

Techno-economics of Hybrid System Electrification of Roll-on/Roll-off Vessels in the Philippines

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The shipping industry is vital for archipelagic countries like the Philippines as they allow transport between islands, but it is a notable contributor of greenhouse gases. In this work, a framework for analyzing the techno-economic potential of hybridizing a sea vessel with solar photovoltaics, lithium-ion batteries, and diesel generators was presented. The roll-on/roll-off vessel Filipinas Ozamis was considered as a case study due to its commercial use. A 3D model of the roll-on/roll-off vessel was used to measure the ship's dimensions. The load profile of the vessel was estimated from the ship's dimensions, operational profile, route, and speed according to the MarineTraffic AIS database. Afterwards, diesel-only and hybrid energy systems were sized in HOMER Pro to power the electrified ship while minimizing its costs and noting the available space on the sea vessel. Lastly, the profitability of the hybrid energy system was determined. The hybrid system was marked with increased capital costs, but the fuel consumption and CO₂ emissions were 18.50 % and 27.90 % lower than those of the diesel-only system, respectively. The hybrid system also had lower generation costs and 23.64 % higher net present value than the diesel-only system. This framework can be used in the absence of measured load profiles and can be extended to other sea vessels to conduct a national techno-economic assessment of hybridizing the country's maritime industry.

1. Introduction

The shipping industry has been crucial towards the economic development of the Philippines because sea vessels provide a direct route between islands for trade and transport. The passenger vessel fleet accounts for 23.27 % of commercial vessels (MARINA, 2018). Under the passenger vessels, there are 402 conventional passenger vessels, 228 roll-on/roll-off (RoRo) vessels, and 68 fastcraft vessels, among which RoRo vessels have the largest capacity (MARINA, 2018). Sea vessels typically use an internal combustion engine (ICE) for propulsion, which consumes fossil fuels during operation. As a result, the shipping industry becomes one of largest contributors of greenhouse gas emissions.

The hybridization of sea vessels is seen as an alternative to the continued reliance on ICEs. Hybridization refers to the integration of renewable energy (RE) technologies, such as solar photovoltaics (PV), into an energy system. This is primarily driven by the rapidly decreasing costs of RE technologies and has the added benefit of reducing CO₂ emissions. Energy storage systems, such as lithium-ion (Li-ion) batteries, are also included to stabilize the intermittent generation of RE. The ICE is then replaced with an electric motor.

There have been studies on the hybridization of sea vessels. Palconit and Abundo (2018) conducted a pilot study of an electric boat system as a reference for the viability of inter-island transport of 15 m-long electric ferries in the Philippines. Lee et al. (2013) also modeled a ferry operating in Geoje Island in South Korea that utilizes a 3.2 kW solar PV + battery + generator system. However, these two studies have limited applicability for commercial ships that have larger power demands. Al-Falahi et al. (2019) proposed a methodology to determine the optimal size for the energy storage system of a hybridized ship considering shore charging. Their study, however only considered the operational costs of the hybridized RoRo vessel and did not

consider the capital costs in their economic analysis. Andersson and Logason (2015) studied the feasibility of a hybrid propulsion system for a longliner fishing vessel. They used cost factors to estimate the capital costs of retrofitting, but they did not consider operational costs in their analysis.

In this work, a framework for assessing the techno-economic potential of a hybrid energy system for a Philippine RoRo vessel is presented. This is performed by first generating the load profile based on the vessel's speed data and dimensions. The energy system components were then sized in HOMER Pro while considering size constraints due to the limited space in the ship. Lastly, the cost of the energy system was analyzed through a techno-economic analysis and a profitability assessment considering the commercial activity of the shipping vessel.

2. Methodology

2.1 Case study

The RoRo vessel M/V Filipinas Ozamis from Cokaliong Shipping Lines is considered for this case study. It operates from the port of Cebu in Central Visayas (10.3118 °N, 123.9230 °E) to the port of Nasipit in Agusan del Norte (8.9826 °N, 125.3461 °E). The vessel uses two 2,211 kW ICEs to drive its single screw propulsion system, and two 400 kW generators to power the auxiliary load (Bureau Veritas, n.d.). Figure 1 shows the route of M/V Filipinas Ozamis.



Figure 1: The Cebu-Nasipit route (roundtrip) of M/V Filipinas Ozamis.

2.2 Load profile

The load profile of the ship was estimated in the absence of measured energy consumption data. The load profile was divided into the propulsion load for moving the ship and the auxiliary load for powering utilities as shown by Figure 2. The first cruising operation (Nasipit to Cebu) has a peak load of 2.53 MW, while the second cruising operation (Cebu to Nasipit) has a peak load of 2.18 MW.

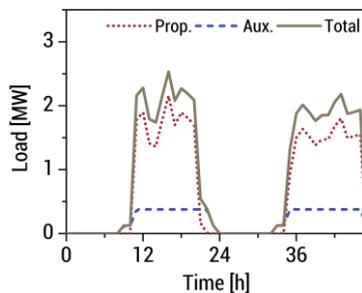


Figure 2: Propulsion (red), auxiliary (blue), and total (gray) load profile of the RoRo vessel.

The propulsion load was calculated using the ITTC 1978 performance prediction method presented by Birk (2019), which requires the hydrodynamic resistance of ship and the propeller type as input. For the propeller type, a warship propeller with model number IOT319L (Cumming and Pallard, 2006) was assumed. The hydrodynamic resistance was calculated via the Holtrop and Mennen method (Birk, 2019) as shown in Eq(1). This method is based on the regression analysis of a vast range of ship model tests, which gives it a wide range of applicability (Birk, 2019). These resistance terms can be calculated based on the ship's dimensions and speed data from MarineTraffic's AIS-collecting database (MarineTraffic, 2021).

$$R_T = (1 + k)R_F + R_{APP} + R_A + R_W + R_B + R_{TR} + R_{AA} \quad (1)$$

The auxiliary load of Filipinas Ozamis was based on the data collected on the subcomponent models from a cruise ship from STX France presented by Marty et al. (2012). The cruise ship's auxiliary load requirements on its docking and cruising operations are averaged and scaled based on Filipinas Ozamis' gross tonnage.

2.3 Scenario modeling

Three scenarios were introduced. The first is the ICE scenario, which is also the current scenario. The fuel consumption of the ICE was estimated using the Ship Traffic Emissions Model (STEAM), which was developed based on the fuel usage and emissions of IHS Fairplay ships (Jalkanen et al., 2011). The ratio of the instantaneous propulsive and auxiliary loads to the engine's maximum output power was defined as the engine load (EL). The fuel consumption (FC) was then calculated based on Eq(2), while the CO₂ emissions was determined via the HOMER Pro software.

$$FC = \frac{260}{820} \times (0.455EL^2 - 0.71EL + 1.28) \quad (2)$$

The next two scenarios are the diesel-only and hybrid scenarios illustrated in Figure 3. The diesel-only scenario contains the two 400 kW diesel generators and a third additional generator. The hybrid scenario consists of solar PV, Li-ion batteries, and the three diesel generators from the diesel-only scenario.

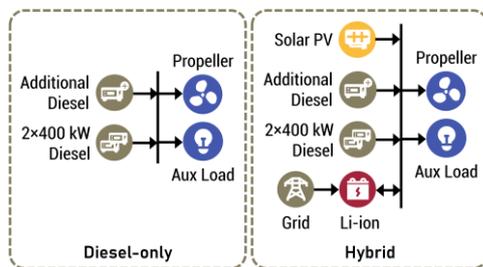


Figure 3: Schematic diagram of the diesel-only (left) and hybrid scenarios (right).

The diesel-only and hybrid scenarios were modeled in HOMER Pro (HOMER Energy, 2021), which determines the optimum sizes (i.e., power and energy ratings) of the components in an energy system that minimize the net present cost (NPC). It also calculates techno-economic metrics, such as the capital cost, fuel consumption, and CO₂ emissions, for comparing the scenarios. A cycle charging dispatch algorithm was assumed to allow the batteries to be charged by the diesel generators and the charging stations. The latter was modeled as a grid component with forced power outages from 9:00 am to 11:00 pm to replicate the ship's docking time. The techno-economic parameters used in the simulations are presented in Table 1. The combined installation cost of the additional diesel generator and electric motor for the hybrid energy system was calculated using a unit cost of 400 USD/kW as given by Ammar and Seddiek (2021), so only the replacement expenses (RepEx) of the additional diesel generator were input into HOMER Pro. Similarly, no capital costs were assumed for the existing generators as they were already present in the ship prior to hybridization.

Table 1: Techno-economic parameters used in the simulations.

Component	Parameter	Value	Ref.	Component	Parameter	Value	Ref.
Li-ion	CapEx [USD/kWh]	619.05	[a]	Grid	Cebu Port [USD/kWh]	0.23	[d]
	OpEx [USD/kWh-y]	0	[a]		Nasipit Port [USD/kWh]	0.15	[e]
	Lifetime [y]	10	[a]		Project	CapEx [USD]	0
Diesel (Addtl.)	RepEx [USD/kW]	124.39	[b]	OpEx [USD/y]		0	[a]
	Diesel (Existing)	RepEx [USD/kW]	123.75	[b]		Discount Rate [%]	5.88
Fuel cost		1	[b]	Project Lifespan [y]	25	[a]	
Lifetime [y]		10	[c]				

[a] Component library of HOMER Pro (HOMER Energy, 2021), [b] (Generator Source, n.d.), [c] (Ocon and Bertheau, 2019), [d] (SunStar Cebu, 2020), [e] (ANECO, n.d)

2.4 Feasibility of solar PV installation

A 3D model of the ship by Sydney M. was obtained from the 3D Warehouse of Trimble Sketchup®, and it was used to set sizing constraints on the solar PV component of the hybrid system. The 220 m² of deck space

allowed the installation of 113 LG400 solar PV panels (LG, n.d.), which corresponds to a power rating of 41.6 kW. This was deemed insignificant in comparison with the power demanded by the ship. Solar PV was omitted from the scenarios because its total power rating does not justify the cost of installation. The installation of solar PV would also yield other problems, such as the variation of solar its power output with the movement of the ship and fluctuations in its power output caused by vibrations (Zhang et al., 2015).

2.5 Profitability assessment

The profitability of the scenarios was quantified based on the net present value (NPV), internal rate of return (IRR), and payback period (PBP). The NPV is defined as the total present value of the cash flows, so a positive NPV suggests a profitable project. The IRR is the discount rate at which the NPV becomes zero, and a higher IRR indicates a faster return of investment. The PBP is the time required for the cumulative cash flow to become zero, so a shorter PBP is ideal.

These quantities require the cash flow to be known. The costs are provided by HOMER Pro during the optimization, while the revenue comes from the salvage value, which was determined by HOMER Pro, and ticket sales, which were assumed to have a margin of 7.52 % higher than the annual operating costs of the ICE scenario. This is based on the recent figures on profitability for the marine transportation industry (CSIMarket, 2021) and corresponds to 370 economy-class daily ticket sales for 360 days of annual operation.

3. Results and discussion

3.1 Techno-economic optimization

The results of the techno-economic optimization are presented in Table 2. The ICE scenario is the current propulsion setup used by Filipinas Ozamis. The diesel-only scenario has a 12.33 % lower fuel consumption and 22.85 % less CO₂ emissions compared to the ICE scenario. The hybrid scenario represents the best-case scenario as it reduces the ship’s fuel consumption by 18.50 % and reduces CO₂ emission by 27.90 % compared to the ICE scenario. Compared to the diesel-only scenario, the hybrid scenario reduces fuel consumption by 7.04 % and reduces CO₂ emissions by 6.69 %. Figure 4 shows the designated engine room space in the 3D model of the RoRo vessel. The available space in the engine room is sufficient for the hybrid system.

Table 2: Techno-economic metrics resulting from the optimized scenarios.

Scenario	Li-ion [kWh]	Diesel* [kW]	CapEx [10 ³ USD]	Fuel Use [10 ⁶ L/y]	CO ₂ [10 ⁶ kg/y]
ICE	0	0	0	2.70	8.10
Diesel-only	0	2,050	820	2.37	6.26
Hybrid	493.5	2,050	1,431	2.20	5.84

*Additional diesel on top of the two 400 kW diesel generators.

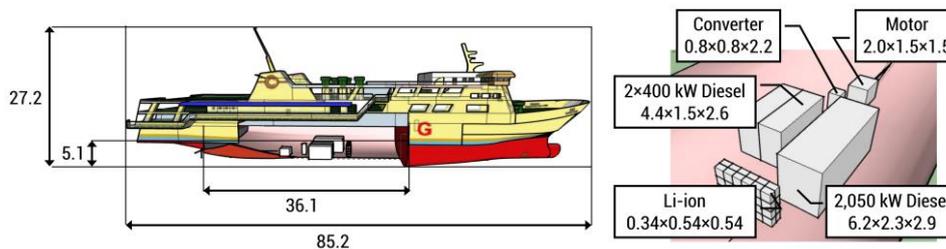


Figure 4: Fitting of the hybrid system components in the engine room of M/V Filipinas Ozamis. Component dimensions are in LxWxH. All dimensions are in meters.

The power flow of the hybrid scenario during two round-trip operations is presented in Figure 5. From 10 a.m. to midnight of each day, the diesel generators supply most of the power demand of the ship. The batteries are used to serve the instantaneous increase in power demands. Once docked, the batteries are connected to the port grid to be charged at full capacity for the operation the next day. An increase in SOC during the hours when the ship is docked can be observed. While the batteries can be charged solely from the grid, and fuel consumption and CO₂ emission will be reduced, the operational costs will significantly increase. This is due to the high electricity costs associated with the Cebu port grid.

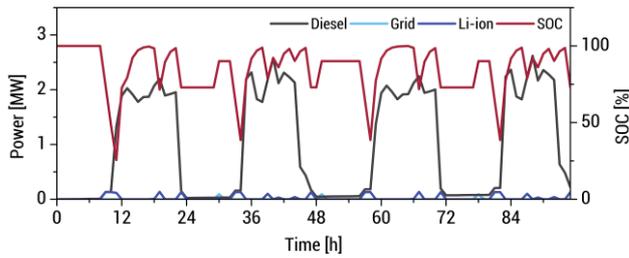


Figure 5: Power output of the diesel, charging station, and Li-ion batteries as well as the state of charge (SOC) of the battery under the optimized hybrid scenario.

3.2 Profitability analysis

The cumulative cash flows and summary metrics of the scenarios are presented in Figure 6 and Table 3, respectively. The NPV of the hybrid scenario is expected to increase by 173 % compared to the ICE scenario and 23.64 % compared to the diesel-only system. Considering the large IRR and low PBP, the electrification of the RoRo vessel is a worthwhile investment. Moreover, the hybrid system's decreased reliance on diesel would reduce CO₂ emissions and increase the industry's resilience against fuel price shocks.

Table 3: Techno-economic metrics resulting from the optimized scenarios.

Scenario	NPV [10 ⁶ USD]	IRR [%]	PBP [y]
ICE	2.625	N/A*	N/A*
Diesel-only	5.790	56	1.12
Hybrid	7.159	40	2.06

*The ICE scenario is the existing setup of Filipinas Ozamis. No investment was involved.

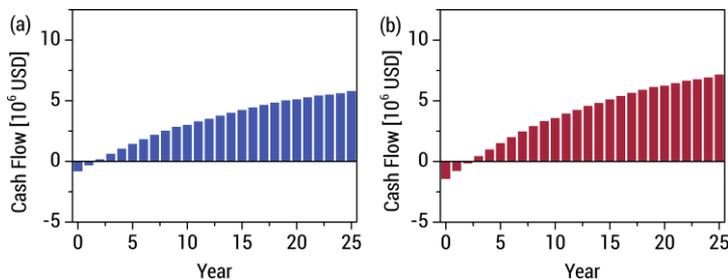


Figure 6: Cumulative cashflow of the diesel-only (a) and hybrid (b) scenarios.

4. Conclusions

In this work, a framework for evaluating the techno-economic feasibility of hybridizing a sea vessel was discussed. The framework was designed for cases where the measured load profile was not available. The hybridized vessel was powered by a 2,050 kW diesel generator, two 400 kW diesel generators, and 493.5 kWh of Li-ion batteries. The fuel consumption was reduced by 18.50 % and the CO₂ emissions by 27.90 % compared to the ICE scenario. Retrofitting the vessel will need USD 1,430,900 initially, but the profitability analysis shows the investment has an IRR of 40 % and a PBP of 2.06 years. This should increase its appeal not only for RoRo vessels, but for other vessels in the Philippines as well.

In future work, the framework can be improved so that a national assessment of ship hybridization can be conducted. A rating system that will look at a ship's size, route, powering requirements, fuel consumption, and CO₂ emissions can be developed to evaluate a ship's potential for hybridization. Exploring the scenario where charging stations will serve as the sole charger for the batteries can be a point of research. Different ports in the country could be examined for their suitability to function as charging stations based on the number of ships that stop at the port, the port's location relative to the route taken by a ship, and the capacity of its grid.

Nomenclature

EL – engine load, -

FC – fuel consumption, L

k – hull form factor, -	R_F – frictional resistance, N
R_A – model-ship correlation resistance, N	R_T – total resistance, N
R_{AA} – air resistance, N	R_{TR} – immense transom resistance, N
R_{APP} – appendage resistance, N	R_W – wave resistance, N
R_B – bulbous bow resistance, N	

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