Integration between Photovoltaic Arrays, Port Energy Requirements, and Pilot Boats to Achieve Net Zero Emission: A Case Study of the Port of Lembar

Noor Muhammad Ridha Fuadi
Maritime Policy and Shipping Management, Cardiff University

Iskendar
Research Center for Transportation Technology, National Research and Innovation Agency

Dwitya Harits Waskito
Research Center for Transportation Technology, National Research and Innovation Agency

Cahyo Sasmito
Research Center for Hydrodynamic Technology, National Research and Innovation Agency

他

https://doi.org/10.5109/7326982

出版情報：Evergreen. 11 (4), pp.3457-3469, 2024-12. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan
バージョン：

Integration between Photovoltaic Arrays, Port Energy Requirements, and Pilot Boats to Achieve Net Zero Emission: A Case Study of the Port of Lembar

Noor Muhammad Ridha Fuadi[1,2], Iskendar[2], Dwitya Harits Waskito[2,*], Cahyo Sasmito[3], Nanda Itohasi Gutami[2], Ade Ratih Ispandiari[2], Nanda Yustina[2], Zulfa Qonita[4], Annissa Roschyntawati[2], Rio Saputra[5]

[1]Maritime Policy and Shipping Management, Cardiff University, Cardiff CF10 3AT, United Kingdom

[2]Research Center for Transportation Technology, National Research and Innovation Agency, South Tangerang, 15314, Indonesia

[3]Research Center for Hydrodynamic Technology, National Research and Innovation Agency, Surabaya, 60112, Indonesia

[4]Research Center for Geological Disaster, National Research and Innovation Agency, Bandung, 40135, Indonesia

[5]Center for Technology Services, National Research and Innovation Agency, Central Jakarta, 10330, Indonesia

*Author to whom correspondence should be addressed:
E-mail: dwit001@brin.go.id

(Received May 6, 2024; Revised October 17, 2024; Accepted November 26, 2024).

Abstract: Ports are essential for global distribution but also contribute to carbon emissions. However, integrating renewable energy in port electrification could help mitigate their carbon footprint. This study employs EnergyPLAN software and proposes an analysis of integrating a photovoltaic array at the Port of Lembar. It involves analysing the power requirements of the port, including pilot boat services, and assessing the power generation potential of the photovoltaic array. The analysis concludes that this integration can meet the port's electricity demands with a Critical Excess Energy Production value of 1 kW, resulting in an annual reduction of CO2 emissions by 33.04 tons.

Keywords: port electrification; pilot boat; photovoltaic array; renewable energy; carbon emission

1. Introduction

The maritime industry accounts for approximately 2.3% of global carbon emissions[1)]. If treated as a nation, the maritime sector would rank as the sixth-largest carbon dioxide emitter, surpassing countries such as Brazil and Germany[2)]. In 2018, emissions from shipping contributed to 2.89% of global anthropogenic emissions, totalling 1,076 million tons of greenhouse gas emissions, with carbon dioxide being the predominant contributor at 1,056 million tonnes[3,4)]. Given the challenges posed by global climate change and an increasing emphasis on sustainability, the maritime transportation sector has become a central focus for research to implement environmentally friendly solutions.

Ports are pivotal hubs in the global distribution chain and contribute substantially to carbon emissions[5)]. Hence, calculating carbon emissions generated by ports, a crucial element of the maritime industry, is of paramount importance[6)]. Several studies have addressed carbon emission calculations for various ports worldwide, including Taipei Port[7)], Port of Busan[8)], and Nanjing Longtan Container Port[9)]. Notably, a recent study conducted in Indonesia, specifically at the Belawan International Container Terminal (BICT), focuses on comprehensive carbon emission calculations across the entire port process. This encompasses activities such as berthing, unloading processes, transfer from piers to stacking spots, stacking, and vice versa[10)]. This article aims to contribute beyond evaluating port carbon emissions by exploring the possibilities of integrating renewable energy sources to establish a net zero-emission port and incorporating the demand for pilot boats, which has not been done in previous studies. Theoretically, this paper serves as a proof of concept that a port can run all its operations using power sourced from renewable energy sources. Building on previous studies, such as those conducted in Croatia[11] and Barbados[12], which investigated the integration of photovoltaic power systems with battery-powered ships and showed significant reductions in excess electricity production, operating expenses, and CO_2 emissions. Similarly, studies in Indonesia have examined the integration of fisheries technology with solar PV[13].

In general, efforts to reduce carbon emissions are a central focus in the field of transportation, including the maritime industry. This is evident through various initiatives aimed at decreasing carbon emissions, such as by improving transportation efficiency[14,15], emphasising the adoption of green energy[16], and implementing cutting-edge technologies to reduce greenhouse gas emissions[17–19]. This article delves into exploring the potential integration of Renewable Energy Sources (RES), particularly Photovoltaic Arrays, to establish a port that operates with net-zero emissions[20]. It addresses the power needs of the port as well as the various services it provides. A notable application of this approach involves transitioning from conventional to electric services, such as using electric-powered pilot boats, presenting an innovative way to create a net zero emission port[21]. Considering the pivotal role of ports in the global distribution chain and their contribution to greenhouse gas emissions, the adoption of Photovoltaic Arrays to meet the power requirements of the port and its services offers an opportunity to investigate sustainable solutions that mitigate the environmental impact of maritime operations. Several studies have been conducted on the electrification of the ships. Such as fishing vessels[22], Ferries[11], and Inland water transport[23]. Moreover, the Life-cycle Assessment (LCA) of battery-powered have also been studied[24–26]. However, investigations regarding pilot boats' routes and energy demands are still scarce.

This research will be conducted through a case study at the Port of Lembar. This choice was determined because the Port of Lembar is close to several renewable energy sources (RES) facilities and offers services that can be converted into environmentally friendly alternatives, such as converting pilot boats to electric-powered vessels. Designated as a mandatory pilotage area by the Ministry of Transportation, pilot boats play a significant role in the port. The study will also consider the Photovoltaic Arrays (PV Arrays) installed in the East Coast area of West Nusa Tenggara.

This study aims to calculate the energy demand and emissions generated throughout the port operations. The energy integration calculation is based on the energy utilised, encompassing the energy demand and emissions from port operations and the fuel emissions resulting from pilot boat operations to generate sustainability in the seaport area. Moreover, this study also evaluates the performance and economic analysis of the photovoltaic arrays to support the port's energy demand. This approach is a novel initiative that has not been previously undertaken in Indonesia. Furthermore, by including the calculation of pilot boats as an important component of the port, this study provides additional information that can be useful for knowledge of where pilot boats are a means for the port to save emissions from CO_2 by electrifying its engine system. Through such innovative endeavours, the maritime industry can take significant steps toward a greener and more sustainable future, offering substantial opportunities to enhance the overall sustainability of the global port sector.

2. Method

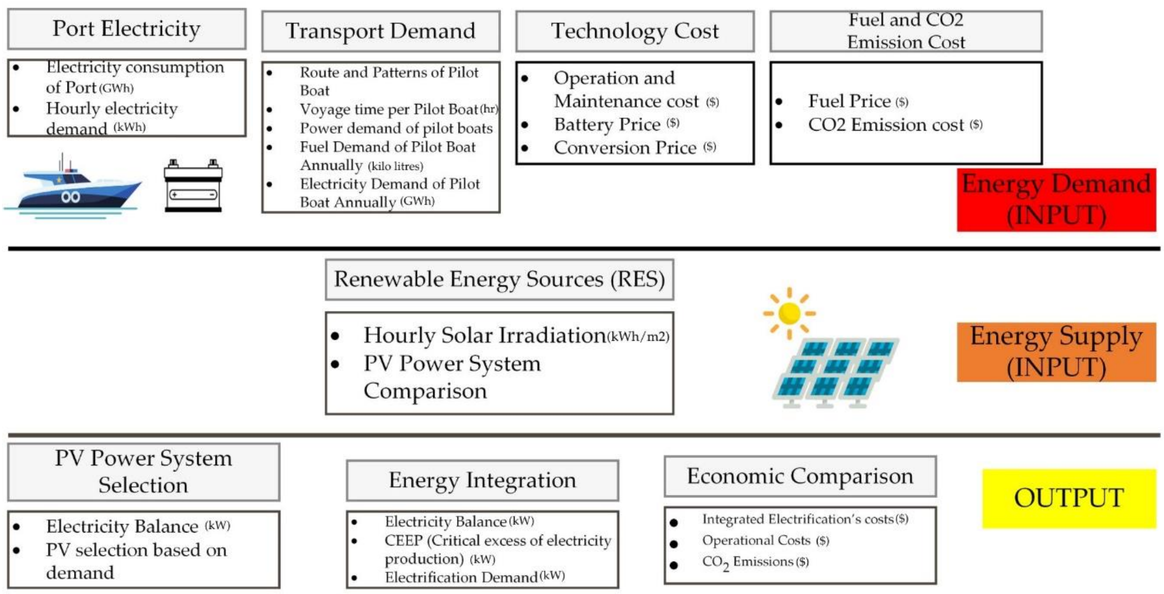


Fig. 1: Simulation Flowchart with EnergyPLAN.

Figure 1 illustrates the methodology of integrating Renewable Energy Sources (RES) for net zero emission Port. Generally, the flowchart consists of three stages. The first stage defines the input from electricity demand. For example, port and transport electricity demand includes hourly, monthly, and annual electricity demand, battery capacity, and the number of batteries needed for pilot boats. Another input for the analysis is the RES generated by the photovoltaic array system installed near the port area. The hourly solar irradiation and power generated are integrated into the system. The second stage is the integration analysis conducted using EnergyPLAN software[27]. Three scenarios were designed to generate a comparison between conventional energy and electrification from RES. Lastly, the final stage is the output analysis of energy integration and cost comparison between several scenarios.

2.1 Location and Route

Port of Lembar is located in the southwest part of Lombok Island and is considered one of the most important seaports in the Nusa Tenggara Area. The Port consists of two terminals: the Lembar terminal, mainly used for ferries and general cargo, and the Gilimas terminal, designated for container terminals as shown in Fig. 2. The Port of Lembar is considered a mandatory pilotage area, according to the regulation of the Ministry of Transportation, where the pilot boats play an essential role in the port area. Currently, the port is supported by one pilot boat covering the entire area. The main task of the boat is to transport the pilot from the PBG (Pilot Boarding Ground) to the terminal. In this study, it was assumed that the pilot boat had two main routes. The first route is from the Lembar Terminal (T1) to PBG, then back to T1, while the second route is from the Gilimas Terminal (T2) to PBG, then back to T2. The daily total distance of the pilot boat can be calculated as Eq. 1:

$$l_{total} = 2(l_{T1}n_{T1} + l_{T2}n_{T2}) \qquad (1)$$

While l_{T1} is the distance from T1 to PBG and l_{T2} is the distance from T2 to PBG, n_{T1} is the daily average number of ships that dock at T1, and n_{T2} is for the T2.

The estimation of boat average power is determined by the average speed per trip $V_{ave,i,j}$, which is based on the journey time or waiting time from the terminal to the PBG (t_{T1}) that has been calculated by[28] and can be estimated by Eq. 2:

$$v_{ave,i,j} = \frac{l_{i,j}}{t_{i,j}} \qquad (2)$$

Fig. 2: Port Lembar's location, consisting of Lembar and Gilimas Terminal.

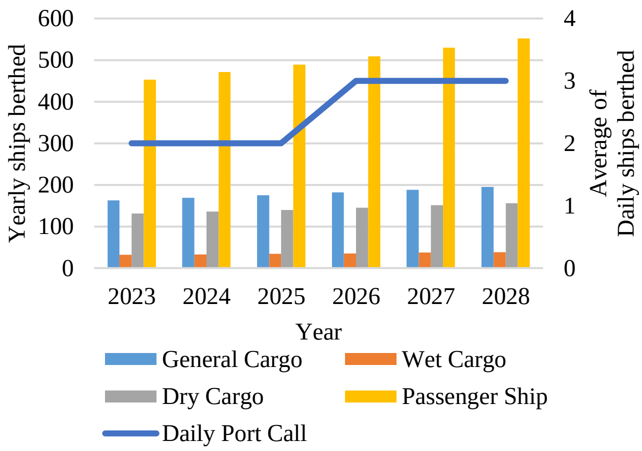


Fig. 3: Prediction of number of ships berthed yearly in Lembar Terminal[29].

The prediction of the number of ships that will be berthed for a port call in Lembar and Gilimas Terminal are depicted in Fig. 3 and Fig. 4. For Lembar terminal, an average of two ships per day will be predicted to be berthed from 2023 until 2025. After that, the number increases to three per day due to an increasing volume of ships. Meanwhile, for Gilimas terminal, the average number of ships berthed remained constant, with one ship per day. It is paramount to obtain the accurate number of daily ships berthed since it affects the number and distance of pilot boats for one day, which will be used to calculate the energy demand for the pilot boats.

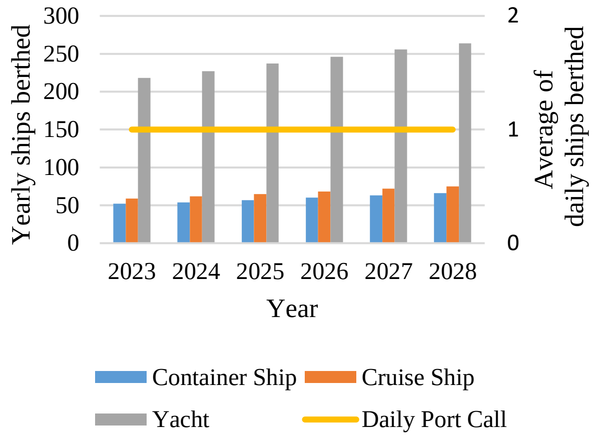


Fig. 4: Prediction of number of ships berthed yearly in Lembar Terminal[29].

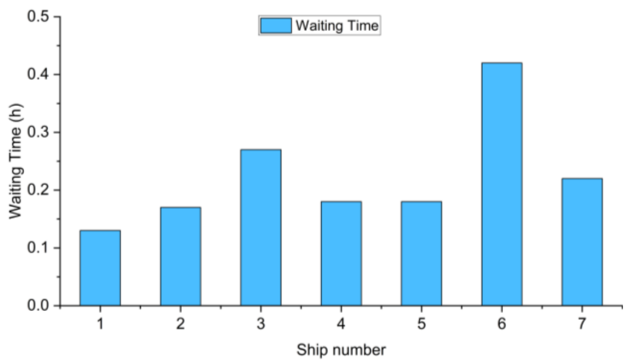


Fig. 5: Waiting time for pilot boat after request[28].

Figure 5 shows the waiting time for the pilot boat to arrive after the request from the ship's Captain for seven ships in the Port of Lembar area. The average waiting time for the Lembar Terminal (t_{T1}) is 0.22 hours, and for the Gilimas Terminal (t_{T2}), it is 0.15 hours.

2.2 Energy Consumption for Pilot Boat

The method for calculating the pilot boat's energy and battery consumption was generally developed by[30]. The average power of the main engine ($P_{ME,ave}$) based on the variations in ship speed was determined through software analysis using the "MARIN DESPPC 1999" program. This analysis was conducted under a license held by the Indonesian Hydrodynamics Laboratory (IHL) on a pilot ship model developed by the National Research and Innovation Agency (BRIN). The power of the auxiliary engine ($P_{AE,ave}$) was determined by the ship's specifications. The average boat engine total power (Pave) can be estimated by Eq. 3:

$$P_{ave} = P_{ME,ave} + P_{AE,ave} \quad (3)$$

The energy consumption of the boat per nautical mile (EC) is determined by Eq. 4:

$$EC = \frac{P_{ave}}{V_{ave}} \quad (4)$$

The daily energy consumption (EC_{daily}) can be determined by multiplying EC by the total distance of the boat, as stated in Eq. 5.

$$EC_{daily} = EC \cdot l_{total} \quad (5)$$

The battery capacity for the pilot boat (BC_{BEP}) can be calculated by Eq 6, and the number of batteries ($n_{battery}$) needed is estimated by Eq 7.

$$BC_{BEP} = EC_{daily} \cdot 1.5 \quad (6)$$

To determine the battery capacity, it is necessary to increase the contingency by 50%, which comprises gradual battery degradation, which can deteriorate battery capacity by 20%, minimum state of charge (SoC) by 20% and 10% as the predicament of safety operations. The number of batteries was determined by dividing the battery capacity and battery power per unit Eq. 7.

$$n_{battery} = \frac{BC_{BEP}}{BP} \quad (7)$$

For the boat with the diesel engine, Eq. 8 was used to estimate the number of CO_2 emissions *(E)* generated. EF_{CO2} is the emission factor of CO_2 3.144[31], while the *SFC* is the specific fuel consumption of diesel engines per kWh value 0.215 kg/kWh[32].

$$E = EC_{daily} \cdot EF_{CO_2} \cdot SFC \quad (8)$$

EnergyPLAN software requires detailed electric vehicle specifications to simulate smart charge. However, the fundamentals are suitable for cars. Consequently, several adjustments were performed regarding the smart charging for pilot boats. S2G (Ship-2-Grid) is the number of boats not operating and cannot source the batteries at any given time[11]. The charger is the maximum system capacity calculated from the maximum power required by one boat in one voyage. Battery storage capacity is the total battery capacity calculated based on daily power requirements. At the same time, the battery efficiency is assumed to be 0.9.

2.3 Energy Demand for Port Electricity

Table 1 shows the list of electricity demands of the Port of Lembar based on data from the Ministry of Transportation of West Nusa Tenggara[33].

The first step in calculating electricity demand is multiplying the area or number by power per area, and the conservative approach was employed, stating that the highest capacity of each piece of equipment will be used in the calculation. The highest power demand is for the main fire pump, which will be used for emergencies only, followed by the electricity for the office and lighthouse, which will be crucial for the port operation.

The second step is to estimate the daily usage or number of hours of electricity used for each piece of equipment. The Port office, warehouse, clinic, and mosque are assumed to operate between 6:00 am and 8:00 pm. At the same time, the port lighting will be activated only during the nighttime. The pumps, auxiliaries, and water treatment plant are assumed to be active in 24 hours since there could be several activities in the port area. During an emergency, the main fire pump is only estimated to be active four hours daily. Table 2 shows the daily energy use per equipment with pump and auxiliary, which have the highest consumption of energy, 362.5 kW per day.

Lastly, after the daily usage has been defined and calculated, the distribution of hourly electricity demand was generated by HOMER PRO[34)] software. Figure 6 depicts the hourly distribution, which increases from three to eight pm and peaks at 5 to 6 pm with 107.2 kW of electricity due to increased port lighting demand and loading and unloading activities during the sunset period[29)]. The average hourly electricity consumption is 63 kW.

Table 1. Detailed electricity consumption of Port of Lembar.

Equipment / Appliances	Area (m^2) or number of lighting	Power (W/m^2)
Port Office and Lighthouse	360	60
Warehouse	720	20
Clinic, Mosque, and Terminal	1153	10.75
Port Lighting	114	150

Table 2. The daily load profile for Port electricity.

Equipment / Appliances	Cumulative Power (kW)	Hours of use per day	Daily energy use (kW/day)
Port Office and Lighthouse	21.6	15	324
Warehouse	14.4	15	215
Clinic, Mosque, and Terminal	12.4	15,17, and 24	256.4
Port Lighting	17.1	16	256.2
Pumps and auxiliary	14.5	24	362.5
Water Treatment Plan	2.2	24	55
Main Fire Pump	55	24	100

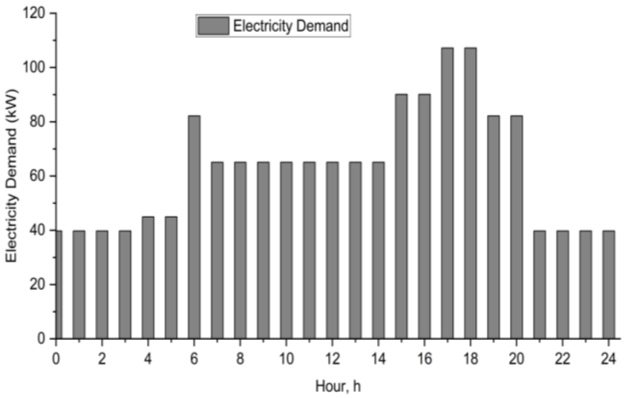


Fig. 6: The hourly electricity demand for Port's electricity.

2.4 Electricity from Renewable Energy Sources – PV Array

Table 3 shows the list of PV arrays installed in the East Coast area of West Nusa Tenggara. The Jeranjang PV array is the nearest to the Port of Lembar, and the others are in the Gili Island area. Considering the distance and the capacity, the Jeranjang and Gili Trawangan PV will be utilised for energy integration simulation. Since Gili Trawangan is also used to generate electricity on Gili Island, only more than half of its power will be allocated for the electrification of the Port of Lembar.

Table 3. List of PV power systems installed in West Nusa Tenggara.

Name of PV power system in	Capacity (kWp)	Utilisation
Jeranjang	75.6	Circuit, Motorsport
Gili Trawangan	600	Island electricity
Gili Air	60	Island electricity
Gili Meno	160	Island electricity

Figure 7 illustrates the solar irradiation of two selected PV arrays considered analogous regarding the trend. The graph was generated using the "PVGIS-ERA" database at the Photovoltaic Geographical Information System on the European Commission Science Hub based on 2020[35)]. Generally, the "Jeranjang" PV array has higher irradiation, with the maximum power reaching 204.22 kWh/m^2 per month in September. On the other hand, the bottommost solar irradiation occurs in December with 143.63 kWh/m^2 per month for the "Jeranjang" PV array, which can be unsettling considering the energy balance of the electricity from the Port and pilot boat.

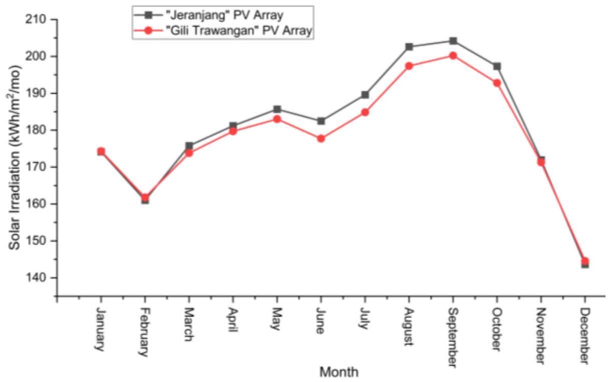


Fig. 7: Comparison of solar irradiation between two PV power systems installed in West Nusa Tenggara Area.

2.5 Scenarios

This study investigates three scenarios to determine the balance between energy supply and demand, which are:

- Scenario 1: Operation as usual (OAU), the pilot boat still using a diesel engine, and the Port's electricity is not generated by the RES
- Scenario 2: The electrification of one pilot boat for two terminals, and the Port's electricity is supplied by the RES, which is the PV power system
- Scenario 3: The electrification of one pilot boat for terminal 1, conversion of one diesel-engine pilot boat for terminal 2, and the Port's electricity supplied by the RES

With regard to Scenarios 2 and 3, the daily charging time is not incorporated into calculations since the charging process will be conducted daily and has an ineffective influence on sailing time.

The CEEP (Critical Excess of Electricity Production) is substantial in this study to assess the energy balance between supply and demand generated by subtracting the total energy demand and supply which is automatically generated by EnergyPLAN software.

2.6 Economic Analysis

As mentioned above, an economic analysis was conducted on three electrification scenarios. The cost for every scenario is stated in Table 4.

Table 4. The component cost of the economic analysis.

Explanation	Scenario 1	Scenario 2	Scenario 3
Battery price ($)	-	✓	✓
Conversion cost ($)	-	✓	✓
Fixed maintenance cost ($)	✓	✓	✓
Annual Fuel cost ($)	✓	-	✓
Annual Electricity cost ($)	✓	✓	✓
Annual CO_2 emission cost ($)	✓	-	✓

Battery price and cost for converting the ship's conventional propulsion to electric propulsion are not required in scenario 1 since it analyses the economic capability of the OAU.

Scenario 2 and 3 require additional investment cost of conversion of one patrol boat to the pilot boat to support the operation between terminal 2 and PBG. Based on the calculation, the existing diesel engine must be replaced with the required power. A diesel-engine pilot boat's operational cost (OpEx) consists of maintenance and diesel fuel costs. The maintenance cost comprises repair, consumables, and annual docking. The cost is assumed by multiplying the boat's annual energy consumption with the factor of 0.015$/kWh[36]. The fuel cost was estimated by multiplying daily fuel consumption with the Indonesian diesel price of 1.3 $/kg[37].

Scenario 2 does not require the annual fuel cost since the pilot boats will be operated on the battery using the RES from PV arrays, and it also does not cost the emission price as a consequence of fully electric propulsion.

The input data for analysis shows that the fuel price of diesel oil is 42 $/GJ[38], and the CO_2 emissions generated by the pilot boat cost was estimated to be 75 $/ton according to the suggestion for the IMO for carbon taxing[39].

The boat electrification's investment cost (CapEX) comprises conversion and battery price. The electrification of the boat will be conducted by converting the conventional diesel engine into an electric boat. The conversion rate is 275 $/kWh[22]. The primary cost for the pilot boat's electrification is the battery and storage system installation. According to the analysis that has been conducted, about 45% of the investment cost of the battery-powered boats relates to the battery price[11]. Therefore, the CapEX can be estimated by Eq. 9.

$$CapEx = \frac{BP}{0.45} \tag{9}$$

BP ($/kWh) is the battery price of the lithium-ion battery with 200 $/kWh[40]. The battery storage system's fixed maintenance cost is the battery replacement price within the pilot boat's lifetime. Consequently, the price is similar to the CapEX of the battery, with a slight reduction of percentage to 50%. It was assumed due to the eviction of the installation cost, which is only retrieved in the building phase. The electricity cost in Indonesia differs depending on the power plant type. The price of the electricity from the PV array, which will be the primary source of the electricity, is 0.1089$/kWh[41]. The annual cost of electricity is calculated by multiplying the pilot boat's annual energy consumption and the electricity price.

The abovementioned prices regarding the cost of electricity, maintenance cost, and emissions are utilised with an analogous case in battery-powered fishing vessels. Although the location was in Croatia, these prices are relevant for the preliminary assumption.

3. Results and Discussion

In this designated section, attention is directed towards examining the energy demand for battery-powered pilot boats and exploring the integration of renewable energy sources (RES) with port and transport demand.

3.1 Energy Demand for Battery-Powered Pilot Boats

A pilot boat model designed by BRIN is utilized for the simulation of a battery-powered pilot boat at Lembar Port. The simulation is carried out using the MARIN DESPPC 1999 software, which is widely applied in naval architecture for analyzing the hydrodynamic performance of different hull forms, resistance calculations, and vessel propulsion systems, helping to optimize the design for efficient operation[42,43)]

Based on simulations conducted in the MARIN DESPPC 1999 program on a pilot ship model developed by BRIN with main dimensions of length overall 14 meters, breadth of 4 meters, height of 1.8 meters, and draft of 0.65 m, the engine power was obtained as depicted in Fig. 8. The software simulation results for calculating the pilot boats' engine power based on the average speed (V_{ave}). The $P_{ME,ave}$ is increasing steadily with the rise of the V_{ave} and starts to experience an exponential increase where the target speed was above 18 knots. The required engine power for the pilot boats for T1 and T2, T1, and T2 are 126 kW for V_{ave} of 14.5 knots, 119 kW for V_{ave} of 14 knots, and 138 kW for V_{ave} of 15.5 knots, respectively. The highest engine power is for the T2 terminal since it has the shortest route.

Table 5 shows the energy demand, daily energy consumption, and the number of batteries needed according to the variations of the routing scenario. As expected, if the pilot boat serves two terminals, the EC_{daily} is considerably higher than the individual terminal route with 164.5 kWh. The total number of batteries needed is 25 on a single pilot boat for two terminals. Based on the calculation, the space arrangement and modification of the battery space should be conducted.

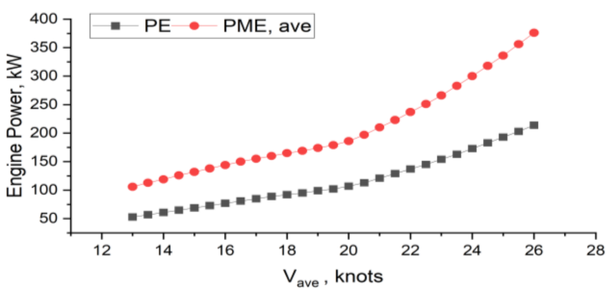


Fig. 8: The main engine power average with the speed variations.

Table 5. The energy demand and battery capacity for battery-powered pilot boats with particular scenarios.

Route Scenario	P_{ave} (kW)	EC (kWh/nm)	EC_{daily} (kWh)	BC_{BEF} (kWh)	$n_{battery}$
T1, T2	126	9.64	164.5	246.76	25
T1	119	9.08	112.4	168.96	17
T2	138	9.17	42.75	64.12	7

Table 6 shows the energy demand results from pilot boats with particular scenarios. Based on the OAU condition, one diesel-engine pilot boat consumes about 10.60 tons of fuel yearly and produces 33.36 tons of CO_2 yearly. Conversion of one electric pilot boat with 49.35 MWh annual electricity demand will eliminate emissions and reduce fuel consumption. The third scenario was designed to reduce the demand and battery capacity and replace the transport demand with a smaller diesel-engine pilot boat to support the pilot service for the T2 terminal, with a shorter route than the T1 terminal. In the third scenario, the electrification of the pilot boat still commences. However, the battery-powered boat has a designated route from and to the T1 terminal with a yearly electricity demand of 33.78 MWh, which is considered a distinct difference from scenario 2. As compensation for using the diesel-engine pilot boat for the T2 terminal, the boat still produces 8.67 tons of CO_2 annually and consumes 2.75 tons of fuel.

Table 6. Yearly fuel and electric demand and emissions generated with specific scenarios.

Scenario	Explanation	Yearly Fuel Consumption (ton)	Yearly Electric Demand (MWh)	CO_2 emission (ton CO_2)
1	1 Diesel Pilot Boat	10.61	-	33.04
2	1 Electric Pilot Boat	-	49.35	-
3	1 Electric and 1 diesel Pilot Boat	2.75	33.78	8.58

3.2 Integration of RES with Port and Transport Demand

Jeranjang PV Array is geographically nearest to the Port of Lembar. However, considering its maximum capacity of 75.6 kWP, it is only sufficient to accommodate energy demand for transportation, i.e. the operation of the pilot boat in scenario 2. Figure 9 illustrates the energy balance between RES and transport demand with the peak power of the Jeranjang PV Array. What can be seen is that the RES supply from the PV array is sufficient to meet the transport demand requirement. The RES reaches its highest in September and October with 20 kW, while the lowest point is experienced in December with a 16 kW monthly average. Since the Jeranjang PV Array is not explicitly utilised for port activities, the analysis was also conducted with half its maximum capacity of 38 kWp. The results show that despite half of the capacity, the electricity generated by RES is still adequate to accommodate the pilot boat's transport demand, as shown in Fig. 10.

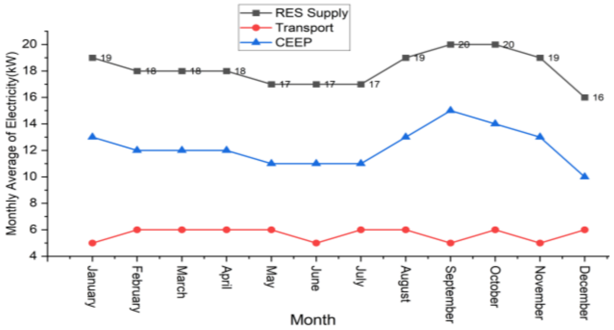


Fig. 9: Monthly Average of RES supply, transport, and CEEP for 75.6 kWP "Jeranjang" PV Array.

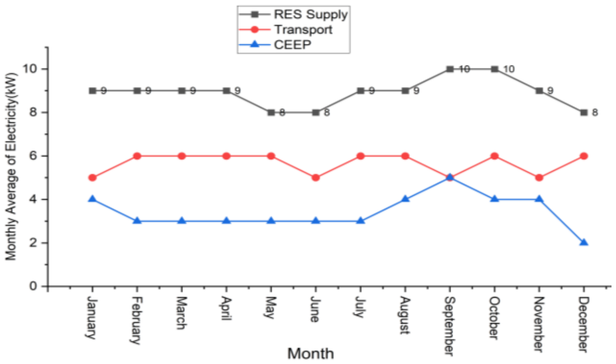


Fig. 10: Monthly Average of RES supply, transport, and CEEP for 38 kW "Jeranjang" PV Array.

Since the nearest PV Array has not generated sufficient electricity for the Port's electricity, another option is to utilise the PV array along the coastline. The "Gili Trawangan" PV power system is located on Gili Island and has a maximum capacity of 600 kWp. It is mainly used to generate electricity for the whole island. Consequently, only 60% of the maximum capacity will be allocated to support the electricity of the Port of Lembar. Figure 10 depicts the energy balance of the integration between port electricity, pilot boat transport, and RES supply. Overall, the energy supplied by the RES is necessary to provide electricity for Port and transport. The Isolated Energy System (IES) peaked in August with 74 kW, comprising 68 kW of port electricity and 6 kW of pilot boat in scenario 2. The main concern for the energy balance is that in December, the RES supply decreased by 25 kW from the maximum power, and the demand from port electricity and transport remains constant. As shown in Fig. 11, the CEEP is approximately 1 kW. The excessive power of 1kW is still significant because it shows that the energy needs of the port and pilot boats are still met by the renewable energy sources even in the December period, where the supply from the PV array decreased due to the start of the rainy season. However, the drop in the supply of RES is considered a problem if there is a technical issue regarding the PV array; there will be a possibility that the RES supply will be insufficient in December. Consequently, the scheme of energy import from another source should be considered.

Figure 12 shows the energy balance for scenario 3, which is the case when the battery-powered pilot boat is only sailing from terminal 1. The graph shows a slight decrease in the transport demand with a 4 kW monthly average, resulting in a drop in the system's total IES. There is a similarity with scenario two regarding the trend, and the maximum power peaked in August. The most compelling part of scenario 3 is that there is a slight increase in CEEP in December to 3 kW compared to scenario 2 with 1 kW.

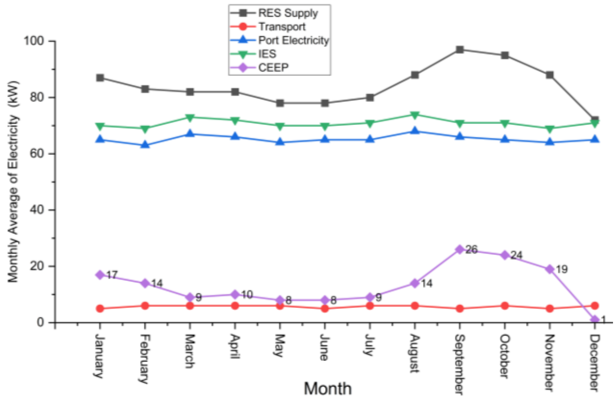


Fig. 11: The monthly average electricity for RES, demand, and CEEP for Scenario 2.

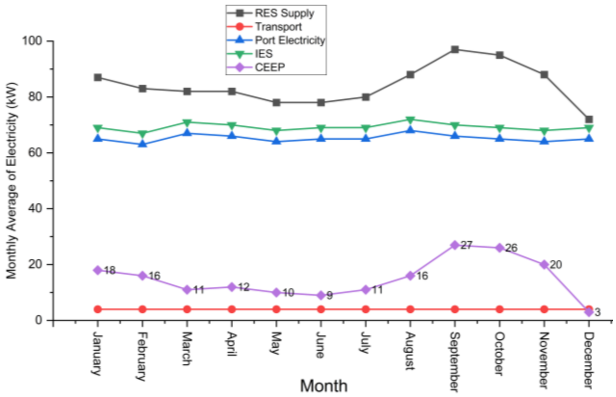


Fig. 12: The monthly average electricity for RES, demand, and CEEP for Scenario 3.

3.3 Economic Analysis

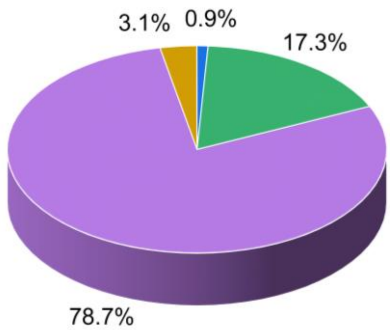
As shown in Table 7, in scenario 1, the OAU cost comprises of the Port's electricity generated by a non-RES power plant, annual fuel cost, and the emission produced by the diesel-engine pilot boat. The analysis of individual costs compared to the total cost in Fig. 13 shows that the electricity cost of the Port is the highest cost at 78.7%, followed by annual fuel cost at 17.3%. There will be additional costs in the boat electrification for scenarios 2 and 3, such as battery installation, boat conversion, and fixed maintenance costs. The battery price of scenario 2 is the highest individual price compared to the total cost of the scenario at 34.1%, followed by fixed maintenance cost at 30.7%, which is the cost of battery replacement.

Table 7. Detailed cost for OAU and port electrification.

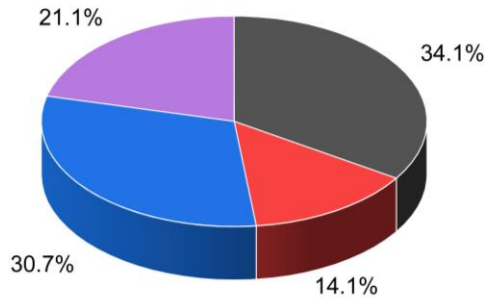
Explanation	Scenario 1	Scenario 2	Scenario 3
Battery price ($)	-	109,671	75,093
Conversion cost ($)	-	45,240	60,732
Fixed maintenance cost ($)	741	98,704	67,584
Annual Fuel cost ($)	13,794	-	3,584
Annual Electricity cost ($)	62,592	67,966	66,272
Annual CO_2 emission cost ($)	2479	-	643

Regarding fixed maintenance cost, for Scenario 1, the highest contribution is the ship repair cost since the fishing vessel is vulnerable to adverse ocean conditions. There is a significant difference between Scenario 1 and the battery-powered fishing vessels because the maintenance cost includes the price of the new batteries. Therefore, for Scenarios 2 and 3, the maintenance cost is slightly under the capital cost.

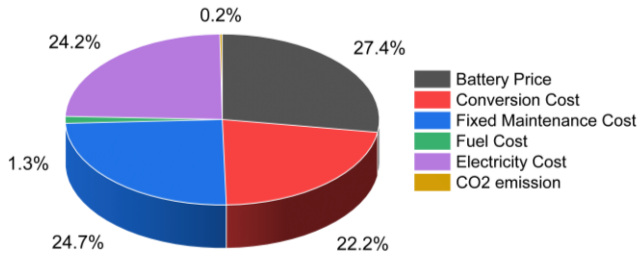
Scenario 3 is an alternative solution to reduce the price of the battery installation by limiting the operation of the electric pilot boat to one terminal scheme and converting one patrol boat into a diesel-powered pilot boat, which will cover the operation of Terminal 2. The findings indicate that Scenario 3 can reduce the cost of electrification by 14.82%, which will benefit the port authority with a restricted budget.



(a)



(b)



(c)

Fig. 13: Share of annual cost for port electrification (a) Scenario 1, (b) Scenario 2, (c) Scenario 3.

3.4 Energy Balance

According to the analysis that has been conducted, the RES generated by the PV power system is sufficient to satisfy the electricity demand of the net zero emission port concept of Port of Lembar. However, in the future, to preserve the sustainability of the net zero emission port concept by harnessing the power from solar irradiation, it should be evident that the plan to construct an additional PV power system designated for the port electricity should be considered.

This finding is also consistent with relevant maritime-related electrification strategies of the vessel's fleet. These results are consistent with[22,44)], which stated that the PV power installed in the island area is generally adequate to support the transport demand from fishing vessels and ferries. However, since the study's location is in the European region, which has a deficient PV power supply in winter, electricity import is required to fulfil the energy demand. In terms of financial analysis, the finding broadly supports other relevant studies regarding ship electrification by using batter[22,23,44)] y, which stated that the investment of the battery-powered propulsion system, which consists of the battery price and maintenance cost, is tremendously more expensive than the conventional one. On the other hand, the investment cost can be reduced by eliminating fuel prices and CO_2 emission costs.

The net-zero emission port concept in this study employs the RES to accommodate the electricity demand for port activities and battery-powered pilot boats, which are part of the port. Nevertheless, to reduce emissions in the port area, several vessels with shorter voyage routes, such as ferries, fishing vessels, and yachts, should be introduced to the electrification technology. Therefore, it is also suggested that calculating the transport demand of battery-powered vessels should be expanded to those mentioned vessels to invigorate the sustainability concept of net zero emission ports by using particular RES.

To achieve net zero emission by port electrification, the port needs massive investment to construct or build its renewable energy sources designated to supply the electricity to the port area, such as solar, tidal, or wave energy. From this study result, it can be indicated that the electricity was generated from an already installed PV array on the island, which will disturb the energy distribution to the island.

Several limitations of this study should be declared. The calculation of engine average power still utilises the conventional computation program based on the model. The numerical software analysis using CFD could enhance the accuracy of the results[45]. Furthermore, battery sizing and capacity should be calculated on various power scenarios and load conditions, such as transit, docking, and idling at the PBG. Moreover, the space arrangement of the battery should be regarded since it will influence the payload and impact the pilot boat's engine power. Furthermore, this study only estimates the energy demand for one year. To reach sustainability, it should be complemented with future scenarios, such as the number of vessels, increased demand for port electricity, and rate of interest for battery prices.

Further research is needed to explore factors that can reduce initial investment costs and ongoing maintenance expenses. Also, studies on more durable, cost-effective, and easily operable components are crucial. These research areas will help identify strategies to optimise the economic feasibility and long-term viability of renewable energy integration at ports.

The findings of this study can provide valuable insights for future renewable energy projects at other ports. By demonstrating the feasibility of operating a port entirely on renewable energy, particularly solar power, this paper offers a compelling case for similar initiatives elsewhere. Port authorities and policymakers can draw upon these findings to design and implement renewable energy projects tailored to their specific contexts, potentially reducing carbon emissions and enhancing sustainability in the maritime industry.

4. Conclusion

This study explores electricity demand and integrating renewable energy sources (RES) using EnergyPLAN software with three scenarios. It aims to assess the feasibility of achieving a net zero emission port. Focusing on the Port of Lembar, a key seaport in southwest Lombok Island, the study analyzes two main pilot boat routes—from Lembar Terminal (T1) to the Pilot Boarding Ground (PBG) and back and from Gilimas Terminal (T2) to the PBG and back. Hourly electricity demand for port operations is also included in the analysis.

Three scenarios have been proposed for the Port of Lembar, which consist of Scenario 1: Operation as Usual (OAU); Scenario 2: electrification of one pilot boat for two terminals with port electricity comes from a photovoltaic (PV) power system; and Scenario 3: full electrification of one pilot boat for Terminal 1, hybrid approach for the pilot boat in Terminal 2, and the RES supplies the port's electricity. Two PV arrays, "Jeranjang" and "Gili-Trawangan", were also incorporated into the system integration calculation using EnergyPLAN Software.

The study indicates that the 360 kWp solar power system in Gili Trawangan can meet the electricity demand for both pilot boats and port operations, with the largest demand coming from the electrification of the pilot boat, which requires a battery capacity of 246.76 kWh, or 25 batteries. Notably, in December, when renewable energy output may decline, energy imports can bridge the gap. This electrification could reduce annual CO2 emissions by 33.04 tons, saving $2,479 in carbon tax. However, it is crucial to note that batteries and maintenance are the largest expenses, accounting for 34.1% and 27.4% of total costs in Scenarios 2 and 3.

This research contributes to reducing carbon emissions and advancing sustainable maritime transport, offering valuable insights for stakeholders such as the Ministry of Transportation, local governments, and port authorities to support green maritime policies.

Acknowledgements

We thank the National Research and Innovation Agency of the Republic of Indonesia and the Ministry of Investment / Indonesia Investment Coordinating Board (BKPM) for funding this research.

Nomenclature

Variables

BC_{BEP}	Battery capacity for a battery-powered pilot boat, kWh
BP	Battery price ($/kWh)
E	CO_2 emissions, tons CO_2
EC	Energy consumption of fishing boat, kWh/nm
EC_{daily}	Daily energy consumption, kWh
EF_{CO2}	Emission Factor of CO_2
l_{total}	Daily total distance of the pilot boat, nm
l_{T1}	Distance from T1 to PBG, nm
l_{T2}	Distance from T2 to PBG, nm
$n_{battery}$	Number of batteries needed
n_{T1}	Daily average number of ships that dock at T1
n_{T2}	Daily average number of ships that dock at T2
P_{ave}	The average boat engine total power, kW

$P_{ME,ave}$	The average power of the main engine, kW
$P_{AE,ave}$	The power of the auxiliary engine, kW
SFC	Specific fuel consumption, kg/kWh
t_{T1}	The average waiting time for the T1, hour
t_{T2}	The average waiting time for the T2, hour
V_{ave}	Average speed of one voyage, knots

Abbreviations

Capex	Boat's investment cost
CEEP	Critical excess of electricity production
CO_2	Carbon dioxide
IES	Isolated energy system
IMO	International Maritime Organization
LCA	Life cycle assessment
EF_{CO2}	Emission Factor of CO_2
OAU	Operation as usual
Opex	Boat's operational Cost
PBG	Pilot boarding ground
PV	Photovoltaic
RES	Renewable energy system
S2G	Ship to Grid
SOC	State of charge

References

1) Clarksons Research, "Shipping Review and Outlook March 2023," London, (2023).
2) P. Balcombe, J. Brierley, C. Lewis, L. Skatvedt, J. Speirs, A. Hawkes, and I. Staffell, "How to decarbonise international shipping: options for fuels, technologies and policies," *Energy Convers Manag*, **182** 72–88 (2019). doi:10.1016/J.ENCONMAN.2018.12.080.
3) P. Serra, and G. Fancello, "Towards the imo's ghg goals: a critical overview of the perspectives and challenges of the main options for decarbonizing international shipping," *Sustainability*, **12** (*8*) 3220 (2020). doi:https://doi.org/10.3390/su12083220.
4) J. Faber, S. Hanayama, S. Zhang, P. Pereda, B. Comer, E. Hauerhof, W. van der Loeff, T. Smith, Y. Zhang, H. Kosaka, and others, "Fourth imo greenhouse gas study. international maritime organization," (2020). https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx (accessed March 20, 2024).
5) B. Wang, Q. Liu, L. Wang, Y. Chen, and J. Wang, "A review of the port carbon emission sources and related emission reduction technical measures," *Environ. Pollut.,* **320** 121000 (2023). doi:10.1016/J.ENVPOL.2023.121000.
6) A. Balbaa, R.A. Swief, and N.H. El-Amary, "Smart integration based on hybrid particle swarm optimization technique for carbon dioxide emission reduction in eco-ports," *Sustainability (Switzerland)*, **11** (*8*) (2019). doi:10.3390/su11082218.
7) C.H. Liao, P.H. Tseng, K. Cullinane, and C.S. Lu, "The impact of an emerging port on the carbon dioxide emissions of inland container transport: an empirical study of taipei port," *Energy Policy*, **38** (*9*) 5251–5257 (2010). doi:10.1016/J.ENPOL.2010.05.018.
8) K. Shin, and J.-P. Cheong, "Estimating transportation-related greenhouse gas emissions in the port of busan, s. korea," *Asian J. Atmos. Environ.*, **5** (*1*) 41–46 (2011). doi:10.5572/ajae.2011.5.1.041.
9) Y. Zhang, Y. Peng, W. Wang, J. Gu, X. Wu, and X. Feng, "Air emission inventory of container ports' cargo handling equipment with activity-based 'bottom-up' method," *Advances in Mechanical Engineering*, **9** (*7*) 1687814017711389 (2017). doi:10.1177/1687814017711389.
10) M.H. Huzaifi, M.A. Budiyanto, and S.J. Sirait, "Study on the carbon emission evaluation in a container port based on energy consumption data," *Evergreen*, **7** (*1*) 97–103 (2020). doi:10.5109/2740964.
11) L. Frković, B. Ćosić, T. Pukšec, and N. Vladimir, "The synergy between the photovoltaic power systems and battery-powered electric ferries in the isolated energy system of an island," *Energy*, **259** (*December 2021*) (2022). doi:10.1016/j.energy.2022.124862.
12) A. Harewood, F. Dettner, and S. Hilpert, "Energy for sustainable development open source modelling of scenarios for a 100 % renewable energy system in barbados incorporating shore-to-ship power and electric vehicles," *Energy for Sustainable Development*, **68** 120–130 (2022). doi:10.1016/j.esd.2022.03.004.
13) S. Ma, E.A. Setiawan, and A.S. Pamitran, "Integration of fisheries technology with solar PV technology in three area of Indonesia Integration of Fisheries Technology with Solar PV Technology in Three Area of Indonesia," in: AIP Conf Proc, AIP Publishing, 2020. doi:https://doi.org/10.1063/5.0014305.
14) N.S. Zulkefly, H. Hishamuddin, F.A.A. Rashid, N. Razali, N. Saibani, and M.N.A. Rahman, "The effect of transportation disruptions on cold chain sustainability," *Evergreen*, **8** (*2*) 262–270 (2021). doi:ttps://doi.org/10.5109/4480702.
15) R. Huerta-Soto, F. Francis, M. Asís-López, and J. Panduro-Ramirez, "Implementation of machine learning in supply chain management process for sustainable development by multiple regression analysis approach (mraa)," *Evergreen*, **10** (*2*) 1113–1119 (2023). doi:10.5109/6793671.
16) A. Habibie, M. Hisjam, W. Sutopo, and M. Nizam, "Sustainability evaluation of internal combustion engine motorcycle to electric motorcycle conversion," *Evergreen*, **8** 469–476 (2021). doi:10.5109/4480731.
17) D.P. Sari, T. Tuswan, T. Muttaqie, M. Soetardjo, T.T.

Putrastyo Murwatono, R. Utina, Y. Yuniati, A.R. Prabowo, and S. Misbahudin, "Critical overview and challenge of representative lng- fuelled ships on potential ghg emission reduction," *Evergreen*, **10** (*3*) 1792–1808 (2023). doi:10.5109/7151729.
18) D.R. Mandasari, K. Yulianto, L. Amelia, A. Aziz, E. Dwi Purnomo, Faisal, and C.S.A. Nandar, "Design and optimization of brushless dc motor for electric boat thruster," *Evergreen*, **10** (*3*) 1928–1937 (2023). doi:10.5109/7151773.
19) L.N. Patil, H.P. Khairnar, J.A. Hole, D.M. Mate, A. V. Dube, R.N. Panchal, and V.B. Hiwase, "An experimental investigation of wear particles emission and noise level from smart braking system," *Evergreen*, **9** (*3*) 711–720 (2022). doi:https://doi.org/10.5109/4843103.
20) N. Sifakis, and T. Tsoutsos, "Planning zero-emissions ports through the nearly zero energy port concept," *J Clean Prod*, **286** 125448 (2021). doi:10.1016/j.jclepro.2020.125448.
21) N.S. Octaviani, D.H. Waskito, Iskendar, A. Muis, N.M.R. Fuadi, Muhajirin, H. Palebangan, K. Ismoyo, D. Kartikasari, N.I. Gutami, and K. Ajidarmo, "The influence of battery-powered engine on the reduction of carbon dioxide production from fishing boats," *Journal of Mechatronics, Electrical Power, and Vehicular Technology*, **14** (*2*) 208–214 (2023). doi:10.14203/j.mev.2023.v14.208-214.
22) M. Korican, L. Frkovic, and N. Vladimir, "Electrification of fishing vessels and their integration into isolated energy systems with a high share of renewables," *J Clean Prod*, **425** (*September*) (2023). doi:10.1016/j.jclepro.2023.138997.
23) A. Fan, J. Wang, Y. He, M. Perčić, N. Vladimir, and L. Yang, "Decarbonising inland ship power system: alternative solution and assessment method," *Energy*, **226** 120266 (2021). doi:10.1016/j.energy.2021.120266.
24) M. Perčić, L. Frković, T. Pukšec, B. Ćosić, O.L. Li, and N. Vladimir, "Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation," *Energy*, **251** (2022). doi:10.1016/j.energy.2022.123895.
25) M. Perčić, N. Vladimir, and A. Fan, "Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: a case study of croatia," *Appl Energy*, **279** (*September*) (2020). doi:10.1016/j.apenergy.2020.115848.
26) M. Perčić, I. Ančić, and N. Vladimir, "Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the croatian short-sea shipping sector," *Renew. Sustain. Energy Rev.*, **131** (*December 2019*) (2020). doi:10.1016/j.rser.2020.110028.
27) H. Lund, J.Z. Thellufsen, P.A. Østergaard, P. Sorknæs, I.R. Skov, and B.V. Mathiesen, "EnergyPLAN – advanced analysis of smart energy systems," *Smart Energy*, **1** 100007 (2021). doi:10.1016/j.segy.2021.100007.
28) D.H. Munah, I.W. Suteja, and I.G.P. Warka, "Analysis on performance of lembar seaport based on the criteria of port performance," *Unmas Denpasar Kampus Mataram*, **01** 1–14 (2016).
29) Ministry of Transportation, "Port of Lembar Master Plan, West Nusa Tenggara Province," 2021.
30) M. Perčić, I. Ančić, and N. Vladimir, "Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the croatian short-sea shipping sector," *Renew. Sustain. Energy Rev.*, **131** (*December 2019*) 110028 (2020). doi:10.1016/j.rser.2020.110028.
31) International Maritime Organization, "MEPC. 364(79), Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for new ships," London, 2022.
32) I. Ančić, N. Vladimir, and D.S. Cho, "Determining environmental pollution from ships using index of energy efficiency and environmental eligibility (i4e)," *Mar Policy*, **95** (*May*) 1–7 (2018). doi:10.1016/j.marpol.2018.06.019.
33) M.R. Kusharyadi, T.M. Sihombing, and S. Suntoro, "OPERATIONAL PERFORMANCE ANALYSIS OF LOADING AND UNLOADING CONTAINER TERMINAL OF LEMBAR SEA PORT BASED ON PORT PERFORMANCE CRITERIA," STIMLOG INDONESIA, (2021).
34) F. Antonio Barrozo Budes, G. Valencia Ochoa, L.G. Obregon, A. Arango-Manrique, and J. Ricardo Núñez Álvarez, "Energy, economic, and environmental evaluation of a proposed solar-wind power on-grid system using homer pro®: a case study in colombia," *Energies (Basel)*, **13** (*7*) 1662 (2020). doi:https://doi.org/10.3390/en13071662.
35) European Comission, "Photovoltaic geographical information system (pvgis)," (n.d.). https://ec.europa.eu/jrc/en/pvgis (accessed May 5, 2023).
36) N.L. Trivyza, A. Rentizelas, and G. Theotokatos, "A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability," *Energy Convers Manag*, **168** (*May*) 128–149 (2018). doi:10.1016/j.enconman.2018.04.020.
37) Iskendar, A. Muis, Waluyo, K. Ismoyo, F.A. Binaruno, M.A. Widodo, D.A. Wibowo, N.I. Gutami, N. Shabrina, S. Sadiah, and K. Ajidarmo, "Comparative analysis of conventional and electric motor propulsion systems for 'sandek' fishing boats in west sulawesi from a sustainable economical aspect," *E3S Web of Conferences*, **484** (2024). doi:10.1051/e3sconf/202448403002.
38) U. Energy Information Administration, "Price of petroleum and other liquids," (2024). https://www.eia.gov/petroleum/gasdiesel/ (accessed January 6, 2024).
39) I. Parry, D. Heine, K. Kizzier, and T. Smith, "Carbon

taxation for international maritime fuels: assessing the options," *IMF Working Papers*, **18** (*203*) 1 (2018). doi:10.5089/9781484374559.001.

40) M. Perčić, L. Frković, T. Pukšec, B. Ćosić, O.L. Li, and N. Vladimir, "Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation," *Energy*, **251** 123895 (2022). doi:10.1016/j.energy.2022.123895.
41) Cabinet Secretariat of Republic of Indonesia, "Gov't adjusts electricity tariffs," (2022).
42) C. Kusuma, I.M. Ariana, W.H. Nugroho, E.B. Djatmiko, A.A. Masroeri, and Sutardi, "Design propeller of fast missile boat 60 m by using gawn series," *IOP Conf Ser Mater Sci Eng*, **1052** (*1*) 012026 (2021). doi:10.1088/1757-899x/1052/1/012026.
43) C. Kusuma, I.M. Ariana, and B. Ali, "Redesign kcr 60m bow with axe bow type to reduce ship resistance," *IOP Conf Ser Earth Environ Sci*, **557** (*1*) 012033 (2020). doi:10.1088/1755-1315/557/1/012033.
44) L. Frković, B. Ćosić, T. Pukšec, and N. Vladimir, "The synergy between the photovoltaic power systems and battery-powered electric ferries in the isolated energy system of an island," *Energy*, **259** 124862 (2022). doi:https://doi.org/10.1016/j.energy.2022.124862.
45) V.K. Agrawal, L.N. Patil, K.V. Chavan, and U.D. Nimbalkar, "A computational analysis of heat transfer in solid and vented disc brakes: cfd simulation and thermal performance assessment," *Multiscale and Multidisciplinary Modeling, Experiments and Design*, **7** 4735–4749 (2024). doi:10.1007/s41939-024-00400-y.