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Performance analysis of ship mounting PV panels deployed in Sungsang Estuary and Bangka Strait, Indonesia

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Abstract
In an archipelago country like Indonesia, maritime transportation is essential. However, the ships, like other modes of transportation, burn fuel, contributing to CO2 emissions and negatively impacting marine life. Alternative renewable energy can help solve this problem while being environmentally friendly and cost-effective. As a result, this research describes installing PV systems to power electronic loads on a pilot ship. The supply-demand scenario was simulated using the System Advisory Model. The experiment lasted 176 days, 32 of which were still hybrid with a diesel generator, and for 144 days, electronics loads were entirely powered by PV systems. The experimental results show that the generated power consistently exceeds what is necessary. MPPT may also control the battery charging to avoid overcharging by ensuring the voltage input is always consistent. The maximum generated power is 2356 W with a peak load of 1669 W, and the average generated power is 1645 W with a load of 720.6 W. According to SIMAPRO's life cycle study results, the most significant environmental impact comes during installation due to using diesel fuel trucks and when the PV system is no longer operational since it will become a landfill, harming the ecosystem. PV systems, on the other hand, have no environmental impact during installation. Economic estimates show significant savings and, of course, profits.

Keywords:
Green Energy;
Life Cycle Analysis;
Pilot Boats;
PV Systems;
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INTRODUCTION

Life in an archipelagic country such as Indonesia is inextricably linked to the availability of modes of transportation in everyday life, both as a means of moving people or products from one location to another and as a means of earning a living. As a result, ship-based transportation plays an increasingly essential role. Maritime transportation holds an important role in economic growth of archipelagic countries [1].

Ships come in various forms, including simple boats propelled by human power using oars, such as canoes and boats, and motorized ships ranging in size from small to big ones. Examples of commonly utilized ships are container ships, bulk carriers, tanker ships, passenger ships, naval ships, offshore ships, and special purpose ships. Large ships that cruise vast oceans necessitate power, which is typically provided by diesel engines [2]. Diesel engines are typically used to generate power for the propulsion system and auxiliary power. As all the transport systems are inseparably connected to the fuel source for propelling the ship and the electricity source for any electronic devices installed on the ship. The regular diesel consumption for diesel engines depletes fossil energy sources, which are currently in restricted availability. Wang et al. 2022 proposed a joint energy consumption using a wing and diesel engine in hybrid to improve efficiency and reduce diesel consumption [2].

Diesel power use has a substantial impact on CO2 gas emissions to the atmosphere, which is increasing by the day [3][4]. Climate change and other pollutants on bodies of water are expanding worldwide, particularly in busy ports and other active waterways such as the Muntok Port and Musi River ports, where ships transport commodities to and from government-owned industries around the Musi River in Palembang. According to IRENA in 2017, transportation has the fastest growing energy consumption among the major end-user sectors, accounting for 28% of overall energy consumption up to 2014 [5][6]. As a result, if sufficient action is not taken to reduce CO2 emissions, they will increase dramatically in the following years. Decarre et al. in 2010 and Martínez-Moya et al. in 2019 discussed the CO2 emission in maritime transportation and how to increase energy efficiency [3][4].

Efforts to reduce CO2 emissions and offset the decline in conventional energy use, which is also declining, are being made through the utilization of renewable energy. Renewable fuels such as Biodiesel, Biogas, Hydrogen, Liquefied Natural Gas, Methanol, Ethanol, solar and wind energy, and PEM fuel cells can be utilized to power a ship. Oh et al. in 2023 hybrid fuel cell and bottoming cycle to power the propulsion ship motor [7]. This renewable energy is also called the clean and environmentally friendly energy [7, 8, 9, 10, 11, 12].

The wind is one of the most environmentally friendly sources of electricity in the sea. Wind can be exploited as a source of electricity for large ships, particularly when sailing, to meet some power demands while reducing greenhouse gas emissions. Solar energy can be harvested by absorbing heat from the sun and using it to run a turbine, which then powers a generator. Large ships can use thermal energy, but direct electricity generation using the photovoltaic concept is the best option for small boats or fishing boats. Solar PV can also be utilized to generate power in ships, albeit the contribution will be minor compared to the power required to propel the ship. However, the implementation of PV system on ship is possible and beneficial as listed by Kobougias et al. in 2013 [13]. The most common implementation of PV systems on Ship is by hybrid the PV system with diesel engine [14, 15, 16], such as Lee et al. in 2013 combined diesel engine and PV for a green ship [14]. The sun irradiation at each position determines the power provided by solar PV, the efficiency of the solar cells, and the amount of deck space available on the ship for the solar PV system.

The utilization of solar energy as the most abundant and easily accessible renewable energy by ships sailing on the sea is currently a perfect option. A sailing ship will constantly be exposed to the sun, with no possibility of being overshadowed by anything, unlike a land vehicle, which may be hindered from getting sunlight owing to buildings, trees, and other factors. Besides being freely available, the PV system's advantage is also environmentally friendly. Life cycle analysis (LCA) is an effective approach for demonstrating the environmental benefits of PV systems [17, 18, 19, 20, 21, 22, 23]. Hendra et al. in 2018 conducted LCA for the feasibility of installing PV system in Indonesia [17], and Park et al. in 2022 conducted a LCA analysis for electric propulsion ship powered by PV system [18]. LCA analysis is commonly utilized by academics conducting economic analyses on the utilization of renewable energy as presented by Qiu et al. in 2019 and Brækken et al. in 2023 [24][25].

Given the significance of the energy transition from conventional to renewable energy, this study explores renewable alternative energy, specifically solar energy, as an energy source for electronic loads on pilot ships. The objective of this paper is to investigate the implementation of a micro-PV system on piloted ships deployed in Indonesia's Sungsang Estuary and Bangka Strait based on load needs, as well as the environmental impact of PV system implementation.

The implementation of the PV system as a source of electricity to power all electronic equipment on board is discussed in this study. The PV system is just used to power electronic equipment and not to drive the ship. A diesel-powered engine still propels the ship. This paper also includes an LCA analysis to show the positive environmental impact of the PV system and to round out the analysis of the PV system's benefits. This paper includes an analysis of the economic benefits at a glance to show the savings in diesel fuel due to using electricity from the PV system. IoT monitoring is installed to monitor the power generated and loads consumed during the experimental study. This paper continues research on floating solar panels in rivers and brackish water because more or less PV systems are used on ships such as floating PV systems [26, 27, 28].

The rest of this paper is organized as follows: Section 2 discusses related work to solar energy implementation and hybrid solar energy; Section 3 discusses the approach for LCA, which includes material, total irradiance, and inventory analysis; and Section 4 discusses the results and discussion. This study concludes with a conclusion that demonstrates the feasibility of this research.

RELATED WORKS

The potential for implementing solar energy in Indonesia appears enormous and promising, as described by IRENA in 2017 and expressed in Indonesian government policy [5][6]. Solar energy utilization can be included in all aspects of human life, such as investigated by Mases et al., Putra et al., and Septiarini et al. by exploring the potential for integrating PV technology in agriculture and robotics is also highly probable [29, 30, 31, 32].

Although PV systems are frequently combined with conventional and renewable energy sources, ship owners can only partially switch from conventional to renewable energy. Therefore, scientists are still investigating how to make this hybrid system more efficient than one that only uses diesel, such as Ghenai et al. 2019 [8] presented a Hybrid solar PV/PEM fuel Cell/Diesel Generator power system for cruise ships implemented in Stockholm, Sweden, which aims to integrate renewable energy in small and large ships for greener and more sustainable marine transport, and Wen et al. 2017 [9] discussed the optimal sizing of hybrid energy storage sub-systems in PV/diesel ship power systems using frequency analysis and a mathematical model of a PV power generation system for a ship by considering the effects of ship rolling. Both researches prove the feasibility of the proposed method by simulation.

Optimizing the hybrid system was also investigated by Lan et al. in 2015, Yuan et al. in 2018, and Zapałowicz and Zeńczak, in 2021 and 2022. Lan et al., 2015 [10] investigate the optimal sizing of hybrid PV/diesel/battery in a ship power system by determining the optimal size of a PV generation system, the diesel generator, and the energy storage system. All the cost needed in a standalone ship power system that minimizes the investment cost, fuel cost and the CO2 emissions along the route from Dalian in China to Aden in Yemen into account, for correcting the output of PV modules is developed in this paper.

While Yuan et al. 2018 designed and investigated the experimental large-scale solar energy/diesel generator-powered hybrid ship by first using a 5000-vehicle space pure car and truck carrier (PCTC) as the substitute of a large ship. Based on the designed data, a unified grid-tied/standalone solar system is designed with a built-in battery energy storage system, and this research shows that using solar energy hybrid power, in theory, can reduce fuel consumption by 4.02% and carbon dioxide (CO2) emissions by 8.55% a year [11].

Zapałowicz and Zeńczak, in 2021 and 2022, presented the possibilities to improve the ship's energy efficiency through PV installation, including cooled modules using the water taken from the ship's power plant cooling system. The results of calculations for PV installation of a selected ro-pax vessel planned for the operation on the Świnoujście –Ystad line [16].

METHOD

This study investigates installing a photovoltaic (PV) system aboard pilot ships as additional electricity for the ship's electronics. Figure 1 shows the steps taken to conduct this research which begins with a feasibility study to determine the potential benefits of putting a PV system on a pilot ship. The following phase is PV system design, which includes panel selection, battery, and inverter capacity calculations. After determining the correct figure, the following step is determining the optimal site for placing the PV panels and the best installation angle.

The first step in proving the feasibility of the proposed approach is to simulate the designed PV system in SAM (System Advisory Model by National Renewable Energy Laboratory (NREL)). The experimental study will last 6 months to demonstrate the generated electricity and how the system would assist the pilot ship in energy savings. At the end of this study, a life cycle analysis (LCA) is performed to demonstrate the environmental impact of installing a PV system on board a pilot ship using SIMAPRO and a techno-economic analysis is provided.

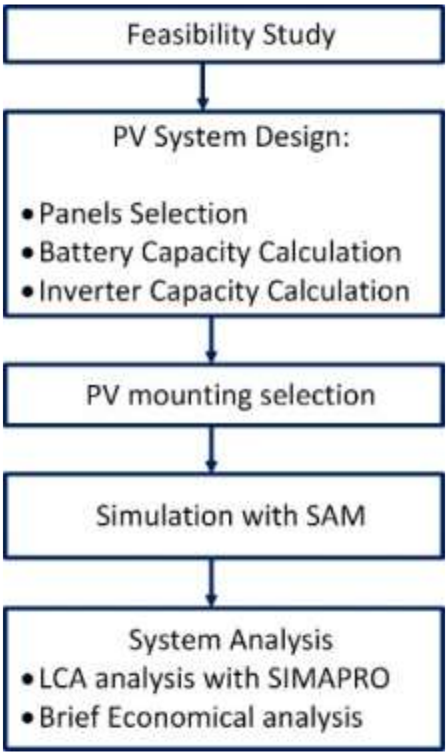


Figure 1. Research block diagram

PV System Design

The PV system design starts by listing demand in Table 1, and the energy supply is designed from the total demand in Table 1. The supply and demand analysis plays an essential role in ensuring the design PV system produces enough electricity to power the electronics on board and, at the same time, provide efficient design in terms of cost.

The solar panels installed for the designed PV system is 500 Wp, and the dimension of each panel is 2176 x 1099 x 35 mm. The monocrystalline PV panel is the most efficient for electricity generation and prices compared to other solar panels. The average solar radiation intensity in Indonesia is 4.67 hours per day, so the number of photovoltaic cells required to meet the energy demand in Table 1 are given in Eqs. Based on the total demand in Table 1, the total energy required (E_r) for on-board PV system is [33]

$$E_r = \frac{E_{daily}}{\eta_{overall}} = 10467.57 \quad (1)$$

where E_{daily} is the daily average energy demand (total demand) and $\eta_{overall}$ is the efficiency of the overall load installed, which in this study is 0.9945. Hence, the number of PV panels (N_P) is calculated by:

$$N_P = \frac{E_r}{\text{Irradiance} \times \text{Panel Rating}} = 4\ PV \text{ panels} \quad (2)$$

After determining the number of PV panels required, the next step is to determine the number of batteries. These batteries are required to store electrical energy during cloudy conditions, rain that blocks sunlight, and at night. The battery has a voltage rating of 48 volts and a storage capacity of 100 Ah. The number of batteries ($N_{battries}$) needed to accommodate (1), and (2) are:

$$N_{battries} = \frac{E_{no\_sun}}{V_{Bat} \times C_b \times M_{DOD}} = 3, \quad (3)$$

Table 1 . Electronics loads on pilot ship

Items	No of items	Load (watt)	Duration (hour/day)	Energy Demand (watt)
AC 1 pk	1	660	24	15840
AC 1/2 pk	2	320	12	7680
TV 42 inch	1	55	6	330
Lamp	12	14,5	8	1392
Spotlights lamp	1	20	8	160
Refrigerator	1	120	24	2880
Load Speaker & HT receiver	1	60	24	1440
Total Demand ($_{Daily}$)				29722

where C_b is battery capacity and M_{DOD} is the maximum depth of discharge of a battery.

In this study, the electric power at the same time is 1729 watts/hour; therefore, the choice of the type of inverter is adjusted to the power requirements at the same time; thus, it requires an inverter with a capacity of 2000 W. The installed charge controller has an MPPT to ensure no overcharging occurs, with a maximum rating of 50 A and 2800 watts [21].

Material

Figure 2 depicts the pilot ship where this project's PV system is mounted. It has a weight of 38 GT and a capacity of 40 passengers and 6 crew members. The ship is 17.2 m long, 4.2 m broad, and 2.2 m tall. The long side deck space required is 55 cm. Two primary engines require 55 liters/hour/unit, and two auxiliary engines require 6 liters/hour/unit. The ship's speed ranges from 18 knots at 2000 rpm to 20 knots at 2300 rpm.

Figure 2a depicts the front view of the pilot ship, whereas Figure 2b depicts the PV panels mounted on the pilot ship's roof. The installation angle was determined by the angle of the ship's roof. Palembang is located at 2.9761°S and 104.7754°E; hence the installation angle should also be 2.9761°. However, the roof's angle is appropriate and does not affect the power generation process.

(a) Front view

(b) Installed PV Panel

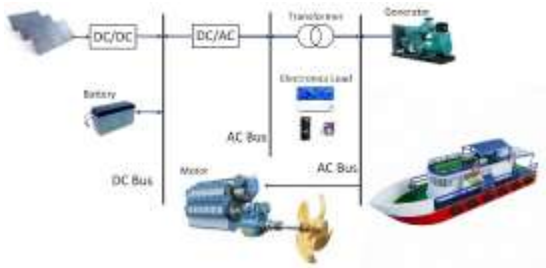
Figure 2. Pilot boat used as the experimental test-bed

The proposed method schematic diagram is shown in Figure 3. Figure 3a depicts the AC and DC bus as the hybrid power generation where the diesel generator propels the ship propulsion motor while PV systems power other electronics loads. Figure 3b depicts a schematic representation of the PV system installed on the pilot ship in Figure 2.

The system is monitored online by an IoT monitoring device to maintain track of the charged powered to batteries, generated voltage, and current, loads demand, and how much supplies are available. This condition can be tracked from the main office or anywhere with an internet connection. As a result, the IoT data is sometimes unavailable when sailing due to the lost internet connection.

Total Irradiance Received by Onboard PV Panels

The total irradiance received by the PV panels' surface are divided by direct and sky diffuse and ground reflected solar irradiance [15].



(a) Hybrid of pilot boat power generation

(b) PV systems schematic diagram
Figure 3. The pilot boat power generation system considered in this study

$$G_T = G_D + G_S + G_G \quad (4)$$

where G_T is the total solar irradiance received by the PV panels, G_D is the direct solar irradiance that comes to the PV panels, G_S is the solar irradiance from sky diffuse, and G_G is the irradiance reflected from the ground. In this study, G_G considered is the irradiance reflected by the water surface (ocean and estuary surface).

The direct solar irradiance G_D received by PV panels is given by:

$$G_D = G_{SD} + G_{SR}, \quad (5)$$

where G_{SD} is the direct solar incident falls on the PV panels and G_{SR} is the solar-diffuse reflection due to PV panel inclination.

In order to consider the scattering irradiance around installed horizontal PV panels, The total direct solar irradiance received (G_{TH}) by PV panels are given by

$$G_{TH} = G_{SD} + G_{SR}A, \quad (6)$$

where A is the anisotropy factor to include the scattering irradiance, while the total irradiance on tilted solar panel (G_{TZ}) is given by

$$G_{TZ} = (G_{SD} + G_{SR}A)R_B, \quad (7)$$

where R_B is the ratio of the solar incident on tilted PV panels to the direct solar irradiance on the horizontal PV panels ($R_B = G_{TZ}/G_{TH}$).

If the sky diffuses and ground reflected irradiance on tilted solar panel are given by

$$G_S = G_{SR}(1-A)\left[\frac{1+\cos B}{2}\right]\left[1+\sqrt{\frac{G_{SR}}{G_T}}\sin^3\left(\frac{B}{2}\right)\right], \quad (8)$$

$$G_G = \rho_g\left[\frac{(1-\cos B)}{2}\right]G_T, \quad (9)$$

where ρ_g is the surface reflectivity which 0.6 on the sea surface and B is damping coefficient of the ship.

The power generated by PV cells are calculated based on the modeling of PV cell as an ideal diode in Figure 4 [33].

$$I_{out} = I_{sc} - I_D, \quad (10)$$

$$I_D = I_0\left(e^{q\frac{V+IR_S}{nKT}} - 1\right), \quad (11)$$

$$I_{out} = I_L - I_0\left(e^{q\frac{V+IR_S}{nKT}} - 1\right) - \frac{V+IR_S}{R_p}, \quad (12)$$

$$I_{sc} = \left[I_{sc\_STC} + K_i(T - T_{STC})\right]\left(\frac{G}{G_{STC}}\right), \quad (13)$$

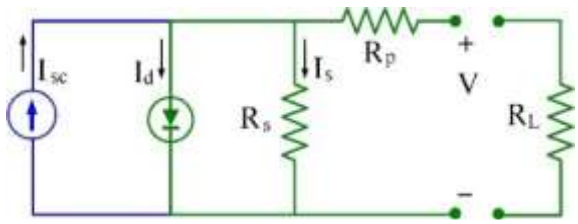


Figure 4. The modeling of PV cell as an ideal diode

where I_{out} is output current (A), I_{sc} is short-circuit current (A), I_D is diode current (A), V is voltage (Volt), R_s is shunt resistance (Ω), R_p is parallel resistance (Ω), K_i is the cell short circuit current temperature, G is the solar irradiance (KW/m^2), q is electron charge $(1.602 \times 10^{-19}C)$, T is temperature (^{o}K), I_0 is initial current (A), STC is standard operating condition. The open-circuit voltage is given by

$$V_{oc} = \frac{nkT}{q} ln\left(\frac{I_{out}}{I_o} + 1\right), \quad (14)$$

where k is the Boltzmann constant $(1.380649 \times 10^{-23}$ m^2 kg s^{-1} K^{-1}).

Inventory Analysis of Installed PV System onboard

The inventory analysis is the first phase in LCA, and it includes listing all of the components, including the expedition truck trip from Jakarta to Palembang, as shown in Table 2.

Table 2. Components of PV systems

Items	Amount
Balance of System	4
PV panels	4
Inverter	1
Battery	3
SCC	1
Cable	50 m
Transport Jakarta -Palembang	528.8 km

The LCA study is necessary to assess the benefits of employing PV systems instead of traditional energy. LCA investigates the direct and indirect effects of PV system implementation. This study's LCA takes into account the PV system's implementation stage.

The steps for implementing LCA analysis are given in Figure 5, which starts with inventory calculation and listing. Since the LCA considered in this study is on the PV system operational stage, the transport, installation, and operation inventory are listed and calculated on their impact on the environment as generated by SIMAPRO, as shown in Table 3 and Table 4. Tables 3 and 4 are generated automatically based on the data entered into SIMAPRO. SIMAPRO is an application software used to analyze the environmental impact of a system.

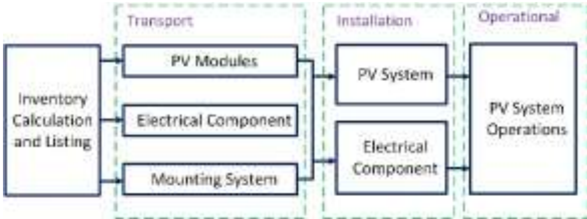


Figure 5. The block diagram of LCA analysis

Table 3. Inventory characterization

Impact Category	Unit	Total	BOS	PV Panel	Inverter	Battery	SCC	Transport	Cable
Global warming	kg CO2 eq	3,16E+03	118	2,38E+03	55,5	1,52E+02	95,2	1,95E-04	361
Stratospheric ozone depletion	kg CFC11 eq	0,0037	5,59E-05	0,00281	2,16E-05	0,000281	6,60E-05	2,64E-11	4,63E-04
Ionizing radiation	kBq Co-60 eq	26,5	0,684	19,8	0,411	0,976	0,756	6,40E-07	3,85
Ozone formation, human health	kg Nox eq	18,6	0,38	15,4	0,186	0,446	0,407	4,95E-07	1,73
Fine particulate matter formation	kg PM2.5 eq	12,4	0,407	6,98	0,0505	1,76	0,22	3,16E-07	3,02
Ozone formation, Terrestrial ecosystem	kg Nox eq	19	0,391	15,7	0,189	0,455	0,413	5,05E-07	1,78
Terrestrial acidification	kg SO2 eq	31	0,482	15,4	0,125	5,72	0,56	9,12E-07	8,74
Freshwater eutrophication	kg ρ eq	3,97	0,0179	2,91	5,85E-05	0,0291	0,189	1,74E-09	0,818
Marine eutrophication	kg N eq	0,109	0,00264	0,0722	7,05E-05	0,00107	0,00293	3,39E-10	0,0306
Terrestrial ecotoxicity	kg 1,4-DCB	8,30E+04	834	2,51E+04	215	1,61E+03	2,10E+03	2,86E-04	5,31E+04
Freshwater ecotoxicity	kg 1,4-DCB	13,7	0,159	10,9	0,0505	0,303	1,24	1,72E-07	1,13
Marine ecotoxicity	kg 1,4-DCB	753	0,688	723	0,167	1,17	3,63	4,22E+07	24,4
Human carcinogenic toxicity	kg 1,4-DCB	38,7	2,16	20,3	0,0623	1,3	0,994	6,64E-07	13,8
Human non-carcinogenic toxicity	kg 1,4-DCB	3,09E+03	32	1,84E+03	5,69	3,51E+01	92	9,65E-06	1,09E+03
Land use	m2a crop eq	145	1,77	114	0,025	2,3	3,51	6,76E-07	23,1
Mineral resource scarcity	kg Cu eq	353	2,74	307	0,000449	8,04	4,6	2,12E-07	30,2
Fossil resource scarcity	kg oil eq	889	33,8	626	18,6	44,3	29,4	6,75E-05	137
Water consumption	m3	49,6	1,68	41,4	0,0809	1,38	0,529	-9,49E-05	4,57

Table 4. Inventory normalization

Impact Category	Total	BOS	PV Panel	Inverter	Battery	SCC	Transport	Cable
Global warming	0,396	0,0148	0,298	0,00695	0,0191	0,0119	2,44E-08	0,0452
Stratospheric ozone depletion	0,0618	0,000934	0,0469	0,00036	0,00469	0,0011	4,42E-10	0,00773
Ionizing radiation	0,551	0,00142	0,0412	0,000855	0,00203	0,00157	1,33E-09	0,00802
Ozone formation, human health	0,903	0,0185	0,75	0,00906	0,0217	0,0198	2,41E-08	0,0839
Fine particulate matter formation	0,486	0,0159	0,273	0,00198	0,0687	0,00859	1,24E-08	0,118
Ozone formation, Terrestrial ecosystem	1,07	0,022	0,887	0,0106	0,0256	0,0232	2,84E-08	0,1
Terrestrial acidification	0,757	0,0118	0,376	0,00306	0,139	0,0137	2,23E-08	0,213
Freshwater eutrophication	6,11	0,0275	4,48	9,01E-05	0,0448	0,291	2,69E-09	1,26
Marine eutrophication	0,0238	0,000573	0,0157	1,53E-05	0,000232	0,000635	7,36E-11	0,00663
Terrestrial ecotoxicity	80,1	0,805	24,3	0,208	1,55	2,03	2,76E-07	51,3
Freshwater ecotoxicity	11,2	0,13	8,85	0,0412	0,247	1,01	1,40E-07	0,923
Marine ecotoxicity	730	0,67	701	0,162	1,13	3,51	4,09E-07	23,6
Human carcinogenic toxicity	14	0,781	7,34	0,0225	0,468	0,359	2,40E-07	4,99
Human non-carcinogenic toxicity	20,7	0,215	12,3	0,03852	0,236	0,617	6,48E-08	7,3
Land use	0,0235	0,000287	0,0185	4,05E-06	0,000373	0,000568	1,09E-10	0,00375
Mineral resource scarcity	0,0029	2,28E-05	0,00256	4,74E-09	6,70E-05	3,83E-05	1,76E-12	2,52E-04
Fossil resource scarcity	0,906	0,0344	0,638	0,019	0,0452	0,03	6,89E-08	0,14
Water consumption	0,186	0,00628	0,155	0,000303	0,00518	0,00198	-3,56E-07	0,0171

RESULTS AND DISCUSSION

This study investigates the implementation of PV systems as the alternative power generation in a pilot boat sailing from Sungsang Port in Palembang to Muntok Port in Bangka Belitung Province as given in Figure 6. The PV panels experiences the atmosphere of freshwater (Musi River), brackish water (Sungsang Estuary), and saltwater (Bangka Strait). The experiment was conducted from Dec 2022 to May 2023.

Simulation Results

A simulation was run using SAM to demonstrate the feasibility of the proposed method by inputting parameters such as location coordinates of Palembang, PV panel type, tilt angle, and inverter selection. This study does not address shading because the ship was deployed in open seas with a minimal likelihood of getting shade.

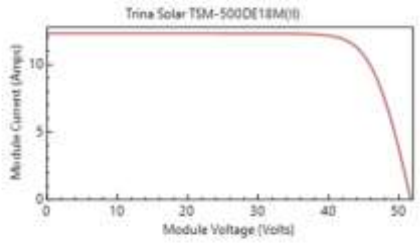
Figure 7 shows the results of entering the specification techniques of PV panels and batteries. Figure 7a illustrates the IV curve of the chosen PV panels, and Figure 7b displays the temperature effect on PV panel output. Figure 7c depicts the battery efficiency relative to the temperature at which the battery was deployed, whereas Figure 7d represents the effective capacity compared to cycle numbers (Depth of Discharge - DOD).

Figure 8 demonstrates the simulation outcome from the settings in Figure 7. Figure 8a shows the power generated in one year, with the most generated in January and the least in June. The energy generated is shown in Figure 8b, which has a result similar to Figure 8b.

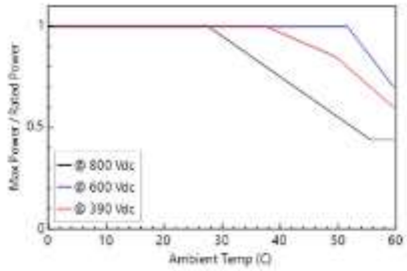
Generated Output PV Panels

Figure 9 depicts the electricity provided by PV systems, where the generated power is always sufficient to meet the demand of the pilot ship's electronic loads. On December 20, 2022, shown in Figure 9a, the highest power generated was 2027.7 W, with the highest PV panel surface temperature of 55ºC and the highest electronics demand of 1458 W.

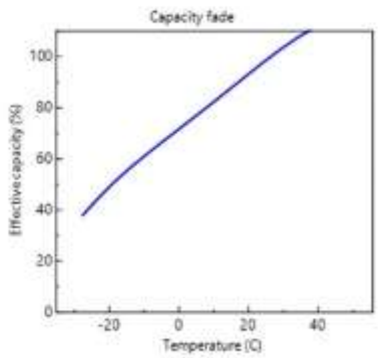
Figure 6. The sailing track from Sungsang port to Muntok port along Bangka strait



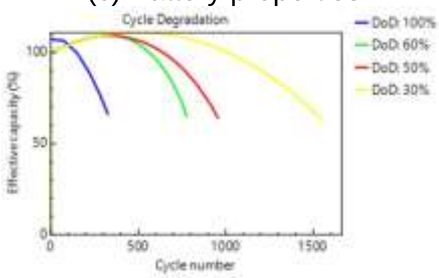
(a) IV Curves



(b) Temperature effect



(c) Battery properties

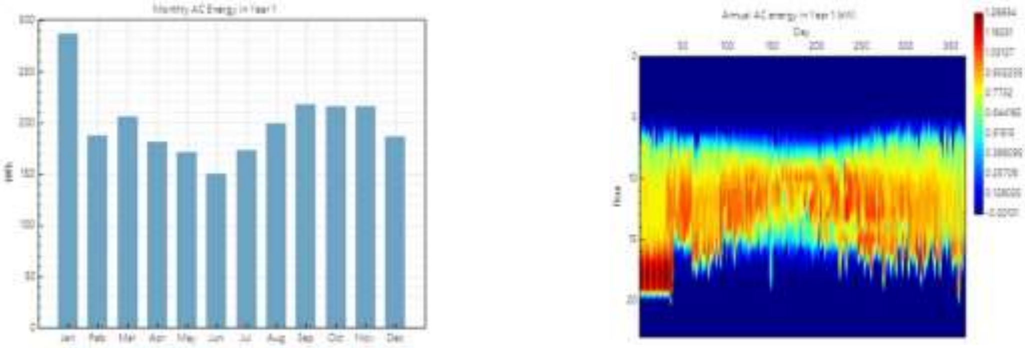


(d) Capacity and cycle numbers

Figure 7. The properties of PV panels and batteries considered in this study

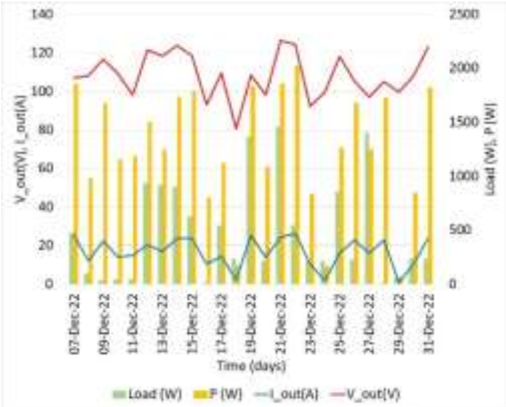
As a result, a maximum surplus of 569.9 W exists. The average power generated in December 2022 is 1269.4 W, with a supply-demand difference of 792.3 W.

On January 2023, the maximum generated power was 2229.55 W for a maximum load of 1669 W, resulting in a 560.6 power surplus, while the average power was 1520.9 W, which is 700.1 W greater than the average load demand as depicted in Figure 9b.

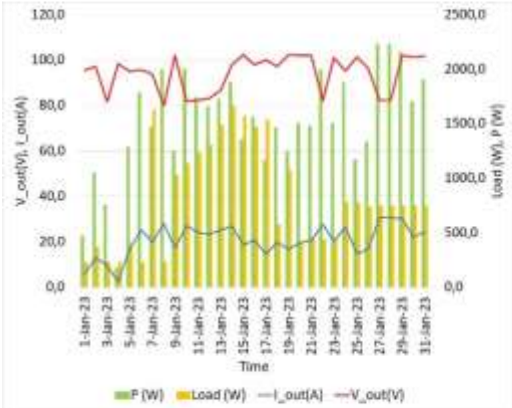


(a) Power generated (b) Energy generated

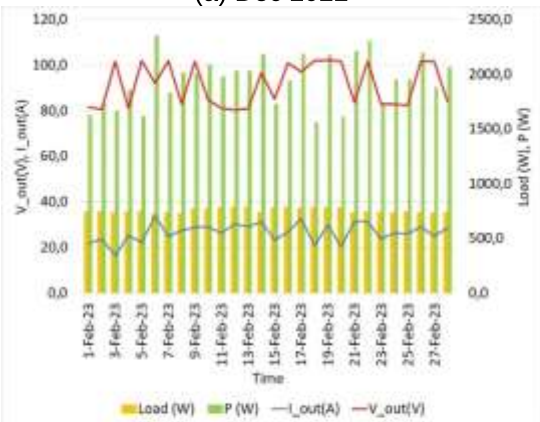
Figure 8. Simulation results



(a) Dec 2022

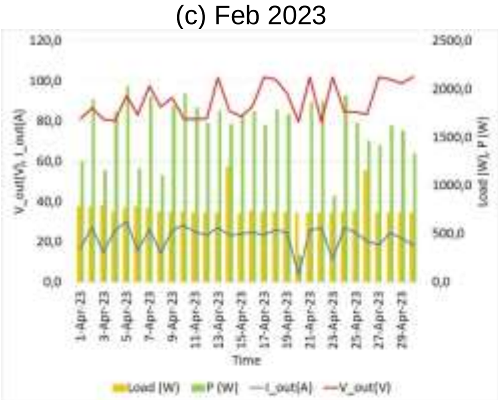


(b) Jan 2023

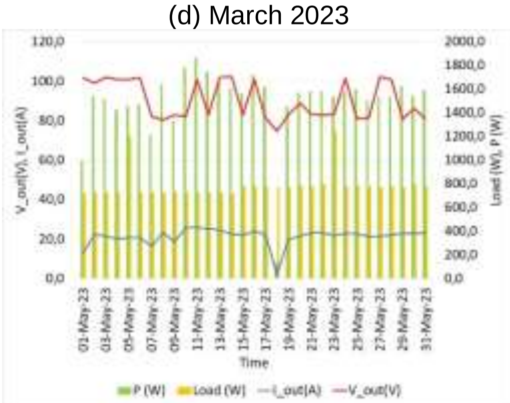


(c) Feb 2023

(d) March 2023



(e) April 2023



(f) May 2023

Figure 9. The generated power during experimental test from Dec 2022-May 2023

In January 2023, the maximum surface temperature of PV panels was 55ºC, with an average temperature of 52ºC. On February 2023, the most outstanding PV panel production was 2356.3 W, with an average of 1949 W and a maximum load of 769 W. At that time, the largest power surplus was 1560.3 W, averaging 1189 W. The maximum and average temperatures were 58ºC and 55.1ºC, respectively, as presented in Figure 9c.

Figure 9d illustrates the power created in March 2023, revealing that the maximum and average power generated was 2293.2 W and 1901.5 W, respectively. As a result, the surplus reached a maximum of 1097.2 W and an average of 1125.3 W this month, with maximum and average temperatures of 55ºC. Figure 9e depicts the electricity produced in April 2023, with the maximum and average power being 2035,48 W, and 1586.4 W, respectively; hence, the supply-demand gap was 838.5 W maximum and 817.7 W average, when the maximum and average loads were 1197 W and 768.7 W. That month's maximum and average temperatures were 55ºC and 54.3ºC, respectively. Figure 9f depicts the last experimental month, May 2023, where the generated power was comparable to earlier months. The maximum power and electronics load were both 1863.54 W. The load was 787.9 W, while the average generated power was 1501.7 W. The maximum and average temperatures in May 2023 were 55°C and 54.5°C, respectively.

The experimental results deviate from the modeling results for January 2023; however, the profile from February through May 2023 is comparable to the simulation results in Figure 7. Figure 10 represents the results of a 6-month experimental test of power generation.

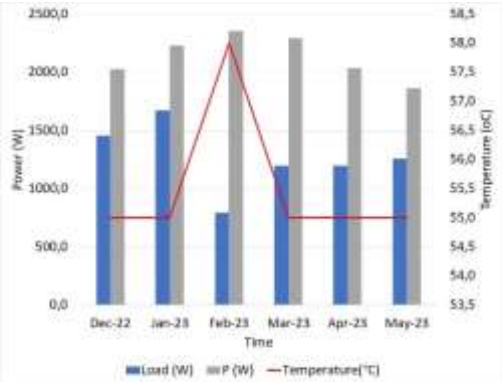


Figure 10. Recapitulation of energy generated during experiment

Figure 11 shows the generated output voltage of PV system and the charged voltage to battery through MPPT (Maximum Power Point Tracker). MPPT in solar charge controller (SOC) is installed to prevent overcharge on batteries. Figure 11 depicts the effectiveness of MPPT installed in this study since the charge voltage was stable through 6 months of experiment.

Life Cycle Analysis of Onboard PV Systems

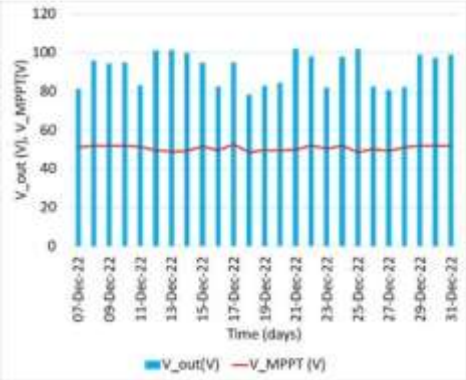
The LCA to demonstrate the environmental impact of the onboard PV systems on the pilot ship began by listing the inventory analysis in Table 3 and Table 4. The SIMAPRO simulation program yields the impact assessment characterization in Figure 11 and the impact evaluation of normalization in Figure 13.

The PV panels have the most significant environmental impact because of the manufacturing process, and when they cease working, they become landfill rubbish. Cables have the second most considerable effect due to their manufacture and landfill waste. Since the process involves traditional fossil fuels, transportation also plays an essential role. The most significant impact is on freshwater and marine ecotoxicity, as well as on humans. However, compared to conventional energy generation, PV systems produce green energy while emitting no CO2.

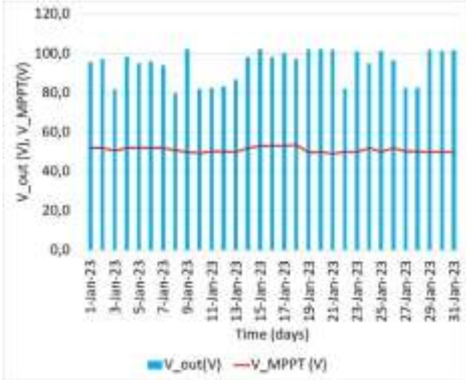
IoT Monitoring of PV systems onboard

Figure 14 shows the IoT monitoring of on-board IoT monitoring in this investigation. Online IoT monitoring displays supply (the generated power, current, and voltage) and demand (the electronics loads). Figure 15 represents the IoT monitoring display, where Figure 15a depicts the generated power versus the loads, similar to Figure 9, showing the generated power can power the loads. PV panel outputs are charged to a battery, which may support loads during no-sun periods (night and cloudy/overcast days).

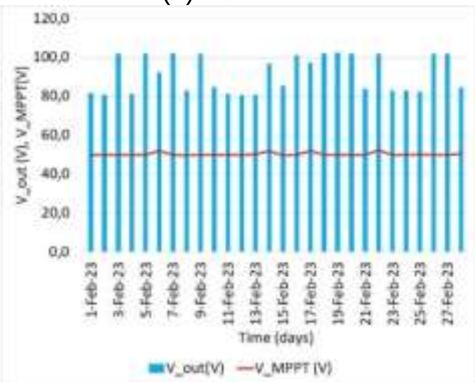
The table in Figure 15b displays the generated power, voltage, current, and loads. The IoT monitoring includes created CSV files that may be downloaded and analyzed. The table in Figure 15b displays the generated power, voltage, current, and loads. The IoT monitoring includes created CSV files that may be downloaded and analyzed.



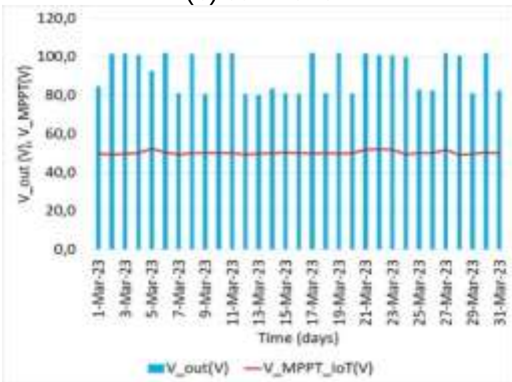
(a) Dec 2022



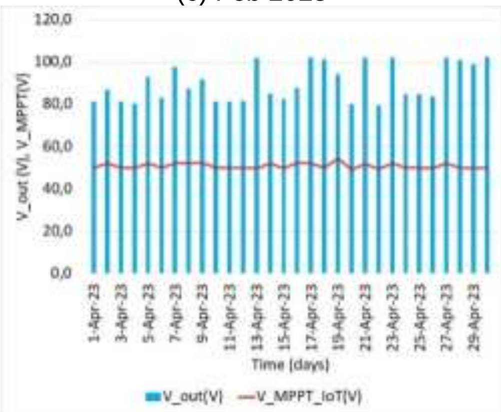
(b) Jan 2023



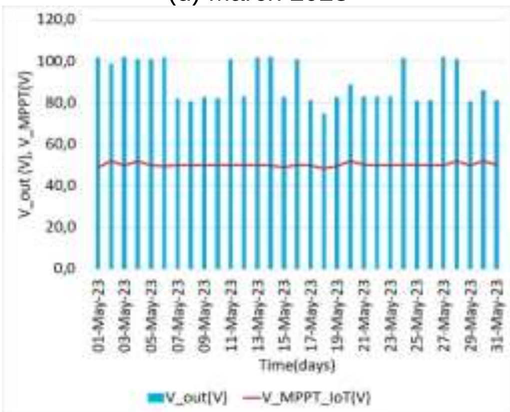
(c) Feb 2023



(d) March 2023



(e) April 2023



(f) May 2023

Figure 11. MPPT effect on battery charging

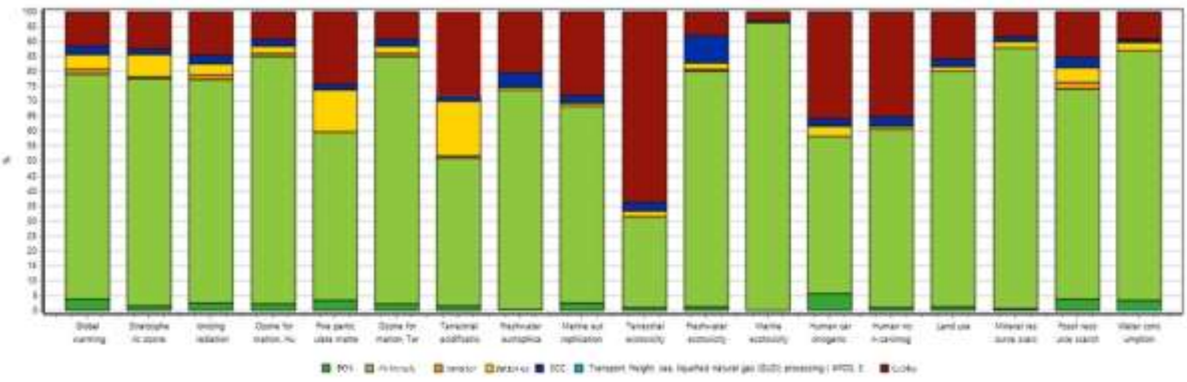


Figure 12. The impact assessment from inventory characterization

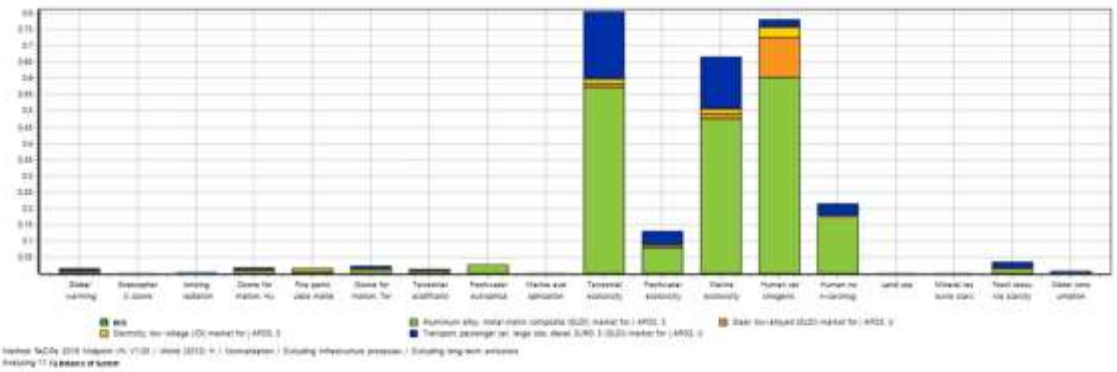


Figure 13. The impact assessment from inventory normalization

Figure 14. On board IoT monitoring in this study

(a) Power generated versus loads

(b) Energy generated
Figure 15. IoT Monitoring Display

Techno-analysis of the onboard PV systems

Table 5 shows the total investment to install on-board PV system on a pilot ship to power the electronics loads. The experimental process for using solar panels on pilot ships was carried out from December 06, 2022, to May 31, 2023, for 176 days on pilot ships. During this process, because only two batteries were installed from December 06, 2022, to January 08, 2023, more was needed for electric power consumption on board. Hence, the electronics loads were powered hybrid with a generator set for 32 days. Whereas, from January 09, 2023, to May 31, 2023, 6 units of batteries were placed for consumption of electricity demands on the ship, exclusively using the installation of solar panels with these batteries as an alternative power generator to replace the generator set on the ship (total 144 days).

When compared to employing generator sets that still consume industrial diesel oil at roughly 4 liters per hour/unit, the savings from 09 January 2023 to 31 May 2023 are as follows:

$$\text{Diesel Consumption} = 13{,}824 \text{ liter}$$

where 144 is the days with the full PV system implementation, 24 is for 24 hours a day, and 4 liter/hour consumption. Hence, the Operational Cost Savings (in IDR) is $13.824 \text{ liter} \times 20{,}700$ or $\text{Rp.}\,286{,}156{,}800$ in total.

Table 5. The total investment for installing On-board PV Systems

No	Items	Specs	No of Item	Price (IDR)	Total (IDR)
1	PV panels	500 Wp	4	3.500.000	14.000.000
2	Battery	48 V 100 Ah	6	6.000.000	36.000.000
3	Inverter	12 VDC 3000 W	1	6.500.000	6.500.000
4	SOC		2	800.000	1.600.000
5	Kabel Slocable	6 mm	1	2.500.000	2.500.000
6	Installation price	-	1		2.000.000
	Investment Fund				62.600.000
	Average cost in per month in 5 years				1.043.333

Table 6. The research contribution

No	Item	Contribution
1	Implementation	Real implementation of PV system on a pilot ship in tropical setting
2	Feasibility	Installed PV system successfully powered the load based on system design
3	IoT Monitoring	IoT Monitoring reports the produced electricity and the power consumed by the load giving the user information whether the system is working as expected
4	LCA	Shows that the installed PV system is environmentally friendly
5	Cost Saving Fuel	The Operational Cost Savings (in IDR) is $13.824\,\text{liter} \times 20{,}700$ or $\text{Rp.}\,286{,}156{,}800$ in total

Table 6 shows the contribution of this study, where experimental results in Figs 7 – 14 confirm the contribution. This study shows the complete analysis of PV system implementation on a ship, starting from PV system design, the feasibility of the proposed method by SAM simulation, IoT monitoring to ease user monitoring of the system 24/7, environmental impact through LCA, and finally, the cost-saving fuel from solar energy implementation. Therefore, implementing PV systems on board is very beneficial not only in terms of green energy and environmentally friendly but also in terms of economic analysis [34].

CONCLUSION

This study presents the implementation of PV systems to power electronic loads on a pilot ship. Given that this is still a pilot project to investigate the feasibility of placing a PV system on ships, the ship's propulsion motor is still powered by a diesel power generator. This study begins with a supply-demand design, which is then simulated using SAM, and the simulation results suggest that the PV system design in this study is sufficient to deliver electronics to ships. The PV system implementation was conducted for 176 days, 32 of which were still hybrid with a diesel generator, and 144 total days used only the PV system to supply the electronics. The experimental results demonstrate that the generated power always surpasses what is required. MPPT can also manage the battery to avoid overcharging by guaranteeing the battery charging is always stable. The maximum generated power is 2356 W with a peak load of 1669 W, and the average generated power is 1645 W with a load of 720.6 W. The LCA analysis results suggest that the most significant environmental impact occurs during installation owing to the usage of diesel fuel trucks and when the PV system is no longer operational since it will become a landfill, endangering the ecosystem. PV systems, on the other hand, have no environmental impact during installation. Economic calculations show significant savings and, of course, profits.

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