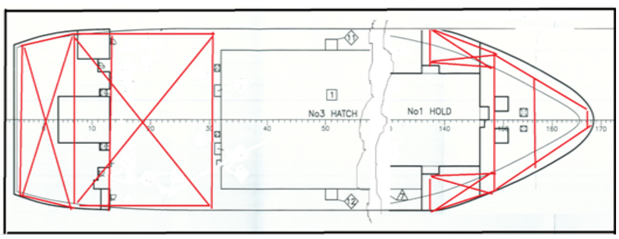

Figure 4. Ship deck plan.

By installing fixed panels above superstructure, poop and forecastle deck and floodable panels between superstructure and No.3 hatch we can secure approximately 600-700 m^2.

3) Solar PV sizing:

The size of PV modules depends on load demand, available solar radiation, battery efficiency, inverter efficiency, module performance etc.

a) Determination of load demand:

From ship energy balance (TABLE II) we already estimate the electrical power requested (P_t) for safety and emergency at 24 KW.

So, the total load energy ($E_t(KWh)$ per day is:

$$E_t = 576 \text{ KWh} \quad (2)$$

The PV array should cover the average daily energy consumption with the nominal operating voltage.

Load demand (Io) in Ampere – hour is defined by formula (3)

$$I_o = \frac{E_t}{\eta_i . V_n . \mu_b} \quad (3)$$

With:

η_i : Inverter efficiency (0.9)

μ_b: Battery efficiency (0.8)

V_n : Nominal voltage (227V).

An example of solar PV panel specifications for industrial use is summarized in TABLE III.

b) Battery capacity:

The required battery capacity (Bc) can be calculated by formula (4):

$$B_c = \frac{I_o . T_d}{DoD_{max}} \quad (4)$$

T_d: Autonomous days.

DoD_{max} : Maximum depth of discharge of battery.

c) PV design current:

PV design load current (peak current) (Id) can be obtained from formula (5):

$$I_d = \frac{I_o}{h_s} \quad (5)$$

h_s is the lowest daily sunshine.

Rated design current (Id) depends on the PV module global performance, formula (6).

$$I_m = \frac{I_d}{\mu_m} \quad (6)$$

$\boldsymbol{\mu_m}$: PV module derate factor, coefficient for losses, it includes all losses.

a) Number of PV module in parallel (Np):

$$N_p = \frac{I_m}{I_p} \quad (7)$$

I_p: Max peak current for selected solar PV panel.

b) Number of PV module in series (Ns):

$$N_s = \frac{V_n}{V_p} \quad (8)$$

V_p: Max voltage of selected solar PV panel.

TABLE III. SPECIFICATIONS OF SELECTED PV MODULE

Type	PERC 350 Wp SPV
Nominal maximum power in watts (W)	350
Open Circuit Voltage (Voc) in Volts	46.4
Short Circuit Current (Isc) in Amps	9.80
Voltage at Maximum Power (Vp) in Volts	37.5
Current at Maximum Power (Ip) in Amps	9.35
Maximum System Voltage in Volts	1000
Module Efficiency (%)	18.5
Length x Width x Thickness (mm)	1960 x 990 x 40

In TABLE IV we summarize the calculation of different parameters as per the formulas (3) to (8).

TABLE IV. CALCUL OF SPV DATA

Parameter	Formula		24KW	12KW	Unit
Total energy demand (E_{Wh})	-		576	288	KWh
Load demand (I_o)	(3)	η_i = 0.9; μ_b = 0.8; V_n = 227V	3.524	1.762	KAh
Battery capacity	(4)	T_d = 1; DoD_{max} =0.8	4.405	2.203	KAh
PV panel rated design current (I_d)	(5) – (6)	h_s= 6; μ_m=0.75	1000	500	KA
Number of panel in parallels (N_p)	(7)	I_p= 9.35	105	53	-
Number of panel in series (N_s)	(8)	V_p=37.5	7	7	-
Total number of panels	$Np \times Ns$	-	740	371	

V. DISCUSSION

From TABLES III and IV we can deduct that for supplying 24 KW consumers power on board, we need to install 740 modules of SPV panels. Each one has $1.9 \times 0.9\ m^2$ surface. Minimum area necessary to accommodate 740 panels is approx. 1300 m^2.

The available deck area in our sample vessel is max. 700 m2 which will cover only the half of the power approx.

12 Kw (TABLE II) which cover emergency lighting, navigation and radio equipment and alarm system.

The limited space for installing PV panels is due to the fact that container vessels are loading containers on the deck.

12 KW represents 0.2 - 0.3% of total power required for supplying all ship electric equipment.

1) Environmental analysis.

The electric on board is produced by diesel generators burning fuel oil. The specific fuel oil consumption for the four-stroke engine is approx. SFOC 210 g/Kwh

Generally, the marine fuel oil used for diesel generators is the IFO 180 and MGO. The emission factor for IFO is approx. 3.15KgCO2/KgFO [16] [17].

Producing 12KW by diesel generator requires 2.4Kg of fuel oil per hour. By using solar energy, this is equivalent to saving 58 kg/day and 575 Kg of CO2.

The fuel oil saved amount is not significant compared to the total fuel oil consumption by ship for propulsion and electric power production (18 ton/day for the case study).

Considering 300 days of solar radiation per year, economy in fuel oil may reach 17 tons of fuel oil and 172 tons of CO2.

Beside environmental benefits and based on average market fuel oil prices [18]: one ton of fuel cost 600-700 USD

$$\begin{aligned} \textit{Fuel cost save per year} &= 17 \times 600 \\ &= 10.200{,}00\ USD. \end{aligned}$$

2) Economic benefits.

Having considered that PV modules are guaranteed for 25 years, batteries for 5 years, inverters and other equipment for minimum 10 years, many economic research studies [19] demonstrated that total investment on PV solar investment will be paid back within period of maximum 10 years.

3) Safety aspects.

For the case study, solar energy is totally independent of the ship's machinery systems and in this regard, is can be a reliable alternative to the ship emergency source of power for supplying emergency lighting, navigation, radio equipment and alarms system.

VI. CONCUSION

The present paper demonstrates that solar energy by PV may be used as supplement to auxiliary power on board small container ships at least for supplying equipment necessary for safety of the ship in case of machinery failure. Hence this will contribute to reduce fuel oil consumption and GHG emissions. Economically research has found that, energy payback estimates for marine PV systems are less than 10. However, the capacity of the marine PV system is still very small compared with the total requirement of a ship, and its achievement in reducing fuel consumption and pollutant emission is accordingly not significant.

The big challenges to meet are:

- The ship deck area exposed to the sun is limited by the size of the ship and cargo needs.
- The solar PV capacity and efficiency are still small to fulfill the needs of ship.

References

[1] S. Joussaume, J. Penner, and F. Tangang, "Intergovernmental Panel on Climate Change, Working Group I contribution to the IPCC 5th Assessment Report Climate Change 2013: *The Physical Science Basis*". Final Draft Underlying Scientific-Technical Assessment, Cambridge University Press.

[2] United Nation Conference on Trade and Development, Review of Maritime Transport, 2017.

[3] O. Buhaug, J. J. Corbett, O. Endresen, V. Eyring, J. Faber, S. Hanayama, D. S. Lee, D. Lee, H. Lindstad, and A. Z. Markowska, "Second IMO GHG study 2009," *International Maritime Organization*, London (UK), 2009

[4] IMO, 2014. MEPC59 - Second IMO Green House Emission Study. International Maritime Organisation

[5] IMO Convention, "Annex VI of MARPOL 73/78: Regulations for the Prevention of Air Pollution from Ships".

[6] I. Djadjev, "How to comply with MARPOL 73/78: A commentary on the IMO's pollution-prevention instrument and the implications for the shipping industry". *SSRN eLibrary*, 2015.

[7] BP p.l.c., "BP Statistical Review of World Energy 2013," London (UK), Jun. 2013.

[8] A. Aijjou, L. Bahatti, and A. Raihani, "Influence of keel coolers use on ship energy efficiency: A case study and evaluation," in *Proc. 4th International Conference on Optimization and Applications,2018*.

[9] IMO Resolution MEPC.203(62) Adopted on 15 July 2011.

[10] J. L. F. Soto, R. G. Seijo, J. A. F. Formoso, G. G. Iglesias, and L. C. Couce, "Alternative sources of energy in shipping", *The Journal of Nnavigation*, vol. 63, no. 3, pp. 435-448, 2010.

[11] P. Bhatt and A. Verma, "Design and cost analysis of PV system using Nano solar cell," *International Journal of Scientific and Research Publications*, vol. 4, no. 3, March 2014.

[12] E. A. Setiawana and F. Yuliania, "Analysis of solar photovoltaic utilization in industrial sector for improving competitiveness in the smart grid," *International Journal of Smart Grid and Clean Energy*, vol. 7, no. 4, pp. 276-285, October 2018.

[13] arek M. E. Abou Saltouh, A. E. A. Nafeh, F. H. Fahmy, H. K. Yousef, "Microcontroller-based sun tracking system for PV module", *International Journal of Smart Grid and Clean Energy*, vol. 7, no. 4, October 2018: pp. 286-296. Doi: 10.12720/sgce.7.4.286-296

[14] R. Kantharia, "A guide to ship's electro-technology: Part1 October' 2013. Marine Insight.

[15] Hermann S, Miketa A, Fichaux N. "Estimating the renewable energy potential in Africa: A GIS-based approach," *The International Renewable Energy Agency*, 2014.

[16] H. O. Kristenen, "Energy demand and exhaust gas emissions of marine engines," *Technical university of Denmark.* Report No.3, September 2015.

[17] CO2 Emission Factors for Fossil Fuels by Kristina Juhrich Emissions Situation (Section I 2.6), German Environment Agency (UBA), June 2016.

[18] Marcon International, Inc. (16 November 2017). *Bunker Price History – October 2017*. [Online]. Available: http://marcon.com/library/articles/Bunker%20History/2017/Bunker%20Prices%2011-17.pdf

[19] A. Glykas, G. Papaioannou, and S. Perissakis, "Application and cost-benefit analysis of solar hybrid power installation on merchant marine vessels," *Ocean Engineering*, vol. 37, no. 7, pp. 592-602, May 2010.

[20] S. Khana, S. H. Imranb, M. Khanb, and N. Khana, "Practical implementation of the on-board solar photovoltaic for the passenger transportation," *International Journal of Smart Grid and Clean Energy*, vol. 5, no. 3, July 2016

Abdallah Aijjou was born in Morocco on 1968-10-13, he is a Senior Surveyor for the Maritime Classification Society DNVGL since 2007. He's graduated in 1992 from maritime studies institute of Casablanca (ISEM) with M.S. degree in Maritime engineering 1992. On 1998 he received from the same institute the diploma of Marine Chief Engineer. After 10 years of experience on sea going vessels, he joined the Moroccan Maritime Administration from 2002 to 2007 as Maritime Administrator. He is PhD candidate at the University Hassan II of Casablanca. His researches are focused on ship energy efficiency.

Lhoussain Bahatti was born in 1969 at MIDELT, Morocco. He is now a Teacher of electrical engineering and researcher at Hassan II University of Casablanca, ENSET Institute, Mohammedia Morocco He received the Aggregation Electrical Engineering degree in 1995 from the ENS CACHAN France. He has his Ph.D. degree in 2013 in musical signal processing from the Faculty of Science and Technology of Mohammedia (FSTM). He has published more than 20 research publications in various National, International conference proceedings and Journals on music information retrieval, signal processing, and machine learning. His research is also focused on the identification and control of renewable energy production systems. He is a supervisor and Co-supervisor of several PhD students in the field of identification, biomedical signal processing, robust control and pattern recognition

Abdelhadi Raihani has born at El Jadida, Morocco in 1968. He is now a Teacher of Electronics Engineering and researcher at Hassan II University of Casablanca, ENSET Institute, Mohammedia Morocco. He received the B.S. degree in Electronics in 1987 and the M.S. degree in Applied Electronics in 1991 from the ENSET Institute. He has his DEA diploma in information processing from the Ben M'sik University of Casablanca in 1994. He received the Ph.D. in Parallel Architectures Application and image processing from the Ain Chok University of Casablanca in 1998.

His research is focused on medical image processing and electrical systems related to wind and solar energy. He has published more than 30 publications in various National, International conference proceedings and Journals.