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Assessing Composite Material Viability and Environmental Sustainability in Vessel Construction: Inland Case Study with Offshore Implications

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Abstract

Inland water transport (IWT) plays a crucial role in global transportation networks, providing an environmentally sustainable alternative to conventional land and sea transport. As part of the growing focus on reducing environmental impact and improving efficiency, innovations in vessel construction and propulsion systems are necessary. This study explores the integration of composite materials and advanced propulsion technologies in inland water transport and offshore industries, addressing shared challenges in both sectors, such as infrastructure limitations and environmental sustainability. The study begins with a historical overview of IWT in India, highlighting the decline of traditional transport methods and the resurgence of interest in inland waterways. The formation of the Inland Waterways Authority of India (IWAI) in 1986 marked a key development in the sector's infrastructure. The classification of waterways and the establishment of National Waterways, including the critical NW-3 in Kerala, further underscores the government's dedication to revitalizing IWT. The diverse vessel types operating on these routes, from houseboats and amphibian dredgers to cargo vessels and patrol boats, emphasize the complexity of the sector's operational demands. As a significant innovation, the use of composite materials in vessel construction offers benefits such as reduced weight, increased payload capacity, and greater durability, contributing to enhanced operational performance. Additionally, the adoption of renewable energy propulsion systems, such as solar-electric propulsion, promises to further minimize the environmental footprint and improve sustainability. The study draws parallels with the offshore industry, where similar materials and technologies are employed to meet stringent environmental standards and efficiency demands. By incorporating composite materials and advanced energy systems, both inland and offshore transport sectors are poised to contribute to a more sustainable future for global marine transportation.

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INTRODUCTION

Inland navigation, alongside road and rail transport, constitutes one of the three primary modes of mainland transportation and is widely acknowledged as the most cost-effective and secure means of transit [1]. Vessels transport both freight and passengers along inland waterways, such as canals, rivers, and lakes, linking inland ports and wharfs [2]. Notably, due to fundamental disparities in design requirements, inland waterway vessels are typically prohibited from sea navigation [3, 4].

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During the 19th and early 20th centuries, inland water transport (IWT) played a pivotal role in facilitating trade and commerce in India, primarily along its rivers and canals. However, the emergence of railways and extensive road network expansion led to a diminishing significance of IWT. The sector faced further marginalization due to inadequate development, except in regions such as Assam, Goa, Kerala, Mumbai, and West Bengal, where geographical advantages sustained its relevance. Recognizing the intrinsic benefits of IWT, various committees since India's independence have advocated for its systematic advancement. This advocacy culminated in the establishment of the Inland Waterways Authority of India (IWAI) in 1986, tasked with regulating and developing the nation's inland waterways. The IWAI categorizes these waterways into seven classes based on their characteristics and vessel accommodation capabilities, facilitating planning and development endeavours [5]. Notably, National Waterway-3 (NW-3) in Kerala holds particular significance, spanning from Kollam to Kottappuram along the West Coast Canal and encompassing vital water bodies such as Champakkara and Udyogmandal canals, covering a total length of 205 km [6].

NW-3 supports a diverse fleet of vessels catering to various transportation requirements and industrial needs. These vessels include houseboats, inland cargo vessels, amphibian dredgers, cutter suction dredgers, patrol boats, survey vessels, and work boats/tugs. Their functions encompass maintaining navigational channels, conducting dredging operations, handling cargo, and facilitating passenger transportation, thereby ensuring the smooth operation of NW-3. This study undertakes an analysis of vessel types, categorizing them based on their operational roles. Various construction materials, such as steel, wood, aluminium, and FRP, are utilized for hull construction.

The study focuses particularly on the utilization of FRP construction for boats operating in the region, highlighting its significance in adapting to solar electric and other environmentally-friendly propulsion systems, leveraging the composite construction's high strength-to-weight ratios. However, it is noted that for certain categories of vessels, the operational aspects render composite materials unsuitable. Notably, passenger boats and tourist boats, including houseboats operating in this region, are identified as suitable candidates for composite construction.

METHODOLOGY

The methodology encompasses a comprehensive review of existing literature on inland water transportation and vessel construction, followed by primary data collection through stakeholders and field observations. Vessels operating on National Waterway-3 (NW-3) in Kerala, India, have been classified based on their operational roles and construction materials. An analysis of different construction materials, including steel, wood, aluminium, and FRP, was conducted to assess their suitability in terms of strength, durability, and compatibility with green propulsion systems. Suitable vessel categories for FRP construction were identified based on this analysis. A comparative study was undertaken to evaluate the performance and environmental impact of FRP vessels compared to those constructed using traditional materials. Stakeholder feedback was solicited and incorporated into the study's findings.

CASE STUDY: NATIONAL WATERWAY-3 (NW-3) IN KERALA

The Inland Waterways Authority of India (IWAI) established classifications for India's inland waterways through the Inland Waterways Authority of India (classification of inland waterways in India) Regulation 2006, grouping them into seven classes based on characteristics and vessel accommodation (Table 1).

National Waterway-3 (NW-3), located in Kerala, falls under the Class-III designation. NW-3 spans approximately 205 km, meandering from Kollam to Kottappuram, predominantly tracing the picturesque route of the West Coast Canal. This classification emphasizes NW-3's importance in the realm of inland water transport, positioning it as a vital artery for economic and social activities within Kerala. The designation as a Class-III waterway underscores the navigational capabilities and vessel accommodation suitability of NW-3, affirming its role in facilitating efficient and sustainable transportation along Kerala's waterways.

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Table 1. Classification details of the National Waterways in India [5].

Class	Depth (m)		Bottom width (m)		HC (m)		VC (m above HFL)	Bend radius (m)	Vessel size (SPV) Comb (t)
	River	*Canal*	*River*	*Canal*	*River*	*Canal*			
1	1.2	1.5	30	20	30	20	4	300	100/200
2	1.4	1.8	40	30	40	30	5	500	300/600
3	1.7	2.2	50	40	50	40	7	700	500/1000
4	2.0	2.5	50	50	50	50	10	800	1000/2000
5	2.0	-	80	-	80	-	10	800	1000/4000
6	2.75	3.5	80	60	80	60	10	900	2000/4000
7	>2.75	-	100	-	100	-	10	900	2000/8000

Table 2. Details of the vessels operating in NW-3.

Vessel type	Name of the vessel	Dimensions (m)	Material of construction	Operational Status
Amphibian dredgers	AD Manimala Classic Watermaster III and TV	10.10×32×1.05 m	Steel	Operational
	AD Narmada Classic watermaster IV	10.10×3.2×1.05 m		Operational
Cutter suction dredgers	CSD Champakkara	180×40×1.25 m		Operational
	CSD Kalada	18.36.11.5		Operational
Patrol boats/inspection boats	Kingfisher-1	7.6×1.9×0.9	FRP	Operational
Work hoats/tugs	W.B Jamanthy	15.05.0×2.0		Operational
	W.B. Chempakumy	15.05.012.0		Operational
Passenger boats	Aditya	20.017.01.60	FRP	Operational
	Sooryamsu			Operational

Source: Inland Water Authority of India -(IWAI)

This waterway encompasses various key water bodies, including Champakkara and Udyogmandal canals, creating a diverse and navigable route that meanders through the lush greenery and backwaters characteristic of Kerala. The unique geography of NW-3 not only adds to its aesthetic appeal but also presents opportunities for efficient inland water transport operations.

Specifications of Vessels Operating in NW-3

NW-3 boasts a bustling ecosystem of inland water transport operations, with a diverse fleet of vessels catering to various transportation needs and industries. Amphibian dredgers, cutter suction dredgers, house boats, inland cargo vessels, patrol boats, survey vessels, Passenger and tourist boats, work boats/tugs are among the vessels that ply the waters of NW-3, performing critical functions such as dredging, cargo handling, maintenance, passenger transportation and tourism. Few vessels from various categories were selected as representative vessels and the material of construction of each vessel were identified (Table 2).

From the data it was evident that the FRP mode of construction is most appropriate for the vessels in which the weight reduction of the hull is an important aspect. This holds significantly high when a designer tries to incorporate innovative technologies like solar electric systems into the vessel. A concept design of a solar ferry is analysed for establishing this approach.

Details of the Concept Design of a Solar Ferry Operating in the NW-3

The vessel is designed as a GRP monohull Solar Boat with a capacity for 30 passengers (Figure 1). The design underscores the significance of its Glass Reinforced Plastic (GRP) construction, particularly in its capacity to drastically reduce weight. This weight reduction not only enhances the vessel's manoeuvrability and efficiency but also plays a pivotal role in reducing the power requirements for propulsion. With lighter weight, the vessel demands less energy to propel forward, thereby amplifying the effectiveness of its solar

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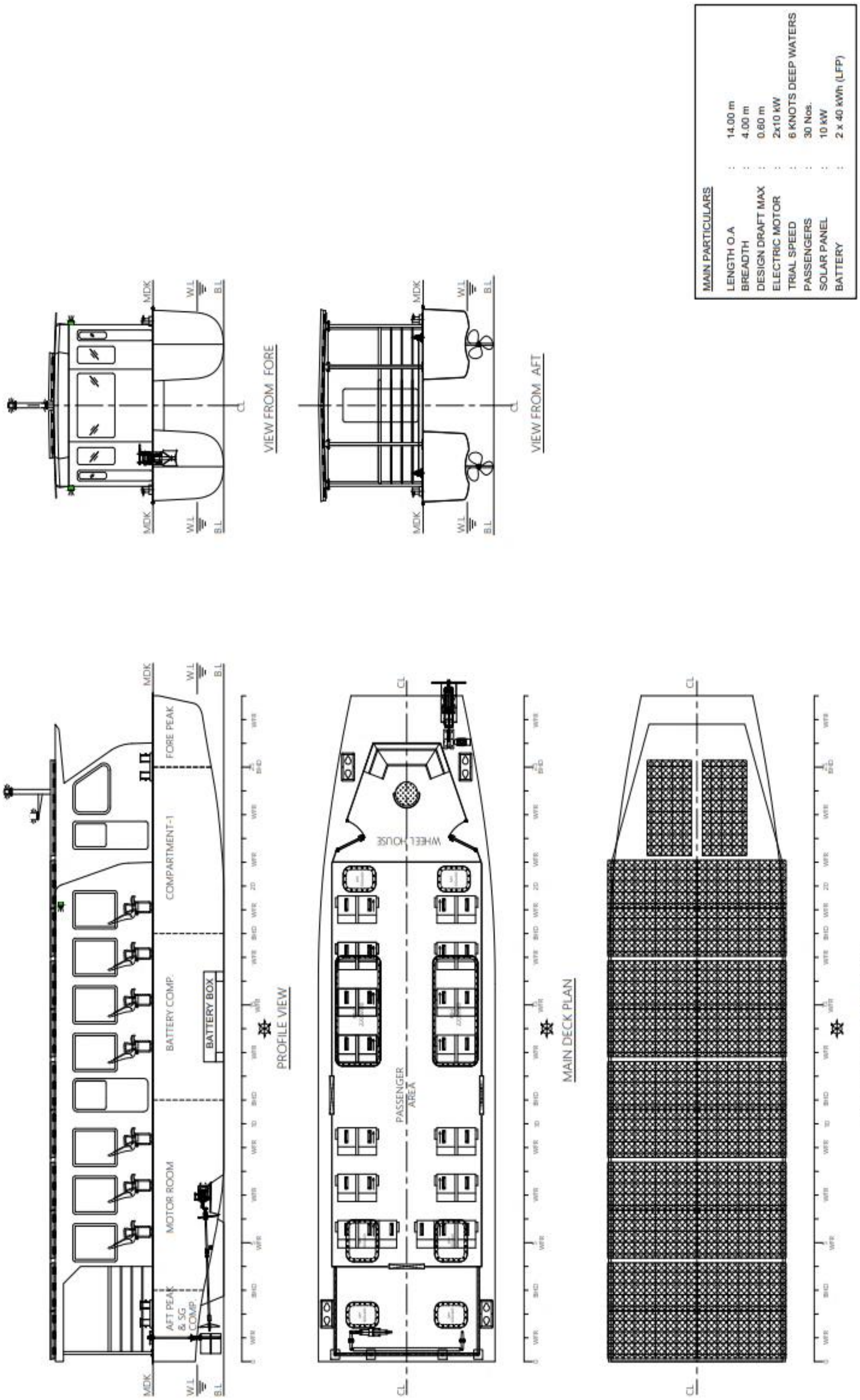

Figure 1. General Arrangement of the GRP Solar ferry.

Table 3. Principal particulars of the concept design.

Type	Catamaran
Length OA	14.00 m
Breadth OA	4.00 m
Draft	0.60 m
Trial Speed	6 knots deep waters
Main engines	2×10 kw Electric Motors
Solar Panels	10 kW
Battery	2×40 kWh (LFP)
Passenger Capacity	30 Nos
Classification	IRS or IACS Inland Vessel Rules

electric propulsion system. By synergizing the lightweight advantages of GRP construction with solar power, the vessel achieves unparalleled levels of sustainability and efficiency in inland waterway transportation, setting a new standard for eco-conscious maritime endeavours. The confirmation of using GRP as the construction material for advanced solar boats operating in NW-3 is provided in Table 3. This data is used to develop an optimal concept design for the vessel.

MARINE APPLICATIONS OF COMPOSITE MATERIALS

Polymeric composites have become firmly established in marine environments, finding application across a spectrum of uses from leisure boats to military vessels and helicopter decks on offshore platforms. Their widespread adoption is largely attributable to their excellent resistance to the harsh environmental conditions [7].

Across the archives of history, technological progress has often been closely intertwined with the development of new materials. Reflecting on different epochs, it becomes evident that materials have not only characterized distinct periods but have also been instrumental in driving progress within those epochs. Key epochs include the Stone Age, Iron Age, Industrial Revolution, Nuclear Age, and Electronic Revolution. In contemporary times, the growing demand for high-performance materials and structural systems underscores the significance of advancements in composite materials, marking a new phase in materials technology [8].

Application of Composites in Boat Industry

For more than half a century, small pleasure boats have been constructed using composite materials. The predominant method of fabrication involves hand lay-up, typically employing glass/polyester composites, although there is emerging interest in injection techniques like Resin Transfer Moulding (RTM) for larger production runs. While wood and aluminium serve as competing materials, the composite's affordability and low maintenance requirements have propelled its market share to approximately 90%. Fiberglass, in particular, dominates the small boat industry due to its ability to facilitate rapid and cost-effective mass production compared to other materials. However, in the realm of large boats and ships, where mass production is less common, fiberglass does not confer a significant construction advantage, leading to greater variability in material selection. Notably, a notable advancement in this sector involves an increasing recognition of the benefits derived from implementing quality control procedures [9].

ADVANTAGES AND DISADVANTAGES OF BOATS BUILT IN FRP

Advantages of using FRP in Boat Building

The reduction of maintenance in FRP (Fiber-Reinforced Plastic) boats is notable for several reasons. Firstly, FRP hulls are constructed as one continuous piece, devoid of joints or gaps, effectively eliminating the risk of leaks typically associated with caulking. Unlike wooden hulls which may suffer from plank shrinkage when exposed to the sun, FRP hulls remain unaffected by such issues, ensuring a

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consistently watertight seal without the need for re-caulking. Moreover, FRP's non-organic composition renders it resistant to rot and immune to marine borers, offering long-term durability. Additionally, FRP's inert nature significantly reduces the risk of corrosion as it does not undergo chemical reactions like metals. The construction process is also simplified with FRP, as once a mould is created, identical hulls can be reproduced efficiently and consistently, requiring less time and labour. Furthermore, the skill level required for FRP boat construction is reduced once basic training is received, contributing to greater accessibility and affordability in boat manufacturing and maintenance.

Disadvantages of using FRP in Boat Building

Once a vessel design is chosen and mould are made, there is little flexibility in altering the choice of vessel, further emphasizing the importance of careful planning and market research. To ensure consistent quality and adherence to safety standards, maintaining a core group of qualified technicians is imperative, although this poses its own challenges in terms of recruitment and retention. Additionally, the use of chemicals in boat manufacturing poses risks of fire and health hazards, necessitating stringent safety protocols and training programs. Furthermore, the initial investment required for establishing a boat manufacturing operation is considerable, requiring careful financial planning and risk assessment to mitigate potential losses.

Comparison of FRP with Other Boatbuilding Materials

Boatbuilding employs a range of materials, each with its own set of advantages and limitations. Wood, a traditional material, relies on a dwindling forest resource and demands highly skilled carpenters. Marine-grade aluminium, prized for its lightweight and durability, necessitates a skilled labour force, whereas ferrocement utilizes inexpensive materials and extensive labour. Steel, more readily available than aluminium, boasts robustness but is prone to corrosion without proper protection, making it a staple in shipbuilding. Table 4 provides a comparison of ultimate strengths per unit weight among FRP, wood, aluminium, and steel for boat construction.

General Precautions to be Followed for FRP Construction

Careful attention must be paid to the correct ratio of catalyst to resin to prevent the occurrence of a “HOT MIX”, which could lead to spontaneous ignition. Any resin emitting smoke should be promptly removed from the shop and doused with water, as should any spills. Other fire hazards, include solvent cleaners, styrene monomer, and rags contaminated with flammable liquids, require appropriate extinguishing methods such as Carbon Dioxide or Dry Powder extinguishers or water spray. In terms of health hazards, all materials used in boatbuilding are toxic if ingested, with catalysts posing a particular risk of burns and potential blindness upon contact with skin or eyes. Adequate fire extinguishers and eye wash stations should be readily available, alongside a comprehensive First Aid Kit. Ventilation in the workshop should facilitate a complete air change every 1–1½ h, with precautions taken to limit atmospheric styrene levels to 100 ppm [10]. Additionally, protective measures like face masks may offer relief during laminating or sanding activities. Delivery and storage of materials, especially resins, present logistical challenges, particularly in tropical climates where shelf life can be compromised by higher temperatures. Attention to storage conditions and timely rotation of stock is essential to ensure material integrity. Reinforcement materials, supplied in sealed packaging, require

Table 4. Comparison of ultimate strengths of FRP with other boat building materials.

Material	Specific weight		Tensile strength	Compressive strength	Elastic modulus
	(1b/ft³)	*(t/m³)*	*(kN/m²×10)*	*(kN/m²×10)*	*(kN/m²×10)*
FRP (CSM)	94	1.5	100	100	6
Wood spruce	42	0.7	55	40	8
ply	40	0.65	16	12	11
Aluminium	170	2.7	120	85	70
Steel	485	7.8	210	190	200

(Source: FAO document on fishing boat construction)

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careful inspection for contamination upon delivery to maintain their bonding properties. These considerations are critical for ensuring safety and quality in boatbuilding operations, particularly in regions where environmental conditions pose additional challenges.

APPLICATION OF FRP IN THE OFFSHORE INDUSTRY

Fiber Reinforced Polymer (FRP) composites have become crucial in the offshore industry, addressing challenges in high-strength, corrosion-resistant applications with minimal maintenance needs. These materials are widely applied to secondary structures such as handrails, ladders, gratings, and safety barriers, where traditional steel is prone to corrosion in harsh marine environments, with FRP now preferred due to its lightweight, strength, and durability characteristics [11–13]. The primary constituents of FRP: glass or carbon fibres within a polyester or epoxy resin matrix, enhance its resilience, making it effective even in extreme offshore conditions. Notably, FRP complies with standards such as those of the American Bureau of Shipping (ABS) and Det Norske Veritas (DNV), proving its suitability for marine environments [14, 15].

Specialized FRP types, like phenolic-based FRPs, demonstrate superior fire resistance, which is essential for offshore platforms that have high fire risk potential [16]. Research shows that the reduced weight of FRP structures decreases platform dead loads, facilitating more efficient structural designs that may reduce construction costs significantly [17, 18]. Furthermore, FRP is highly effective in repair applications, especially for corroded steel pipelines, where FRP wraps provide an extended service life with minimal interruption, a critical advantage in the high-cost, high-risk offshore sector [19, 20]. The adaptability of FRP in complex geometries and its resistance to extreme pressures and temperatures makes it a practical solution for subsea applications, as supported by multiple field studies and case reports [21, 22].

One of the most significant advantages of FRP in offshore use is its low maintenance requirement. Unlike metal structures, FRP materials resist most marine fouling and environmental degradation, leading to less frequent and costly maintenance cycles [23, 24]. As sustainability and cost-efficiency pressures mount, FRP's adoption in offshore sectors, including dynamic installations like wind turbine platforms, is projected to grow [25, 26]. These platforms benefit from FRP's lightweight and corrosion-resistant properties, highlighting the broad potential for FRP's use across offshore industries [27].

CONCLUSION

In conclusion, the integration of composite materials and advanced propulsion systems offers a transformative solution for enhancing the viability and environmental sustainability of both inland and offshore vessel construction. As demonstrated in the case study of Kerala’s waterway network, the use of composite materials, particularly fiberglass reinforced plastic (FRP), significantly reduces maintenance costs, improves durability, and enhances the manoeuvrability of vessels, thereby contributing to operational efficiency. Additionally, the adoption of advanced propulsion systems, such as solar-electric propulsion, aligns with the goal of minimizing environmental impact and improving the sustainability of transport operations in both sectors. Offshore industries, similarly, have witnessed significant advancements in the use of composites and energy-efficient propulsion technologies, addressing similar environmental concerns. However, challenges remain, including the dependence on imported materials, regulatory constraints, and high initial investment costs, which must be overcome to fully unlock the potential of these innovations in both inland and offshore vessel construction. By fostering technological innovation, adopting renewable energy solutions, and encouraging strategic investments, both inland water transport and offshore industries can chart a course towards a greener and more sustainable future, offering viable alternatives to traditional transport methods.

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