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Electrification of Inland Waterway Transport: Analysing Lifetime Emissions and Costs - A Case Study of Bolgatty-Wellington Island Route in Cochin

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ABSTRACT

This research investigates the feasibility and sustainability of inland waterway transportation in Kerala, focusing on Ro-Ro ships operating between Wellington Island and Bolgatty. Utilizing the GREET 2022 software, comprehensive life-cycle assessments (LCAs) are conducted for three ship configurations: a conventional diesel engine-powered Ro-Ro ship, a battery-powered variant and lastly a variant integrating the photovoltaic system. The primary objective is to evaluate the economic viability of these configurations using concept design data, equipment supplier information, and regional ship operator data. Findings reveal environmental and economic factors with the photovoltaic-enhanced battery-powered Ro-Ro ship identified as the environmentally superior option. This study offers insights into the sustainable development of Kerala's inland waterways, presenting a versatile methodology applicable to Ro-Ro ship fleets seeking to minimize environmental impact and enhance economic viability.

1. Introduction.

The shipping industry's priorities have changed throughout the years, passing from increasing the size and power of the vessels throughout the second half of the 20th century to adopting a greener and more efficient approach in recent years. [1] In fact, the efficiency and eco-friendliness of ships has now become the top priority. This can be seen as international maritime regulators are imposing strict standards, such as MARPOL's Annex VI on NOx (Nitrogen Oxides) and SOx (Sulphur Oxides) emission limits which are the most dangerous gases emitted to the atmosphere. In particular, this issue is even more concerning to the maritime industry as it accounts for 15% and 4–9% of the global NOx and SOx emissions respectively [2,3,4]

The Earth is increasingly facing environmental challenges due to human activities [4,5], with transportation being a major contributor to global warming and air pollution [6,7]. The maritime sector, which handles the majority of international trade, currently accounts for 3% of anthropogenic greenhouse gas emissions [8,9]. However, projections indicate a drastic increase of 150–250% in carbon dioxide emissions by 2050 [8], posing a direct challenge to the goals of the Paris Climate Agreement [13]. These emissions, resulting from the combustion of marine engine fuel, include harmful substances such as SOX, NOX, CO, PM, and greenhouse gases (GHGs) like CO2, CH4, and N2O [14].

In response, the International Maritime Organization (IMO) implemented stringent standards to enforce regulations in specific regions [15, 16, 17]. Beyond environmental concerns, ship exhaust significantly affects human health, notably in ports and shipping routes [18, 19]. Consequently, decarbonization emerges as a primary research goal in the maritime industry [20], focusing on enhancing energy efficiency to reduce fuel consumption, thereby curbing GHG emissions and pollutants [21]. Effective measures like voluntary speed reduction have shown promise in cutting CO_2 emissions [22, 23]. Exploring alternative fuels (biodiesel, hydrogen, electricity, etc.) and transi-

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tioning to hybrid or integrated propulsion systems gain traction [24, 25, 26].

The implementation of renewable power sources onboard leads to a reduction of emitted GHGs, as indicated in many studies. Geertsma et al. [27] presented a review of developments in the field of design and control of Hybrid Propulsion System (HPS) for smart ships analyzing their trends, challenges, and opportunities and finally claiming that a combination of torque, angle of attack, and relevant control strategy could improve their fuel consumption and consequently environmental footprint. In the design and operation of ships with HPS, optimal sizing of power generation units plays a key role, where regularly minimum investment and operating costs are set as objectives [28]. However, most often, expenses related to emission allowance are not taken into account. Ghenai et al. [29] presented an HPS for a cruise ship, where the total power is generated by photovoltaic (PV) cells, fuel cells, and a diesel generator, which also resulted in reduced emissions. The inclusion of a battery system for a diesel mechanical short sea ship was investigated by Ritari et al. [30], who claimed that the battery system can result in significant fuel savings, which become more important with the increase in fuel price.

By investigating a PV cell diesel engine powered ship, Yuan et al. [31] showed that its operation leads to a reduction in both diesel consumption and GHG emissions. Wu et al. studied cost-effective energy management strategies considering hybrid fuel cell and battery propulsion systems for coastal ships, providing a novel so-called reinforcement learning approach for their optimal use [32]. Energy management itself represents an important research topic for both hybrid and all-electric vessels, as can be seen in [32,33]. HPSs are presented for different ship types differing in their purposes and operative performances, as for instance tankers [28], cruise ships [29], passenger ferries [32], offshore platform supply vessels [34], etc., but in most cases, investment costs represent a key issue in their wider application. However, life-cycle assessment (LCA) of a new-build HPS for a ro-ro cargo ship performed by Ling-Chin and Roskilly, ref. [35], by means of GaBi software, resulted in a rather high impact on the environment, human beings, and natural reserves. Furthermore, as reported by Lindstad et al. [36], a combination of battery and internal combustion engines on an existing ship resulted in reduced emissions, but the main obstacle for this retrofit was the price of the battery.

One way to evaluate the profitability of a retrofit is to consider the total life-cycle costs (LCCs) by performing a life-cycle cost assessment (LCCA). Wang et al. [37] investigated the implementation of a solar panel array onboard a ferry where the LCCA results showed that the investment payback period is only three years, which makes a solar panel array not only an environmentally friendly technology but also an economical one. It is necessary to mention that these findings are generally applicable but strongly dependent on a set of assumptions and considered operative conditions [38]

2. Methodology.

A prototype ship on the Bolgatty to Willington Island route in Cochin was investigated for fuel consumption data, crucial for evaluating potential fuel savings by transitioning to renewable energy. Retrofitting the vessel was deemed impractical due to its heavy steel hull. Thus, a concept design integrating weight, sustainability, and efficiency was formulated, leading to a solar-electric Roll-on/Roll-off (Ro-Ro) ferry design, a significant advancement in maritime technology emphasizing sustainability and operational efficacy. A Cost Comparison Analysis between diesel and electric options was conducted using concept design data, equipment supplier information, and regional ship operator data. Additionally, a Life Cycle Analysis (LCA) was performed using the GREET 2022 database to understand the environmental impact of diesel, electric, and solar electric configurations.

3. Comprehensive Overview of the Prototype Vessel.

The prototype Roll-on/Roll-off (Ro-Ro) vessel, M/V C.V. Raman, holds the distinction of being the largest and most energy-intensive ship navigating the Willington and Bolgatty Island route. The Principal Particulars of the vessel is given on **Table 1.**

Table 1: Principal Particulars of the Prototype Vessel.

Type	**Double Ended Catamaran**
Length Overall (LoA)	56.0 m
Length Between Perpendicular (LBP)	54.0 m
Breadth	13.50 m
Depth mld	3.0 m
Design Draft	1.80 m
Design Speed	8 knots in deep water
Main propulsion	2 x 250 kW @100 % MCR
Generator	90 kW Gensets (Greaves Make)
Vehicle Capacity	9 nos. 20ft trucks 3 nos. 40ft trailer trucks (15 TEU in total)
Passenger Capacity	30 Pax and 8 Crew Members

Source: Authors.

From the deck log book data, it was evident that the vessel routinely conducted 14 to 16 trips daily, with each trip between Willington and Bolgatty averaging a duration of approximately 30 minutes. The recorded data indicated an average container number ranging from 5 to 8 TEUs per trip. Additionally, examination of the engine log data unveiled an average daily fuel consumption of approximately 358 litres of high-speed diesel per voyage.

Figure 1: The prototype vessel at the Bolgatty Jetty.

Source: Authors.

This data is used for incorporating an optimum concept design of the vessel.

Table 2: Principal Particulars of the concept Solar Electric Ro-Ro vessel.

Type	Double Ended Catamaran
Length on Deck	35.0 m
Breadth on Deck	10.0 m
Depth mld	1.8 m
Design Draft	0.8 m
Design Speed	6 knots in deep water
Main propulsion	2 x 60 kW pods
Battery	2 x 60 kWh lithium-titanium-oxide (LTO)
Vehicle Capacity	3 nos. 20ft trucks 2nos. 40ft trailer trucks (7 TEU in total)
Generator	50 kW Gensets
Passenger Capacity	25 Pax and 5 Crew Members

Source: Authors.

4. Details of the Concept Design of the Vessel Developed.

The decision to forgo retrofitting, due to the impracticality posed by the significant weight of the current steel hull, prompted the authors to pursue an innovative conceptual design inspired by the M/V C.V. Raman. This new design aims at tailoring optimization for the efficient integration of solar electric systems while prioritizing weight optimization, sustainability, and operational efficiency.

Analysing the deck log book data from the prototype vessel revealed that despite its maximum capacity of 15 TEUs, the average container transport ranged between 5 to 8 TEUs. This observation led to the decision to optimize the concept for a targeted capacity of 7 TEUs, aligning it more closely with observed operational trends. Furthermore, considering the material of construction of the prototype vessel as marine-grade mild steel, the recommended concept proposes the utilization of marine-grade aluminium of 5000 series or an equivalent grade. This shift in material aims to achieve weight reduction, facilitating the incorporation of solar electric systems into the vessel's design.

The proposed design approach strategically addresses crucial considerations such as weight optimization, sustainability, and operational efficiency. By aligning the vessel's capacity with observed operational trends and utilizing lighter materials, the concept aims to enhance overall efficiency while reducing environmental impact. This innovative approach not only addresses the limitations posed by the current steel hull but also sets the stage for the development of a more sustainable and efficient vessel design tailored for the integration of solar electric systems.

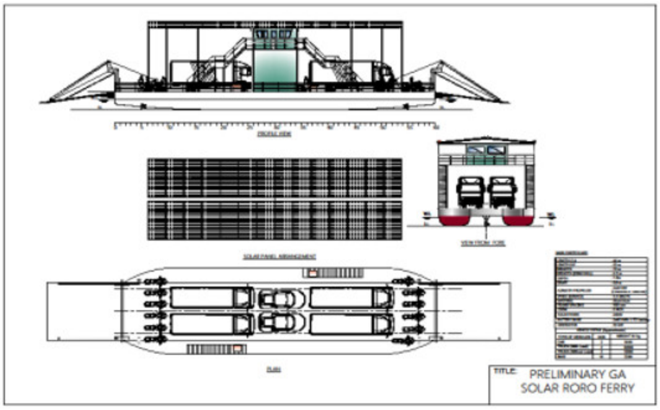
4.1. Comprehensive Methodology for Conceptual Design Development.

The solar-electric RO-RO ferry, featuring an aluminium (marine grade 5000 series or equivalent) double-ended catamaran design, represents a strategic approach to optimizing stability, efficiency, and environmental impact. The choice of aluminium, known for its lightweight yet robust properties, significantly contributes to reduced energy consumption during operation. This design also incorporates a double-ended configuration, enhancing manoeuvrability and mitigating the necessity for complex turning manoeuvres, thereby saving energy and time. With a carefully calibrated carrying capacity of 80 tons, the ferry is engineered to efficiently accommodate both passengers and cargo, minimizing the need for multiple trips, resulting in substantial energy savings, reduced emissions, and heightened operational efficiency.

The vessel's versatility in handling various cargo types, including vehicles and goods, renders it well-suited to meet the diverse transportation needs of the region. In the pursuit of enhanced sustainability and operational efficiency, the design prioritizes seamless integration of solar energy, utilizing sunlight to propel the vessel's operations. This integration is meticulously orchestrated to maximize energy capture and utilization, ensuring sustained and eco-friendly performance throughout its operational cycle. A distinctive feature of the solar-electric Ro-Ro ferry is the strategic placement of solar panels **(Fig 2)** across its deck and superstructure. These panels are positioned thoughtfully to receive direct exposure to the sun's rays for the majority of the vessel's operational time, facilitating optimal energy absorption and conversion, effectively channelling sunlight into electrical energy to power various on-board systems.

The solar-electric Ro-Ro ferry relies on strategically positioned solar panels as its primary energy source, with advanced lithium-titanium-oxide batteries storing excess solar energy during peak sunlight hours. The batteries, arranged independently in each demi-hull for redundancy, provide continuous and reliable power, preventing propulsion system blackouts. Continuous monitoring and remote state-of-charge readings ensure efficient battery management, with cooling and ventilation to maximize battery life expectancy. This integrated

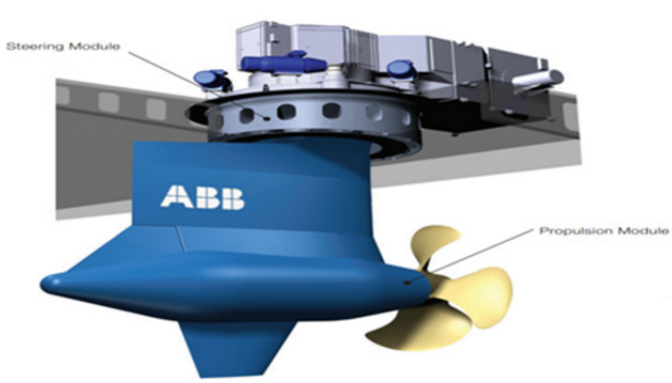
Figure 2: Preliminary General Arrangement drawing showing the arrangement of Solar Panels.



Source: Authors.

approach highlights technological advancements in battery systems and underscores the vessel's autonomy from traditional energy sources. With over 150 hybrid and full battery ships globally [39] the solar-electric RO-RO ferry stands as a sustainable transportation model, setting a benchmark for eco-conscious design practices in the maritime industry. The selection of the dual-podded propulsion system for the vessel is a strategic decision tailored to specific operational needs and environmental challenges [40]. Comprising 2 x 60 kW azimuth podded propulsion units (**Fig 3**), this system perfectly complements the double-ended ferry design, enabling efficient propulsion in both forward and reverse directions, ensuring superior manoeuvrability and operational adaptability. Furthermore, the incorporated electric motors are engineered to endure rigorous environmental conditions, capable of functioning in a robust temperature range and relative humidity, and resistant to salt and chemical corrosion prevalent in tropical coastal regions. The system's motor options range from direct mechanical connection to diesel engines or electrical motors powered by generators (commonly diesel engines) elsewhere on the vessel.

Figure 3: Basic arrangement of the Azipod XO (Ref: ABB Oy, Marine and Cranes).



Source: Authors.

Furthermore, the incorporated electric motors are engineered to endure rigorous environmental conditions, capable of functioning in robust temperature range and relative humidity, and resistant to salt and chemical corrosion prevalent in tropical coastal regions. The system's motor options range from direct mechanical connection to diesel engines or electrical motors powered by generators (commonly diesel engines) elsewhere on the [40].

5. Cost Analysis of Diesel vs. Solar Propulsion Systems for RO-RO Ferries

The initial costs of the project are pivotal in determining its feasibility and potential benefits. This encompasses various components, including design, construction, solar panel installation, lithium-titanium-oxide integration, and the implementation of an electric podded propulsion system. In the design and engineering phase, architectural plans and engineering blueprints are developed, requiring professional expertise to ensure structural integrity, energy efficiency, and overall functionality. The construction phase involves skilled labour and materials to bring the project to life. Solar panel installation costs are influenced by panel type and efficiency. Lithium-Titanium Oxide battery integration involves the batteries and infrastructure for consistent power supply. An electric podded propulsion system, if needed, includes costs for motors, pods, control systems, and installation. Ancillary costs like permits, land acquisition, project management, and contingencies should not be overlooked.

5.1. Capital Expenditure.

The building cost incurred for the construction of the Solar ferry is analysed by splitting up the components of the ferry in to sub systems and analysing the cost of each component. The detailed split up is given on the **Table 3.** The capital expenditure for the proposed Solar Ro-Ro vessel is approximately 954 Lakhs.

5.2. Operational Costs.

The assessment of the operational expenditure pertaining to the prototype diesel ferry's (M/V C.V. Raman) operating along a designated route involves a field study and an examination of engine log data spanning a month. **Table 4** presents a sample subset of the engine log data. This dataset illustrates an average fuel consumption of 358 liters encompassing both the primary and auxiliary engines. The actual consumption value in litres is converted in terms of grams/kwh to calculate the Specific Fuel Oil Consumption (SFOC). The SFOC was arrived as 200g/kwh. The Break Power (P_B) of the prototype is 500 kw @100 % Maximum Continuous Rating (MCR). The engine power for the new concept deign is analysed and optimised as per the preliminary resistance calculation data and the field data obtained. The Break Power (P_B) for the concept design is derived as 60 kw.

Table 3: Capital expenditure components for the solar Ro-Ro ferry.

ITEM	DETAILS
Aluminum Hull	about 33T @ 3.5 lakhs/tonne for marine grade (5000 and 6000 series) and 1 lakh/tonne for fabrication
Superstructure	GRP
Solar Panels	40kW poly-crystalline solar panels, charge controller, cabling etc
Batteries and cabling	60 kWh x 2 sets, LTO Batteries, cabling and connection, plug in charge etc.
Electric Propulsion Motors	Motos in Pods 2 Nos., 600 V DC System, Power Management system
Back up generator	45 kW Generator, low noise; battery charging system
Other Electric	Lighting, Depth sounder, GPS, safety devices
Outfitting	Mooring & Anchoring fittings
Installation	Installation charge of each equipment
Design & Approval charges	Design, Statutory approvals, tests, trials, registration

Source: Authors.

Table 4: Sample engine log data collected from M/V C.V. Raman.

Time	FWD - Port Main Engine			Azimuth Thruster		Thruster Hydraulic Power Pack		AFT - Star Board Main Engine				Azimuth Thruster		Thruster Hydraulic Power Pack	
	RPM	CW PR	CW Temp	Temp	Pressure	Temp	Pressure	RPM	LO Temp	CW PR	CW Temp	Temp	Pressure	Temp	Pressure
8.00	656	0.8	32	25	0	25	18	650	33	0.9	32	25	0	26	18
11.00	1100	0.8	74.1	48	21.3	48	24	1200	81	0.9	74	49	21.2	47	24
13.00	1210	0.8	74	50	21.3	49	36	1110	81.1	0.9	74	50	21.3	50	36
13.45	650	0.8	67	45	0	47	18	650	68	0.9	67	47	0	45	18
18.00	1100	0.8	74	50	21.3	49	32	1210	81.1	0.9	74	50	21.3	50	32
20.40	1200	0.8	74	49	31.4	50	43	1100	81	0.9	74	49	21.2	44	49

Running Hours				Time
	Port M/E	STBD M/E	A/E 1	A/E 2
Previous	65.4	65.4	81.2	103
Current	9.9	9.9	12.8	
Total	75.3	75.3	94	

	Consumption					
	Diesel	M/E Oil	A/E Oil	Thruster Hyd Oil	Winch Hyd Oil	Fresh Water
Previous	11210				5781.1	5491
Received					5779.1	5789
Consumed	358				3817.7	3830.5
Balance	10852				4301.6	

Source: Authors.

Table 5 and Table 6 gives an outline detailing the diverse cost considerations linked to the operational costs of a solar ferry. The economic viability of the solar Ro-Ro concept was thoroughly assessed through a comprehensive break-even analysis. Results given on **Fig 4** indicate that the break-even point can be attained within a timeframe of 6.8 years, starting from the initiation of operations.

Figure 4: Break ? Even analysis for the solar Ro-Ro ferry.

Source: Authors.

Table 5: Operational cost components and the revenue for the Solar Ro-Ro ferry.

Item	Unit	
Vessel capacity	DWT	80
Vessel Speed	Knots	6
Power Required	kW	60
Trip Time	hrs	0.5
Energy Required per Trip	kWh	30
Cost of Grid per kWh	Rs./kWh	7.5
No of Trips per Day	Nos	15
Energy Required per Day	Daily	450
Solar Panel size	kW	40
Average Energy from Sun per day	kWh	140
Energy required from Grid per day	kWh	310
Percentage of Energy from Sun	%	31.1
Energy Cost per day	Rs	2325
Maintenance cost @ 5% of Enegy cost	Rs	116
Total Fuel + Maintenace per Day	**Rs**	**2441**
Number of Staff per day		4
Per Day Rate of Staff	Rs	1500
Cost of Staff per day	Rs.	**6000**
Total Operating Cost per day	Rs	**8441**
Running Days per year	Days	350
Annual Operating Cost	Rs	2954438
Vessel Cost	Rs (Lakhs)	**954**
Depreciation		10%
Depreciation value	Rs	9539250
Average Revenue per Trip	Rs	4000
Occupancy		80%
Total Revenue per day	**Rs**	**48000**
Total Profit per day	**Rs**	**39559**

Source: Authors.

Table 6: Economic analysis comparing with Diesel option.

Item	Unit	Amount
Propulsion time engine load (Assuming a twin Diesel Engines of 60 hp each is installed and @ 85% MCR)	hp	102
	kW	75
Non-propulsion time engine load @40% Main Engine load and rounded upto next higher value	hp	41
	kW	30
SFOC	gm/kWh	200
Propulsion time	hrs	8
Non-propulsion time	hrs	4
Daily fuel consumption	kg	144
Daily fuel consumption(@ 0.85 gm/litre)	litres	169
Annual fuel consumption(@ 360 days /year)	litre	60,964
Annual fuel cost (Rs. 97/litre)	Rs (Lakh)	59
Comparable energy cost for Electric (@ Rs. 2325/day)	Rs. (Lakh)	8
Saving per year	Rs. (Lakh)	51

Source: Authors.

6. Assessment Of Environmental Benefits Of Solar Ferry By Applying LCA Analysis.

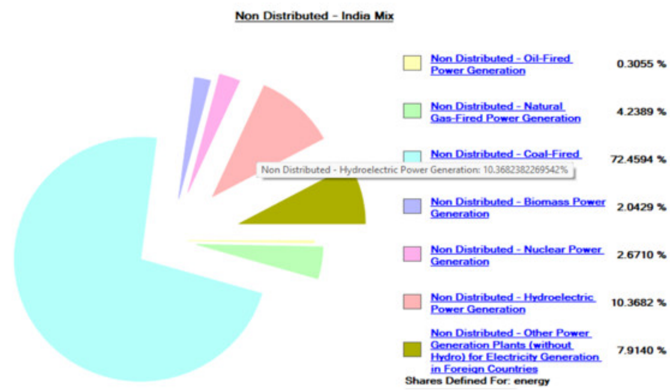
Even though the preliminary investigation suggests the solar-electric ferry option as feasible and viable, extensive Life Cycle Analysis (LCA) is imperative to comprehend the environmental impact of both the solar and diesel options. To conduct this analysis, the authors utilize Life Cycle Assessments (LCAs) employing the GREET 2022 software [41].

This chosen tool offers two options for defining analysis boundaries. The first option involves scrutinizing processes related to raw material recovery, power source production, and its supply to the ship, known as ”well-to-pump” (WTP). The second option expands the analysis to encompass both WTP processes and the utilization of power sources during ship operation, referred to as ”pump-to-wake” (PTW) or ”well-to-wake” (WTW). It is noteworthy that while various life-cycle tools exist with their respective databases, the GREET software is deemed reliable for analyzing relatively straightforward pathways at the level discussed in this paper, as indicated in recent literature [42,43,44].

The comprehensive environmental impact of the power system configuration is represented by WTW emissions and emissions released during the manufacturing process. This inclusive assessment accounts for WTP and PTW emissions as well as emissions from manufacturing processes related to significant elements in the power. system configuration, such as battery, diesel engine, and PV cell materials.

The analysis focuses on emissions originating from diesel production and combustion for propulsion, Subsequently, an examination is conducted on the electric option and its corresponding emissions. Notably, the electric propulsion system entails virtually zero tailpipe emissions, necessitating attention on the electricity generation process for grid charging of batteries. The study further evaluates various sources of electricity production in India, as illustrated in **Figure 5**, to provide a comprehensive understanding of the environmental implications associated with the electric propulsion alternative.

Figure 5: Non-distributed electricity mix of India.

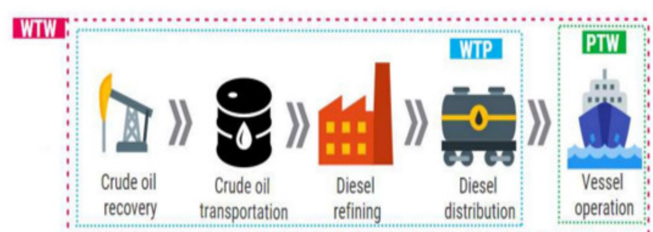


Source: GREET 2022.

7. LCA of Diesel Engine Powered Ship Configuration.

To evaluate the lifetime emissions of diesel engine-powered ships, the entire life cycle must be considered, encompassing crude oil recovery, transportation to the refinery, diesel refining, distribution, and combustion in the engine, as depicted in Figure 6.

Figure 6: The life-cycle of the diesel engine-powered ship configuration.



Source: GREET 2022.

Environmental impact assessment of diesel engines entails two stages: well-to-pump and pump-to-wake scenarios. The well-to-pump results for conventional diesel utilize data from the GREET 2022 database, revealing emissions of 0.42 kg CO_2, 0.658g NOx, 0.167g SOx, and 39.58 mg PM2.5 per litre of crude oil refined (based on US refinery data). Pump-to-wake data indicates a range of emissions, including 3.05 kg CO_2, 10.38 g NOx, 0.187g SOx, and 0.8489g PM2.5. The overall emissions from diesel engine operation are analysed considering an operational profile of 360 days per year over a span of 20 years.

8. LCA of Batery Powered Ship Configiration.

The life-cycle of a battery-powered ship configuration is notably simpler. As detailed in preceding sections, a fully electric ship generates zero pump-to-wake (PTW) emissions, with manufacturing emissions contingent upon the battery type utilized. The well-to-pump (WTP) emissions associated with electricity production constitute the primary emission source in a battery-powered configuration. As discussed earlier, this factor hinges on the electricity generation process specific to the implementing country. From Table 5, it becomes apparent that the daily energy demand stands at 450 kWh. The WTP for generating this power is extrapolated from the GREET 2022 database. The calculated values for CO_2, NOx, SOx, and PM 2.5 emissions are 317.49 kg, 0.2664 kg, 0.339 kg, and 24.66 g, respectively, for producing the requisite kWh for a single day of voyage.

9. LCA of Diesel-Powered Vessel with Solar Panels.

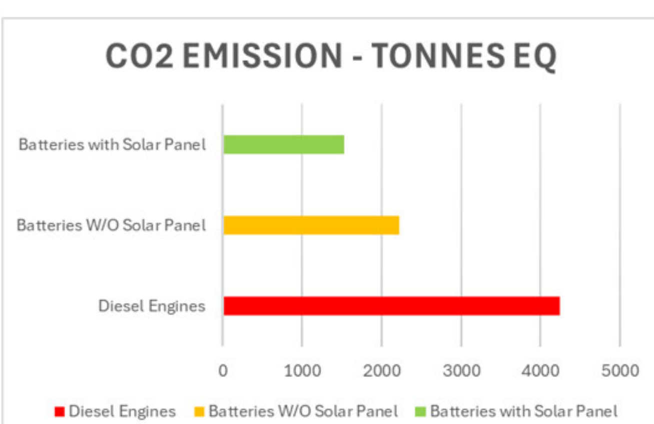
The daily requirement of 450kwh, 140 kwh can be met from the solar panels which is a greener option. The carbon footprint for manufacturing the solar panels is not considered in this study. The integration of solar panels has significantly reduced the emission of CO_2 to 218 kg, NOx to 0.1835 kg, SOx to 0.2341 kg and PM 2.5 to 16.99 gms.

10. Results.

The environmental impact assessment compares three configurations: diesel engines, battery-powered ships, and battery-powered ships with solar panel integration. In the diesel engine configuration, emissions occur during both the well-to-pump and pump-to-wake stages, with significant outputs of CO_2, NOx, SOx, and PM2.5. These emissions stem from refining crude oil and the operational use of diesel engines over a 20-year span.

Battery-powered ships, on the other hand, boast zero emissions during operation, offering an environmentally cleaner alternative. However, it's noteworthy that manufacturing emissions are incurred, predominantly contingent upon the electricity generation process, resulting in outputs of CO2, NOx, SOx, and PM2.5.

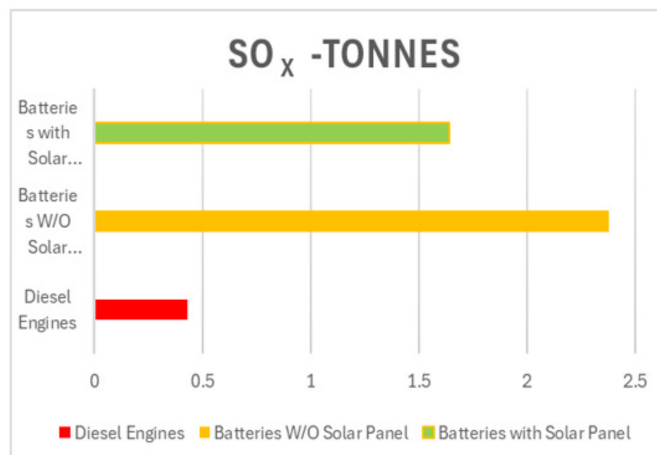
Figure 7: CO2 Emissions in tonnes for various engine configurations.



Source: GREET 2022.

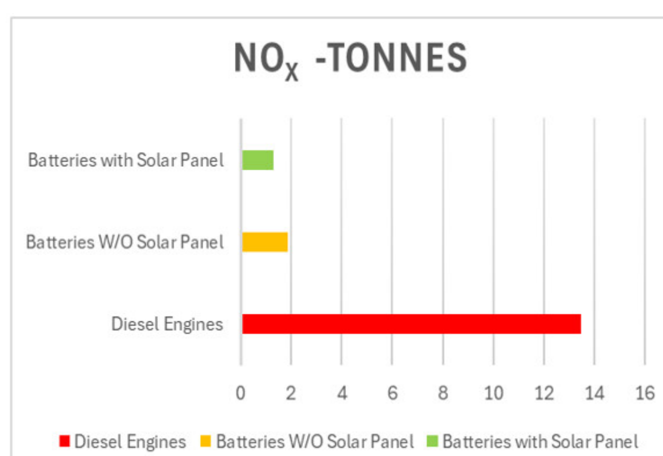
Notably, the emissions of SOx and PM2.5 are particularly pronounced for the electric variant without on board solar panels. This can be attributed to the substantial production of SOx and PM2.5 during electricity generation in India, primarily sourced from coal, which constitutes a significant 72% of the energy mix and is known for its polluting nature. Mitigation strategies could involve transitioning towards greener energy production methods such as hydroelectric and solar alternatives. On a more positive note, the integration of solar panels on the vessel offers a significant reduction in emissions during operation, leveraging renewable energy sources to fulfil a portion of the daily energy requirement. This underscores the potential of solar energy to contribute to mitigating the environmental impact of transportation systems.

Figure 8: SOx Emissions in tonnes for various engine configurations.



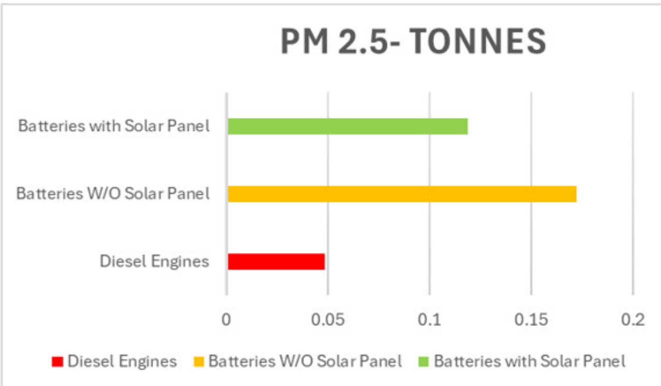
Source: GREET 2022.

Figure 9: NOx Emissions in tonnes for various engine configurations.



Source: GREET 2022.

Figure 10: Particulate Matter (PM) 2.5 Emissions in tonnes for various engine configurations.



Source: GREET 2022.

Conclusions.

Based on the results obtained from the comprehensive life-cycle assessments (LCAs) conducted for three ship configurations, it is evident that the integration of photovoltaic systems significantly enhances the environmental sustainability of inland waterway transportation in Kerala. While the conventional diesel engine-powered Ro-Ro ship and battery-powered variants exhibit varying levels of environmental impact and economic feasibility, the photovoltaic-enhanced battery-powered Ro-Ro ship emerges as the environmentally superior option. This conclusion aligns with the primary objective of the study, which focuses on evaluating the economic viability and sustainability of ship configurations. By leveraging the GREET 2022 software and incorporating concept design data, equipment supplier information, and regional ship operator data, the research provides valuable insights into the development of sustainable inland waterway transportation solutions.

Acknowledgements.

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Data availability statement.

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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