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AN EXAMINATION OF THE PHOTOVOLTAIC, ENERGY STORAGE, AND DIESEL HYBRID POWER SYSTEM FOR THE SHIP APPLICATIONS

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ABSTRACT

Today, most of the ships use different types of marine fuel in their auxiliary engines to meet electrical energy demand. This situation causes of an important environmental pollution of the ships. The International Maritime Organization has begun to set strict standards and regulations to provide sustainability and energy efficiency from the ships. Therefore, the maritime sector is focused on the use of renewable and alternative energy sources on the ships. Especially, the use of photovoltaic energy and energy storage systems on the ships is becoming increasingly popular among the sector representatives.

In this study, the usability of the photovoltaic, energy storage, and diesel hybrid power system on the ships is examined. Differences of the hybrid power system between on the land and ship applications are discussed. The advantages and disadvantages of the hybrid ship power system are also mentioned.

The aim of this paper is to present the global perspective about the use of alternative energy sources on the shipboard for the maritime sector representatives.

Keywords: *Ship, Electricity, Photovoltaic, Energy Storage, Hybrid System*

INTRODUCTION

The maritime sector plays a critical role in the transportation sectors. Today, the ships carry more than 80% of the goods in the world, and they have a significant impact in terms of air quality. The ships responsible for about 3% of Carbon Dioxide (CO_2), 4% of Sulphur Oxide (SO_x), and 11% of Nitrogen Oxide (NO_x) of the global anthropogenic emissions [1, 2]. International Maritime Organization (IMO) develops the global standards to increase safety, security, efficiency, and environmental quality of worldwide shipping. Some of the standards and regulations for the environmental issues such as Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP), and International Convention for the Prevention of Pollution from Ships (MARPOL) have entered into force. EEDI and SEEMP are put into practice to the control of CO_2 emissions from ships. Especially, MARPOL: Annex VI set restrictions for SO_x, NO_x and Particulate Matter (PM) emissions. Hence, the maritime sector representatives try to find the alternative solutions to meet global regulations, sustainable shipping, environmental quality, and economic growth [3].

The use of Photovoltaic (PV) and Energy Storage System (ESS) on the ships has become a hot topic for the researchers. Hua et al. performed a survey about the preference for Renewable Energy System (RES) on the ships in the marine transportation of Taiwan. The survey results show that the most suggested RES are hydrogen combustion, PV, Fuel Cells, wind, and wave, respectively [4]. Sun et al. examined the design and application of PV system on the ships [5]. Glykas et al. examined the economic feasibility of installing PV systems on merchant ships [6]. Sulaiman O. studied the feasibility of using PV as a supporting power for Auxiliary Engines (AEs) [7].

Babu and Jain examined the application of PV system for small-scale distant-water fishing vessels in India, which is supported by several institutions, member fishers, and solar equipment vendors [8]. Cristea presented the experimental results of PV panel installed on the ship named "NS Mircea" [9]. Kirkpatrick examined the effectiveness of PV systems for the Navy ships [10]. Kobougias et al. examined the specifications of PV system for the ships [11]. Utama et al. studied the solar-powered catamaran fishing vessel [12]. Yufang et al. presented the fuel-free ship design based on the solar and wind energy [13]. Alfonsín et al. presented a conceptual model of hybrid hydrogen and renewable energy (eolic, solar and hydro) system to electric propulsion in sailboats [14]. Cristea et al. investigated the correlation between simulated and real PV system on the training ship named “Mircea” in naval conditions. They noticed that the horizontal installed PV panels are more efficient than the vertical type [15]. Hussein and Ahmed studied the potential of using PV system on the ships as an auxiliary power to reduce fossil-fuel consumption [16]. Moustafa and El-bokl presented a case study about the installation of PV system for cruiser ships on the River Nile in Egypt [17]. Peng et al. simulated the ship model integrated PV system by using the PSCAD software [18]. Lan et al. proposed the method for determining the optimal size of the PV/Diesel/Battery hybrid system for ship power systems to minimize the investment cost, fuel cost, and exhaust emissions [19]. Lan et al. studied on the optimization of tilt angle of PV panels on a large oil tanker ship. While the tilt angle increases, power generation of PV decreases according to the result of study [20]. Tang et al. introduced a power management system of “Tengfei” ship, which is integrated in the PV system [21]. Wen et al. studied the PV/ESS/Diesel hybrid ship power system considering the motions of the ship, based on a Chinese project named "Study on the Application of Photovoltaic Technology in the Oil Tanker Ship" [22]. Diab et al compared the hybrid renewable-energy systems between on the land and ship applications [23]. The mentioned studies present a global perspective and contribute to applicability of the PV/ESS/Diesel hybrid ship power system for the maritime sector. This study, the hybrid ship power system components is detailed and their effects for the ship applications are examined. This paper aims at contributing to a better understanding of PV and ESS application on the ships for the maritime sector.

SYSTEM DESCRIPTION

Ship Power System

A ship is like a mobile power plant, and its electric power system is commonly similar for all ships. The ship power system can be separated four parts: Main Engine (ME), AEs, main power distribution bus, and electrical loads. While the ME provides to ship’s move, AEs meet the electrical energy demand of ship. The output voltages and frequencies of AEs changes from 3 kV to 13.8 kV and 50 Hz to 60 Hz according to the ship type. The generated electricity is transferred by the power distribution bus with using the transformers and power converters according to the characteristic of appliances. The electrical loads are operated at different voltages and frequencies on the ships such as 24 V and 400 V for the Direct Current (DC) bus (for communication systems, etc.); 100-230 V and 50-60 Hz for single-phase AC bus (for lighting and low power supplies, etc.); and 400-440 V and 50-60 Hz for three-phase Alternative Current (AC) bus (for motor and pump groups, etc.) [24].

Photovoltaic System

PV systems convert solar energy into electrical energy. The main components are PV module, charge controller, ESS, converter, and electrical appliance. PV system components are shown in Figure 1. PV modules charge ESS with using the charge controller. ESS provides DC output for DC loads. The DC/AC converter is used to provide AC output for AC loads.

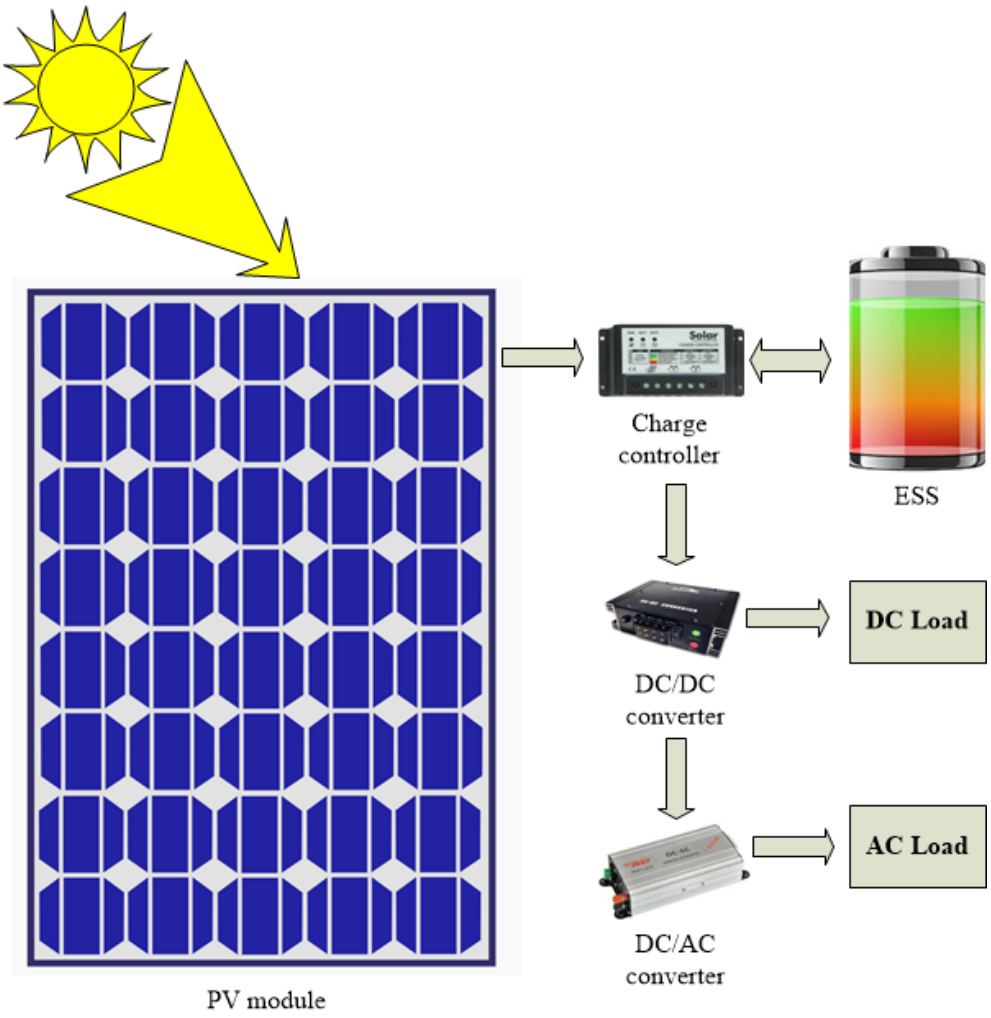


Figure 1. PV system components

The output power of PV system can be given as Equation 1 [25]:

$$P_{PV} = I_{Solar} \times A_{PV} \times cos\,\delta \times \mu_{PV}\ (W) \quad (1)$$

Also μ_{PV} depends on PV module, ESS, and inverter efficiencies. Total PV efficiency can also be given as Equation 2.

$$\mu_{PV} = \mu_{module} \times \mu_{ESS} \times \mu_{inverter}\ (\%) \quad (2)$$

PV modules use to convert sunlight into electrical energy. PV module types can be classified into three basic groups. First group is called as conventional or wafer based solar cell technologies. They include mono-crystalline and multi-crystalline materials, and they have high efficiency and cost. Efficiency of the mono-crystalline solar cell changes from 15% to 18%, whereas the multi-crystalline type changes between 13% and 15%. The second group is called as thin film technologies. They include amorphous Silicon (Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Diselenide (CIGS) materials, and they have low efficiency (Si: 5-7%, CdTe: 5–8.5%, and CIGS: 9–11%) and cost. Third group is called as future technology. They include a number of thin-film crystalline Si. They have high efficiency and low cost. They are also still in the development phase. Today, the commercial PV module's life time is at least 20 years, and their performance reaches up to 24.7% in the laboratory [26, 11].

Power converter is another important part of PV system. It plays a major role in transforming the different types and value of electricity, to make the suitable electrical energy for end users. The classification of converters can be described as follows:

- AC to DC converter: It is known as rectifiers, and converts AC input to DC output.
- DC to AC converter: It is known as inverters, and converts DC power input into AC power output.
- AC to AC converter: It is defined as a cycloconverters, and converts fixed voltage and frequency AC power input to variable voltage and frequency AC power output.
- DC to DC converter: It is defined as a chopper, and converts fixed voltage DC power input to a variable voltage DC power output.

There are four power converter types that are commonly used for PV system: power optimizer, module/micro inverter, string inverter, and central inverter. Power optimizer is known as DC to DC converter. It is integrated into each PV panel. It produces higher or lower DC output voltage from DC input voltage. Then DC output is sent to string inverter. In this way, maximum energy production is provided from RES. Its efficiency is about 99.5%. It is equipped with Maximum Power Point Tracking (MPPT) technology to optimize the power conversion from PV system to ESS, DC load or central inverter. Power optimizer is cheaper than module/micro inverter, and it is more expensive than the string inverter. Module or micro inverter converts DC input into AC output. It is installed on each PV panel. Then it can be connected to load or grid, directly. Its efficiency is about 96%. It is also equipped with MPPT. It is more expensive than power optimizer or string inverter. String inverter converts DC power into AC power. It is connected to each string of PV panels. It is used for PV system capacity up to 10 kW, and it is connected main grid, directly. It is also equipped with MPPT technology. It has been used for decades and is more suitable for non-shadow places. In addition, it is also combined with power optimizers to reduce shading effects. Central inverter is similar to string inverter, but it is used for large PV power system that higher than 10 kW. It is the most suitable solution for the ships, which have large power demand [27, 28]. Power converter structures in PV system are also described in Figure 2.

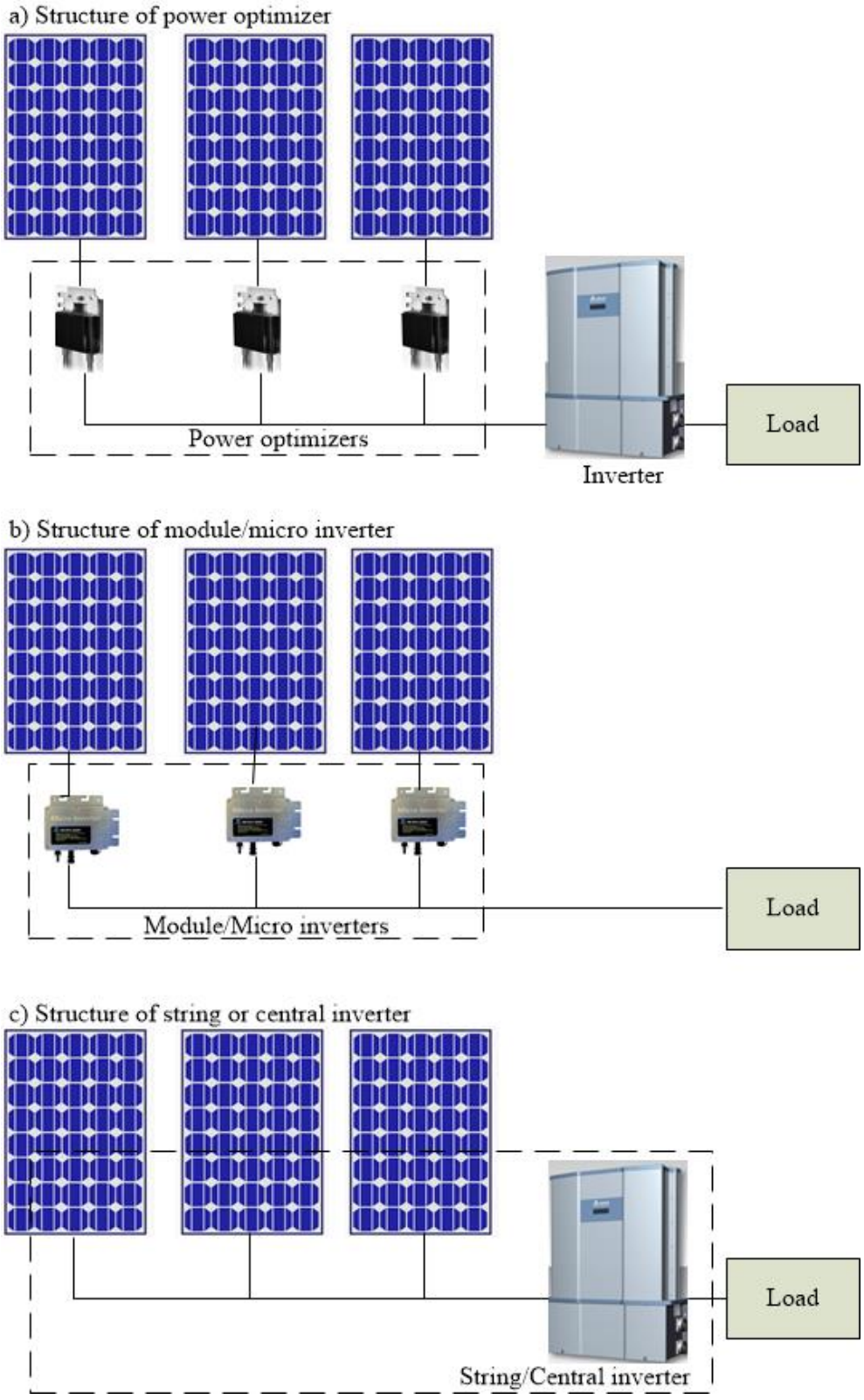


Figure 2. Power converter structures in PV system

Charge controllers are also known as charge regulator or battery regulator. It adjusts the voltage and current generated from PV modules, then transfer energy to ESS. Thus, ESS prevents from overcharge, deep discharge and damage. There are two general types of the charge controller in PV system. The first type of controller has Pulse-Width Modulation (PWM) technology. It can be useful for places with constant, steady and strong solar radiation. The second type of controller has MPPT technology. The MPPT algorithm optimizes the

production of PV. Thus, it provides higher performance than the PWM technology. It is preferable for larger system designs [29].

Energy Storage System

Generally, ESS refers to the process of transforming electrical energy to a storable form and preserving it in different mediums. ESS can provide positive impact to the local or national electricity grid such as reducing the electrical energy consumption during the peak time, preventing the intermittence of RES generation, improving the power quality, and helping the distributed power generation. ESS systems can be classified into electrical, chemical, electrochemical, mechanical, and thermal. Classification of ESS considering the energy form is summarized in Figure 3 [30].

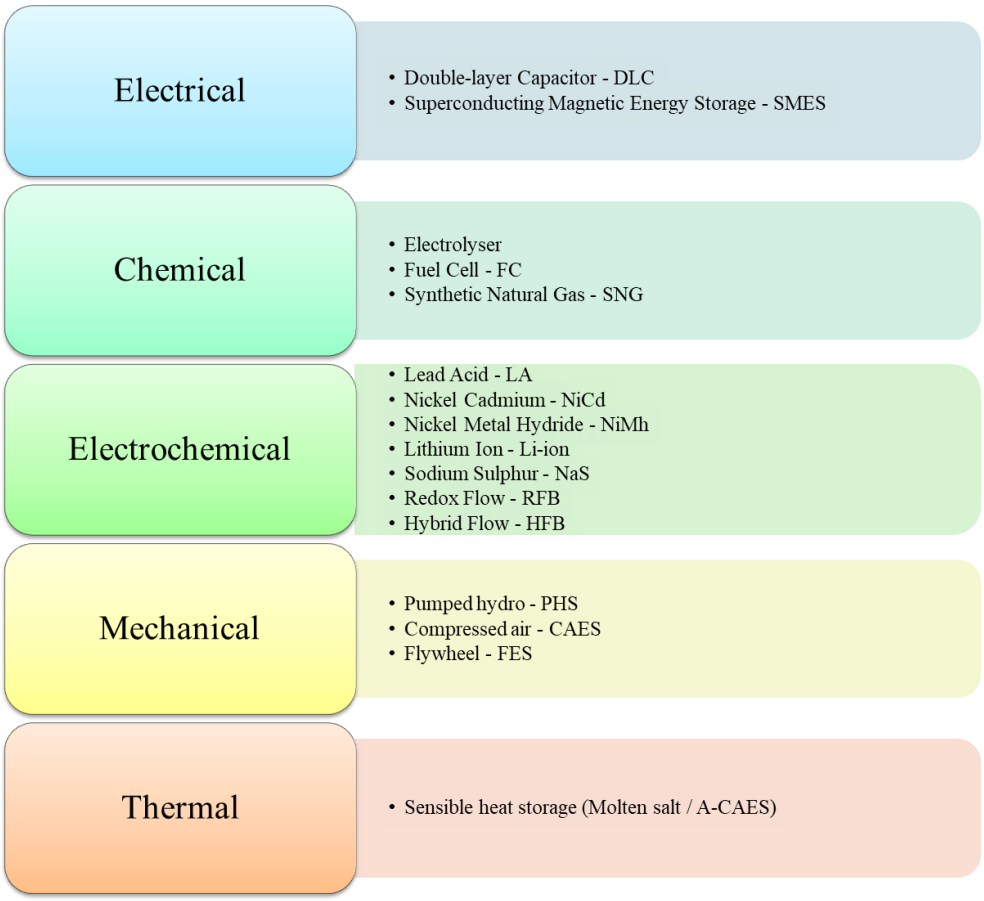


Figure 3. Classification of ESS

The electrochemical batteries are the most widely used ESS technologies in different applications such as energy management, power quality, RES, and transportation systems. Some characteristics of the electrochemical batteries are summarized in Table 1.

Table 1. Comparison of the electrochemical batteries

Technology	Energy density (Wh/L)	Power density (W/L)	Specific energy (Wh/kg)	Specific power (W/kg)	Lifetime (years)	Cost ($/kWh)
Lead-Acid (LA)	50~90	10~400	25~50	75~300	5~15	200~300
Nickel Cadmium (NiCd)	15~150	80~600	45~80	150~300	3~20	1500
Lithium-Ion (Li-ion)	50~90	1500~10000	75~200	150~2000	5~16	500~800

Size and weight of ESS are the significant factors for many applications. While the energy and power densities of ESS are higher, its size becomes smaller. When the specific power and energy of ESS are higher, its weight will be lighter. In addition, lifetime of ESS affects the overall investment cost. If its lifetime is lower, the cost of replacement and maintenance will increase. The suitable EES should be selected considering the size, weight, performance, and cost of the applications. ESS also regulates the excess or deficit generated electricity power considering the state of charge. If the total generated power bigger than the load, ESS is charged. Otherwise, ESS is discharged.

Photovoltaic, energy storage system, and diesel hybrid ship power system

The main objective in the PV/ESS/Diesel hybrid system is to provide cleaner and economical energy usage. However, the main power source of the ship in the hybrid system depends on PV and ESS capacities. It is determined by the available area of ship. If ship has high-power demand and small available area, AEs will be the main power source instead of PV system. Otherwise, PV can be considered as a primary power source for ship. The PV/ESS/Diesel hybrid ship power system can be given in Figure 4.

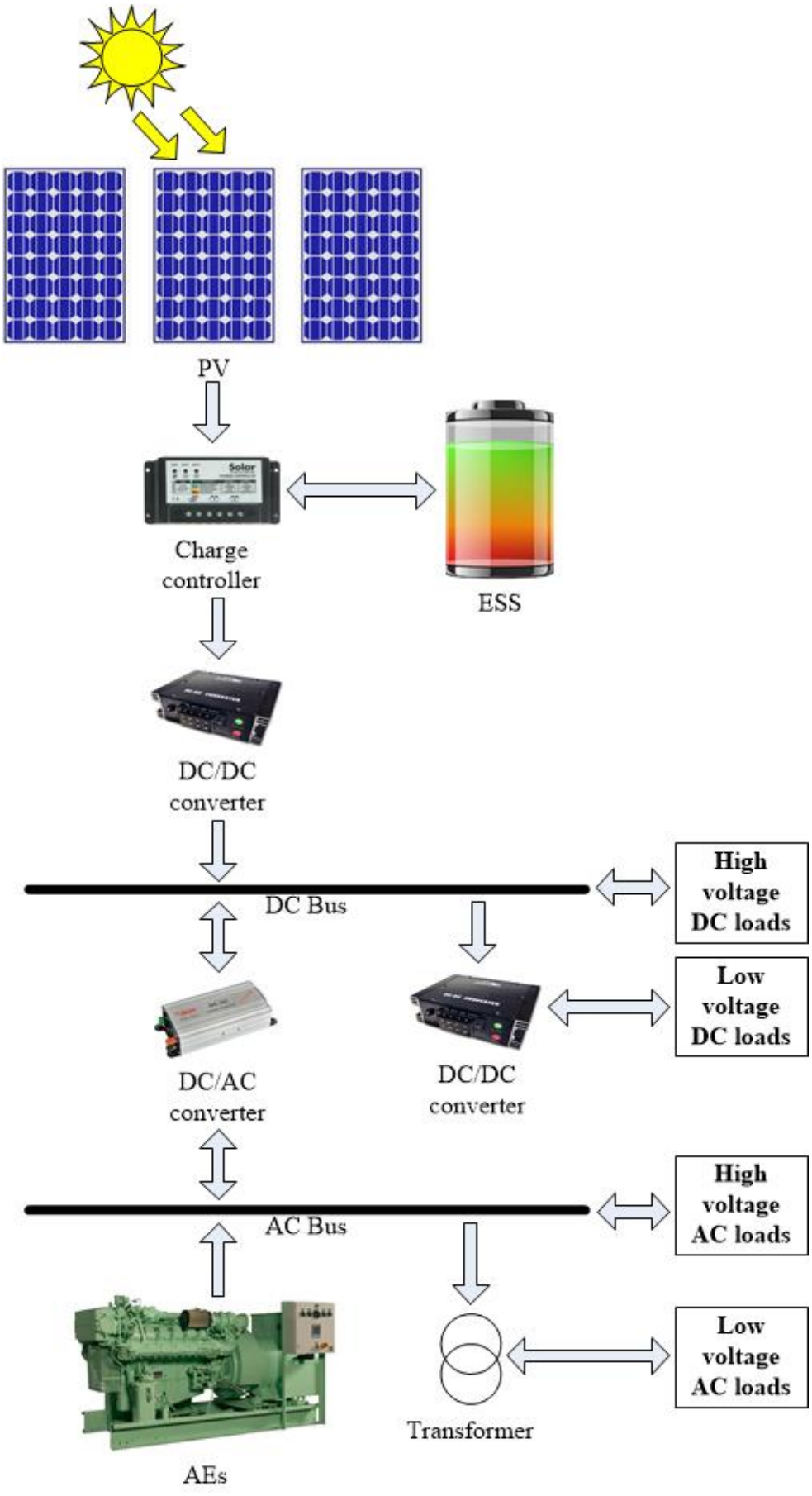


Figure 4. PV/ESS/Diesel hybrid ship power system

When PV capacity greater than the load demand, the requirements of load will meet without using AEs and excess energy will be charged by ESS. If PV capacity smaller than the ship's loads, ESS will be discharged to provide energy. When PV and ESS do not meet the electrical loads, AEs will become to run for the adjust power demand.

RESULTS AND DISCUSSION

The use of the hybrid power system on the ships can provide some benefits such as energy efficiency, lower marine fuel consumption, energy cost and exhaust gas emissions. On the other hand, there are some differences of the PV/ESS/Diesel hybrid power system between on the land and ship applications. These differences can be summarized as follows:

- PV module receives fixed solar radiation on the land applications. The solar radiation always changes when the ships are on a voyage. Because, it depends on the latitude and longitude factors.
- The angle of incidence between the solar radiation and PV module is fixed on the land application generally. These angles can be variable on the ships due to the fluctuations of sea.
- Solar tracking systems for PV panels can increase the generation of power on the land applications. However, it cannot be useful for the ship applications due to have been numerous moving parts on the tracking system, which are weak for the ocean storms.
- The optimum tilt angle of PV panels can be specified on the land application to obtain maximum power output. The horizontally installed PV panels provide more efficiency than the vertically for the ship applications according to the results of the some studies. When the tilt angle of PV panel is zero, the air resistance and solar radiation losses can be minimized for the ship applications.
- The hybrid power system on the ship applications should also be more tolerant of sea conditions such as extreme winds, atmospheric humidity, and salt water than the land application. Therefore, weatherproof devices should be used for the protection of components.

In addition, the hybrid power system has the advantages and disadvantages for the ship applications. The advantages of the PV/ESS/Diesel hybrid ship power system can be summarized as follows:

- It can be placed different available surface on the ship.
- It can be installed and replaced, easily due to have a few parts.
- It has the acceptable life time.
- The exhaust gas emission, marine fuel consumption, vibration, and noise from the ship can be decreased due to the reduce operation time of AEs.
- The level of safety and comfort of ship's crews can be improved.
- The overhaul and operating costs can be reduced.
- The risk of fire related to marine fuel can be minimized due to less usage.

The disadvantages of the PV/ESS/Diesel hybrid ship power system can also be given as follows:

- It has high initial investment cost. However, the payback period of the investment is fast. It has long life time, and the investment cost is reducing day by day because of develop and use of the hybrid technology.
- Some parts of the system can be needed extra protection due to the sea condition.

CONCLUSIONS

In this study, the hybrid PV/ESS/Diesel power system for the ship applications is examined, and their differences according to the land applications are discussed. The advantages and disadvantages of the hybrid ship power system are presented. The important issues to be considered in the ship applications are also highlighted.

As a result, the use of hybrid PV/ESS/Diesel power system on the ships can provide more benefits for the maritime sector. The marine fuel consumption, exhaust gas emissions, vibration, energy cost can be reduced with using the hybrid power system. It can also help to meet the international regulations and restrictions for the sea and port areas. Therefore, research and development of the sustainable and green shipping technologies should be more encouraged by the governments and sector representatives.

NOMENCLATURE

δ	Solar angle (degree)
μ_{PV}	PV conversion efficiency (%)

μ_{module}	PV module efficiency (%)
μ_{ESS}	ESS efficiency (%)
$\mu_{inverter}$	Inverter efficiency (%)
A_{PV}	PV module area (m^2)
I_{Solar}	Solar radiation (W/m^2)
P_{PV}	Output power of PV
CO_2	Carbon Dioxide
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Diselenide
SO_x	Sulphur Oxide
NiCd	Nickel Cadmium
NO_x	Nitrogen Oxide
AC	Alternative Current
AEs	Auxiliary Engines
DC	Direct Current
EEDI	Energy Efficiency Design Index
ESS	Energy Storage System
IMO	International Maritime Organization
LA	Lead-Acid
Li-ion	Lithium-Ion
MARPOL	International Convention for the Prevention of Pollution from Ships
ME	Main Engine
MPPT	Maximum Power Point Tracking
PM	Particulate Matter
PV	Photovoltaic
PWM	Pulse-Width Modulation
RES	Renewable Energy System
SEEMP	Ship Energy Efficiency Management Plan
Si	Silicon

REFERENCES

[1] Endresen, Ø., Sørgård, E., Sundet, J.K., Dalsøren, S.B., Isaksen, I.S., Berglen, T.F., and Gravir, G., "Emission from international sea transportation and environmental impact", Journal of Geophysical Research: Atmospheres, 108(D17), 2003.

[2] Lee, K.J., Shin, D., Yoo, D.W., Choi, H.K., and Kim, H.J, "Hybrid photovoltaic/diesel green ship operating in standalone and grid-connected mode–Experimental investigation", Energy, 49, 475-483, 2013.

[3] IMO, International Maritime Organization, http://www.imo.org/en/About/Pages/Default.aspx (Access: 20 November 2017).

[4] Hua, J., Wu, Y.H., and Jin, P.F., "Prospects for renewable energy for seaborne transportation—Taiwan example", Renewable energy, 33(5), 1056-1063, 2008.

[5] Sun, Y.W., Yan, X.P., Yuan, C.Q., and Lei, C.W., "Research progress in marine grid-connected photovoltaic technology", In The 47th Annual Conference of the Australian and New Zealand Solar Energy Society (ANZSES 2009), Zahedi A. Australia Townsville, 2009.

[6] Glykas, A., Papaioannou, G., and Perissakis, S., "Application and cost–benefit analysis of solar hybrid power installation on merchant marine vessels", Ocean Engineering, 37(7), 592-602, 2010.

[7] Sulaiman, O., "Feasibility of Using solar as a Supporting Hybrid Power System for Marine Diesel Engine: UMT Vessel Experimentation Experience", Global Journal for Information Technology and Computer Science, 1(1), 1-7, 2012.

[8] Babu, S., and Jain, J.V., "On-board solar power for small-scale distant-water fishing vessels", IEEE Global Humanitarian Technology Conference (GHTC), 1-4, 2013.

[9] Cristea, O., "Testing of PV module efficiency in naval conditions", IEEE 8th International Symposium on Advanced Topics in Electrical Engineering (ATEE), 1-4, 2013.

[10] Kirkpatrick, J.P., "An investigation of the effectiveness of solar power on Navy surface combatants", Naval Postgraduate School, Monterey, CA, 2013.

[11] Kobougias, I., Tatakis, E., and Prousalidis, J., "PV systems installed in marine vessels: technologies and specifications", Advances in Power Electronics, 2013.

[12] Utama, I.K.A.P., Santosa, P.I., Chao, R.M., and Nasiruddin, A., "New concept of solar-powered catamaran fishing vessel", Proceedings of the 7th International Conference on Asian and Pacific Coasts (APAC 2013), Bali, Indonesia, September 24-26, 2013.

[13] Yufang, Z., Peng, Q., and Hong, Y., “Fuel free ship, design for next generation”, In IEEE 8th International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER), 1-5, 2013.
[14] Alfonsín, V., Suarez, A., Cancela, A., Sanchez, A., and Maceiras, R., “Modelization of hybrid systems with hydrogen and renewable energy oriented to electric propulsion in sailboats”, International Journal of Hydrogen Energy, 39(22), 11763-11773, 2014.
[15] Cristea, O., Popescu, M.O., and Calinciuc, A.S., “A correlation between simulated and real PV system in naval conditions”, In IEEE International Symposium on Fundamentals of Electrical Engineering (ISFEE), 1-6, 2014.
[16] Hussein, A.W., and Ahmed, M.W., “Solar Energy: Solution to fuel dilemma”, International Journal of Research in Engineering & Technology, 2(8), 99-108, 2014.
[17] Moustafa, M.M., and El-bokl, E.E., “Solar energy for River Nile cruisers”, Brodogradnja, 65(2), 61-72, 2014.
[18] Peng, C., Shounan, S., Hai, L., and Qiang, Z., “Modeling and simulation of ship power system integration of solar energy”. In IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), 1-5, 2014.
[19] Lan, H., Wen, S., Hong, Y.Y., David, C.Y., and Zhang, L., “Optimal sizing of hybrid PV/diesel/battery in ship power system”, Applied Energy, 158, 26-34, 2015.
[20] Lan, H., Dai, J., Wen, S., Hong, Y.Y., Yu, D.C., and Bai, Y., “Optimal Tilt Angle of Photovoltaic Arrays and Economic Allocation of Energy Storage System on Large Oil Tanker Ship”, Energies, 8(10), 11515-11530, 2015.
[21] Tang, X.J., Wang, T., Zhi, C., and Huang, Y.M., “The design of power management system for solar ship”, In IEEE International Conference on Transportation Information and Safety (ICTIS), 548-553, 2015.
[22] Wen, S., Lan, H., Hong, Y.Y., David, C.Y., Zhang, L., and Cheng, P., “Allocation of ESS by interval optimization method considering impact of ship swinging on hybrid PV/diesel ship power system”, Applied Energy, 175, 158-167, 2016.
[23] Diab, F., Lan, H., and Ali, S., “Novel comparison study between the hybrid renewable energy systems on land and on ship”, Renewable and Sustainable Energy Reviews, 63, 452-463, 2016.
[24] Hall, D.T., “Practical marine electrical knowledge”, Witherby, 1999.
[25] Patel, M.R., “Shipboard propulsion, power electronics, and ocean energy”, CRC Press, 2012).
[26] Patel, P.B., and Patel, N.B., “An analysis of 2 MW PV solar power plant design”, Development, 3(1), 2016.
[27] Types of power converters in a PV system, http://solarlove.org/types-power-converters-pv-system/ (Access: 22 November 2017).
[28] String inverters vs. Microinverters vs. Power optimizers, https://www.energysage.com/solar/101/string-inverters-microinverters-power-optimizers/ (Access: 22 November 2017).
[29] Solar charge controller: What is its function?, http://www.solarpowerworldonline.com/2015/07/what-is-a-charge-controllers-function/ (Access: 25 November 2017).
[30] Luo, X., Wang, J., Dooner, M., and Clarke, J., “Overview of current development in electrical energy storage technologies and the application potential in power system operation”, Applied Energy, 137, 511-536, 2015.