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MESSAGE FROM THE CHIEF PATRON

It's an honor and privilege for me as we launch this third volume of the Journal of Engineering and Technology (JET), published by the Faculty of Engineering and Technology (FET), Bangladesh Maritime University (BMU). As the Vice Chancellor and Chief Patron of this esteemed journal, I feel very proud to see this journal's contributions towards the emerging fields of engineering and technology.

Our university has always been striving to enhance academic quality and innovation, and this journal is one of the indications of our support for research, knowledge sharing and enhancement. The articles featured in this volume represent a diverse array of research interests and perspectives, reflecting the dedication and expertise of our faculty members, researchers, and contributors towards engineering and technology. This volume of JET encompasses a variety of engineering topics such as ship recycling, artificial intelligence, renewable energy, energy efficiency, emerging technologies, etc.

I would like to express my sincere appreciation to the editorial board for their continued dedication in upholding the standards of this journal and ethical publishing. I also extend my gratitude to all contributing authors and peer reviewers, whose work and collaboration are vital to the journal's success.

As we move forward, I encourage all researchers, faculty members, and students fromhome and abroad to remain actively engaged in scholarly research and to consider the Journal of Engineering and Technology (JET) as a vital platform for sharing their work. Your contributions are instrumental in strengthening our academic environment and reinforcing our university's reputation as a center of maritime excellence.

May this volume 3 of JET inspire further exploration, collaboration, and excellence. I look forward to witnessing the continued growth and success of this distinguished journal in the years to come.

Rear Admiral Dr. Khandakar Akhter Hossain, NUP, ndc, psc, PhD
Vice-Chancellor
Bangladesh Maritime University and
Chief Patron, Journal of Engineering and Technology

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EDITOR'S NOTE

It is my honor and pleasure to welcome you to Volume 3 (2025) of the Journal of Engineering and Technology (JET), published by the Faculty of Engineering and Technology (FET) at Bangladesh Maritime University (BMU). As Chief Editor, I am delighted to present this volume—a curated collection of original research articles and scholarly contributions that reflect the latest advancements and emerging trends across diverse fields of engineering and technology.

Over the past two years, we have worked diligently to establish JET as a platform that promotes high-quality research and encourages interdisciplinary collaboration. This progress has been made possible by the dedication and commitment of our editorial team, advisory board, expert reviewers, and contributing authors. The journal's steady growth is a reflection of our collective commitment to academic rigor, integrity, and innovation.

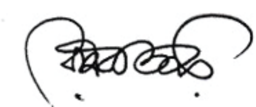
This volume features thought-provoking research on a range of contemporary topics, including ship recycling, renewable energy, artificial intelligence, robotics, energy efficiency, and digital technologies, among others. Each submission has undergone a rigorous double-blind peer review to ensure clarity, scholarly merit, and real-world relevance.

I extend my sincere appreciation to all the authors for submitting their valuable research, to our reviewers for their thoughtful and thorough evaluations, and to the editorial team for their tireless efforts in maintaining the high standards of this journal. Your contributions are the cornerstone of JET's academic integrity and growing reputation.

Looking ahead, I am excited about the future of our journal. We aspire to expand our reach and impact by fostering greater interdisciplinary collaboration, welcoming more international submissions, and further strengthening our peer-review processes—while upholding the highest standards of academic excellence.

I warmly encourage researchers, engineers, and practitioners—both within BMU and beyond—to consider JET as a platform to publish their work or contribute as reviewers. Your continued engagement is vital to the growth and success of our publication.

Thank you for your ongoing support and enthusiasm. Together, let us continue advancing knowledge and shaping a future that is innovative, sustainable, and inclusive. Warm regards,



Commodore Rajib Tripura (E), ndc, psc, BN
Chief Editor
Journal of Engineering and Technology (JET)
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Unified Model for Local Ship Recycling: Better Perspective and Sustainable Practice

Rear Admiral Dr. Khandakar Akhter Hossain, NUP, ndc, psc, PhD[1*], Naval Architect Saiful Islam[2], Dr. S M Rashidul Hasan[3], M. Jurkovič[4]

Abstract

The global maritime industry faces increasing pressure to dismantle end-of-life (EOL) vessels in ways that are both safe and environmentally responsible. As a major center for ship recycling, Bangladesh plays a critical role in recovering valuable materials while managing hazardous waste. This study examines the country's ship recycling practices using seven years of field data (2009–2016) from 26 dismantled vessels of various types. Material Flow Analysis (MFA) was used to track and quantify outputs, showing that reusable materials account for approximately 73% to 95% of Light Displacement Tons (LDT), translating to 1.83 to 1.99 million metric tons annually. Hazardous waste represents around 1+% of LDT, or 17,215 to 22,702 metric tons per year. The findings highlight the current recycling processes, material recovery pathways, and handling of waste, offering insights into areas where safety, efficiency, and environmental management can be improved. While the industry continues to face challenges—including some dependence on manual labor and limited infrastructure and there has been noticeable progress in areas like personal protective equipment (PPE) usage and waste segregation. A positive example of regulatory advancement like around 20 local yards has received (or going to receive) HKC certificate and a dozen are preparing. Overall, the study provides evidence-based direction for developing safer and more sustainable ship recycling practices in Bangladesh.

Keywords: Ship recycling, reusable materials, hazardous waste, HKC, MFA, SRFP

1. Introduction

Ship recycling, as defined by the International Maritime Organization (IMO) in Resolution A.951, encompasses a series of intricate operations—including mooring, beaching, dismantling, material recovery, and reprocessing—aimed at disposing of end-of-life (EOL) ships in a manner that is both safe and environmentally sound. This process is critical for recovering valuable materials, such as steel and machinery, while managing hazardous waste, such as asbestos and oil sludge, in compliance with international regulations. Globally, approximately 1,000 large ocean-going vessels reach the end of their operational life annually, with South Asia, comprising Bangladesh, India, and Pakistan, dominating the industry by handling 85–90% of global

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ship recycling activities. Among these, Bangladesh stands as the foremost hub, processing ~30% of global EOL ships, equivalent to approximately 2,000,000 Light Displacement Tons (LDT) or ~200 ships per year. This activity occurs across ~50 registered ship recycling yards along Chittagong's 20 km coastal belt, with ~35 yards actively operational, making it a cornerstone of the nation's industrial and economic landscape [1,2].

The origins of Bangladesh's ship recycling industry trace back to the 1960s, sparked by the accidental beaching of the Greek ship M D Alpine during a cyclone. Since then, the industry has grown exponentially, driven by favorable geographical conditions, including high tidal variations and flat, muddy shores that facilitate the beaching method—a cost-effective approach where ships are grounded during high tides for manual dismantling. Economically, the industry is a powerhouse, sustaining around 200,000 direct/indirect jobs and ~1 million dependence, while supplying ~50% of Bangladesh's steel demand, significantly supporting local shipbuilding, construction, and secondary industries. The proximity of Chittagong's recycling yards to industrial markets and the availability of low-cost labor further enhance the sector's competitiveness, positioning Bangladesh as the global leader in ship recycling [3,4]. As we know that materials such as asbestos, polychlorinated biphenyls (PCBs), and bilge water coming from EOL ships contribute to soil, air, and water contamination, posing risks to workers and coastal ecosystems. Regulatory frameworks, including the Bangladesh Environment Conservation Act (1995), Ship Breaking and Recycling Rules (2011), Basel Convention (1989), and Hong Kong International Convention (HKC, 2009), aim to address these issues by mandating safe and environmentally sound practices [5].

The current state of Bangladesh's ship recycling industry, however, is somehow unstable. For several decades, India has been Bangladesh's closest competitor in this sector. Presently, approximately 82% of India's ship recycling yards (almost 120 yards) have already achieved compliance with the standards prescribed by the Hong Kong Convention (HKC). In contrast, the picture of Bangladesh on HKC certification by local yards are not up to the standard or acceptable (around 50% of active/operational yards is still unsatisfactory). Through strategic policymaking and substantial investment, India has successfully modernized its ship recycling facilities to meet international benchmarks [Industrial 2025]. Crucially, India did not treat ship recycling merely as an environmental liability; instead, it recognized the sector's immense potential as a global business opportunity and positioned itself accordingly from an early stage. Bangladesh, by contrast, has lagged behind due to gaps in information dissemination, a lack of sustained/stable political commitment, and inadequate government support. Nonetheless, all is not lost; rather international law still offers Bangladesh a lawful pathway for phased implementation of the HKC [5,6].

This study draws on detailed field data from 26 end-of-life (EOL) ships dismantled in Bangladesh to quantify material recovery outputs and associated waste streams across the entire recycling process. Employing Material Flow Analysis (MFA), the study estimates reusable materials at 73–95% of LDT (1,833,461–1,989,252 MT annually) and hazardous waste at 1+% of LDT (17,215–22,702 MT annually). It proposes a sustainable ship recycling process model and material distribution channel, emphasizing improvements in safety, environmental management, and regulatory compliance. By comparing Bangladesh's practices with those of other nations, such as India's Alang Port, this study aims to provide a robust framework for stakeholders to enhance the industry's sustainability and better practice while maintaining its economic viability [7, 8, 9].

2. Methodology

The methodology employed in this research is designed to provide a robust and localized analysis of Bangladesh's ship recycling industry, addressing the gaps in prior studies that relied on foreign benchmarks. Data collection spanned seven years (2009–2016) and was conducted at multiple ship recycling yards in Chittagong, focusing on 26 EOL ships of diverse types and sizes: 5 bulk carriers, 5 tankers, 6 container carriers, 5 cargo ships, and 5 other vessel types (e.g., passenger ships, offshore vessels). The selection of ships was purposive to ensure a representative sample, capturing variations in ship design, age (15–25 years), and origin (e.g., Asia, Europe, Americas). Ship selection criteria included LDT range (8,000–60,000 MT), operational history, and compliance with regulatory requirements for dismantling. Data was gathered through direct involvement of the author, a naval architect, in collaboration with the Bangladesh Ship Breakers Association (BSBA), yard operators, and regulatory bodies such as the Department of Environment (DoE), Ship Building and Ship Recycling Board (SBSRB), Chittagong Port Authority, and Bangladesh Navy. This multi-stakeholder approach ensured comprehensive and accurate data collection, reflecting real-world practices and operational nuances [1,2,10,11].

A dedicated team comprising six trained data entry workers and a supervising manager was employed to compile detailed inventories of materials and items extracted from each ship. The data collection process, spanning 6–11 months per vessel, involved systematic documentation during pre-beaching, dismantling, and post-dismantling phases. Standardized templates, aligned with HKC (2009) guidelines, were used to categorize materials into reusable (Economic Value Stream, EVS) and hazardous waste (Non-Economic Value Stream, NEVS). Physical measurements were conducted using calibrated industrial scales (accuracy ±0.1%) to weigh steel plates, machinery, and other components, replacing earlier visual estimation methods to enhance precision. Hazardous waste, including asbestos, bilge water, and heavy metals, was quantified through on-site sampling and laboratory analysis at BUET's Environmental Engineering Laboratory, following protocols outlined in the Bangladesh Environment Conservation Act (1995). For instance, asbestos samples were analyzed for fiber content, and bilge water was tested for oil and chemical contaminants, ensuring compliance with national and international standards [4,12,13].

Material Flow Analysis (MFA) was employed as the primary analytical tool to quantify material outputs and waste streams, utilizing STAN software (version 2.5) and Microsoft Excel Broadsheets (version 2010) for data processing. MFA enabled the tracking of material flows from ship dismantling to final distribution or disposal, providing a systematic framework to assess resource recovery and waste management efficiency. Input data included ship specifications (like LDT, dimensions, and material composition), detailed material inventories, and disposal records obtained from yard operators and BSBA. Outputs were categorized into EVS (like steel, machinery, electrical items) and NEVS (like asbestos, oil sludge), expressed as percentages of LDT. To ensure reliability, manual calculations were performed alongside STAN outputs, revealing a minimal variation of ~0.4%, while Excel outputs showed no variation, confirming data consistency. Sensitivity analysis was conducted to assess the impact of ship type and age on material outputs, with results cross-verified against BSBA and DoE records [14,15,16].

Validation of data was achieved through multiple methods. Quantitative data was cross-checked with yard weight logs, BSBA annual reports, and regulatory documentation from the DoE and SBSRB. Qualitative insights were gathered through semi-structured interviews with 15 yard managers, 30 workers, and 5 naval architects, focusing on operational challenges, safety practices, and regulatory compliance. These interviews, conducted in Bangla and translated to English, provided context for quantitative findings, particularly regarding PPE usage and waste management practices. External validation was performed by comparing results with studies from Alang, India, and international benchmarks, ensuring alignment with global standards [7,17]. Nuclear waste and atmospheric/water emissions were excluded from the scope to focus on solid and liquid waste streams, aligning with the study's objectives. The methodology drew on established literature for MFA application in ship recycling and was supplemented by the author's expertise and global best practices [11, 18,19].

Table 1: Summary of 26 Sample EOL Ships (2009–2016)

Ship Type	Number	LDT Range (MT)	Average LDT (MT)	Recycling Duration (Months)
Bulk Carrier	5	15,000–50,000	32,500	6–10
Tanker	5	20,000–60,000	40,000	7–11
Container Carrier	6	10,000–45,000	27,500	6–9
Cargo Ship	5	12,000–40,000	26,000	6–10
Other Types	5	8,000–35,000	21,500	5.5–9

Source: Compiled from Hossain [1,2,20,21].

3. Ship Recycling Practices in Bangladesh

3.1 Industry Overview

The ship recycling industry in Bangladesh, centered in Chittagong, leverages the beaching method to capitalize on high tidal variations and shallow basins, enabling the grounding of EOL ships for dismantling. The process is predominantly manual, utilizing gas cutting torches to segment steel hulls and machinery into manageable pieces, which are transported to stack locations either manually or via small cranes. This labor-intensive approach underscores the industry's reliance on abundant, low-cost labor and proximity to industrial markets, contributing significantly to socio-economic development through employment and steel supply [1,3].

- **Geographical Advantage**: High tidal differences and flat, muddy shores facilitate beaching operations.
- **Economic Drivers**: Low labor costs and robust demand for scrap materials drive industry growth.
- **Employment Impact**: Around 200,000 direct/indirect and ~1 million dependence are sustained, supporting local economies.

3.2 Regulatory Framework

The regulatory framework governing Bangladesh's ship recycling industry integrates national and international standards to ensure safe and environmentally sound practices. Nationally, the industry adheres to the Bangladesh Environment Conservation Act (1995) and Ship Breaking and Recycling Rules (2011), overseen by the Department of Environment (DoE) and Ship Building and Ship Recycling Board (SBSRB). Internationally, compliance with the Basel Convention (1989), HKC (2009), and EU Ship Recycling Regulation (2006) is progressively being adopted, mandating an Inventory of Hazardous Materials (IHM) and Ship Recycling Plans (SRP) [12,13,22].

- **National Regulations**: Require Environmental Clearance Certificates (ECC) and hazardous waste authorizations.
- **International Conventions**: Promote safe and environmentally sound recycling, and has achieved HKC certificate by 13 recycling local yards and another dozen are preparing.
- **Progress**: Ongoing efforts to align with global standards, with another dozen local yards are going achieved HKC certification soon.

3.3 Challenges

Despite its economic contributions, the industry faces significant obstacles that hinder sustainable development. Still there are manual dismantling processes, coupled with inadequate SHE standards, result in few accidents and environmental pollution. The reliance on foreign benchmarks in prior studies has limited the accuracy of local policy formulation, necessitating comprehensive, localized research [15,23,24].

- **Safety and Health**: Still some manual operations and insufficient PPE lead to accidents (e.g., explosions, injuries).
- **Environmental Impact**: Still some hazardous waste, including asbestos and bilge water, contributes to soil, air, and water pollution.

- **Data Limitations**: Lack of localized data has historically impeded robust policy-making.

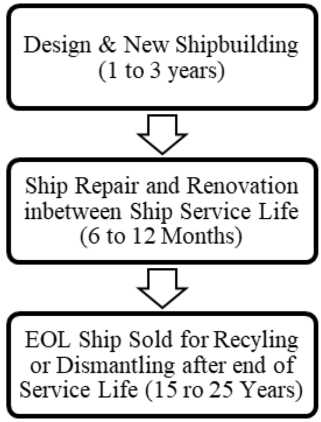

Figure 1: Typical Life Cycle of a Ship (15–25 Years)

Figure 1 illustrates the major phases in a ship's lifecycle, from initial design and construction (typically 1 to 3 years), through its operational service life (usually 15 to 25 years), including periodic repairs and refurbishments (lasting 6 to 12 months per cycle), to its final decommissioning and sale for recycling. The transition to EOL status is influenced by various factors, including the owner's discretion, prevailing market conditions for scrap and second-hand vessels, maintenance costs, and the structural integrity of the ship's hull. This lifecycle representation underscores the economic and operational considerations that shape when and how a vessel is retired from service and prepared for dismantling in recycling yards.

4. Proposed Ship Recycling Process Model

To improve operational safety, environmental management, and material recovery in Bangladesh's ship recycling industry, a structured process model has been developed (see Figure 2). This model reflects the actual sequence of engineering and managerial activities in beaching-based yards and spans approximately 5.5 to 10.5 months, depending on ship size and yard capacity. The process is organized into three major phases: Pre-Beaching, Dismantling, and Post-Dismantling, each comprising multiple work activities.

Pre-Beaching Phase (2–11 weeks):

This initial stage involves the transfer of ship ownership via intermediaries or brokers, who handle all legal documentation, including import permissions, tax payments, and certifications. Upon arrival, ships are inspected by port and government authorities—such as the Chittagong Port Authority and Bangladesh Navy—to ensure compliance with safety protocols. Key inspections include verification of the ship's navigation system, residual fuel removal, and issuance of "man entry" and "hot work" certificates. Ships are then beached during high tides, positioning them for dismantling.

Dismantling Phase:

In this core phase, the ship is cut using gas torches, following a top-to-bottom and bow-to-stern sequence. Large structural blocks are manually or mechanically removed. However, the absence of systematic weight-lifting calculations presents safety challenges for workers. This phase involves the disconnection and removal of equipment, outfitting components, and partially used materials. Hazardous substances—such as bilge water, sludge, and insulation—are also handled here.

Post-Dismantling Phase:

Recovered materials are sorted into environmentally valuable streams (EVS) and non-environmentally valuable streams (NEVS). EVS—including steel plates, machinery parts, and electrical fixtures—are sold to local markets or re-used in domestic shipyards. NEVS—comprising hazardous waste, insulation, and contaminated liquids—are transported to designated Treatment, Storage, and Disposal Facilities (TSDF) or landfills.

As visualized in Figure 2, the model clearly maps the inputs (labor, transport, power), work activities (from oil draining to metal melting), and outputs (usable parts, waste streams, emissions) of each stage.

Proposed Improvements:

To modernize the beaching method and align with the Hong Kong Convention (HKC, 2009) and EU waste management standards, the following improvements are recommended:

I. Reorganizing yard layouts for smoother logistics and safer movement.

II. Adopting scientific cutting and material handling procedures [25].

III. Increasing the use of Personal Protective Equipment (PPE) and offering worker training programs.

IV. Implementing professional hazardous waste management practices.

V. Establish additional TSDF facilities to manage hazardous waste effectively.

VI. Follow more green recycling method

VII. local recycling yards must have Ship Recycling Facilities Plan (SRFP)

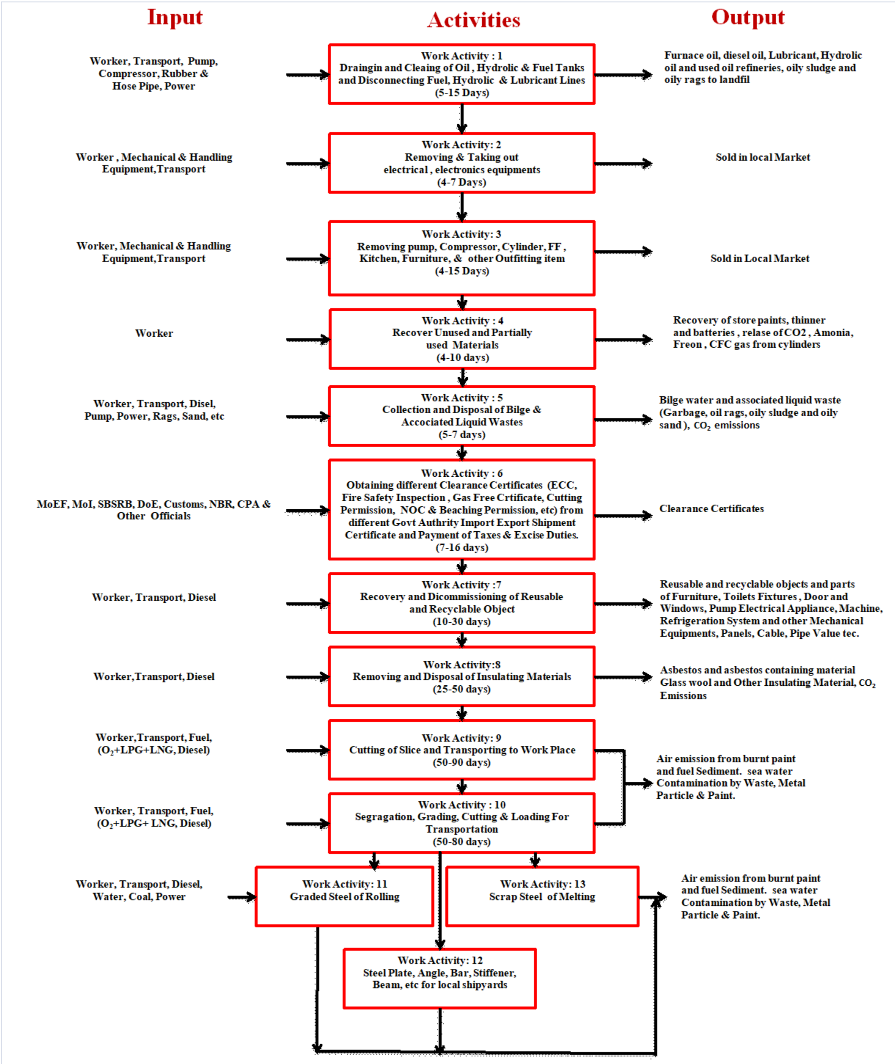

Figure 2: Developed Ship Recycling Process Model for Bangladesh [11].

5. Material Distribution Channels

5.1 Reusable Materials (Economic Value Stream, EVS)

Reusable materials, constituting ~73–95% of LDT (1,833,461–1,989,252 MT annually), are categorized per HKC (2009) guidelines into four groups to facilitate compilation and market distribution. These materials are integral to local industries, supporting shipbuilding, construction, and small-scale enterprises [1,19].

- **Metal Items**: Steel plates (heavy/light), brass, copper, aluminum, stainless steel, sold to re-rolling mills and shipbuilding industries.

- **Machinery Equipment**: Main engines, generators, pumps, lifeboats, fire extinguishers.
- **Electrical Items**: Cables, motors, navigation equipment (e.g., radar, GPS), computers.
- **Outfit and Other Items**: Doors, windows, valves, furniture, sanitary equipment.

Approximately 97% of materials, such as glass wool insulation (valued at USD 110/ton in Bangladesh vs. USD 100/ton in India), are recycled locally, driven by strong demand in secondary markets [2,4].

Table 2: Reusable Material Factors and Annual Output (2009–2016)

Ship Type	Reusable Factor (% LDT)	Annual Output (MT, Min–Max)
Bulk Carrier	75–92	450,000–550,000
Tanker	73–90	500,000–600,000
Container Carrier	78–95	400,000–480,000
Cargo Ship	76–93	350,000–420,000
Other Types	74–91	133,461–139,252
Total	73–95	1,833,461–1,989,252

5.2 Hazardous Waste (Non-Economic Value Stream, NEVS)

Hazardous waste, comprising ~1+ % of LDT (17,215–22,702 MT annually), is categorized into six groups per HKC (2009) and Bangladesh Environment Conservation Act (1995) to ensure systematic management and disposal. Effective management of these materials is critical to mitigating environmental and health risks [13, 26].

- **Group A (Asbestos)**: Asbestos-containing insulation (e.g., glass wool, ceramic wool).
- **Group B (Landfillable)**: Cement, rust, glass dust, incinerator ash.
- **Group C (Incinerable)**: Paint, polyvinyl chloride (PVC), polychlorinated biphenyls (PCB), sludge.
- **Group D (Bilge/Liquids)**: Fuel oil, lubricants, solvents, bilge water.
- **Group E (Heavy Metals)**: Lead, mercury, cadmium in batteries, sensors, cables.
- **Group F (Ozone-Depleting Substances)**: Chlorofluorocarbons (CFCs), halon, fire-fighting liquids.

Approximately 97% of glass wool is recycled locally, with only 3% sent to TSDF. Bilge water, waste oil (USD 10–16/barrel), and solvents are sold to local industries (e.g., brick kilns). Incineration is technically viable but costly, while landfilling, though cost-effective, poses long-term environmental risks [2, 27].

Table 3: Hazardous Waste Factors and Annual Output (2009–2016)

Waste Category	Waste Factor (kg/LDT)	Annual Output (MT, Min–Max)
Asbestos (Group A)	0.5–2.0	1,000–4,000
Landfillable (B)	0.3–1.5	600–3,000
Incinerable (C)	0.2–1.2	400–2,400
Bilge/Liquids (D)	0.3–1.8	600–3,600
Heavy Metals (E)	0.1–0.5	200–1,000
Ozone-Depleting (F)	0.05–0.3	100–600
Total	1.45–7.3	17,215–22,702

5.3 Distribution Channel Model

The proposed material distribution channel (Figure 3) for a typical container ship illustrates the flow of materials from recycling yards to end markets or disposal facilities, optimized through MFA to maximize resource efficiency and minimize environmental impact [14,16,17].

- **EVS Flow**: Directed to re-rolling mills, shipbuilding industries, and secondary markets (e.g., construction, cold storage).
- **NEVS Flow**: Transported to TSDF or landfills, with ~20–30% of NEVS extracted as EVS during segregation.
- **MFA Results**:
    I. Precutting: 2–4% EVS, 1–2% NEVS.
    II. Primary/Secondary Cutting: 72–93% EVS, 1.5–5.5% NEVS.
    III. Post-Cutting: 73–95% EVS, 1–3.5% NEVS.

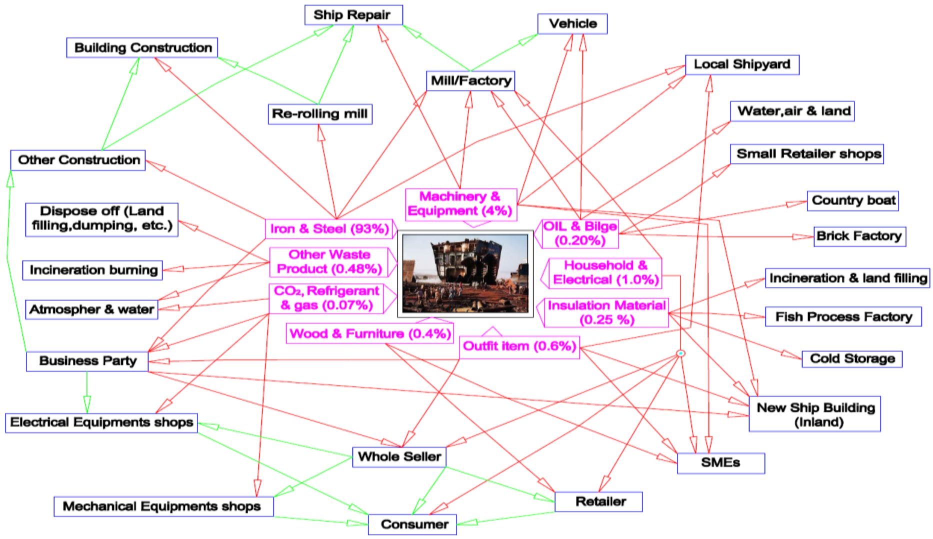

Figure 3: Distribution channel model of scrapped items from a typical EOL ship [16].

6. Comparative Analysis with Other Countries

A comparative assessment with Alang in India, based on a field survey of 241 ships dismantled between 2011 and 2013, highlights both similarities and clear differences in ship recycling practices. Bangladesh shows a higher average recovery of reusable materials per Light Displacement Ton (LDT), largely due to strong local market demand and fewer resale restrictions. In Table 4, Bangladesh achieves greater material recovery across most categories. Reusable outputs range from 750 to 920 metric tons per 1,000 tons of LDT, compared to 600 to 725 metric tons in Alang. In contrast, hazardous waste outputs, including asbestos, incinerables, and bilge liquids, show relatively similar levels between the two locations, pointing to shared challenges in waste handling. Bar charts present (Figure 4) average annual outputs of reusable materials and waste for different ship types, including bulk carriers, tankers, container ships, and general cargo vessels. The data shows that:

- Bangladesh records higher maximum recovery across all vessel types, especially bulk carriers and tankers.
- Waste generation remains steady across ship types, but the methods of disposal, such as landfilling and incineration, vary with local management capacity.

Table 4: Comparison of Material Factors (Bangladesh vs. Alang, India)

Material Type	Bangladesh (kg/LDT)	Alang, India (kg/LDT)
Reusable (EVS)	730–950	700–900
Asbestos	0.5–2.0	0.6–2.2
Landfillable	0.3–1.5	0.4–1.8
Incinerable	0.2–1.2	0.3–1.5
Bilge/Liquids	0.3–1.8	0.3–2.0

A closer comparison reveals that Alang benefits from tighter regulatory oversight, primarily administered by the Gujarat Maritime Board and related agencies. In contrast, Bangladesh relies on the Ship Breaking and Ship Recycling Board (SBSRB) and the Department of Environment (DoE), indicating a greater need for institutional strengthening and monitoring capacity. While Bangladesh achieves efficient material recovery due to strong local demand and an active informal resale network, this also limits transparency and traceability in the supply chain. Moreover, documentation practices in Bangladesh are gradually improving, shifting from informal estimates to more structured inventory records, although notable gaps in data accuracy and consistency still remain.

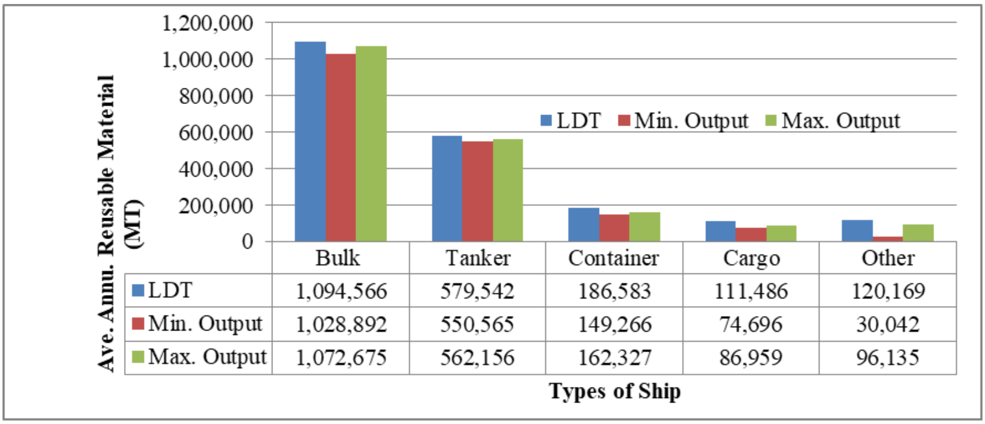

Figure 4: Average Annuual Reuseable Material Output (MT)

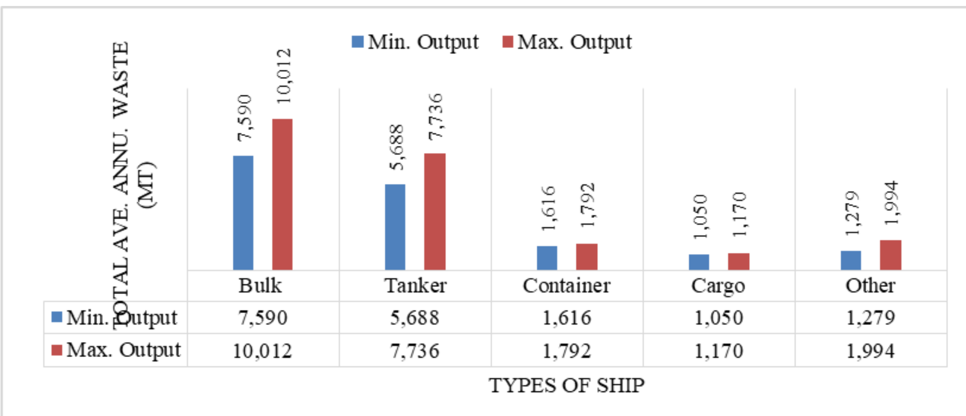

Figure 5: Reusable and Waste Material Output (MT)

7. Present Ship Recycling Status

The current state of Bangladesh's ship recycling industry, however, is increasingly somehow unstable. For several decades, India has been Bangladesh's closest competitor in this sector. Today, approximately 82% of India's ship recycling yards (120 yards) have already achieved compliance with the standards prescribed by the HKC [28]. In contrast, the picture of Bangladesh on HKC certification (around 50% of active/operational yards is still unsatisfactory) by local yards are not up to the standard or acceptable. Through strategic policymaking and substantial investment, India has successfully modernized its ship recycling facilities to meet international benchmarks. Crucially, India did not treat ship recycling merely as an environmental liability; instead, it recognized the sector's immense potential as a global business opportunity and positioned itself accordingly from an early stage. Bangladesh, by contrast, has lagged behind due to gaps in information dissemination, a lack of sustained political commitment, and inadequate government support. Nonetheless, all is not lost. International law still offers Bangladesh a lawful pathway for phased implementation of the HKC.

Pakistan is only beginning to develop a modern framework. It ratified the HKC in December 2023 and is drafting new laws (known as Federal Ship Recycling Act and provincial bills in Balochistan are in the works). Currently, enforcement is weak: yards in Gadani operate under outdated rules with minimal oversight, raising serious safety and pollution concerns. The ILO/IMO is assisting Pakistan to identify legal gaps and map a road-map for HKC enforcement; in particular, Pakistan must institute yard authorization, worker safety regulations and hazardous waste controls to meet its HKC obligations. Until these reforms are implemented, Bangladesh will face competition from Pakistan only after Pakistan's sector addresses its "outdated infrastructure and weak regulatory enforcement" in other words, once Pakistan fully modernizes its framework [29]. At present, nearly 50% of Bangladesh's yards remain not fully compliant with the HKC requirements. 13+4 or 17 recycling yards are HKC certified out of 35+ active/operational yards. Within next year rest of recycling yards hope to get the HKC certification. But continue to hold the leading position of Bangladesh in the global recycling market, there should more than 40 active/operation HKC certified local yards within next year [30].

8. Sustainability Efforts and Future Prospects

8.1 Recent Advancements

Significant strides have been made in Bangladesh's ship recycling industry to align with global standards, driven by regulatory pressures and stakeholder initiatives. These advancements reflect a shift toward professionalization and environmental responsibility [2, 31, 6].

- **Safety Enhancements**: Increased PPE utilization, training in confined space entry, and fire prevention measures have reduced accident rates.
- **Environmental Management**: Improved handling of hazardous waste, with ~97% of glass wool recycled locally and only 3% sent to TSDF.
- **Regulatory Compliance**: Adoption of HKC (2009) and EU Regulation (2006) standards. Around 20 Recycling yards has achieved (or going to achieve) HKC certificate.

- **Documentation**: Transition from visual estimations to weighed inventories, enhancing data accuracy.
- **Professionalization**: Employment of naval architects and technical personnel, alongside regular training programs.

8.2 Persistent Challenges and Way Forward

Bangladesh's ship-breaking industry now faces severe competition from modernizing yards in India and Pakistan, especially as international rules tighten. Bangladesh ratified the Hong Kong Convention (HKC) in June 2023 [32], but by mid-2025 only a dozen yards meet HKC standards. Latest industry data show India has **120** HKC certified/compliant yards, while Bangladesh has only **13** (soon to be 20) HKC compliant yards. In practice, roughly 82% of India's yards are HKC certified versus only about 50% of Bangladesh's (rest 50% not fully compliant). This gap threatens Bangladesh's market share as it was in 2023 Bangladesh handled ~46% of global recycling tonnage whereas India handle ~33% [32, 28]. The analysts warn Bangladesh has an potential risks and going to losing her position to Indian yards (where India has managed large donor backed "green yards") and surely going to capture more business in coming years ahead [33]. At the same time, Pakistan, which accounts for ~16.6% of global recycling share (in 2022) has only just ratified the HKC (Dec 2023) and is scrambling to upgrade Gadani [29]. In short, **environmental compliance** is a key challenge for Bangladesh. So, local recycling yards of Bangladesh need to be earned HKC certificate within short span of time and need to be upgraded rest of the incompliant yards to remain competitive, or else EOL vessels will flow increasingly to Indian and modernizing Pakistani yards. Now, India already mandates 'Ready for Recycling' certificates and strict waste management under its 2019 'Recycling of Ships Act' [33, 34], while Pakistan's government has approved major investments to build a "model green" yard at Gadani [35, 36].

Despite progress, the industry faces structural and operational challenges that impede full compliance with global standards and sustainable development [15, 37].

- **Infrastructure Deficiencies**: Suboptimal yard layouts and reliance on limited manual processes hinder operational efficiency.
- **Cost Constraints**: Incineration, a robust disposal method, requires high investment; landfilling, while cost-effective, poses environmental risks.
- **Compliance Gaps**: Only ~50% of active/operational local yards meet global standards, necessitating broader adoption of HKC and EU regulations.

8.3 Future Directions

The current geopolitical situation, with the lingering effects of Ukraine-Russia conflict, Isreal-Iran war, and the effect of COVID-19 pandemic, has significantly impacted global businesses. Inflation has risen and pervasive uncertainty has created a challenging environment for global business including ship recycling industry [38]. Today, it becomes essential for local ship recycling yards to change their attitude and implement appropriate and corporate culture in order to reach their objectives like other global competitors (India, Pakistan, and Turkey). By taking inspiration from highly efficient industrial nations and implementing suitable strategies and practices, local yards can be successful in business and remain competitive in global recycling business [39]. Local recycling yards need to take necessary steps to maintain health, hygiene and safety standard as per ILO and IMO regulations [9]. We need to institutionalize a training and certification framework through the Bangladesh Institute of Marine Technology (BIMT) or a new Ship Recycling Safety Academy under BMU. We may introduce performance-based incentives which offer incentives (e.g., carbon credits, scrapping subsidies, export rebates) to yards demonstrating continuous improvement in safety, compliance, and environmental performance. The future of Bangladesh's ship recycling industry hinges on aligning current practices with global sustainability standards while preserving economic viability. Strict regulations and technological advancements offer opportunities for improvement [40, 41].

Regulatory Impact: The International Convention for the Safety of Life at Sea (SOLAS) and HKC (2009) will reduce hazardous materials (e.g., asbestos) in future ships, enhancing reusable material quality.

- **Viable Green Recycling**: Merging beaching with sustainable practices can reduce hazardous waste disposal by up to 98%, maintaining cost-effectiveness.

9. Recommendations:

- Invest in modern infrastructure, modern cutting and dismantling system, including concrete flooring and mechanical lifting equipment [42].
- Establish additional TSDF facilities to manage hazardous waste effectively.
- Enhance worker training and enforce mandatory PPE usage.
- Create a dedicated monitoring and controlling body similar to India's Gujarat Maritime Board.
- Foster stakeholder collaboration to secure financing and technical support.
- Government financial and technical support.
- Arrange foreign support/investment.
- Implement and ensure sustainable recycling system.
- As an essential part of being HKC compliant, local recycling yards must have Ship Recycling Facilities Plan (SRFP) [24, 38].
- Local yards need to prepare themselves to ratify HKC and some sort of EU RRC within shortest time, otherwise it will be more challenging and complicating to continue with local recycling business in future [38].
- Government may provide fiscal incentives (tax rebates, accelerated depreciation, and import duty waivers) for investments in green yard infrastructure such as

impermeable floors, drainage systems, shore-based cranes, and waste treatment units [9, 39].

- We can establish On-site Medical and Safety Facilities which require every major yard cluster to have on-site clinics**,** safety response units, and trained emergency personnel.
- We may use multilateral funding (e.g., from IMO, World Bank, ADB, JICA) and national budget allocations to create a blended financing mechanism supporting local recycling yards upgrades, particularly for small and medium recyclers.

10. Conclusion

Bangladesh's ship recycling industry, the global leader, processes ~2,000,000 LDT annually, yielding substantial economic benefits through employment and steel supply. However, challenges such as manual dismantling, environmental pollution, and inadequate SHE standards persist. This study, based on seven years of on-ground data from 26 EOL ships, quantifies reusable materials (73–95% LDT, 1,833,461–1,989,252 MT) and hazardous waste (1–5.5% LDT, 17,215–22,702 MT). The proposed ship recycling process model and material distribution channel provide a framework for sustainable practices, leveraging Bangladesh's low-cost labor and robust market demand. By addressing safety, environmental, and regulatory gaps through infrastructure upgrades, professional training, and compliance with HKC and EU standards, Bangladesh can maintain its global leadership while achieving sustainability. Continuous monitoring, balanced leadership, financing, and stakeholder support are imperative for the industry's long-term viability. We may facilitate access to commercial credit to Partner with state and private banks to develop low-interest green loans with technical evaluation support for upgrading recycling infrastructure. We can **f**inalize and enforce the draft *Ship Recycling Act* that fully integrates HKC provisions and aligns with Basel, Rotterdam, and Stockholm conventions. This law should mandate facility authorization, hazardous material inventory tracking, waste disposal compliance, and environmental impact audits. We may create a dedicated Ship Recycling Regulatory Authority (SRRA) with representatives from the Ministry of Industries, Ministry of Environment, Ministry of Shipping, Department of Labor, BUET, Bangladesh Maritime University or BMU (as academic advisor), etc. to coordinate oversight, inspections, and certifications. We can make it compulsory for all yards to submit approved SRFP**s** and obtain HKC certification within a fixed transition period (within couple of years). Regular third-party audits should be institutionalized with penalties for non-compliance.

50% of Bangladesh's yards are remained in compliant with the HKC requirements. Only 13+4 or 17 local recycling yards are HKC certified out of 40+ active/operational yards. Bangladesh's regulatory delays and unclear enforcement mechanisms reflect a critical bottleneck. Stakeholder interviews reveal skepticism about the efficacy of government audits, and many operators are waiting for clarity on whether non-compliant yards will be officially delisted. This limbo state has slowed investment and discouraged long-term planning, a challenge that may intensify post-2025 when global compliance expectations harden. The pathway forward for Bangladesh lies not in resisting global environmental and labor norms, but in strategically aligning with them to capture a new generation of demand for ethical and green ship recycling. The time to act is now—before the market shifts irrevocably toward better-prepared competitors. Within next year rest of the local recycling yards should get the HKC certification. But continue to hold the top position of global market; Bangladesh should have 40+ active/operation HKC certified yards.

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Exclusive Study on Artificial Intelligence (AI), Robot and Consequences of the World

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Abstract

The explosion of technology in the modern era has coincided with an equally seismic shift in how we think and talk about it. Artificial Intelligence (AI) is a technology that can replicate the human brain or intelligence. It allows computer programs to learn from experience through iterative processing and algorithmic training. Every day, AI has become more practical and innovative in almost all aspects of life. AI has become a crucial issue in the 21st century, as it might affect the job market and general employment. Most individuals wish to claim that the widespread usage of AI would result in employment losses for people. However, People are gradually realizing that AI can improve the creative, lucrative, constructive, adaptable, and accessible nature of professions. AI could lead to a more innovative, diversified, and skilled economy. We must need to change the education system, including the curriculum, teaching methods, and many things that need to be done for schooling. Our mass or general education system needs to be aligned with modern and advanced technology, which will change the whole school system and must be purposeful and sustainable for the long term. It is an analytical study in which the researcher has tried to evaluate the diversified use of AI and robots and the consequences for the human future, emphasizing the global education system.

Keywords: AI, ML, KM, logic, algorithm, networks, robot, singularity

1. Introduction

A procedure or formula used to solve a problem or a series of instructions that tell a computer how to transform a data set into helpful information. All branches of information technology heavily rely on algorithms. Computer science's multidisciplinary field of artificial intelligence (AI) develops intelligent machines. AI is the replication of the human brain or intelligence by machines, like computers, to accomplish tasks requiring human aptitude or talent, such as seeing, hearing, making decisions, translating between languages, and operating equipment. Common uses of AI include Siri by Apple [1], Alexa by Amazon [2], Maps by Google [3], and ChatGPT by OpenAI. AI systems improve with data processing, making them faster and more precise than humans. This ability allows AI to become an authoritative and priceless technology that essentially allows computers to think and behave like humans. Machine

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Learning (ML), a subset of AI, analyzes data to solve real-world problems, while Deep Learning addresses more complex challenges. Robotics, another AI branch, focuses on diverse applications, including self-driving cars and healthcare advancements.

Robotics, AI, and machine learning have significantly advanced. Automation and AI improve quality, accuracy, and efficiency in production and services. Peter Norvig, Google's director of research, highlighted that AI could benefit society broadly. Studies show automation could boost global productivity by 0.8% to 1.4% annually, impacting thousands of tasks [4]. However, job displacement and inequality remain concerns, especially in developing economies reliant on labor and natural resources. Declining returns and new technology dynamics could undermine progress in these regions, slowing poverty reduction and increasing inequality worldwide.

The great thinker of AI, Professor Yann LeCun, dismissed fears of AI being a threat to humanity, calling them projections of human nature onto machines. LeCun emphasized that artificial general intelligence (AGI) is far from realization. AI's regional economic contributions depend on prevalent economic activities. It can foster innovative opportunities and productivity, but also demands education systems to prepare the new generation with advanced skills.[5]

AI already influences daily life extensively. It impacts decisions ranging from consumer goods to job applications. Tech giants like Amazon, Facebook, Google, and Microsoft invest in AI research [6]. Although AI revolutionizes modern life, concerns about job losses persist. Economic theory suggests technology creates winners and losers, necessitating policies to balance societal impacts. This study explores AI's benefits, impacts, and future concerns, particularly regarding education transformation and technological adoption.

Figure 1: Robots working with human and digital revolution relate technology and human

2. History of AI

New digital tools generate new terms and phrases, as well as new conceptual frameworks for comprehending how these tools affect and interact with society. Words like disinformation and doxing have entered the mainstream as we deal with new and increased forms of harm. Moreover, concepts like digital rights and data governance have come into existence amidst the push to align today's technology with our vision for a better future. The voices of women, girls, and other marginalized groups, historically sidelined or absent in tech spaces, are urgently needed in decision-making processes [7]. AI first appeared as a storytelling device in antiquity and has since become prevalent in literature, such as in Mary Shelley's "Frankenstein" [8]. In the first half of the 20th century, science fiction familiarized the world with the concept of AI robots, starting with the Tin Man in "The Wizard of Oz" and the humanoid robot impersonating Maria in "Metropolis" [9]. By the 1950s, scientists like Alan Turing were exploring the mathematical foundations of AI. His 1950 paper, "Computing Machinery and Intelligence," outlined how machines could think and how to test their intelligence [10].

Before 1949, computers were unable to remember commands, which limited their intelligence. In the 1950s, renting a computer could cost up to $200,000 per month, making them accessible only to large organizations [11]. AI research formally began in 1956 during the Dartmouth College workshop, which brought together pioneers in the field. These researchers created programs that learned strategies, solved algebra problems, and proved logical theorems [12]. By the mid-1960s, AI research gained substantial funding from the U.S. Department of Defense and other global institutions [13]. Optimistic predictions by Herbert Simon and Marvin Minsky claimed that machines would rival human capabilities within a generation [14]. Between 1957 and 1974, AI experienced improvements in affordability, storage capacity, and algorithm development.

Despite setbacks, AI's most significant objectives were achieved in the 1990s and 2000s. For example, IBM's Deep Blue defeated chess champion Garry Kasparov in 1997, marking a milestone in AI's ability to make independent decisions. In the 1980s, researchers like Geoffrey Hinton reignited interest in neural networks and soft computing techniques, including fuzzy systems and evolutionary computation [15]. During the late 1990s, AI regained credibility by solving practical problems and collaborating with other scientific disciplines [16].

We now live in the era of "big data," which allows the collection of vast datasets too cumbersome for manual analysis. Industries such as healthcare, banking, and entertainment have leveraged AI for transformative benefits. Advances in deep learning since 2012 have driven improvements in AI language models and perception systems [17]. In 2015, a surge in AI-related software projects marked a landmark year for the technology [18]. A 2017 survey revealed that one in five companies had incorporated AI into their operations [19]. In 2023, Jaron Lanier argued in "The New Yorker" that people are the solution to AI challenges, emphasizing the importance of human-centered approaches [20]

In the long term, AI aspires to achieve general intelligence, a level surpassing human cognitive abilities across all tasks. This goal faces significant ethical and technical challenges. While discussions about machine ethics continue, AI has already reshaped industries like agriculture, healthcare, and transportation. Technologies such as driverless cars and IoT systems demonstrate AI's potential to revolutionize human life [21].

3. The Impact of AI on Society and Near Future

Modern AI, often referred to as 'narrow AI', predominantly utilizes data-trained models and frequently incorporates deep learning or machine learning techniques. This influence has been especially pronounced in recent years due to the surge in data collection and analysis facilitated by robust IoT connectivity, the increasing number of connected devices, and rapid advancements in computer processing. Companies are investing billions of dollars annually into AI products and services. Tech giants such as Google, Apple, Microsoft, and Amazon are at the forefront, pouring billions into the development of these AI-driven offerings. Concurrently, universities are placing greater emphasis on AI within their curricula, and the military forces of developed nations are enhancing their tactical use of AI. Andrew Ng, the former leader of Google Brain and a top scientist at Baidu, observed that many industries experience periods he describes as "winter, winter, and an eternal spring." He suggests that we might currently be in the "endless spring" phase of AI [22].

Today, some sectors are at the start of their AI journey, whereas others are expert travelers. However, both have a long way to go. Whatever impact AI is having on our present-day lives is hard to overlook. Nobody can stop or slow the very fast journey of AI. Today, AI-enabled machines can perform specific jobs better and faster than humans and imitate human actions nicely. There are four types of AI. Reactive machines AI is the most superficial level of AI, capable of basic operations but lacking memory or the ability to use past experiences, such as IBM’s Deep Blue [23]. Limited memory AI can store existing data and create better output, exemplified by Tesla’s self-driving cars. Theory of mind AI can connect with human thoughts and interpret them better, though it remains a work in progress. Self-aware AI, anticipated in the future, will possess independent intelligence and make its own decisions, marking a new chapter in civilization.

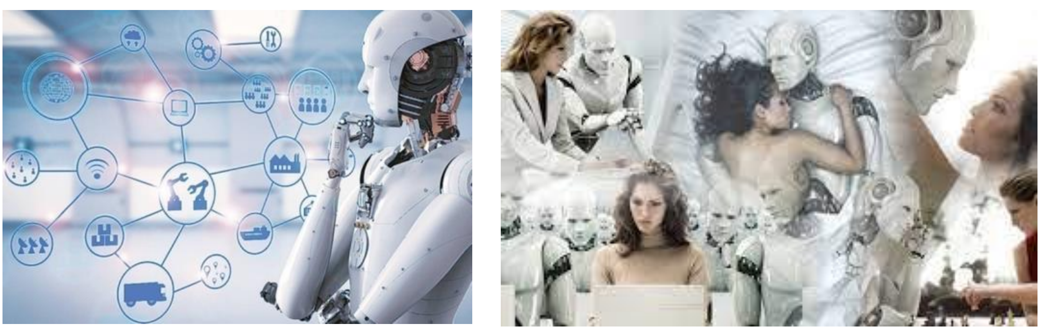

Figure 2: AI define humanity’s future and the emotional relationship between human and robots

AI has played a significant role in the manufacturing sector for decades. Since the 1960s and 1970s, AI has been integrated into robotic arms and other industrial robots. These robots collaborate with humans, performing specialized tasks like assembly and stacking. Predictive analytics sensors also ensure equipment operates efficiently. The transportation sector is on the brink of significant transformation due to AI, with innovations like self-driving cars, AI-based trip planners, and intelligent traffic management systems. The healthcare industry has also been profoundly impacted by AI, enabling quicker and more accurate disease diagnoses, efficient drug discoveries, and patient monitoring via virtual nursing assistants.

AI in education transforms learning experiences by using machine learning (ML), natural language processing, and facial recognition to digitize textbooks, detect plagiarism, and gauge student emotions. AI tailors education to individual needs, enhancing engagement and outcomes. Journalism also utilizes AI, as seen with the Associated Press employing Automated Insights to generate thousands of earnings reports annually. Concerns arise with generative AI tools like ChatGPT potentially impacting journalistic integrity. Similarly, AI in customer service improves efficiency through chatbots and virtual assistants, though automation raises workforce concerns.

Professor Klara Nahrstedt of the University of Illinois emphasizes the importance of education to prepare individuals for AI-driven opportunities, likening programming to learning a new language. This aligns with historical trends where technological advances, while displacing certain jobs, create new opportunities. Transitioning to AI-intensive industries mirrors shifts during the Industrial Revolution and underscores the importance of proactive adaptation. [24]

AI research explores areas like reinforcement learning, which relies on rewards and punishments instead of labeled data, and generative adversarial networks (GANs), which enable creative output by pitting networks against each other [25]. Applications in sustainability and climate change include smart sensors reducing congestion and pollution in cities. While these innovations promise societal benefits, they also raise concerns about data privacy and ethical implications. Incidents like Cambridge Analytica's misuse of Facebook data highlight the need for stringent regulations [26].

Stuart Russell, an internationally renowned AI scientist, stated in 2018 that significant breakthroughs are needed before achieving human-level AI. He highlighted that AI must fully understand languages to rival human cognition [27]. Professor John Laird's research on cognitive architecture emphasizes the complexity of intelligence systems, which include procedural, semantic, and episodic memory [28]. AI's dependence on vast data quantities underscores its transformative potential, yet also necessitates careful consideration of its societal and ethical impacts.

4. Human Error and Use of AI

While the benefits of analytics are widely recognized, such as enhancing shopping experiences, optimizing train and truck routes, identifying extraterrestrial life, and forecasting diseases, organizations globally have been confronting the challenge of human errors creeping into their analytical endeavors, sometimes leading to catastrophic results. Human error in data processing has far-reaching consequences for organizations, from crashing spacecraft to sinking ships, transferring billions of dollars to unintended recipients, and causing deaths due to pharmaceutical overdose. Human mistakes in data analysis can occur for a variety of reasons, including a lack of expertise, exhaustion or loss of focus, a lack of information, or the all-too-common biases in data interpretation. On the other hand, the most prevalent human errors are related to humans reading, processing, analyzing, and interpreting data. AI can successfully tackle human mistakes by parsing, analyzing, drilling down, and dissecting enormous amounts of data. It can also do high-level arithmetic, logical, and statistical functions on a human-led scale, whereas self-service analytics cannot. AI-driven analytics has numerous advantages, from giving actionable insights in minutes to removing errors or biases in self-service analytics. We may expect to see increased adoption of AI in analytics worldwide as more business executives look to AI for insights that fuel their businesses. There are five most common human errors observed, as discussed below, and that can be eliminated by using AI easily.

Confirmation bias. If you're constantly on the lookout for a yellow car, you'll always spot it. In the corporate world, confirmation bias skews our approach to collecting, processing, and remembering information. Intuition often takes precedence over hard data, leading to the manipulation, exclusion, misrepresentation, or misinterpretation of facts to back up individual views. When data goes against these beliefs, it's frequently challenged and disregarded. Artificial intelligence avoids this method of cherry-picking data by examining past data for trends, patterns, and outliers, yielding reliable, bias-free conclusions [29]. Lockheed Martin, one of the world's leading aerospace companies, uses historical project data, also called dark data, to manage its projects proactively. By analyzing and correlating numerous metrics, the company was able to pinpoint early and trailing signs of program development, forecast potential program setbacks, and enhance project insight by 3% [30].

Inability to break silos. The Silo Mentality, as described in the business dictionary, refers to a situation where specific departments or groups in a company are reluctant to share information with others within the same organization. Such an attitude can hinder overall productivity and negatively impact team morale. It may contribute to the decrease in productive company culture [31]. Too many organizations have trouble with data-related problems, such as keeping track of various sources of data, not being able to work together on data, and having data that is not accurate or that is hard to get to. Utilizing relational data modeling, AI can seamlessly bridge gaps by interfacing with and linking vast data sets from diverse databases, applications, or sources. For instance, several state governments in India collaborated with the National Green Tribunal on Project Elephant to investigate and prevent elephant fatalities on train tracks spanning multiple states. This initiative was sparked by an investigative piece in *The Hindu* newspaper, which compiled data from the railway and forest reserve departments to highlight the patterns, timings, and frequency of elephant deaths [31].

Downplaying losses. Humans naturally dislike losses. Toyota minimized the issues related to defective brakes in their vehicles, leading to the removal of certain Toyota models from Consumer Reports' recommended list. BP downplayed the impact of the Gulf of Mexico oil spill by putting out polished ads apologizing for a 'minor spill,' until it received severe backlash. Downplaying loss fosters tunnel vision and impairs leaders' ability to make good judgments. Moreover, this might be costly to the organization in the long run. Owing to the objective nature of artificial intelligence, it processes and evaluates data without bias, avoiding the human tendency to lean towards positive results. AI-driven analytics serves as an ideal partner for leaders who aim to base their decisions on complete data rather than a skewed perspective [32].

Inflated predictions. A limitation of human-led analytics is its potential for overly optimistic projections. Often, individuals may overstate the future financial needs of an organization, overpredict the impact of natural occurrences, or make assumptions about deficits or inflation based on prior experiences and assumptions. On the other hand, AI-led analytics tends to be more accurate because it makes predictions based on what is moving or stopping something and what is happening in the outside world. The US Navy uses AI and ML to plan preventive repairs for its ships and planes and to predict when parts will break down. This enables sailors to spend more time focused on missions and less time on repairing aircraft when they fail [33].

Inability to go beyond surface-level analytics. Companies that delve deep to understand the root causes of challenges often significantly surpass their rivals. By analyzing the sources of a problem, they can determine its genesis, propose effective solutions, and anticipate and prevent similar challenges in the future. Humans are not able to collect, analyze, and drill down through so many layers of data to find the root cause of a problem when there are too many data sources, structures, and silos. AI-driven analytics can bypass these barriers by smoothly digging into numerous levels of data simultaneously. In addition, AI can also overlay several possible situations to come up with the most probable cause of a problem [34].

5. Contribution of AI in Different Sectors

AI has become an influential force in various industries, businesses, and aspects of our daily lives. Its transformative potential is being recognized and harnessed across numerous sectors. Applications powered by AI have gained prominence in many fields, reflecting our shift towards a more digitalized world. Today, leveraging AI can significantly enhance efficiency and smooth operations across businesses. Numerous enterprises, organizations, and firms have already incorporated AI into their operations. In the following sections, we will delve into the impact of AI across diverse fields and business domains.

An automated information system (AIS). An AIS is a combination of hardware, software, and equipment designed to manage information with minimal human intervention. This system can encompass computers, software, and telecommunication devices. The specific information an AIS manages varies based on its purpose. For instance, a library may use a Library Management System to assist staff in tracking and organizing books. If a book is overdue, the system will send an alert containing details like the borrower's name and contact number. Conversely, an accounting firm might employ a distinct AIS to gather and analyze financial data, generate and dispatch invoices, and compute taxes. Such systems also facilitate easier information dissemination. For example, a Library Management System could message the customer about the specific book and any fees charged [35]. There are general AIS types common across industries, and we will discuss a few below.

- **Management Information System (MIS):** An MIS assists an organization's leadership in overseeing operations. Through MIS, managers produce reports that provide insights into the company's operations, HR, sales, and more. Examples of such systems are HRM, sales management, and inventory management systems.
- **Transaction Processing System (TPS):** A Transaction Processing System (TPS) manages data related to business transactions like sales, expenses, inventory, and payroll. Its main function is to maintain and update transaction records for reports or further analysis in a Management Information System (MIS). Billing and payroll systems are examples of TPSs.
- **Office Automation System:** While MISs and TPSs are tailored to assist specific users or departments, Office Automation Systems facilitate processes across all levels. They can handle administrative tasks like setting up meetings and managing calendars, as well as managerial functions like creating reports and evaluating performance.
- **Expert System:** Expert systems are sophisticated AI applications that leverage artificial intelligence. In the healthcare sector, these medical expert systems can identify prevalent illnesses without a doctor's intervention.

Payroll, billing, inventory control, human resources (HR), and medical expert systems are all types of AISs. These systems are also integrated into our everyday lives beyond the workplace. They can instantly alert communities when a child goes missing. These notifications aren't just sent via text or email but are also broadcasted on TV, radio, and digital displays. AISs are also used by disaster management groups to let people know about floods, earthquakes, and other events that could affect them. Even Siri, Alexa, and other AI-based systems are classified as AISs since they use all of the data; we enter daily to make recommendations. AISs are already embedded in our personal and professional lives. They assist people in making better, faster decisions, thereby saving time and, in some circumstances, lives. However, we must recognize some of the difficulties that AISs provide. One of the key issues is the security risk that these systems, like any digital device, pose. Hacking, data leaks, and various forms of cybercrime can afflict AIS users. As such, AIS providers and users are encouraged to implement robust cybersecurity measures [36]. AIS benefits us:

- **Better decision-making:** With AISs, managers can make calculated and data-based decisions that benefit their whole organization.
- **Faster decision-making:** Besides making better decisions, people using AISs can also make decisions quickly. That is crucial, especially for time-critical events, such as ordering stocks before inventory runs out, spotting child abductors before they harm the victim, and evacuating residents from disaster-prone areas.
- **Efficiency:** Employing AISs reduces the need for allocating HR to mundane tasks. AISs can be left alone while employees perform high-level activities.

Travel and Transportation. AI has significantly impacted various industries, and the travel sector is no exception [36]. Today, the travel industry extensively uses AI-driven tools and solutions for everything from trip planning to the actual journey. AI has emerged as a dominant trend in travel and transportation. It does more than just provide the quickest routes for drivers; it also facilitates remote travel arrangements [37]. Recognizing the power of AI, numerous travel firms have integrated it into their systems, capitalizing on the fact that people frequently use their smartphones for travel-related searches. In fact, a recent study revealed that 82% of individuals use their smartphones to explore local attractions and dining options. Take Google Maps, for instance, an application where many might not realize the extent of AI's role. It can scan roads by using an advanced algorithm to look for and suggest more competent routes and guide us about future traffic conditions in real-time, whether we are in a car, on a bus, train, or on foot. [38]

Manufacturing. AI greatly enhances the production industry by addressing internal challenges. Today, with AI, manufacturing facilities can seamlessly automate, streamline decisions, integrate, and orchestrate their operations more efficiently. Such technological advancements significantly influence manufacturing speed and quality. It's projected that AI could amplify production by 40% by 2035. One of the key advantages of AI is its ability to make decisions rooted in data, optimizing efficiency, increasing output, and reducing operational expenses. This not only simplifies scaling efforts but also refines product development. Manufacturers employing AI can monitor equipment health and proactively schedule maintenance. By leveraging machine learning for predictive maintenance, factories can decrease downtime and repair costs by up to 30%. Systems grounded in deep learning can enhance defect detection by nearly 90%, ensuring unparalleled product quality. AI provides a comprehensive view of factories, assembly lines, and storage areas. Such insights empower operators to identify quality issues, reduce waste, and tweak production processes. This capability enables manufacturers to boost their production rates by 20% and enhance quality by 35% [39].

Agriculture. The journey of products like flour or rice from the farm to the grocery store involves numerous steps. Agriculture is a complex industry where getting things right can be challenging. AI and autonomous farming can significantly enhance agricultural efficiency by predicting customer demands, regional supply chain behaviors, and the necessary raw materials for specific yields. Such technology can also identify significant weather patterns that might impact crops, such as heavy rain or extreme heat. Additionally, AI can aid in other farming challenges, including optimizing fertilization, combating pests, and addressing diseases. These advancements can mitigate challenges posed by climate change, population growth, workforce shortages in agriculture, and food safety concerns. AI has revolutionized farming by simplifying the processes of growing, monitoring, harvesting, processing, and selling crops. Cutting-edge digital solutions are being developed to tackle key issues such as weed detection, crop yield forecasting, and quality assessment [40].

Healthcare. According to a forecast by CB Insights, a staggering 86% of healthcare organizations are expected to adopt AI technologies soon. The integration of advanced AI in healthcare holds immense potential. From managing medical records, interpreting tests and X-rays, to providing virtual nursing and handling data entry, AI stands as a transformative force in medical settings. Industry professionals are optimistic about the combined power of AI and the Internet of Medical Things, predicting groundbreaking advancements in early disease detection and medical research [41]. Consumer-facing AI apps, often backed by healthcare chatbots, are guiding individuals towards healthier living choices. One standout application of AI in healthcare is its capability in pathology. AI and ML-driven systems assist pathologists in analyzing tissue samples, leading to more accurate diagnoses [42].

AI-operated healthcare systems can handle most tasks previously handled by humans faster and more cost-effectively. Modern ML solutions now act, learn, understand, and predict diseases more effectively. These advancements go beyond surgery-assisting robots and linking genetic codes. However, AI development poses risks and challenges such as system errors and patient privacy concerns [43]. The benefits of AI in healthcare are as follows:

1. **Access to Standard Healthcare:** Developing countries struggle with limited access to standard healthcare systems. AI-backed digital systems can provide diagnosis, treatment, and medication, bridging this gap [44].
2. **Mobile Health Apps:** AI-powered health apps integrate sensors, social media, and location-tracking to monitor wellness and diagnose diseases. These low-cost, user-friendly tools are evolving into digital diagnostics and therapeutics [45].
3. **Precision Diagnosis and Medicine**: AI systems analyze vast amounts of patient data, enabling quick information retrieval and facilitating better decision-making [46]. Wearable devices and glucose monitoring systems are examples of AI enhancing chronic disease management.
4. **Health Predictions:** AI-driven applications like Verily forecast hereditary and non-contagious diseases. These tools enable healthcare professionals to prepare for potential health threats and improve operational management [47].
5. **Cost Efficiency:** AI algorithms streamline patient examination, diagnosis, and treatment processes, significantly reducing costs. AI's predictive capabilities minimize manual effort, making healthcare methods more affordable and accessible [48].
6. **Enhanced Patient Experience:** AI solutions help patients navigate crowded healthcare facilities, improving communication and efficiency. Advanced AI apps offer round-the-clock support, addressing common frustrations like poor communication [49].

7. **Surgical and Recovery Advancements:** AI-powered surgical systems execute complex movements with precision, reducing risks and enhancing recovery. Antibacterial nanorobots and real-time condition monitoring further support surgical outcomes [50].

8. **Advanced Robotics:** Exoskeleton robots assist paralyzed individuals, while AI-backed prosthetics and companion robots enhance patient care. Advanced robots support mental health, monitor vitals, and promote positive patient experiences [51].

Customer Service and Call Centers. AI offers transformative benefits in customer service, extensively integrated into industries like retail, finance, and insurance. Through AI-driven solutions, businesses deliver prompt and tailored interactions, enhancing both customer satisfaction and employee productivity. In call centers, AI accelerates data retrieval and aids agents with faster response times and better first-call resolution rates. Advanced AI tools identify effective strategies, automating simple tasks while providing in-depth analysis [52].

Cybersecurity. Cybersecurity is becoming a bigger problem all over the world. With everything being digitalized, organizations need help dealing with the security problems that are happening right now. Utilizing AI in defense significantly enhances security. This technology can proactively detect potential hackers and learn from current business vulnerabilities. It's crucial to bolster security to ensure the safe application of AI. By harnessing AI for defense, experts aim to reduce instances of fraud and hacking. With the advent of AI-powered cloud security, businesses are better equipped against cyber threats, gaining an advantage over cybercriminals. However, cybercriminals are also adapting, using advanced AI-driven ransomware and malware that can infiltrate and damage systems efficiently, putting everyone in jeopardy. Furthermore, there's an emerging threat of AI-driven industrial and political espionage which focuses on data acquisition. AI tools like ML and natural language processing help analysts react to threats more quickly and confidently. AI can help keep track of hardware failures. Some multinational companies already have a team of experts in cybersecurity, IT infrastructure, and budgets to build products for working with massive data, coming up with a good plan to deal with threats [53].

Figure 3: Cybersecurity vs information and network security AI in the finance sector

Construction. AI can open many new avenues in the construction industry. Advanced forms of AI are making related operations simpler and more user-friendly. By using AI in this field, it is possible to reduce human effort and achieve efficiency. Moreover, AI is proficient in collecting and processing data and predicting outcomes [54]. AI technology can be advantageous at various stages of the project's design, construction, and post-completion. AL and ML are pushing the construction industry's potential to new heights at every engineering and construction stage, from design to preconstruction to operations and asset management. AI can be used for project conception, design bidding, financing, transportation management, operation, equipment, and asset management [55].

Software Development. In the field of software development, the world will surely see significant disruption from AI with new tools and libraries enabling the generation of code through natural language. Moreover, technology ensures we can automate anything as desired. Using information from AI-based tools can lead to new ways of building software and using it to help a growing business. Most AI systems use technologies that work together. For example, speech synthesis and speech detection technologies are often used together. Collaboration remains vital, and AI can streamline these processes to enhance efficiency [56].

Finance. Today, financial institutions like banks, insurance companies, and hotels are using AI to provide improved information and recommendations to customers/users, helping them make thoughtful decisions. AI is perfectly suited for accuracy, real-time data reporting, and processing large volumes of data. ML, adaptive intelligence, algorithmic trading, automation, and chatbots are transforming financial processes. Robo-advisors create tailored profiles for investors based on their goals. Banks using AI offer improved client experiences with 24/7 account access and fraud prevention mechanisms. AI’s ability to detect abnormalities in patterns has become a crucial tool against cyberattacks and fraud [57].

Gaming. AI has revolutionized gaming by making games more responsive, adaptive, and challenging [79]. From NPCs to pathfinding, AI enhances player experiences in real-time. Developers use AI to create procedurally generated game levels, ensuring games remain fresh and engaging. AI also aids in modeling policy questions and scientific studies, expanding its impact beyond entertainment [58].

E-Commerce. Organizations implement ML algorithms to enhance customer relationships and provide customized experiences [82]. These technologies increase sales and profits. Amazon exemplifies AI's integration, employing it at every step of the customer life cycle to optimize operations [59].

Business. AI enables businesses to increase efficiency, save time, and reduce costs. It supports automation and enhances decision-making processes, particularly in sectors like the automobile industry. Autonomous driving technology and AI-backed assistants are transforming business operations and transportation [60].

Energy Sector. AI is rapidly transforming the energy sector, contributing to automation, efficiency, and the transition to renewable energy sources. It supports network management, power theft prevention, and outage predictions. Client-side AI applications gather data for efficient consumption, enhancing sustainability [61].

Automobile Industry. AI is revolutionizing the automobile industry through enhanced production processes and driver assistance systems. AI can identify defective parts, optimize quality control, and streamline operations. Driver-assistance technologies, such as steering aids and self-parking systems, are examples of AI's transformative impact [62].

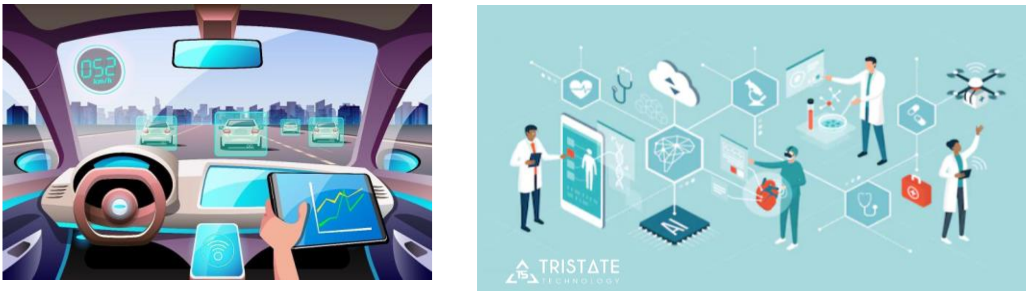

Figure 4: Benefit of AI in automobiles and benefit of AI in healthcare

Some models have similar ideas about how to deal with traffic jams. The AI sometimes takes the wheel in the most literal way. In cars, AI also includes cruise control and systems that help you stay in your lane [92]. Cars of the future may be able to drive themselves. At the moment, AI-based, fully driverless driving is not quite possible, but it is a goal for the future. Here, the driver does not do any steering; instead, a system, for this reason, does it. Automated parking and traffic systems in everyday driving are the start of progress. There are different levels of technology when it comes to driving by itself [62]. Depending on the level, the driver can intervene or be prompted by the system. In the case of the highest automation tier, this is neither required nor possible, and the driver becomes a passenger. So, autonomous driving is conceivable for, but not limited to, passenger cars, public transportation, and freight transport. However, prototypes and tests for some of these ideas already exist. Shortly, we will see more automation in automobiles. The legal framework is supposed to apply in the techno-loving country for various possible fields and become favourite, developed, and realized.

Discussing automotive machine learning initiatives without including self-driving automobile solutions is challenging. Automakers like Toyota and General Motors, as well as other major technology companies like Lyft and Waymo, have spent billions of dollars developing self-driving cars. Autonomous buses and shuttles are already being used in cities and airports in many countries. Driverless trucks are already delivering goods over large distances, and autonomous flying taxis will soon appear to be a reality. Moreover, there is a strong reason for the car industry's quick adoption of machine learning [63]. Many people wonder how driverless cars can recognize potential threats and react to the environment in real-time. Self-driving cars use neural networks and specific algorithms, which have the power of autonomous vehicle perception. These neural networks enable driverless vehicles to orient themselves on the street and avoid collisions [64]. Today, the automotive industry is seeing increased competition, cost pressure, and volatility; even a small disruption can make or break an enterprise's image. Including AI and machine learning capabilities can be a game-changer for the automotive industry. Automotive manufacturers can deploy AI technologies for designing and building new prototypes, improving supply chain efficiency, and enabling efficient maintenance of both factory equipment and vehicles on the road. The high time to adopt these AI technologies is now [65]. Act on it before it is too late if you can leverage the same.

Telecommunication Industry. AI has already arrived and is widely used in the telecommunications industry. It is important in network administration, among other things, especially in network maintenance and governance. Experts believe that AI will be responsible for making redundant certain individuals who have previously performed this function in the future. AI can be especially useful in enhancing customer service in this sector. It can ensure that consumers do not have to wait as long for any company to respond to specific issues [66]. It can concurrently make various other processes more efficient and also ensure that errors in customer service are gradually avoided. AI systems are trained by 'feeding' the algorithms with appropriate training data sets. For machines, data is the same as experience is for humans. There should be as much of this as possible to achieve an optimal training goal. The best AI training data is therefore obtained from a large number of different people [67].

6. AI and Future Education

AI has immense potential in the education sector, transforming learning programs and teaching methodologies. It enables personalized learning, adapts tasks to students' needs, and supports children with special needs. Applications of AI in education include 24/7 chatbots, personalized learning algorithms, automated grading systems, and insights derived from big data analytics to improve strategies and plans [68].

Education 4.0 aligns with the Fourth Industrial Revolution (4IR), emphasizing innovation, interdisciplinarity, and integrating advanced technologies like AI, IoT, and cloud computing. It aims to prepare students for global challenges by ensuring they gain practical skills and sustainable knowledge through on-ground practice, research, virtual classrooms, and tailored educational modules. The relationship between education and society in this era underscores the need for education to adapt to socioeconomic and technological trends [69].

The 4IR shifts the focus from jobs to skills, promoting human-machine collaboration. This requires institutions to transform traditional educational methods and align them with the demands of a global, technology-driven society. Education 4.0 fosters adaptability, innovation, and ethical use of technology, aiming to equip students with knowledge and skills that ensure competitiveness in the global workforce [70].

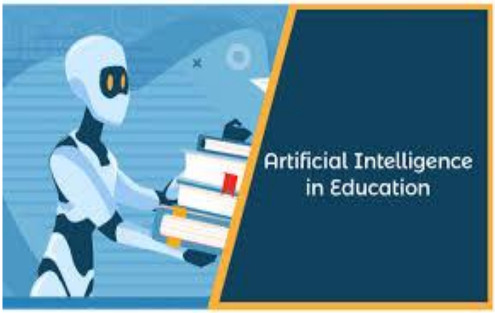

Figure 5: AI in Education and Robots and AI are helping in education

Key Features of Education 4.0:

- **Personalized Learning:** AI customizes tasks based on individual student needs, providing real-time feedback, identifying strengths and weaknesses, and tailoring learning experiences [71].
- **Remote and Active Learning:** E-learning tools facilitate anytime, anywhere learning, blending face-to-face and online components. Active learning environments enhance creativity, critical thinking, and collaborative problem-solving [72].
- **Project-Based Learning:** Students work on curriculum-based, interdisciplinary projects to solve real-world problems, developing collaboration, time management, and practical skills essential for future careers [73].
- **Assessment and Data Analytics:** AI-driven tools enhance assessment accuracy, track student performance, and enable predictive modeling to identify areas for improvement. These tools also help institutions make data-informed decisions to optimize learning outcomes [74].
- **Availability of Education Tools:** Collaborative tools like flipped classrooms and blended learning models support diverse learning needs, making education accessible and inclusive [75].
- **Remodeling of Education Curriculum:** Educational institutions must align curricula with industry standards and focus on skill-based education to meet the needs of Industry 4.0. This includes developing competencies in interoperability, virtualization, decentralization, and real-time capabilities for engineering students [76].
- **Building Digital Skills:** Training faculty and students in digital and disruptive technologies like machine learning is crucial. Educational programs should also emphasize soft skills such as problem-solving and social skills to prepare students for the workplace.

- **Virtual Learning Environments (VLEs**): Digital tools in VLEs facilitate flexible learning, enabling access to course content, collaborations, and discussions during flexible hours [77].
- **Technology-Built Classrooms: Smart** classrooms incorporate advanced tools such as AI and robotics, digitized textbooks, and interactive applications. AI-powered platforms like Netex Learning provide custom curriculums and support independent study [78].

By integrating advanced technologies, Education 4.0 ensures a comprehensive, adaptable, and efficient learning system. Institutions must adopt modern tools and innovative strategies to prepare students for the dynamic challenges of the 4IR era while maintaining a focus on ethical and sustainable practices.

7. Impact of AI in the Era of 4IR

AI has become a transformative force across various industries, steadily improving everyday life. From robots assisting in shopping centers to AI systems powering online search engines, the technology simulates human intelligence in unprecedented ways. AI programs can think, learn, and perform tasks traditionally requiring human analysis. Today, processes are more efficient, technologies more accessible, and forecasts increasingly accurate. Experts predict AI advancements will make most people better off over the next decade while raising concerns about the implications for humanity, productivity, and autonomy [79].

AI's impact extends across the agricultural and food value chain, automotive technologies, global aviation, aerospace sectors, construction, and civil engineering. It transforms smartphones, tablets, wearable tech, and other gadgets, influencing how people live, work, and consume services. In healthcare [80]. AI applications include diagnosing and treating patients, managing public-health programs, and enhancing senior care. AI also supports formal and informal education systems, enabling personalized learning and broader access to information. These examples highlight how AI is redefining societal norms and creating opportunities across various sectors [81].

Figure 5: Future robotic teacher in the classroom and No books and no physical library

The integration of AI with IoT in daily operations is evident in customized internet shopping recommendations, AI-powered health checkups, and smart systems for cars, buildings, and utilities. These innovations save time, money, and lives, fostering a more personalized future. AI can simplify processes, enhance decision-making, and address problems beyond human capacity. Despite these advantages, concerns persist about job displacement and reduced human intelligence. Speed, precision, efficiency, and scalability remain AI's most significant benefits [82].

The Fourth Industrial Revolution (4IR) will drastically transform industries, services, and education systems. Many jobs today may not exist in 25 years. Graduates face a technologically transformed world where AI, IoT, ML, Big Data, Cloud, and Edge Computing redefine opportunities and challenges. Formal education systems must adapt to these changes, preparing students for a post-work era where social concepts shift alongside technological advancements. AI is projected to become a US$15 trillion industry within the next seven years, creating millions of hi-tech jobs while rendering traditional roles obsolete. These shifts necessitate a focus on modern, hi-tech skills to thrive in the evolving landscape [83].

8. Future of Robotics and Robots

An algorithm is a step-by-step procedure for solving problems or achieving specific outcomes. In AI, algorithms are automated instructions that manipulate data, perform tasks, or solve problems using structured mathematical models. Machine learning (ML) can be supervised, unsupervised, semi-supervised, or involve reinforcement learning, depending on input data and expected outputs. Deep learning, a subset of ML, uses neural networks with billions of nodes to process and pass information through layers, mimicking human neurons [84].

Future robotics and automation will revolutionize roles across industries, serving as assistants, workmates, surgeons, drivers, and more. Robots are increasingly integrated into daily life, replacing humans in hazardous, repetitive, or labor-intensive jobs. However, safety remains a concern. High-profile incidents, such as a semi-autonomous Tesla crash and industrial robot accidents, highlight the need for stringent safety protocols and periodic training [116]. Organizations like MIT and BMW are advancing robotic safety through simulations and predictive algorithms to ensure seamless human-robot collaboration on production lines [85].

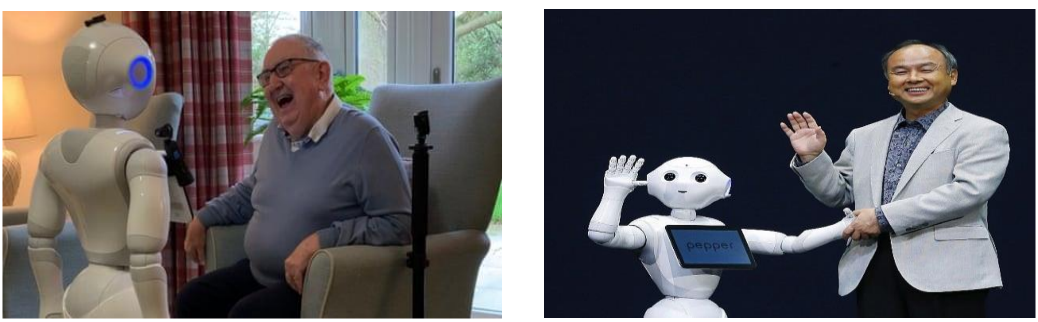

Figure 6: Example of few modern robots (Home care robot, Emotional robot)

Upskilling is critical as industries embrace automation. Initiatives like Amazon's "Upskilling 2025" invest heavily in retraining workers. Training must focus on both safety and technology adoption to minimize risks and maximize productivity. Reports from PricewaterhouseCoopers emphasize creating a digital culture and providing ongoing training to adapt to evolving national safety guidelines [86].

Robots are also making strides in social interaction. Examples include:

- **Sophia:** A humanoid robot designed as a companion for older adults and the first robot to receive citizenship (Saudi Arabia).
- **Miko:** A robot capable of recognizing human emotions, engaging in conversations, and encouraging interactive play.
- **PARO:** A therapeutic robot used in healthcare facilities to replicate the benefits of animal therapy.
- **TRINA**: A tele-robotic intelligent nursing assistant developed at Duke University to reduce infection risks for healthcare workers.
- **Buddy:** A home robot enhancing connectivity and convenience [87].

The role of nurses and other professionals will evolve as robots take on non-core tasks such as vital sign measurement and medication administration. TRINA, for instance, performs about 60% of predefined nursing tasks but is currently slower than human counterparts. Robots will complement rather than replace human professionals, enabling them to focus on critical care and decision-making [88].

Reports from McKinsey Global Institute predict that by 2030, up to 375 million workers may need to reskill as automation transforms industries. However, new roles and opportunities will emerge, driven by advancements in AI and robotics. Research breakthroughs, such as Andrew Ng's experiments with unsupervised object learning, demonstrate AI's potential to redefine tasks. Global AI healthcare spending is expected to reach $36.1 billion by 2025, highlighting its growing influence in critical sectors [89].

Countries are racing to lead in AI and robotics innovation. China aims to dominate AI by 2030, while the U.S. prioritizes maintaining leadership through federal initiatives. The future of robotics and AI holds immense promise for economic growth, improved safety, and enhanced quality of life worldwide.

9. AI and Next Global Consequence

With every new use of AI comes the pressing question: will robots replace human jobs? Experts are divided. While some believe AI will automate numerous roles, displacing millions, others see AI as a creator of wealth and new job opportunities. Many agree that workforce structures are evolving, driven by AI's integration into various sectors. Optimistic analysts predict that AI will fragment traditional workflows, creating new human-centric roles to manage and enhance these processes. On the other hand, skeptics worry about long-term job displacement, raising questions about the societal value of human labor when technology dominates [90].

The transition into the age of AI and the Fourth Industrial Revolution (4IR) will take years or even decades. However, its effects on jobs are already evident. Self-driving cars and AI assistants like Siri and Cortana could displace millions of jobs in the U.S. alone, with global ramifications. As technology advances, society must redefine productivity and individual value. What makes humans useful in a world where robots excel at repetitive and analytical tasks? This existential question calls for a "moonshot mindset"—to create intelligent digital networks imbued with empathy and aligned with social and ethical responsibilities [91].

Figure 7: AI and the Singularity and that may collapse the earth

AI-driven solutions must address data and knowledge inference, focusing on security, ethics, and civil rights. As AI integrates into critical sectors like transportation and healthcare, building trust and ensuring ethical use is essential. Policies must address privacy, security, and ethical challenges while promoting AI's potential to benefit humanity. International collaboration is necessary to regulate AI advancements responsibly [92].

Despite fears, experts believe human employment will evolve rather than vanish. The workforce will become increasingly specialized, requiring skills that automation cannot replace, such as creativity, problem-solving, and qualitative analysis. Technical skill sets will be in higher demand, and new professions will emerge. As humans and robots coexist, their roles may overlap, but collaboration will likely define their relationship.

The future of AI remains unwritten. While robots may never fully replace humans, their growing capabilities challenge us to innovate, adapt, and coexist. Whether this leads to harmonious collaboration or a competitive divide depends on how humanity embraces technological progress while safeguarding ethical and social values.

10. Conclusion

Today, AI robots are closer than ever to becoming integral to our lives, performing tasks that traditionally required human intelligence. Machine learning (ML) and deep learning are revolutionizing industries by simplifying complex processes. Data for AI is as valuable as experience for humans, enabling companies to enhance service quality, boost productivity, increase customer satisfaction, and optimize resources. AI is now prevalent in automotive, healthcare, financial, manufacturing, agriculture, military, cybersecurity, and other sectors, marking the beginning of a new economic era [93].

AI is significantly impacting the financial and healthcare sectors. In finance, AI's precision and real-time data analysis enable algorithmic trading, adaptive intelligence, and automation. In healthcare, AI surpasses human capabilities in diagnostics, drug discovery, surgery, and disease prevention. Self-driving cars exemplify AI's potential, with projections of 33 million autonomous vehicles by 2040, signaling a transition from science fiction to reality [94].

However, the advancement of AI carries risks. Automation may lead to job displacement, reducing the need for human labor and altering global economic dynamics. While AI aids education by enhancing learning experiences, ethical, privacy, and security concerns must guide its integration. The concept of AI "Singularity" poses a significant threat, with fears of AI systems gaining autonomous control over critical assets like nuclear weapons or creating harmful agents. To mitigate such risks, global collaboration is essential to establish ethical and regulatory frameworks for AI development [95].

AI's transformative potential mirrors historical milestones like the industrial revolution. It promises to redefine industries and improve lives but may also exacerbate inequality if unchecked. Policies must address disparities, ensuring equitable benefits from technological advancements. Certain sectors, including creative problem-solving, nursing, physiotherapy, and other care-oriented professions, will remain dependent on human expertise. These roles will demand higher technological proficiency and adaptability [96].

The education system must evolve to prepare individuals for AI-driven economies. Curricula should emphasize skill development, technological literacy, and adaptive learning to meet future challenges. AI will streamline workflows and create opportunities for skilled professionals, offering competitive salaries and new career paths. As we move forward, balanced integration of AI can ensure sustainable progress, benefiting both humanity and technological innovation.

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Prediction of Added Resistance of a Very Large Crude Carrier in Head Wave

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Abstract

In recent years, with the growing concern about energy efficiency and emission reduction, more attention has been placed on the accurate estimation of ship resistance. Therefore, it is crucial to predict the added resistance of ships in the sea way precisely. There are various methods for predicting the added resistance of a ship, including far-field, near-field methods, and strip theory, among others. Over the past few decades, Computational Fluid Dynamics (CFD) has gained significant popularity. In the present study, the added resistance of a very large crude oil carrier KVLLC2 is predicted using Maruo's method, Salvesen's method and CFD. First, a validation and verification study is done in calm water to assess the numerical accuracy and stability. An open source CFD solver, OpenFOAM has been used in the present study and MATLAB codes have been used for Maruo's and Salvesen's method to predict the added resistance in the head wave. The CFD results show a good agreement with experimental results, where the results obtained from Maruo's and Salvesen's methods show a little discrepancy specially at short wave.

Keywords: CFD, KVLCC2, Maruo, Salvensen, OpenFOAM, MATLAB

1. Introduction

Added resistance due to the wave is one of the major causes for the increment of power in a real sea. One of the primary concerns for the engineers and the designers is to accurately estimate the propulsive power of a ship in the early stage of the design. Traditionally, the power of a ship is estimated based on calm water resistance with a sea margin of 15 to 20 %. In recent years, the International Maritime Organization (IMO) has implemented strict rules to reduce emissions from ships, which put limits on these kinds of practices.

A lot of research works have been carried out by researchers for years to predict the added resistance of ships. Havelock [1] was one of the first to formulate an analytical method for the added resistance of ships in a head wave. The far field method, which was based on conservation of momentum, was introduced by Maruo in 1962 [2].

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Garritsma and Beukelman [3] used near near-field method based on the radiated energy to predict the added resistance of the ships. The strip theory was introduced in the 1970s by Salvesen, which could accurately predict the motion of ships in waves and hence the added resistance [4]. For accurate estimation of added resistance in short waves a formula was proposed by Fuji and Takashi in 1975 [5]. Faltinsen et al proposed an asymptotic formula to calculate the added resistance of ships due to the reflection of waves [6].

With the rapid development of computational power, numerical methods have become popular among researchers. Orihara et al. used an overlapping grid technique to predict the added resistance of a blunt bow shape using an in-house CFD code WISDOM X [7]. Seo et al. estimated the added resistance of different types of hull forms using both the panel method and cartesian grid method [8]. The peak value of the panel method was shifted towards the high frequency region, where the peak value of cartesian grid method was shifted towards the low frequency region. Despite this, both of methods showed a good approximation with experimental results. Soizic et al. [9] used a 3D high-order boundary element method to calculate the added resistance of a ship using both pressure integration and momentum conservation principles. Both of the methods provide a quite good approximation for a simple geometrical shape. The radiated energy theory, along with the strip method, was developed Duan et al. [10]. The comparison with experimental results showed a good approximation with the proposed method. A comparative study was made by Solding et al. to predict the added resistance of ships in waves using Rankine source, strip theory and RANS method [11]. The panel method and RANS solver appeared to be inaccurate for short wavelengths. Inaccurate results were provided by the Strip theory at higher wavelengths. Martic et al. [12] evaluate the added resistance of ships coupled with a sloshing tank using a potential flow-based solver. Their calculated results underestimated the experimental results. Islam et al. [13] investigated the effect of the degree of freedom on the added resistance of a VLCC ship. Their result showed a minor effect of changing the degree of freedom, especially at lower wavelengths. Qiming et al. modified the source density function of Maruo’s method to make it suitable for complex geometries [14]. The formula could predict the radiation-added resistance in a short time. Islam et al. [15] made a comparison between RANS and Potential flow-based solvers for predicting added resistance and motion of the Japan Bulk Carrier in waves. The potential flow-based solver Hydrostar correlated with the RANS-based solver SHIP Motion. Martic el al. [16] the effect of trim angle, prismatic coefficient and position of longitudinal center of buoyancy on added resistance of a ship. Their study concluded that increasing the prismatic coefficient, shifting the LCB towards the stern and trimming by stern moderately reduced the added resistance.

Recently, some semi-empirical formulas have been developed and frequently used by the designers. Liu et al. [17] provided a semi-empirical formula for fast and accurate prediction of the added resistance of ships in a head wave with some simple input parameters of the ships. Wang et al. validate the newly developed SHOPERA-NTUA-NTU-MARIC (SNNM) method [18]. The method was developed based on regression analysis of over 1477 added resistance experimental data samples collected from 8 different institutions.

However, most of the studies are conducted on commercial or in house developed solvers which are not free to access. So, the present study aims to validate the results obtained from Maruo's, Salvesen's methods and Computational Fluid Dynamics with the experimental results of a fuller ship in a head wave using open source codes. Also, assess the validity of the methods for predicting added resistance of fuller ships, particularly at short waves.

2. Ship Model

In the present study the KRISO Very Large Crude Carrier 2 (KVLCC2) introduced by the SIMMAN 2008 CFD work shop has been used [19]. The profile view of the hull are mentioned in **Fig. 1.** and principal particulars of the hull are mentioned in **Table 1** respectively.

Figure 1 Profile view of KVLCC2 hull.

Table 1 Principal Particulars of KVLCC2 hull.

Specification	Symbol	Full Scale	Model Scale	Unit
Length between perpendiculars	L_{PP}	320	5.517	[m]
Length of waterline	L_{WL}	325.5	5.612	[m]
Maximum beam	B_{Max}	58.0	1.000	[m]
Depth	D	30.0	0.517	[m]
Draft	T	20.8	0.359	[m]
Block Co-efficient	C_B	0.810	0.810	--
Wetted surface area	S_W	27194	8.084	[m^2]
Longitudinal center of buoyancy (fwd+)	LCB[%Lpp]	3.48	3.48	--
Scale	λ	1:1	1:58	--

3. Research Methodology

The present study is conducted on an opensource frame work. An open source CFD solver OpenFOAM version 11 is used for simulations in calm water and head wave. A MATLAB code developed by DTU (Technical University of Denmark) for predicting added resistance by Maruo's [20] method and Salvesen's [21] method in head wave is used in the present study. Initially, a validation and verification study in calm water have been performed for numerical stability of CFD solver. Then, the head wave simulations are performed. All the calculations are performed at Froude number 0.142. The experimental results are provided by Yu et al.. The wave conditions considered are shown in Table 2.

Table 2 Head wave simulations condition.

Case	C1	C2	C3	C4	C5
λ/L	0.301	0.498	1.096	1.395	1.903
$H\ (m)$	0.036	0.040	0.027	0.028	0.029
$T_e\,(s)$	0.6256	0.8819	1.4695	1.7062	2.0613

The parameters ($H, \lambda,\ T_e$) are defined as wave height, wave length, encountering frequency and encountering period respectively.

Maruo's Method:

It is basically a far-field method that considers diffracted energy due to the interference of the wave with the ship and energy radiated from the ship, along with momentum flux at infinity. This leads to calculating the added resistance by the rate of change of momentum. The expression of added resistance is given by the equation (1).

$$R_W = \frac{\rho}{4\pi}\left\{-\int_{-\infty}^{\bar{k}_1} + \int_{\bar{k}_2}^{\bar{k}_3} + \int_{\bar{k}_4}^{\infty}\right\}\frac{\bar{k}(m-k\cos\beta)}{\sqrt{\bar{k}^2-m^2}}\left|H(m)\right|^2 dm \quad (1)$$

The 2D potentials of radiation ψ_k for mode k and the Kochin function $H(m)$ is defined by the equation (2).

$$H_k(m) = \int_L e^{ixm}\left[\int_{C_x} e^{vz}e^{ivy}\left\{(ivN_y + vN_z)\psi_k - \left(\frac{\partial\psi_K}{\partial N}\right)\right\}dl\right]dx \quad (2)$$

After considering the scattering wave, the velocity potential becomes ψ_s and the expression of Kotchin function is given by the equation (3).

$$H_s(m) = \int_L e^{ixm}\left[\int_{C_x} e^{Kz}e^{iKy}\left\{(iKN_y + KN_z)\psi_s - \left(\frac{\partial\psi_s}{\partial N}\right)\right\}dl\right]dx \quad (3)$$

Where, $v = \omega^2/g$ with ω the encounering frequency, $\bar{k}(m) = (\omega + mU)^2/g$, $K = 2\pi/\lambda$ and N_y , N_Z are the normal in y and z direction at each section C_x respectively. For calculating the added resistance of ships in a head wave, the Kochin function is integrated twice i.e., over each 2D section and along the length of the ship. Finally, the line integrals in the equation (3) is performed.

Salvesen's Method:

In 1978 Salvensen used an approximated formulation inside the strip theory to calculated the resistance due to wave given by the equation (4).

$$R_W = \frac{pAgK\cos\beta}{2\omega_0}\Re\left\{\int_L e^{iKx\cos\beta}\left[\int_{C_x}\left(\psi_B\frac{\partial}{\partial N}-\frac{\partial\psi_B}{\partial N}\right)e^{Kz}e^{iKy\sin\beta}dl\right]dx\right\}+ \\ \frac{1}{4}\rho\Re\left\{\int_L\int_{C_x}\left(\psi_B\frac{\partial}{\partial N}-\frac{\partial\psi_B}{\partial N}\right)\frac{\partial\psi_B^*}{\partial x}dldx\right\} \tag{4}$$

Here the conjugate and the real part of the equation is noted by the $*$ and $\mathcal{R}$ marks, ω_0 is the wave frequency, A is the amplitude of the wave, ψ_B is the disturbance velocity potential. Salvensen omitted the second part of the integration and for long wave the following assumptions are made given by the equations (5) and (6).

$$e^{Kz} \approx e^{-Ksd} \tag{5}$$

$$e^{iK_y\sin\beta} \approx e^{iK\left(\pm\frac{1}{2}b\right)s\sin\beta} \tag{6}$$

Here, b , d , s_0 , s defines the beam, draft, sectional area and sectional area coefficient of the ship respectively. Finally, the added resistance of the ship is obtained by the equation after performing the line integral along the length of the ship.

Numerical Method:

The numerical analysis is carried out in an open-source computational fluid dynamics solver, OpenFOAM. It has an extensive range of libraries to solve the problem of laminar to turbulent multiphase flow. It was elaborately described by Jasak in 2009 (Jasak 2009). An incompressible two-phase flow (air-water) solver has been used in the present study. The solver follows the earth and body-fixed cartesian grid system to solve the problem. The governing equations are based on continuity and Reynolds Averaged Navier Stoke’s equations (momentum) given by equation (7) and equation (8) respectively.

$$\nabla . v = 0 \tag{7}$$

$$\rho\left(\frac{\partial u}{\partial t} + u.\nabla u\right) = -\nabla p + \mu\nabla^2 u + \rho g \tag{8}$$

Volume of fluid method (VOF) has been used to model the fluid as a continuum of mixed property air and water. The Finite volume method is used to discretize the governing equations and the mesh morphing technique is used to accommodate the hull motion. OpenFOAM’s built-in motion solver dynamicMesh dictionary, has been used to solve the motion. All the simulations are run at heave and pitch free motion (2 dof). The pressure velocity coupling is done by using the PIMPLE algorithm. The sst-k omega turbulence model is used in the present study. The wave is modeled by Stokes' second-order wave given by the equation (9) below.

$$\eta = \frac{H}{2}COS(\kappa x - \omega t + \phi) + \kappa\frac{H^2}{4}\frac{3-\sigma^2}{4\sigma^3}COS(2(\kappa x - \omega t + \varphi)) \tag{9}$$

Here, η, H, k, ω, σ, φ, t mean modeled wave height, actual wave height, angular wave frequency, radian wave frequency, phase shift, time respectively. The crest of the wave is set at the bow of the ship and damping is done at the inlet for better propagation of the wave.

Mesh Generation:

Two different types of mesh configurations have been used for calm water and wave simulations, respectively. For calm water simulation, the inlet is placed 1 L_{pp} from the fore perpendicular, the outlet is placed 2 L_{pp} from the aft perpendicular, the side is placed 1 L_{pp} from the centerline, the bottom of the domain is placed 1 L_{pp} from the free-surface and the top of the domain is placed 0.5 L_{pp} from the free surface according to ITTC-2011 guideline. In the head wave simulation, the domain is generated according to the description provided by Alfaz Hossain et.al [18]. The Inlet of the domain is placed 0.5 L_{pp} for short waves ($\lambda/L = 0.301, 0.498$) and 0.6 L_{pp} long waves $(\lambda/L = 1.469,\ 2.06)$, outlet is placed 1.35 L_{pp} from the outlet of the domain. The sides, top and bottom of the domain are kept the same as calm water simulation. OpenFOAM's built in blockMeshDict is used to generate the computational domain. To place the hull within the domain, snappyHexMeshDict has been used. Multiple refinements are done using the six-topoSetDict to capture the free surface and mesh motion. In case of wave simulations, multiple refinements are done up to the inlet of the domain to avoid wave reflection near the inlet. Three boundary layers are generated over the hull to satisfy the y+ criteria. The mesh assembly for calm and wave conditions is shown in Fig. 2.

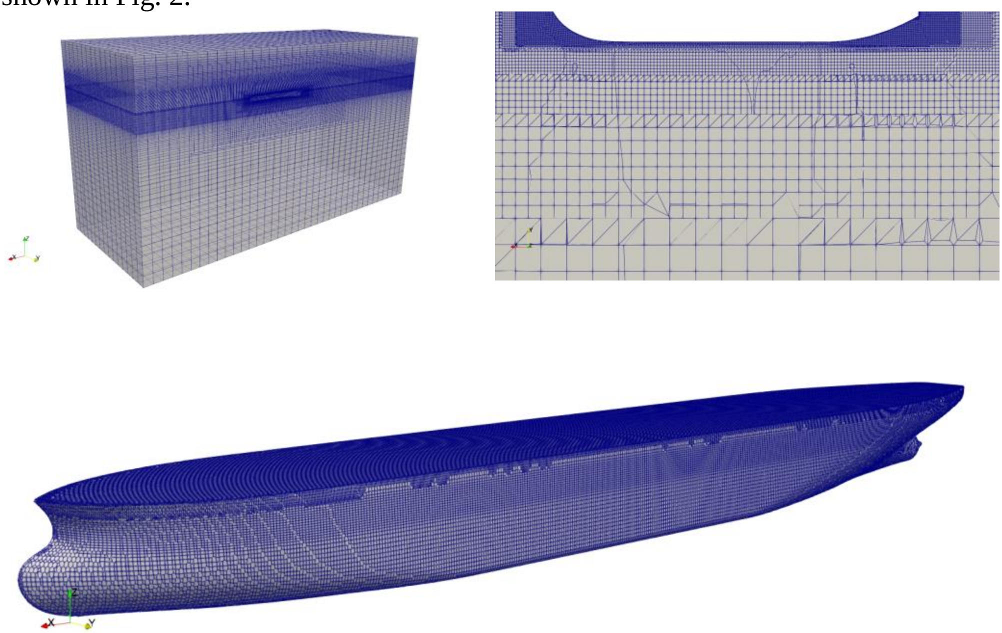


Figure 2 Computational mesh of KVLCC2 hull in calm water.

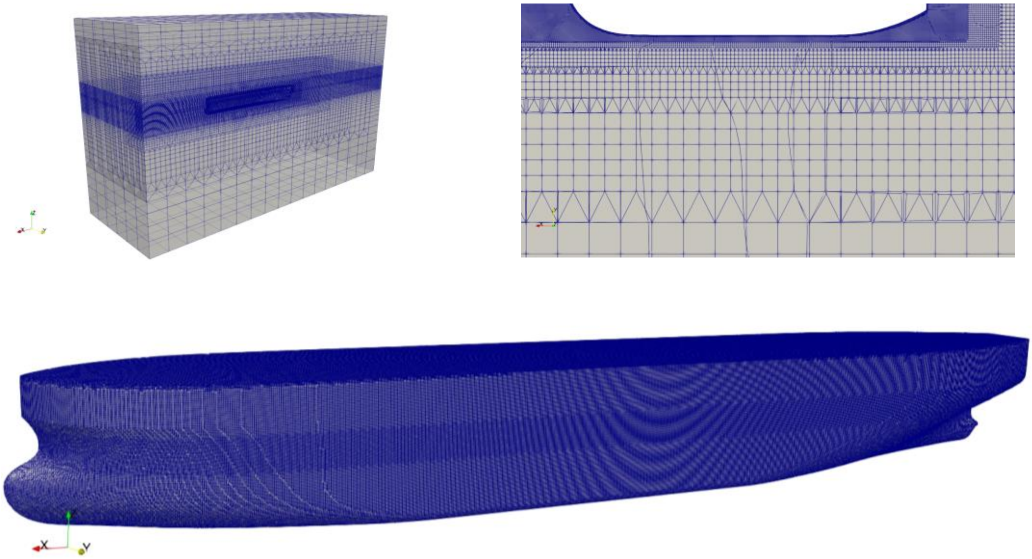


Figure 3 Computational mesh of KVLCC2 hull in wave.

The grid density is increased for wave simulations. Average cell number for calm water simulation and head wave simulations are 1.577 million and 2.40 million respectively. The deck of KVLCC2 model is extended to avoid deck wetness.

4. Result and Discussion

First, the calm water resistance of KVLCC2 is validated with the experimental results. After that, a comparison of the added resistance predicted by Maruo's, Salvensen's method and CFD has been done with the experimental results. The experimental results are provided by Yu et al. Finally, a flow field analysis is done.

Verification and Validation Study:

Verification study is related to consistency of the CFD code while validation study is related to the accuracy of the simulation compared to real life physical phenomenon. In the present study verification study is performed using Celik et al. [22]. According to the method the grid convergence ratio is calculated by the following equation (10).

$$R = \frac{\epsilon_{21}}{\epsilon_{32}} \tag{10}$$

The relative difference between the results of medium-fine and coarse-medium grid's solutions are represented by ϵ_{21} and ϵ_{32} respectively. For $0 < R < 1$ defines monotonic convergence $R < 0$ defines oscillatory convergence and $R > 1$ defines divergence. The order of accuracy (p) is calculated by using following equation (11).

$$p = \frac{1}{\ln(r_{21})} \left| \ln \left| \epsilon_{32}/\epsilon_{21} \right| + q(p) \right| \tag{11}$$

$q(p) = 0$ for constant grid refinement ratio.
The grid convergence index is estimated using equation (12).

$$GCI_{fine}^{21} = \frac{1.25e_a^{21}}{r_{21}^p - 1} \quad (12)$$

Where, e_a^{21} defines relative approximate error. The verification study of total resistance, trim and sinkage are mentioned in Table 3.

Table 3 Verification of CFD results in calm water.

Parameter	Cell No. (million)	R_T (10^{-3})	Trim (deg)	Sinkage (m)
Mesh 1 (Fine)	1.577	17.3908	-0.119	-0.00478
Mesh 2 (Medium)	0.834	18.355	-0.12	-0.0068
Mesh 3 (Coarse)	0.302	19.510	-0.129	-0.0060
Convergence $\varepsilon_{21}/\varepsilon_{32}$	--	0.8424	-2.525	0.11
Order of accuracy (p)	--	1.038	5.596	13.275
Grid Convergence Index $GCI_{(21)}$	--	0.369	0.346	0.001313
Grid Convergence Index $GCI_{(32)}$	--	0.415	0.0964	0.011719

Here, total resistance and sinkage show monotonic convergence and trim shows oscillatory convergence.

Validation of numerical results in calm water are done at Froude number 0.142 which corresponding to speed of 15.5 knots in full scale. For validation of numerical results total resistance, trim and sinkage are considered. The validation of results are mentioned in Table 4.

Table 4 Validation of CFD results in calm water.

Result	$R_T(N)$	$Trim\ (deg.)$	$Sinkage\ (m)$
EFD	17.8800	-0.15	-0.0062
CFD	17.3908	-0.119	-0.00478
Error	2.73 %	-22.90 %	-20.66 %

Minimum deviation is obtained for total resistance value. The error for trim and sinkage are quite high due to insufficient mesh resolution and exact value of COG (centre of gravity) is not known. However, the error for sinkage is in millimetre scale.

Added Resistance:

The added resistance of ships in waves is mainly due to energy loss by the radiation of waves caused by the ship's motion and diffraction of the incident wave by the hull. The added resistance of the ship is obtained by the increment of resistance due to the wave, that in calm water, is defined by the equation (13).

$$R_{AW} = \bar{R}_{wave} - R_{calm} \quad (13)$$

The added resistance coefficient is defined by Equation (14).

$$C_{AW} = \frac{R_{AW}}{\rho g \zeta^2 B^2 / L} \tag{14}$$

It is seen that there is a general trend of decrease in added resistance up to $\lambda/L_w = 1$ due to increase in wave steepness. Some discrepancies have been observed for Maruo's and Salvensen's methods at short wavelength, particularly below $\lambda,/L_w = 1$ with the experimental results. Because, Maruo's method is based on diffraction of energy, while in shorter wavelengths the added resistance is due to radiation of energy to the wave. The nonlinearity nature of the added resistance increases with increasing wave steepness H/λ which is much more pronounced at shorter wave lengths which affects the accuracy of Salvensen's method. Actually, at short wave length the added resistance of ship mainly depends of the wave reflection. The calculated added resistance coefficients are plotted against the ratio of wave to ship length in Figure .

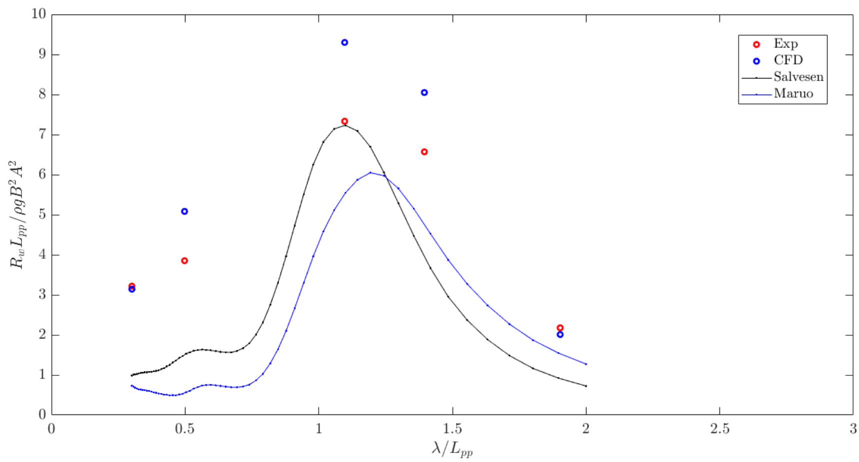
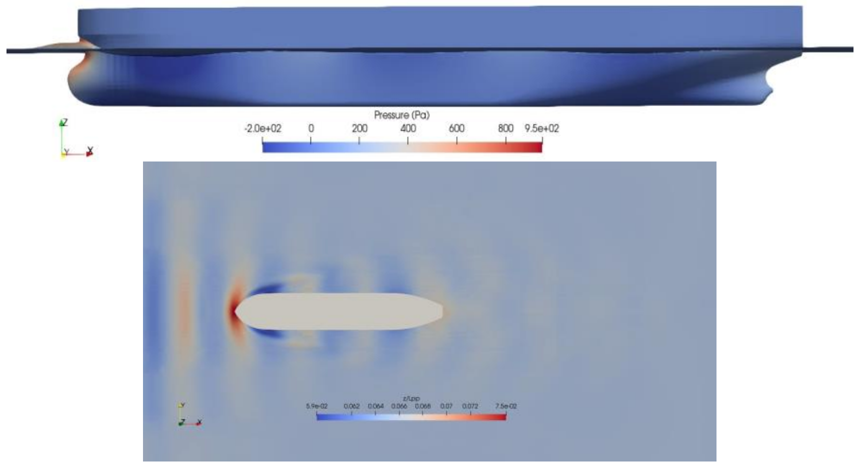


Figure 4 Added resistance coefficient of KVLCC2 hull in head wave at different wave length.

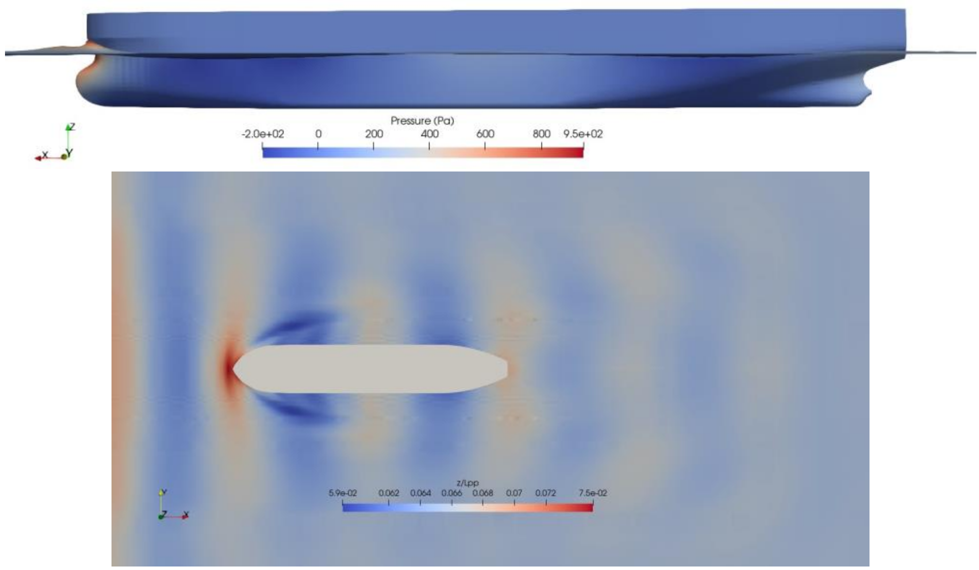
That effect becomes much more severe especially when the bow shape is blunt. On the other hand, the results obtained from CFD show an overall good approximation with the experimental results. However, deviation is quite higher when the wave length approaches to the length of the ship at $\lambda/L_w = 1.096$. The possible reason is occurance of resonace when the natural becomes equal to the frequency of the encountering wave. A severe oscillation and increase of hydrodynamic drag have been seen at that region.

Flow Field Analysis:

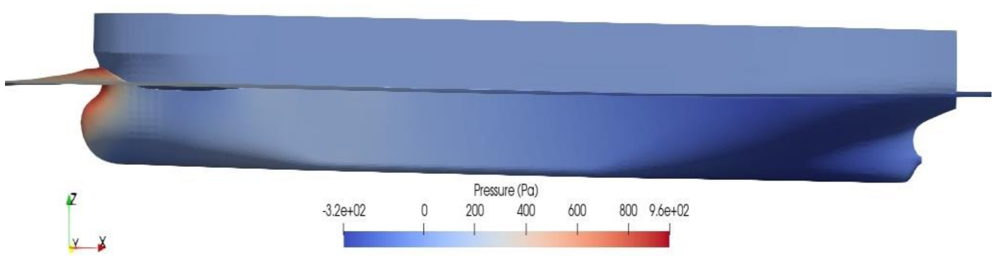
An in-depth representation of pressure distribution on the hull is important for a physical understanding of the added resistance due to the wave. On the other hand, free-surface elevation analysis is important as it indicates the wave field around the hull. The snapshots of the hydrodynamic pressure field and the free-surface elevation are shown in Figure 5.

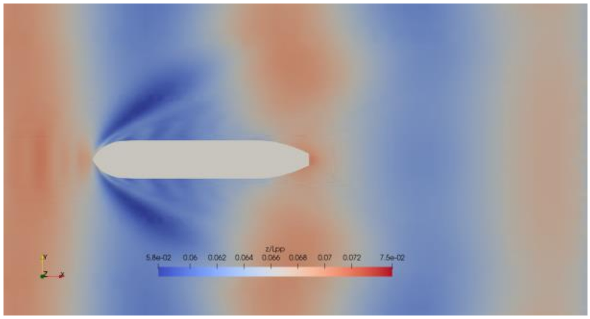


$\lambda/L = 0.301$

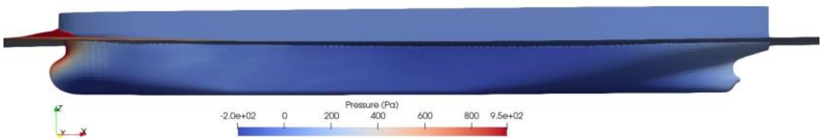


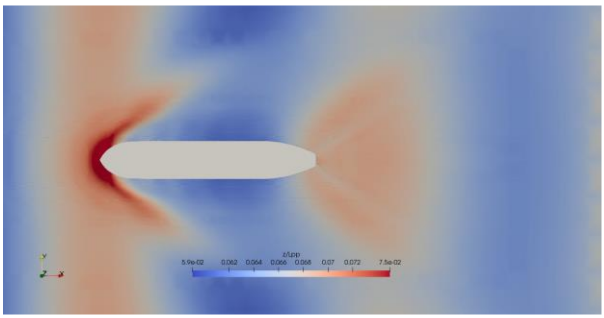
$\lambda/L = 0.498$



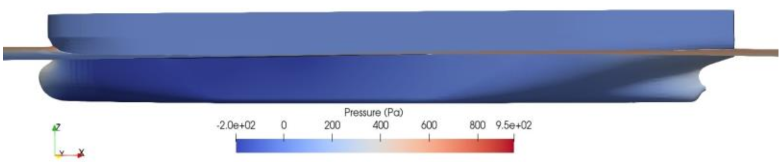


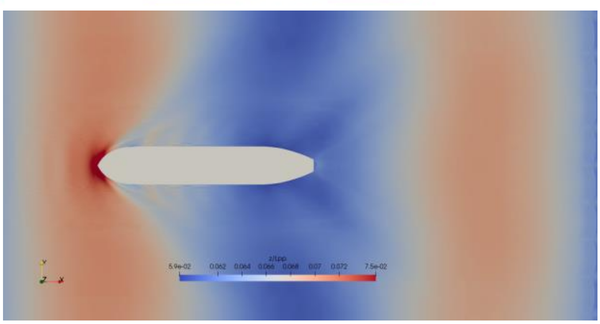
$\lambda/L = 1.096$





$\lambda/L = 1.3956$





$\lambda/L = 1.903$

Figure 5 Pressure distribution on hull and freesurface elevation of KVLCC2 hull in head wave at different wave length.

The increment of pressure due to wave reflection is much more prominent at the bulbous bow region of the hull. A high positive area near the pressure of the bow has been seen when the wave crest hits the bow. The distribution of hydrodynamic pressure around the stern changes significantly from case to case at different wavelengths, magnifying the complex phenomenon of ship motion and wave reflection. From the free-surface contours analysis, it has been seen that the wave height increases near the bow of the ship, highlighting the mechanism of wave reflection. Wavelength plays an important role when it reaches close to ship's length, the motion becomes rigorous then. At much shorter wavelengths and much higher wavelengths, the added resistance decreases significantly, corresponding to smooth interaction of hull with waves.

5. Conclusion

The present study presents an overview of the potential of some well-known traditional methods and computational fluid dynamics to predict the added resistance of ships. A popular benchmark hull KVLCC2, has been used in the study because of the availability of experimental results. The following conclusion can be drawn from the analysis:

Maruo's and Salvesen's methods provide approximately good results except for shorter wavelengths.

Computational fluid dynamics (CFD) is advantageous for dealing with nonlinear problems, especially for better representation of the free-surface flow phenomenon without any explicit assumption.

In all methods, the added resistance decreases at very short and long wavelengths, which highlights the inherent features of ship motion interaction with wavelength.

The added resistance at a wavelength very close to the ship length is over-predicted due to resonance.

Predicting ship resistance using computational fluid dynamics has gained popularity for over a decade. It is possible to treat higher-order problems and take the viscous effects with reasonable accuracy. But it should be mentioned that it is time-consuming. On the other hand, the traditional theory-based methods provide results with approximate accuracy.

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Environmental Pollution from the Shipping Industry in Bangladesh: Assessment of Sources and Mitigation Strategies

Md. Riad Khan[1], Md. Mahedi Hasan Bappy[2*]

Abstract

The shipping industry plays a crucial role in global trade, transporting approximately 90% of the world's goods. However, it contributes significantly to environmental pollution across its lifecycle, including shipbuilding, operation, and recycling. This research focuses on the environmental impact of each phase, with a particular emphasis on Bangladesh, a major shipbreaking hub. Shipbuilding in Bangladesh generates air, water, and soil pollution from raw material extraction, manufacturing processes, and the use of toxic coatings. The operational phase contributes to air pollution through emissions from fuel combustion and marine pollution from ballast water discharge and oil spills. Ship recycling, especially in developing countries, presents severe risks due to improper handling of hazardous materials like asbestos and heavy metals. This study employs a mixed-methods approach, utilizing both qualitative and quantitative data to assess the environmental impact of the shipping industry at each stage of its lifecycle. Additionally, the study evaluates the effectiveness of local and international regulations, such as the MARPOL and Hong Kong Conventions, in addressing these challenges. Despite regulatory frameworks, enforcement remains weak, especially in regions with inadequate infrastructure. This study calls for stronger enforcement, improved waste management, and the adoption of sustainable technologies to reduce pollution in the maritime industry.

Keywords: Shipbuilding, ship operation, ship recycling, environmental pollution, Bangladesh.

1. Introduction

The shipping industry plays a pivotal role in global trade, responsible for transporting approximately 90% of the world's goods [1]. It contributes to economic growth by facilitating the movement of raw materials, energy resources, and finished products across continents. Despite its essential role, the environmental impact of shipping has gained significant attention in recent decades due to its contribution to pollution during different stages of its lifecycle: shipbuilding, operation, and recycling.

The maritime industry contributes 3% of global greenhouse gas (GHG) emissions, with pollutants like sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) exacerbating air quality degradation and ocean acidification [2]. Landmark disasters

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such as the *Torrey Canyon* (1967) and *Exxon Valdez* (1989) oil spills spurred international action, leading to frameworks like the MARPOL Convention (1973) and the Hong Kong International Convention for Ship Recycling (2009). Despite these efforts, invasive species from ballast water discharge, toxic antifouling coatings, and hazardous shipbreaking practices remain unresolved challenges. The focus on reducing the environmental impact of shipping has spurred modern technologies and stringent laws to prevent pollution, though challenges remain, particularly in developing countries where ship recycling activities continue to pose significant risks to the environment and public health.

Globally, the International Maritime Organization (IMO) and various environmental conventions have made strides in reducing pollution from ships, particularly focusing on controlling greenhouse gas emissions, marine pollution, and the safe disposal of hazardous materials.

South Asia dominates global ship recycling, with Bangladesh, India, and Pakistan collectively dismantling 85% of end-of-life vessels [3]. However, these regions often prioritize economic gains over environmental safeguards, resulting in severe pollution and labor exploitation. Chittagong is home to one of the largest shipbreaking yards in the world, where improper handling of hazardous materials contributes significantly to environmental pollution. Despite the implementation of some regulations, weak enforcement and limited infrastructure for waste disposal remain ongoing issues.

In Bangladesh, the challenges of pollution in shipbuilding, operation, and recycling are particularly pronounced. Shipyards and recycling yards face regulatory gaps that exacerbate environmental risks. Hazardous waste such as asbestos, heavy metals, and oil residues continues to be improperly disposed of, causing widespread contamination of land and marine ecosystems. Local communities and ecosystems around these shipyards suffer from the adverse effects of this pollution. This research aims to investigate the types of pollution caused by ships, the responsible activities at each stage, and the effectiveness of local and international regulations in mitigating the environmental impact. The primary objectives of this research are:

- To identify the key pollutants released during shipbuilding, operation, and recycling.
- To analyze the activities responsible for each type of pollution.
- To examine the local and international regulations addressing ship pollution and assess their enforcement and effectiveness.

The researcher is motivated by the growing environmental concerns surrounding the maritime industry, particularly in regions like Bangladesh, where ship recycling contributes to substantial environmental degradation. The need for comprehensive solutions to reduce pollution and enhance regulatory measures is paramount to ensuring sustainable development in the global shipping industry.

This study is significant for policymakers, environmental scientists, and stakeholders in the maritime industry. By understanding the sources of pollution in the shipping industry and assessing existing regulatory measures, the study can provide recommendations for reducing pollution and improving sustainability in shipbuilding, operation, and recycling. Additionally, it will inform the development of modern technologies and regulations to minimize environmental harm from the maritime industry.

2. Existing Literature Review

The environmental impacts of shipbuilding, operation, and recycling have been extensively studied, highlighting significant concerns and challenges across these stages.

Shipbuilding is a significant contributor to global pollution, starting with raw material extraction and processing. Steel and aluminum production for shipbuilding is responsible for a substantial portion of industrial CO_2 emissions, with studies like those from Sonter et al. [4] noting that these processes contribute around 7% of global emissions. Mining activities in regions such as China and India further degrade ecosystems, often resulting in deforestation and water contamination. Georgiev er al. [5] emphasize that energy-intensive smelting processes in shipbuilding rely heavily on coal, contributing to particulate matter (PM2.5) emissions exceeding WHO guidelines by 400% in industrial zones. Shipbuilding's manufacturing and assembly stages also contribute to air pollution. Welding and cutting processes in shipyards release significant amounts of nitrogen oxides (NOx) and volatile organic compounds (VOCs), which worsen urban air quality. Ledoux et al. [6] highlight that France shipyards, for instance, emit 12,000 tons of NOx annually, contributing to regional smog. In contrast, in Europe, automated welding has reduced emissions, yet many developing countries still rely on manual methods due to cost constraints. Additionally, shipyards also produce prominent levels of noise pollution, which disrupts marine mammals in coastal regions. The IMO’s 2023 study reveals that shipyard noise, sometimes reaching 110 dB, significantly impacts marine communication. Toxic coating and antifouling paints used in shipbuilding are another major source of environmental pollution. Tributyltin (TBT), banned globally in 2008, persists in sediments around shipyards and has caused serious harm to marine life, particularly mollusks, by inducing imposex. Newer copper-based coatings, though less toxic than TBT, still pose risks to coral reefs, as highlighted by Cima and Varello [7].

The operational phase of ships significantly contributes to air pollution, primarily due to the burning of heavy fuel oil (HFO) and marine diesel oil (MDO). This combustion results in the release of sulfur oxides (SOx), nitrogen oxides (NOx), and carbon dioxide (CO2), all of which degrade air quality and contribute to climate change. Aakko-Saksa et al. [8] note that SOx emissions from maritime vessels represent 90% of global maritime SOx emissions. In 2020, the IMO’s MARPOL Annex VI reduced the sulfur content in marine fuels to 0.5%, but developing countries still struggle to comply with this regulation [9]. Ships like the Panamax, which burn large amounts of fuel, emit significant CO_2, with a single vessel emitting as much CO_2 as 50,000 cars annually [10]. Regional disparities in compliance are notable, with regions such as the EU and North America reporting up to 70% lower SOx emissions than South Asia. Ballast water discharge is another significant source of marine pollution. The Ballast Water Management Convention, established by the IMO in 2004, mandates the treatment of ballast water before discharge. However, studies show that 60% of older vessels still fail to comply with these standards (IMO, 2023). Oil spills and chemical leaks continue to be a significant issue for maritime pollution. While major oil spills, such as the Deepwater Horizon disaster, grab global attention, chronic leaks from bilge water discharge contribute 1.3 million tons of oil annually into the oceans, according to [11]. Furthermore, incidents like the 2021 X-Press Pearl disaster, which involved the release of nitric acid and plastic pellets, severely impacted Sri Lankan coastlines. These types of chemical leaks and spills remain a major challenge for marine pollution management. Underwater noise pollution from ship operations is also a growing concern. Propeller noise and engine sounds from vessels, reaching up to 180 dB, disrupt the echolocation of cetaceans like whales and dolphins. Veirs et al. [12] suggest that this disturbance correlates with a 30% decline in blue whale populations. While some innovations, such as Mitsubishi's "Azipod" propulsion system, have reduced noise by 50%, these quiet designs are mostly used in luxury cruise vessels and have not been widely adopted in commercial shipping.

Ship recycling, particularly in developing countries like Bangladesh, poses significant environmental risks due to the handling of hazardous materials. South Asia is responsible for recycling more than 85% of the world's ships [3], but 80% of yards lack proper protocols for managing hazardous waste. Shipbreaking yards in Chittagong, Bangladesh, for example, report lead levels in soil averaging 1,200 ppm, well above the WHO limit of 100 ppm, which can lead to serious health issues, including neurotoxicity in children [13]. The effectiveness of regulations to mitigate the environmental impacts of ship recycling is limited. The Hong Kong Convention (2009) [14] mandates certified recycling facilities, but only 5% of yards in Bangladesh comply due to issues like corruption and weak enforcement [13]. In contrast, the EU Ship Recycling Regulation requires EU-flagged ships to be recycled in approved facilities, leading to the diversion of 40% of EU ships from South Asian yards. Ship recycling also brings significant socioeconomic and health challenges. In Alang, India, around 80% of workers suffer from respiratory diseases due to asbestos exposure. In Chattogram, Bangladesh, communities living near shipbreaking yards have reported a 200% increase in miscarriages linked to cadmium contamination [15]. These health issues highlight the lack of safety and regulation in ship recycling practices.

Recent studies highlight the significant environmental and health risks associated with shipbreaking in Bangladesh, especially in the Sitakunda region. Alam et al. [16] assessed soil contamination in shipbreaking yards, finding high levels of toxic elements like cadmium, chromium, and manganese. These pollutants exceed safety limits and pose severe health risks to workers and local communities, stressing the need for improved regulations and waste management. Barua et al. [17] focused on PAH contamination in the Sitakunda shipbreaking area, revealing concentrations that far exceed global standards. The study highlights the ecological risks of these persistent pollutants, underlining the need for stricter environmental control. Dewan [18] explored the socio-economic impact of shipbreaking, noting that marginalized communities, particularly shipbreaking workers and fishermen, face disproportionate exposure to toxins. This research emphasizes the need to address both environmental and social inequalities in the region.

These studies emphasize the urgent need for stronger environmental regulations and policies to mitigate the pollution and socio-economic disparities caused by shipbreaking in Bangladesh.

2.1 Synthesis and Critical Gaps

The existing literature suggests that shipbuilding and operation are major contributors to global greenhouse gas (GHG) and sulfur oxide (SOx) emissions, while recycling in developing countries perpetuates environmental and health injustices. While international conventions like MARPOL and the Hong Kong Convention lay the foundation for reducing maritime pollution, they require more stringent enforcement. One contradiction is that developed nations advocate greener practices but outsource about 80% of ship recycling to regions with weak environmental regulations. Key research gaps include understanding the long-term ecological impacts of emerging pollutants like microplastics from ship coatings, exploring the socioeconomic drivers behind non-compliance in ship recycling, and evaluating the scalability of alternative fuels such as ammonia and hydrogen in maritime transport. Addressing these gaps will be crucial for achieving a more sustainable and equitable maritime industry.

3. Methodology

The existing study presents a cumulative overview and aptitude outline of the environmental pollution caused by shipbuilding, ship operation, and ship recycling in Bangladesh. This research employs a mixed-methods approach, utilizing both qualitative and quantitative data collection techniques to gain comprehensive insights into the types and sources of pollution at each phase of the ship lifecycle.

The study utilizes document analysis as the primary research method. Qualitative data is collected from existing literature, including journals, conference papers, reports, government publications, and other related materials, both published and unpublished. These secondary data sources are critically analyzed to identify pollution types, sources, and the effectiveness of regulatory frameworks in managing pollution. The research design follows a descriptive survey research methodology, which is a suitable approach for understanding the current state of pollution in the shipbuilding, operation, and recycling industries in Bangladesh. Qualitative research design is employed to allow the researcher to achieve a deep understanding of the topic based on existing secondary data sources. This design also supports the formulation of a research framework that aligns with the objectives of the study.

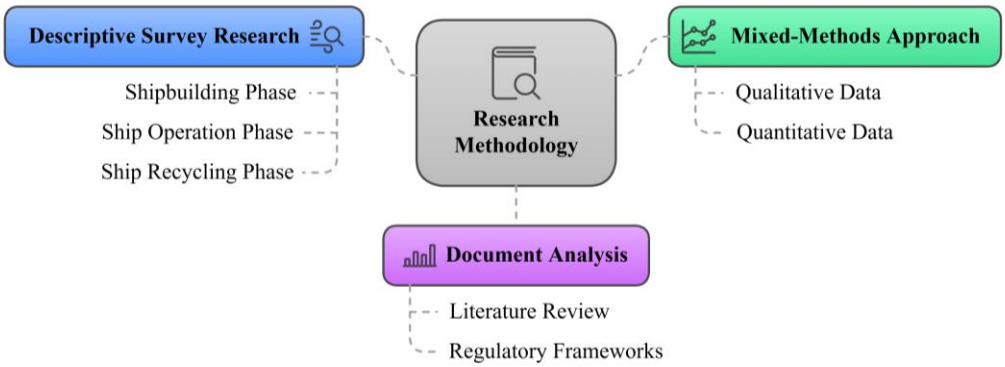

Figure 1: Diagram presenting the Research Methodology used for this study (Compiled by the researcher).

4. Results & Discussion

This study highlights the significant environmental challenges faced by the maritime industry in Bangladesh, especially in the areas of shipbuilding, operation, and recycling. While various international frameworks and regulations, such as the MARPOL and Hong Kong Conventions, provide a foundation for addressing pollution, the findings of this research emphasize the urgent need for stronger enforcement and comprehensive strategies to reduce environmental harm.

4.1 Pollution in Shipbuilding

Bangladesh has a rich history in shipbuilding, with its roots tracing back to the 15th to 16th centuries when it became a hub for sea-going ship manufacturing in Asia. In the 19th century, Chittagong emerged as a center for shipbuilding, with several companies engaged in the construction of commercial ships. Today, Bangladesh has more than 12,500 vessels operating across the country, transporting goods and passengers through its vast river systems and coastal waters. With over 20 internationally accredited shipyards and 100 local ships and dockyards, the country has built ships with capacities up to 10,000 DWT (Deadweight Tonnage). Shipbuilding in Bangladesh continues to grow, and the industry holds great promise, especially with the increasing export of locally made vessels. Currently, over 200 shipbuilding companies operate across various regions, including Chattogram, Dhaka, and Khulna.

Figure 2: Ship under construction in a Bangladeshi shipyard [19].

Shipbuilding in Bangladesh plays a pivotal role in the economy, but it comes at a high environmental cost. Raw material extraction, particularly for steel and aluminum production, and the energy-intensive manufacturing processes result in significant carbon emissions. This study aligns with previous research that shows the shipbuilding industry contributes heavily to global industrial CO_2 emissions. In Bangladesh, the problem is exacerbated by the widespread use of toxic coatings, which continue to affect local water and soil quality. The persistence of hazardous materials like tributyltin (TBT) in sediments around shipyards underscores the long-term environmental degradation caused by traditional shipbuilding practices.

The overuse of toxic paints and coatings, despite global bans, further aggravates marine pollution. The findings suggest that while some technological advancements, such as automated welding, have been adopted in certain parts of the world to reduce emissions, many Bangladeshi shipyards still rely on manual methods due to cost constraints. This illustrates a gap between global environmental standards and local practices. Efforts to introduce cleaner technologies in shipbuilding, especially in developing nations, must be accompanied by government incentives, technological support, and international collaboration to ensure that economic growth does not come at the expense of environmental sustainability.

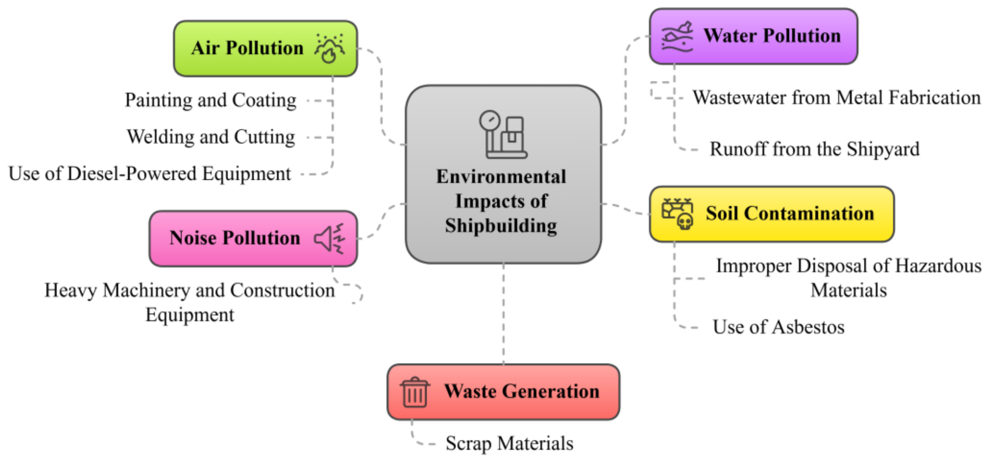

Figure 3: Distinct types of pollution involved in ship building phase (Compiled by the researcher).

4.1.1 Air Pollution

Air pollution in shipbuilding is caused by the release of volatile organic compounds (VOCs) during painting, coating, and welding. These chemicals can harm health when not oversaw properly. Welding also emits particulate matter and harmful gases like carbon monoxide (CO) and nitrogen oxides (NOx), affecting air quality and human health. Diesel-powered machinery releases carbon dioxide (CO_2), a major contributor to global warming. Additionally, the blasting grit used in shipyards may contain harmful substances like zinc, copper, and magnesium, which can contaminate the air and water if not managed properly.

4.1.2 Water Pollution

Water pollution is caused by the discharge of harmful chemicals, oils, and heavy metals during ship construction. Wastewater from processes like painting and cleaning can contaminate local waters, and oil spills during operations further worsen this problem. Anti-fouling paints, which contain toxic chemicals like copper oxide and tributyltin (TBT), still pose risks despite the ban on TBT. Heavy metals like lead, mercury, and cadmium can also leach into the water. Runoff from shipyards, carrying oil and grease, can pollute nearby rivers and coastal areas, endangering marine life and drinking water sources.

4.1.3 Soil Contamination

Toxic chemicals and heavy metals used in shipbuilding can seep into the soil, especially if waste is not properly disposed of. This contamination harms local biodiversity and poses health risks to nearby communities.

4.1.4 Noise Pollution

Shipbuilding is noisy, with machinery, cranes, and welding equipment generating prominent levels of sound. This can affect workers' health and disturb nearby communities. The noise also disrupts local wildlife, especially marine animals like whales and dolphins, which rely on sound to communicate and navigate.

4.1.5 Waste Generation

Shipbuilding produces substantial amounts of solid waste, including scrap metal, plastics, and wood. Improper disposal of these wastes, especially toxic materials, adds to pollution. Spent grit, used in paint strips, and sludge from wastewater treatment must be overseen carefully to avoid further contamination. Additionally, asbestos used in ship insulation poses serious health and environmental risks if not properly disposed of.

4.2 Pollution in Ship Operation

The operational phase of shipping continues to be a major contributor to global air pollution, particularly due to the burning of heavy fuel oils (HFO) and marine diesel oils (MDO). The study reinforces findings from previous research, noting that maritime vessels account for a generous portion of global sulfur oxide (SOx) and nitrogen oxide (NOx) emissions, pollutants that significantly affect both air quality and global climate. Although the MARPOL Annex VI regulations are designed to curb these emissions, compliance remains inconsistent, especially in regions like Bangladesh, where monitoring systems and infrastructure are inadequate.

In this regard, the implementation of cleaner, alternative fuels such as liquefied natural gas (LNG) or hydrogen could significantly reduce harmful emissions. The study highlights the need for greater investment in such technologies, which have shown promise in reducing sulfur emissions in other parts of the world. However, for these technologies to be viable in the Bangladeshi context, it is crucial to consider the economic constraints, the availability of infrastructure, and the cost-effectiveness of transitioning to cleaner fuels.

Figure 4: Ocean going vessels emitted different kind of pollutants and dump different types of wastage [20].

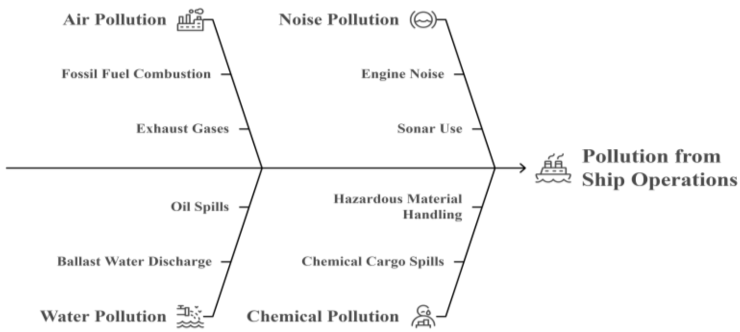

Figure 5: Distinct types of pollution involved in ship operation phase (Compiled by the researcher).

4.2.1 Air pollution

Air pollution in ship operation comes from burning fossil fuels like heavy fuel oil (HFO) or marine diesel oil (MDO) in ship engines. This combustion process produces sulfur oxides (SOx), which contribute to acid rain, damaging ecosystems and posing health risks. Nitrogen oxides (NOx), another byproduct, form ground-level ozone and contribute to smog, causing respiratory problems. Carbon dioxide (CO2) is also released, and shipping accounts for about 3% of global CO2 emissions, exacerbating climate change. Additionally, particulate matter (PM), which includes fine particles from fuel combustion, can enter the lungs and cause serious health problems.

4.2.2 Marine pollution

Marine pollution from ship operation is a major concern. Oil spills, while rare, have devastating effects on marine life and coastal ecosystems. These spills typically result from equipment failure or accidents, releasing petroleum that suffocates marine organisms, poisons them, and destroys habitats like coral reefs and mangroves.

Table 1 Oil spills from land-based and ship-based sources in the Bay of Bengal, Bangladesh [21].

Sources	**Location and Operation**	**Quantity (tons/Yr.)**	**Remarks**
Land Sources	ERL, Oil depots, Power Station (oil), and other oil handling facilities on land	200-300	Excludes loading/unloading operations from/to ships
Ship Sources	Shipbreaking area	500	Sitakunda area, Chittagong
	Loading/Unloading	100-200	> 40,000 times per year
	Deballasting	600-1,200	0.02% remaining
	Debilging	100-200	0.2% discharged
	Other routine operations	-100	Bunkering
Total		1,500 - 2,500	

Ballast water, taken on by ships for stability, often contains invasive species that can disrupt local ecosystems when discharged into foreign waters. Although the International Maritime Organization (IMO) has regulations requiring ballast water treatment, enforcement is still a challenge. Ships also produce sewage and graywater, and if untreated, these discharges lead to nutrient pollution, harming marine life and causing disease in coastal areas. Additionally, water pollution arises from oil spills, ballast water discharge, and untreated sewage or garbage, threatening marine ecosystems [22]. Marine litter, including plastics and fishing gear, is another major contributor to pollution, as it harms wildlife and disrupts marine ecosystems.

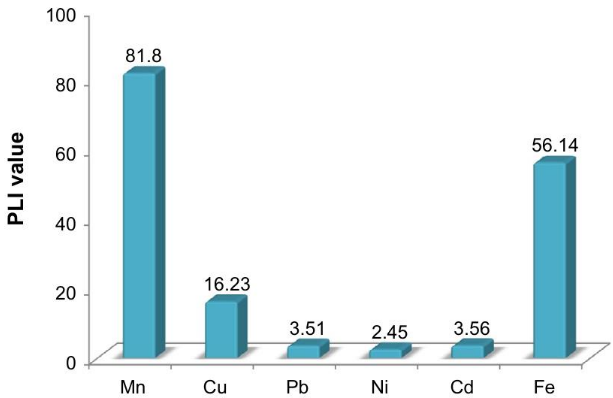

Figure 6: Water contamination in the coastal region caused by shipping activities [23].

4.2.3 Noise pollution

Noise pollution from ship engines, propellers, and other underwater machinery also disrupts marine species, particularly whales, dolphins, and other mammals that rely on sound for communication and navigation. Prolonged exposure to this noise can disorient marine animals, disrupt their migration, and cause chronic stress, affecting their ability to feed and reproduce. Finally, ships transporting hazardous cargo, such as chemicals and fuels, can pose significant risks if accidents occur. Even small leaks of toxic substances like pesticides, heavy metals, or radioactive materials can cause widespread environmental damage, sometimes taking years or decades to fully remediate.

4.3 Pollution During Ship Recycling

The ship recycling process in Bangladesh presents the most severe environmental and health risks, primarily due to the improper handling of hazardous materials such as asbestos, heavy metals, and hydrocarbons. The study confirms the alarming presence of lead and other toxic substances in the soil surrounding shipbreaking yards in Chattogram, where concentrations far exceed international safety limits. This raise concerns not only about the environmental impact but also about the health of workers and nearby communities who are exposed to these hazardous materials.

Despite the existence of the Hong Kong International Convention, which mandates the proper disposal of hazardous materials in ship recycling, Bangladesh's compliance remains minimal. The study indicates that corruption, weak enforcement, and a lack of infrastructure contribute to this non-compliance. There is an urgent need for more robust waste management systems and the widespread adoption of green ship recycling technologies, which prioritize worker safety and environmental protection. These technologies, though currently expensive, could significantly reduce the risks associated with traditional shipbreaking methods.

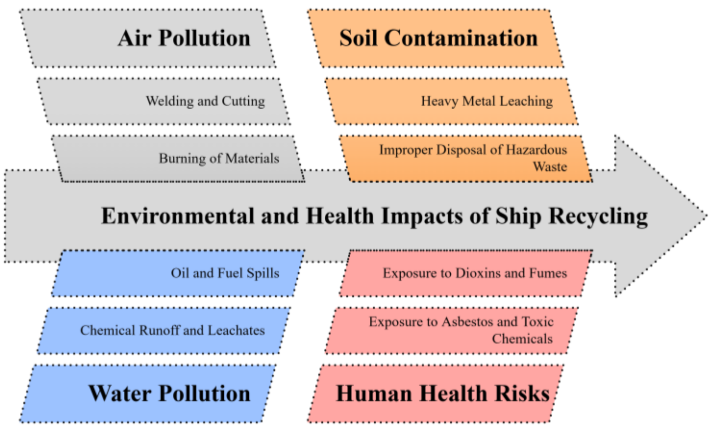

Figure 7: Several types of pollution involved in ship recycling phase (Compiled by the researcher).

4.3.1 Toxic Chemical Pollution

One of the main environmental hazards in ship recycling is the release of toxic chemicals, particularly from older ships. Asbestos, once used in insulation and fireproofing, can be released during dismantling and poses significant health risks, including respiratory diseases and cancers. Polychlorinated Biphenyls (PCBs), found in electrical equipment, are carcinogenic and can cause neurological damage. Additionally, ships contain toxic heavy metals such as lead, mercury, and cadmium in batteries, paints, and coatings. These metals can leak into the environment, harming both wildlife and human health. Hydrocarbons and oil residues are another concern, as these can spill during the recycling process, contaminating nearby soil and water.

4.3.2 Water Pollution

The release of hazardous chemicals and waste during ship recycling can severely pollute local water bodies. Runoff from shipbreaking yards often carries untreated waste, including paints, solvents, and asbestos dust, which degrades aquatic ecosystems and disrupts marine biodiversity. Oil and fuel leaks are common during dismantling, and if not properly contained, they lead to water contamination, harming marine life and affecting the health of communities dependent on these waters.

4.3.3 Air Pollution

Ship recycling generates significant air pollution, especially during the dismantling of metal components. The cutting and burning of steel plates and other materials produce particulate matter that can be harmful to workers and surrounding communities. These fine particles often contain toxic metals, leading to respiratory and cardiovascular diseases. Additionally, burning ship components that are treated with chemicals, such as plastics and coatings, releases harmful gases like dioxins and furans, which can cause skin problems, cancer, and damage to the nervous system.

4.3.4 Soil Contamination

Soil contamination is another significant risk during ship recycling. Hazardous materials like heavy metals, oils, and chemicals can seep into the ground, creating toxic hot spots. These contaminants degrade soil fertility, harm plant life, and may contaminate groundwater, posing long-term environmental and health risks.

Table 2. Soil contamination discovered along the coast of Chittagong's ship recycling yards [24].

Contaminant	**Range (mg/kg)**
Oil	485 to 4430
Cadmium	0.6 to 2.2
Mercury	0.078 to 0.158
Lead	11.3 to 197.7
Chromium	2.42 to 22.12

4.3.5 Human Health Risks

The pollution associated with ship recycling poses severe health risks to workers and nearby communities. Workers are often exposed to toxic substances like asbestos, PCBs, and heavy metals without adequate protective equipment, leading to respiratory diseases, skin disorders, and even cancer. Prolonged exposure to toxic chemicals also affects reproductive health, leading to birth defects and infertility.

4.3.6 Waste Generation and Disposal

Ship recycling produces enormous amounts of waste, including metals, plastics, and electronic components. If not disposed of properly, these materials contribute to the global waste crisis, particularly plastic pollution. Recycling these materials is essential, but improper disposal can lead to severe environmental degradation, harming wildlife and blocking waterways. Proper waste management and recycling practices are crucial to minimizing these impacts.

4.4 Mitigation Strategies

Based on the findings, several key recommendations emerge for mitigating the environmental impact of the shipping industry in Bangladesh:

4.4.1 Adoption of Cleaner Technologies in Shipbuilding

Bangladesh should encourage the adoption of environmentally friendly materials and technologies, such as eco-friendly coatings and energy-efficient manufacturing processes, through government incentives and international collaboration.

4.4.2 Stronger Enforcement of MARPOL and Other Regulations

The study calls for stronger enforcement of MARPOL Annex VI and the Ballast Water Management Convention, particularly in Bangladesh, where compliance is still lacking. International cooperation is essential to improve monitoring and ensure stricter penalties for non-compliance.

4.4.3 Transition to Alternative Fuels

The shipping industry in Bangladesh should prioritize the transition to cleaner fuels, such as LNG and hydrogen, which can significantly reduce harmful emissions. However, this requires investment in infrastructure, regulatory incentives, and international partnerships.

4.4.4 Improved Ship Recycling Practices

The introduction of green ship recycling technologies, alongside stricter enforcement of the Hong Kong Convention, is crucial for reducing environmental and health risks associated with shipbreaking. Bangladesh must invest in proper waste management facilities and improve worker safety protocols.

4.4.5 Public Awareness and Education

The government and industry stakeholders must work together to raise awareness about the environmental impacts of shipping activities and promote sustainable practices across all sectors, from shipbuilding to operation and recycling.

5. Laws and Regulations

In this section, the key local and international regulations were reviewed that address pollution in the maritime sector and their effectiveness in mitigating the environmental impacts of shipbuilding, operation, and recycling, particularly in Bangladesh.

5.1 Local Regulations in Bangladesh

Bangladesh has several laws and regulations designed to control environmental pollution resulting from its significant role in shipbuilding and shipbreaking activities. The Ship Breaking and Recycling Rules (2011) [25] aim to ensure safe and environmentally sound dismantling of ships, focusing on the handling of hazardous materials like asbestos, heavy metals, and oils. These rules mandate ship owners to submit detailed inventories of hazardous materials before ships are dismantled, and recycling yards must adhere to safety protocols and proper waste management procedures to avoid environmental contamination. The Environmental Conservation Act (1995) [26] provides a broader framework for environmental protection, including setting limits on emissions and discharges from industrial activities, including shipbreaking. This act empowers the Department of Environment (DoE) to enforce compliance through fines and legal action against violators. Similarly, the Bangladesh Ship Recycling Act (2018) [27] aligns local practices with international standards, focusing on hazardous material management and worker safety. The Bangladesh National Environmental Policy (1992) and the Water Act (2013) further emphasize pollution control across various industrial sectors, ensuring sustainable practices and reducing water pollution caused by ship operations.

Despite these regulations, enforcement remains weak, particularly in the shipbreaking sector, where violations are common due to insufficient infrastructure and inadequate monitoring.

5.2 International Regulations

International conventions play a significant role in regulating pollution from the maritime industry. The MARPOL Convention, particularly its Annexes, addresses pollution from ships by regulating the discharge of oil, sewage, garbage, and air pollutants, including sulfur oxides (SOx) and nitrogen oxides (NOx). Bangladesh, being a signatory to this convention, is required to implement these standards, though challenges in enforcement persist. The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, which Bangladesh ratified in 2019, focuses on improving the conditions of ship recycling by mandating the preparation of hazardous material inventories and requiring shipbreaking yards to comply with international environmental and safety standards. This convention aims to mitigate the pollution associated with ship recycling but requires more robust implementation at the local level. The Basel Convention regulates the movement of hazardous waste, including waste generated during ship recycling, ensuring that such waste is disposed of in an environmentally sound manner. Bangladesh's compliance with this convention is critical in managing the toxic materials from shipbreaking. Lastly, the IMO Ballast Water Management Convention (2004) addresses the environmental risks posed by ballast water discharges, which can introduce invasive species into marine ecosystems. Ships operating in Bangladeshi waters are required to treat ballast water before discharging it, although enforcement remains a challenge.

5.3 Effectiveness and Gaps

While Bangladesh has made progress in aligning its laws with international standards, several challenges remain, particularly in enforcing regulations in the shipbreaking sector. Issues such as poor waste management, weak oversight, and inadequate infrastructure hinder the effective implementation of these laws. Additionally, despite the presence of regulatory frameworks, the local enforcement agencies, such as the DoE, face difficulties in ensuring compliance due to limited resources and political challenges. International conventions like MARPOL and the Hong Kong Convention set global standards, but their effectiveness depends on national-level enforcement. In Bangladesh, the shipbreaking industry's reliance on unsafe practices and lack of proper facilities for hazardous waste management continue to pose significant environmental and health risks.

6. Conclusion

In conclusion, the environmental impact of the shipping industry, from shipbuilding to operation and recycling, is extensive and requires urgent attention. The lifecycle of ships, which spans from raw material extraction to dismantling, introduces a range of pollutants that significantly degrade air, water, and soil quality, while also posing a serious threat to marine ecosystems. Despite the introduction of international regulations, such as MARPOL and the Hong Kong Convention, their enforcement remains inconsistent, particularly in developing countries like Bangladesh. While Bangladesh has implemented several national policies to curb pollution from shipbuilding, operation, and recycling, weak enforcement and inadequate infrastructure continue to undermine their effectiveness. The shipping industry, particularly shipbreaking yards in Chattogram, operates under unsafe and environmentally harmful conditions due to lax regulatory oversight. The Department of Environment (DoE) also faces limited capacity to monitor and ensure compliance with environmental regulations. This gap in enforcement exacerbates environmental pollution and poses significant public health risks to communities surrounding these shipyards.

To address these challenges, it is essential to strengthen regulatory enforcement, improve waste management infrastructure, and enhance the monitoring capabilities of the DoE. National and international laws, such as the Bangladesh Environment Conservation Act of 1995, have set valuable guidelines for pollution control, but their implementation is hindered by political will and inadequate oversight. The Ship Breaking and Recycling Rules introduced in 2011, while a step in the right direction, are yet to be fully enacted, limiting their potential impact.

To mitigate the significant environmental harm caused by the shipping industry, it is crucial to adopt sustainable technologies and practices that reduce pollution at every stage of a ship's lifecycle. Strengthening regulatory frameworks, ensuring robust enforcement, and increasing the capacity for monitoring and waste disposal will be key in addressing the environmental and health risks posed by shipbuilding, operation, and recycling, especially in regions like Bangladesh.

The key problems identified in this study include inadequate waste management practices in shipbuilding and ship recycling, significant pollution from ship operations (including air and water pollution), and insufficient regulatory enforcement coupled with a lack of infrastructure in ship recycling yards. Addressing these challenges will be essential in mitigating the environmental risks associated with the shipping industry.

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Evolution and Classification of Wind Turbine Technologies with Emphasis on Offshore Development

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Abstract

Wind energy has emerged as an important renewable energy source, offering significant potential to mitigate climate change and enhance energy security. This review paper comprehensively describes the evolution, technological advancements, and contemporary applications of wind turbines, focusing on their different types, design innovations and offshore developments. Beginning with the historical development from ancient windmills to modern multi-megawatt turbines, the paper systematically classifies wind turbines into Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs), analyzing their respective advantages, limitations, and suitability for diverse environments. Special attention is given to offshore wind technologies, including fixed-bottom and floating. The paper also highlights global trends, such as the projected 380 GW expansion in offshore wind capacity by 2033, and addresses key challenges, including noise reduction, blade stability, and deep-water installation. By synthesizing recent research data, this review paper provides valuable insights on wind turbines, their classifications and key characteristics.

Keywords: Wind turbines, HAWT, VAWT, Offshore Wind Energy, Renewable Energy.

1.Introduction

Wind energy is an important renewable energy source that helps to protect the environment by lowering greenhouse gas emissions and mitigating climate change. It provides energy independence by reducing dependency on imported fossil fuels, hence increasing energy security [1]. Recent technical developments have reduced costs and enhanced efficiency, making wind energy one of the most competitive electricity sources worldwide. The rapid advancements in wind turbine technology over the past century have transformed wind energy into one of the most competitive electricity generation methods worldwide [2].

This paper reviews the historical development, design innovations, and modern applications of wind turbines, with a particular focus on offshore wind energy systems. The historical overview traces the journey from early wind-driven sailboats in ancient Mesopotamia to the sophisticated multi-megawatt turbines of today, highlighting key milestones such as the Industrial Revolution and the development of the first megawatt-scale turbines in the 20th century. The review then categorizes wind turbines into HAWTs and VAWTs, discussing their structural and operational differences, efficiency, and suitability for varying wind conditions.

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A significant portion of the paper is dedicated to offshore wind turbines, which harness stronger and more consistent winds at sea. The analysis covers fixed-bottom foundations (e.g., monopile, jacket, gravity-based) and floating systems (e.g., spar-buoy, semi-submersible, TLP), emphasizing their engineering challenges, environmental impacts, and economic viability. With the global offshore wind capacity expected to reach 380 GW by 2033 [3], this review underscores the importance of addressing technical and logistical barriers to maximize the potential of wind energy.

By integrating findings from recent studies and industry reports, this paper aims to provide a comprehensive resource for researchers, engineers, and policymakers, facilitating informed decision-making in the pursuit of a sustainable energy future.

2. Historical Development of Wind Energy Systems

The historical development of wind energy systems spans thousands of years, beginning with early uses in ancient civilizations such as Mesopotamia and Egypt, where wind-driven, sail-propelled vessels were found. Persians implemented vertical-sailed windmills (Figure 1) for grain grinding around 200 AD [2]. In medieval Europe, windmills became important, particularly in the Netherlands and England. By the 13th century, grain grinding mills were popular in most of Europe.

Figure 1: Windmills in Spain [4].

The Industrial Revolution in the 19th century saw the emergence of wind turbines designed for electricity generation. Inventors like Charles F. Brush created small turbines for homes.

The era of wind electric generators began close to the 1900's. In the 1930s, Palmer Putman turbine was developed to produce 1.25 MW of electric power. The late 20th and early 21st centuries witnessed rapid growth in wind energy, driven by larger, more efficient turbines and increased environmental awareness, with Denmark and Germany leading the way. Today, wind energy is one of the fastest-growing sources of renewable energy globally, marked by considerable investments in both onshore and offshore wind farms, showing its vital role in transitioning to a sustainable energy future.

Figure 2: The Gedser wind turbine, one of the pioneer wind turbines [5].

3. Types of Wind Turbines

Wind turbines can be classified based on the size of the rotor diameter and axis of rotation. Figure 3 shows the classification of wind turbines. Based on the axis of rotation, there are primarily two types of wind turbines: horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT), each designed for specific applications and operating conditions [6,7,8].

3.1 Horizontal Axis Wind Turbine (HAWT)

This is the most common type of wind turbine, characterized by a horizontal rotor shaft and blades that rotate around a horizontal axis. HAWTs typically have two or three blades and are designed to face the wind. HAWTs are generally more efficient and valuable for converting wind energy into electricity at large scales [9,10].

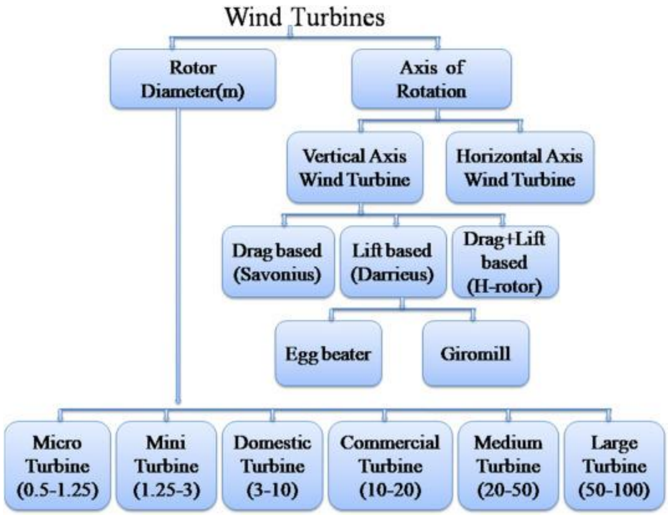

Figure 3: Classification of wind turbines [11].

HAWT (Figure 4) can be found in both onshore and offshore wind farms, with larger models capable of producing significant amounts of electricity [12]. HAWT design allows for higher wind speeds and more consistent energy generation, making it suitable for utility-scale projects.

Upwind and downwind are two configurations of HAWT that refer to the positioning of the rotor relative to the tower and the direction of the wind. Each design has specific characteristics and advantages, influencing their use in various applications.

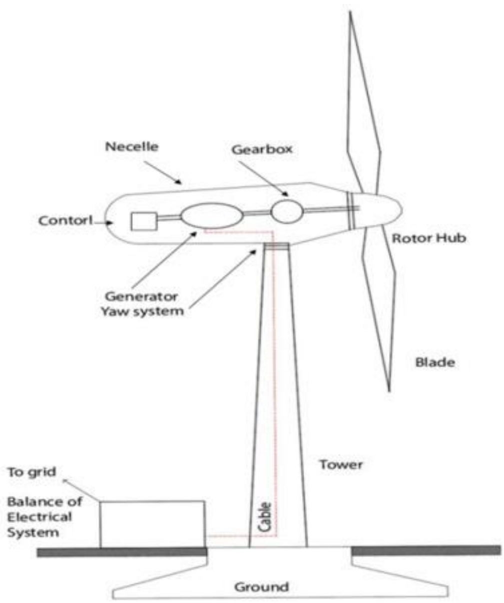

Figure 4: Schematic representation of HAWT [11].

3.1.1. Upwind HAWTs

In upwind turbines, the rotor is positioned in front of the tower, facing into the wind. This design allows the blades to catch the wind without obstruction from the tower, which can enhance energy capture and overall efficiency [13]. Upwind turbines tend to have better performance in terms of energy output, particularly in strong winds. However, they require a yaw mechanism to orient the rotor towards the wind direction a system that allows the turbine to adjust its position. Because of their design, upwind turbines are generally quieter, as the noise generated by the rotor blades is less likely to interact with the tower structure. Additionally, upwind turbine blades can be longer due to spacing considerations, enabling them to capture more wind energy [14].

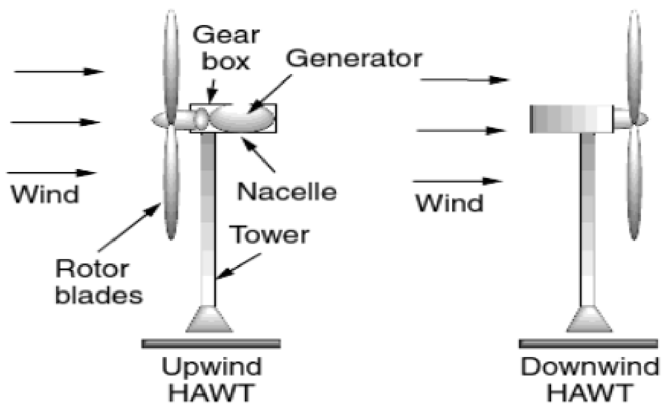

Figure 5: Upwind and downwind HAWT [15].

3.1.2 Downwind HAWTs

Downwind turbines have their rotor positioned behind the tower, allowing the wind to flow past the tower before hitting the blades. This configuration eliminates potential turbulence that could arise if the wind hits the tower first, particularly in gusty conditions [16]. However, downwind turbines tend to be less common because they have challenges such as potential blade flex due to wind turbulence created by the tower, which can lead to increased wear and tear. To address these issues, downwind turbines often incorporate features like passive yawing, allowing the rotor to turn with the wind after the gusts pass. Additionally, while the downwind design can be quieter in low wind conditions, it might produce more noise from blade interaction with the tower in strong winds [17]. Figure 5 shows Upwind and downwind HAWT.

3.1.3. Different Configurations of HAWT

Horizontal Axis Wind Turbines (HAWTs) are the most commonly used type of wind turbines for generating electricity. Their design involves a rotor that is mounted horizontally and rotates about a horizontal axis. There are several configurations and variations of HAWTs, each with unique characteristics and applications (Figure 6).

Two-blade configuration features two blades attached to a vertical hub. Two-blade HAWTs are typically lighter, have lower material costs, and can reach higher speeds. However, they can be less stable in strong winds and maybe noisier compared to three-blade designs [18].

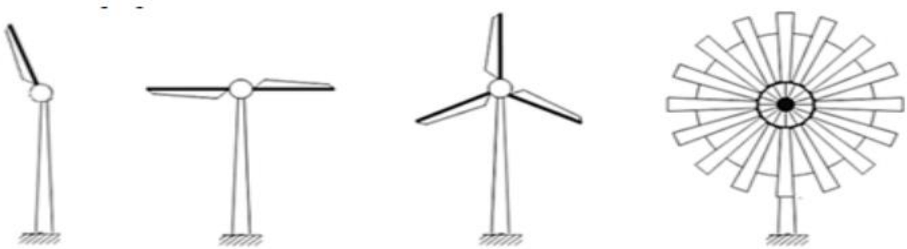

Figure 6: Different configurations of HAWTs [19].

The three-blade HAWT is the most popular design due to its balance of aerodynamic efficiency and stability. This configuration reduces noise levels and is more effective at capturing wind energy, making it suitable for both onshore and offshore applications. Three blades also allow for smoother operation and better aesthetics [20,21].

3.2 Vertical Axis Wind Turbine (VAWT)

Vertical Axis Wind Turbines (VAWTs) are characterized by their vertical rotor orientation, which allows them to capture wind from any direction without the need for a yaw mechanism [22]. This design makes VAWTs particularly effective in turbulent wind conditions and urban environments where wind flow is often unpredictable. There are two primary types of VAWTs: the Darrieus and the Savonius [23]. The Darrieus turbine features curved blades that resemble an eggbeater and is known for its efficient energy conversion, particularly in high wind conditions.

However, it requires a certain starting speed to operate effectively [6]. The Savonius turbine, on the other hand, consists of two or more scooped blades that catch the wind, making it better suited for lower wind speeds and providing good starting torque [24]. Each type has its own advantages depending on the specific application, making VAWTs a versatile choice for renewable energy generation [25]. Figure 7 shows different types of VAWTs.

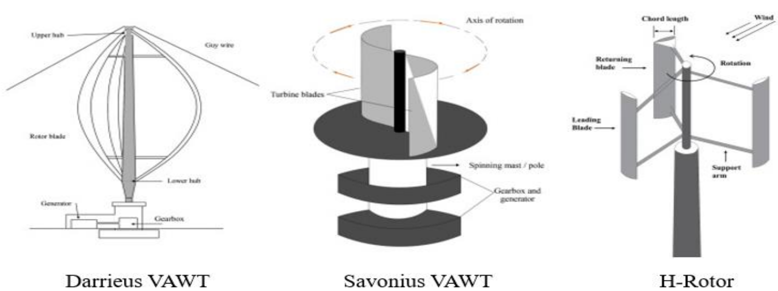

Figure 7: Illustration of different types of VAWT [26].

4. Offshore Wind Turbines

Offshore wind turbines are giant structures designed to harness wind energy in marine environments, typically located several miles away from shore. These turbines can reach heights of over 250 feet (76 meters) above sea level, with rotor diameters often exceeding 500 feet (152 meters). As of 2023, the largest installed offshore wind turbine is the Siemens Gamesa SG 14-222 DD, featuring a capacity of 14 MW per unit and capable of generating enough electricity to power around 18,000 homes annually [27]. Offshore wind farms take advantage of stronger and more consistent winds found at sea, resulting in higher energy efficiency compared to onshore areas.

The installed capacity for offshore wind energy worldwide reached approximately 54 GW by the end of 2022, with leading countries in this sector including China, the United Kingdom, and Germany. Moreover, 380 GW of offshore wind capacity, across 32 markets, is predicted to be added in the next ten years [3]. Offshore wind projects not only contribute to reducing carbon emissions but also help in achieving energy independence and creating job opportunities in maritime and renewable energy sectors. Figure 8 shows a typical wind farm.

Figure 8: Representation of offshore wind farm [28].

4.1 Classification of Offshore Wind Turbines (OWT)

Based on the design, OWTs can be classified as fixed bottom turbines and floating bottom turbines. The classification of OWTs is shown in Figure 9.

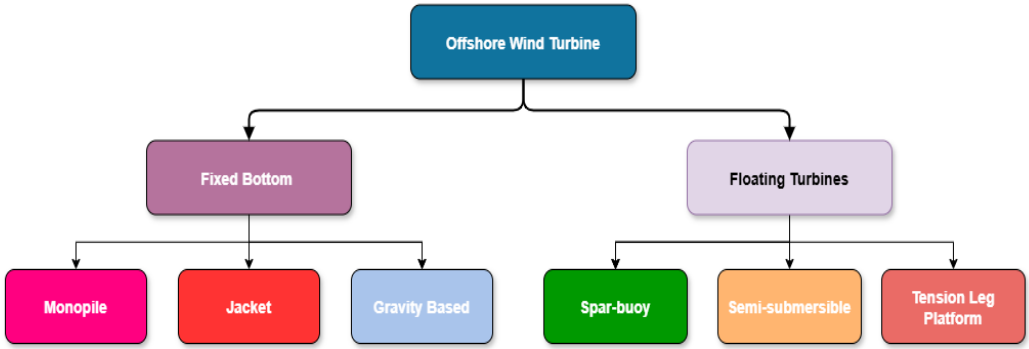

Figure 9: Classification of offshore wind turbines.

4.1.1. Fixed-bottom Turbines

These are anchored to the seabed using various foundation types, suitable for shallow waters (typically up to 70 meters) [29]. Common foundation types include:

- Monopile: A single large cylinder driven into the seabed.

- Jacket: A lattice structure made of steel resting on the seabed.

- Gravity Base: Heavy concrete structures that rest on the seabed, relying on their weight for stability.

Figure 10 shows schematic diagrams of fixed-bottom OWTs, and Table 1 shows the advantages and disadvantages of three types of fixed-bottom OWTs.

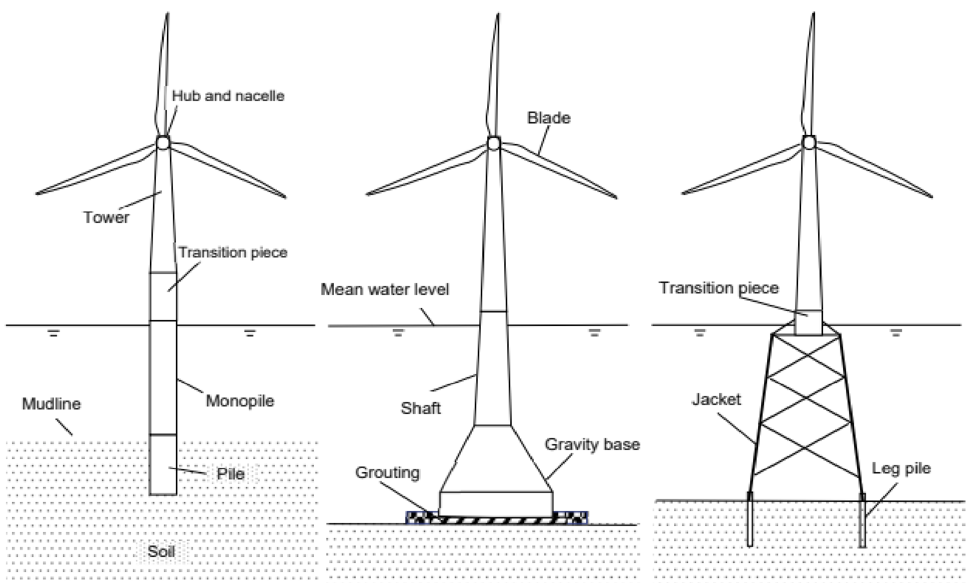

Figure 10: Illustration of monopile, gravity based and jacket type offshore wind turbines [30].

Table 1: Advantages and disadvantages of three types of fixed bottom wind turbines [31,32].

Type	Advantages	Disadvantages
Monopile- A single, large-diameter cylindrical structure driven deep into the seabed.	- Simplicity and ease of installation, particularly in shallow waters. - Cost-effective for projects with less extreme environmental conditions. - Suitable for large turbine sizes, commonly used for turbines ranging from 3 MW to 12 MW.	- Installation can be more challenging in rocky or hard seabeds. - Limited to relatively shallow water depths (up to around 30 meters).
Jacket- A lattice work of tubular steel legs that form a framework, resembling a "jacket" around the turbine.	- Greater stability in deeper waters compared to monopiles. - Reduced material use and weight due to its design. - Better suited for harsher marine environments.	- Higher fabrication and installation costs compared to monopile foundations. - More complex installation process requiring specialized vessels.
Gravity Based- Heavy structures, often made of concrete, that rest on the seabed.	- Suitable for a wide range of seabed conditions, including softer substrates. - Easier to remove and relocate compared to some other foundation types.	- Heavy and cumbersome, which can increase transportation and installation costs. - Requires a larger footprint, potentially affecting marine ecosystems more noticeably.

4.1.2. Floating Offshore Wind Turbines (FOWT)

FOWT are Designed for deeper waters (beyond 70 meters), these turbines are mounted on floating structures that are anchored to the seabed. The floating designs include:

- Spar-buoy: A deep-draft floating structure that is anchored to the seabed with tendons.
- Semi-submersible: A buoyant platform with columns that float, providing stability in waves.
- Tension Leg Platforms (TLP): Vertical floaters tethered to the seabed with tensioned tendons.

Figure 11 shows schematic diagrams of floating OWTs, and Table 2 shows the advantages and disadvantages of three types of floating OWTs.

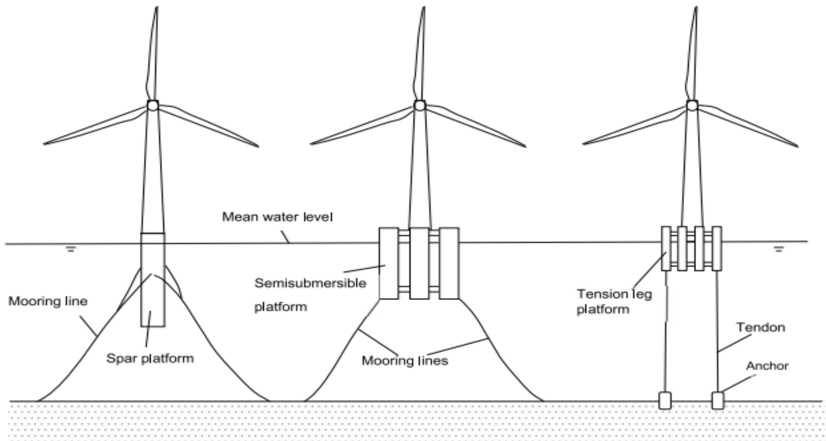

Figure 11: Illustration of spar, semi-submersible and tension leg type offshore wind turbines [30].

Table 2: Advantages and disadvantages of three types of floating offshore wind turbines [33,34,35].

Type	Advantages	Disadvantages
Spar-buoy- A floating structure that consists of a vertical cylindrical column with a heavy ballast at the bottom, allowing it to remain upright and stable.	- Suitable for deep waters (typically 100+ meters). - Minimal seabed interaction, reducing environmental impact. - Can be moved easily once assembled, which is advantageous for maintenance.	- Complexity and cost of mooring systems. - Requires advanced construction and installation techniques.
Semi-submersible- A floating platform designed with multiple buoyant columns that keep the turbine elevated above the water while remaining stable in waves.	- Excellent stability in rough sea conditions. - Can accommodate larger turbines due to their stability. - Allows for greater flexibility in location, as it can be deployed in various marine environments.	- More complex engineering and higher costs due to the need for robust design and installation procedures.
Tension Leg Platforms (TLP)- A floating platform that is anchored to the seabed using vertical tethers known as tendons, maintaining tension and stability.	- Highly stable, reducing motion from waves and wind. - Suitable for deep waters, with less environmental disturbance due to limited seabed contact. - Expansive movement range with minimal impact on the sea surface.	- High engineering complexity and installation costs. - Requires precise tension control, making maintenance more challenging.

5. Technological Advancements and Innovations in Wind Turbines

In the wind energy sector, technological development has seen revolutionary changes, with new designs meeting different environments when operated onshore or at sea. For offshore wind turbines, the most recent prototypes have larger rotor blades, over 200 metres in diameter: greater capacity, with some exceeding 15 MW. Figure 12 shows the evaluation of rotor diameter and capacity of wind turbines.

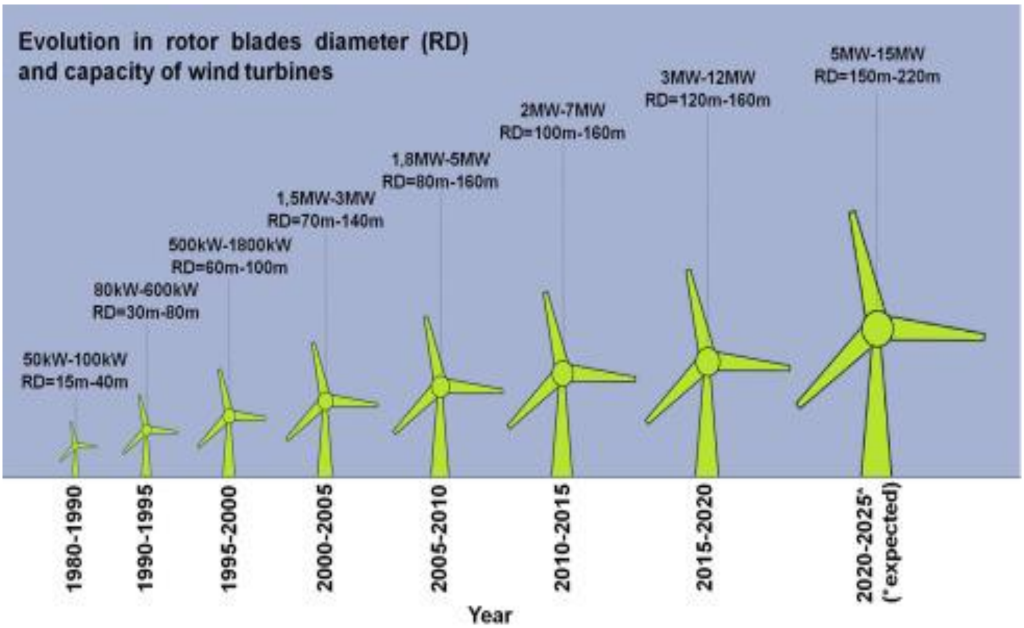

Figure 12: Evaluation of rotor diameter and capacity of wind turbines [36].

Wind turbine designs rely on the sea wind speed which is even more robust and continuous than wind speed on land. Floating wind turbine technologies such as spar platforms and semi-submersibles are now making it feasible to deploy systems in waters deeper than 60 m. Dynamic cables, self-installing platforms are new concepts which reduce logistical costs. Recently in offshore systems AI-driven predictive maintenance and digital twins are implemented to counteract tough sea conditions. Hybrid solutions like wind-wave-solar platforms are employed wherever possible in order to maximize energy production too. On the other hand, onshore wind turbines have been mainly developed into two key principles. One is cost optimization and the other, efficient use of land. Now developments like modular tower construction and lightweight carbon-fiber blades are being used. Figure 13 shows material innovation in wind turbines.

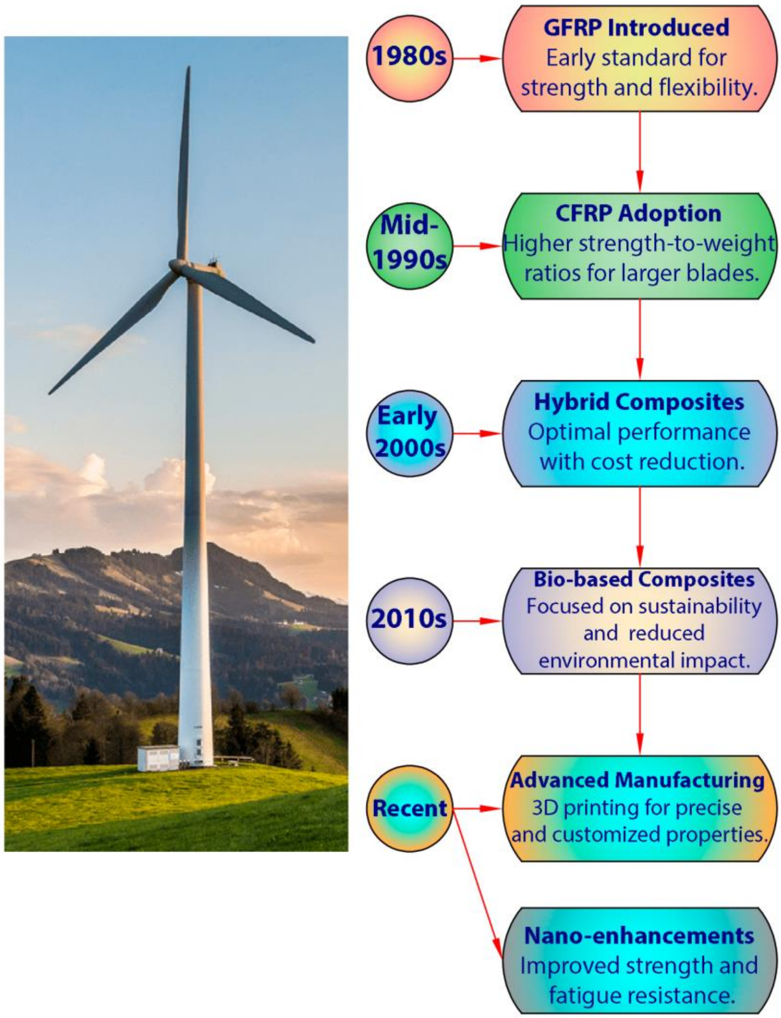

Figure 13: Material innovation in wind turbines [37].

More and more onshore wind turbine projects are now adopting repowering methods, using fewer but more powerful turbines to replace older models and thus increase energy output without expanding their footprint. Recycling old turbines is a matter of priority for the wind industry. Although today around 85% of wind turbines' total mass can be recycled. A wind turbine's life cycle starts with manufacturing components, transporting them to often-remote wind farms, and installing (commissioning) the turbine. During operation, routine preventive and corrective maintenance occurs. At end-of-life, the turbine can be repowered with newer technology or decommissioned for component recycling. Research, development, and innovation are essential for improving this entire process and wind power technology. Figure 14 shows the lifecycle of a wind turbine.

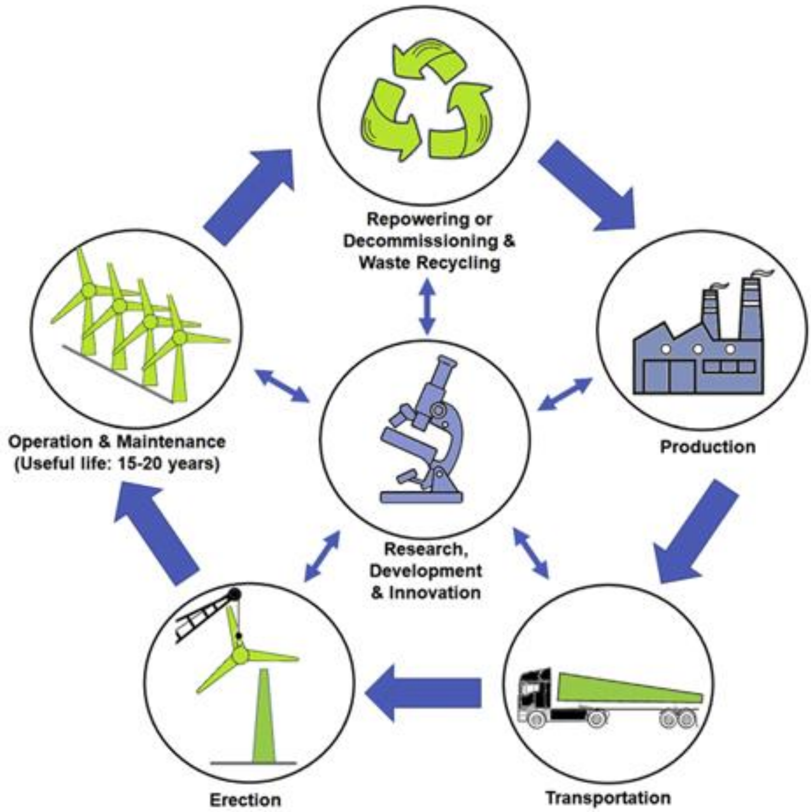

Figure 14: Lifecycle of a wind turbine [36].

Both onshore and offshore sectors can rely on artificial intelligence programs for wind forecasting and automated drones to conduct inspections. Yet the challenges facing offshore systems are greater in terms of resistance to corrosion (which has been solved by coatings that do not attract biofouling), or grid connection (for instance transmitted via high-voltage direct-current cables). While offshore wind turbine developers are finding solutions for Arctic environments and floating mega projects on sea, onshore wind turbine researchers and experts are trying to refine noise-reduction techniques, sustainable materials usage etc. Together these ongoing changes are speeding the transition throughout the world away from fossil fuels towards renewable energy sources.

6. Challenges and Prospects for Onshore and Offshore Wind Power Systems

Both onshore and offshore installations of wind energy have their own distinct set of problems, which need to be solved if the requirement for global energy transformation is ever going to be met. For offshore wind installations, the high cost of offshore vessels equipped with subsea operation equipments are very insufficient in number and these vessels are highly costly, especially when it comes to floating turbines in deeper waters. The harsh marine environment causes higher corrosion and biofouling rates, and the need to carry out complex logistics in hard-to-reach places leads to increased maintenance costs. A further obstacle in this sector is grid integration. Expensive High Voltage Direct Current (HVDC) cables are needed to transmit power from out at sea. Environmental factors such as its impact on marine ecosystems and fishing zones are also needed to be considered before choosing a site for offshore wind turbine. Compared to offshore sites, onshore wind turbines tends to produce lower and more variable amounts of power, as a result the capacity factor isn't achieved in many cases. Major challenges of wind turbines can be illustrated as shown in Figure 15.

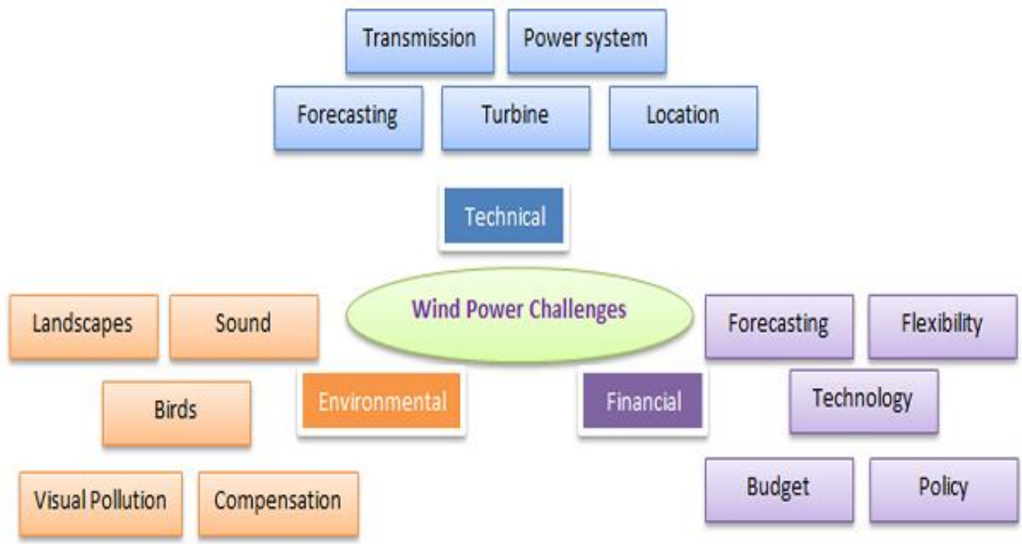

Figure 15: Major challenges of wind turbines [38].

Looking ahead, the future outlook for wind energy remains promising, with technological innovations to overcome these barriers. Offshore wind is moving toward floating turbine commercialization, with projects targeting 20+ MW turbines and hybrid platforms integrating energy storage or hydrogen production. Advances in robotics and digital twins will reduce maintenance costs, while new anti-corrosion materials and modular installation methods aim to cut capital expenditures. Onshore wind is evolving through repowering strategies, noise-reduction technologies, and community benefit-sharing models to improve social acceptance. Both sectors will benefit from AI-optimized wind farm layouts, recycled blade materials, and manufacturing scaling to ease supply constraints. As global capacity targets expand particularly in emerging markets onshore and offshore wind are set to play complementary roles in achieving net-zero goals, provided these challenges are met with coordinated policy support, R&D investment, and stakeholder collaboration.

7. Conclusion

Wind energy has established itself as a keystone of the global renewable energy transition, with both onshore and offshore technologies playing pivotal roles in decarbonizing the power sector. This review paper has highlighted the remarkable progress in wind turbine design, from the evolution of Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) to the cutting-edge innovations in offshore systems, including floating platforms and hybrid energy solutions. For offshore wind, the shift toward larger turbines (15+ MW) and floating foundations promises to unlock vast deep-water potential, while advancements in digital twins, corrosion-resistant materials, and dynamic grid integration address key challenges. Meanwhile, onshore wind continues to evolve through repowering strategies, noise reduction technologies, and community-centric approaches, ensuring sustainable land use and social acceptance. Despite these advancements, challenges such as high capital costs, supply chain constraints, and environmental concerns require coordinated efforts from policymakers, industry leaders, and researchers. The future of wind energy highly depends on continued innovation in AI-driven optimization, recyclable materials, and hybrid systems, alongside supportive policies and international collaboration. By addressing these challenges, wind energy both onshore and offshore can fully unlock its potential as a key player of a net-zero future, delivering clean, reliable power while fostering economic growth and environmental stewardship.

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Pathways Toward Net-Zero Emissions in the Maritime Sector: Evaluation of IMO's Strategic Framework

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Abstract

The move from fossil fuels to alternatives that are less harmful to the environment presents the maritime industry with a diverse variety of opportunities as well as obstacles. This research investigates the possibilities and challenges that are associated with marine technology, bearing in mind the objective of the international maritime industry to achieve zero emissions from ships by the year 2050. The objectives of this paper are to analyse the process of decarbonizing shipping and to determine the most effective methods for reducing emissions of greenhouse gases. Additionally, this will be done in order to offer a comprehensive analysis of the emissions that were produced by international shipping from the years 2012 into 2018. The findings of the research suggest that important impediments include increasing prices, limitations imposed by technological and infrastructure constraints, challenges posed by legal and regulatory agencies, limitations imposed by market and economic demands, as well as concerns regarding social and environmental issues. This study might be beneficial for port and shipping stakeholders, policy makers and researchers.

Keywords: De-carbonization; IMO's Net-Zero Emission; Greenhouse Gas Emissions; Emission Control Technologies; Maritime Technology Challenges.

1. Introduction

The International Maritime Organization (IMO) in 2014 released a report regarding Global warming gas (GHG) emissions from shipping. It is found that, the shipping industry was around 2.2% of the world's total CO_2 emissions in 2012, with emissions of about 800 million tons. [1]

Attributing greenhouse gas emissions to specific national entities is a significant challenge in the inherently transnational industries of international shipping. Policy development for specific sectors is the responsibility of two specialized United Nations organizations: The International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO).

In order to minimize GHG emissions from maritime sector, the IMO sets measurable targets:

I. Lowering the sector's carbon intensity (CO_2 emissions per unit of transportation) by a minimum of 40% by 2030 in comparison to 2008;

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II. Reducing by at least 50% the industry's overall annual GHG emissions from international shipping by 2050 in comparison to 2008;

III. Eliminating the sector's GHG emissions as soon as feasible this century [1]

Even before the IMO Strategy, the global shipping industry took steps to reduce GHG emissions, including implementing the Energy Efficiency Design Index (EEDI) for new ships. But in order to meet the targets set forth in the IMO Strategy particularly the targets for 2050 and beyond it will also be necessary to step up and accelerate actions that go beyond the conventional ones, like switching from fossil fuels and other conventional fuels to low- and zero-carbon fuels and introducing innovative technologies. [2]

The Net-Zero Emission Strategy, specifically the International Maritime Organization's (IMO) objective to achieve net-zero greenhouse gas (GHG) emissions by 2050, is paramount as it represents a significant advancement in combating climate change by tackling the maritime industry's substantial contribution to global emissions, fostering technological innovation, and establishing a standard for other sectors in their de-carbonization initiatives [2]. This paper intends to comprehensively explore the maritime technology challenges and opportunities associated with Zero Emission from ships by 2050 for decarbonizing the global shipping industry.

2. Review of Existing Literature

Maritime transport remains the most cost-effective and dominant mode of global trade, handling over four-fifths of international commerce despite a slight decline in 2018. However, while shipping is considered more environmentally efficient than air and road transport, it still has significant negative environmental impacts. As people's knowledge of environmental issues and climate change grows, shipping emissions in particular are coming under more scrutiny and attention. [3]

When compared to terrestrial or aviation choices, maritime shipping is an increasingly carbon efficient way to transport big and bulk commodities; yet, if nothing is done, maritime GHG emissions are expected to rise. These emissions are expected to rise by up to 250 percent by 2050 under normal circumstances, such as doubling global trade. This puts pressure on the maritime sector to help achieve the necessary considerable reductions in GHG emissions. [4]

Numerous environmental issues are related to the toxins emitted by ships. The primary greenhouse gas (GHG) emitted by ships is carbon dioxide (CO_2). Greenhouse gases (GHGs) are the primary contributors to the Earth's warming. Acid rain is a detrimental phenomenon caused by the adverse effects of sulphur oxides (SO_x) and nitrogen oxides (NO_x). Human health is influenced by particulate matter (PM), volatile organic compounds (VOCs), and carbon monoxide (CO). Black carbon (BC), present in particulate matter (PM), adversely affects human health and is the second most significant contributor to climate change after CO_2. This search mostly concerns greenhouse gas emissions, despite not being a comprehensive list. This segment of the global economy is anticipated to expand rapidly. [4] The International Maritime

Organization's (IMO) 2014 said that Third Greenhouse Gas Study indicates that in 2012, international shipping accounted for 2.2% of global CO_2 emissions. Moreover, increase in global trade would significantly contribute to a potential rise in these emissions by 2050, estimated to be between 50% and an alarming 250%. [1]

Shifting focus, projections from the IMO further suggested that maritime transportation could account for as much as 15% of worldwide CO_2 emissions by mid-century. Looking ahead, 2019 data reinforces the gravity of the situation, anticipating a 39% rise in seaborne trade demand by 2050. Particularly noteworthy is the estimation that approximately 80% of the global fleet's CO_2 emissions stem from the deep-sea shipping sector. Finding technically sound and economically viable emission reduction strategies for this industry is therefore crucial. [5]

In May 2019, the IMO's Marine Environment Protection Committee (MEPC) announced the start of the Fourth IMO GHG Study, which will include projections of international shipping emissions from 2018 to 2050 and an inventory of global GHG emissions from 2012 to 2018, with the final report expected in fall 2020. The policy, based on a 2008 baseline, aims to reduce carbon intensity by 40% by 2030, 70% by mid-century, and halve shipping's overall GHG emissions by 2050. [1]

The IMO's preliminary contribution to the global climate change goals of the Paris Agreement is outlined in its Strategy. The marine industry must significantly adjust its emissions pathway to meet international mitigation limits, with policymakers and stakeholders urged to implement strategies to reduce the carbon footprint of maritime operations. The growing interest in this area is reflected in the relevant transport environmental literature, which is increasingly focused on initiatives, legislation, and methods intended to decrease the environmental effect of shipping. [6]

Approaching the shipping industry's de-carbonization challenge necessitates a dual-faceted analysis, one that acknowledges the distinct, yet intertwined, viewpoints of maritime operators and policymakers. Operators and ship owners face critical, long-term business decisions, while policymakers grapple with the imperative of achieving stringent decarbonization targets. Meeting the IMO's ambitious 50% emission reduction goal will likely demand a comprehensive strategy. This strategy must extend beyond operational and market-based initiatives, and almost certainly require the substantial adoption of low- and zero-carbon fuels. This study provides a critical assessment of the main strategies available for lowering shipping emissions in an attempt to improve the broad understanding of the decarbonization problem for the shipping sector. The main organizational, technological, political, and economical obstacles and constraints to implementation are also covered, along with any potential enablers that might promote a wider deployment. The framework that has been outlined is complex and brings to light a number of important debates that are ongoing in the economic and scientific domains about shipping's de-carbonization. [2]

3. Methodology

In this study we adopted qualitative data that are examined in this work. This study draws data from various sources, including daily newspapers, academic journals, conference papers, NGO reports, and steel industry analyses. After data collection, it is organized and divided, with key information presented in graphical and tabular formats to highlight the Maritime Technology Challenges in achieving the IMO's net-zero emission strategy.

4. Shipping industry and GHG emissions

The shipping industry is one of the most internationalized sectors, handling approximately 90% of global trade. Ships predominantly use "bunker fuels," which are considered cheap but are also among the dirtiest diesel fuels with high carbon content. [7] Heavy Fuel Oil (HFO), used by 80% of the world’s shipping fleet, is particularly carbon-intensive and contributes to greenhouse gas emissions as well as air pollutants. [8]

4.1 Rising Concerns and Projections

The industry's reliance on high-carbon fuel is seen as a significant obstacle to global pollution reduction efforts, and if unchecked, its carbon footprint could offset progress in other sectors. Projections suggest a potential increase in carbon emissions from shipping by 250% by 2050, driven by the growth of global trade and the expected doubling of international trade by 2035 [9]. According to the International Transport Forum, if shipping is not controlled, its emissions could make up 17% of the world's CO2 emissions by 2050.

4.1.1 IMO and its regulation

The international nature of the shipping industry makes emissions estimation and control difficult for individual countries, prompting the IMO, a UN agency, to regulate the industry and address climate change. In 2018, the International Maritime Organization (IMO) put into effect a policy with the objective of lowering the amount of greenhouse gas emissions produced by the shipping industry by at least fifty percent by the year 2050 and lowering the amount of carbon intensity by forty percent by the year 2030 [1].

4.1.2 Challenges and Progress

Despite the existence of regulatory frameworks, the rate of de-carbonization in the shipping sector is nevertheless closely monitored. This shift is hampered by a number of issues, including the industry's long-standing reliance on high-carbon fuels, the complexity of international trade networks, and the difficulties in precisely measuring and controlling emissions. By analysing ongoing efforts, outlining enduring challenges, and assessing the likelihood of achieving the International Maritime Organization's (IMO) 2030 green shipping goals, this study aims to critically analyse the shipping industry's de-carbonization trajectory.

I. Global Maritime Energy Efficiency Partnerships (GloMEEP):

Started in 2015 in cooperation with the United Nations Development Program and the Global Environment Facility, this project aims to enable the marine industry to adopt and implement energy-efficient solutions. Advocates energy-efficient technologies and operational approaches to help to reduce greenhouse gas emissions from shipping.

II. Global Industry Alliance (GIA) to Support Low Carbon Shipping:

Started in 2017 in line with the GloMEEP project finds and develops ways to overcome challenges preventing the marine sector's acceptance of energy-efficient technologies and operational guidelines. Aims to support sector-wide innovation and cooperation so facilitating the change to low-carbon shipping.

III. Global Maritime Technology Cooperation Centre Network (GMN):

The GMN project, financed by the European Union, has created a network of five Maritime Technology Cooperation Centre (MTCCs) across Africa, Asia, the Caribbean, Latin America, and the Pacific. Since 2018, the MTCCs have concentrated on assisting nations in formulating national marine energy-efficiency policies and initiatives. Their objective is to encourage the use of low-carbon technology and practices in maritime transport and to construct voluntary pilot data gathering and reporting systems.

IV. Green Voyage 2050 Project:

Initiated in 2019, this initiative is a collaboration between the International Maritime Organization (IMO) and the Government of Norway. Its objective is to catalyse and advocate for global endeavours to showcase and evaluate technical solutions aimed at mitigating greenhouse gas emissions within the shipping sector. Concentrates on augmenting knowledge and information dissemination to bolster the IMO's GHG reduction strategy.

4.2 IMO's Net Zero Emission Strategy

The targets for reducing GHG emissions from ships can be approached in two ways: by examining the industry's objectives for 2030 and 2040 as a whole, and by examining the specific targets for individual ships. One method of understanding the latter is to focus on the intensity of greenhouse gas emissions. This determines the greenhouse gas emissions for each ship, or more precisely, for each transport task. This intensity is determined by dividing the total amount of emissions that must be reduced by the total amount of shipping activity. This suggests that fluctuations in commerce quantities have an effect on the intensity of greenhouse gas emissions. In other words, the emissions produced per ship must decrease as the volume of trade or maritime activity increases in order to achieve the emission reduction targets. Currently, the objectives are being evaluated in comparison to those of 2008. Subsequently, trade volumes have expanded substantially, which has an effect on the overall objectives for reducing GHG intensity that must be achieved to achieve the absolute targets. The absolute emissions reduction targets for 2030 and 2040 can be revised in light of this increase in trade volumes.

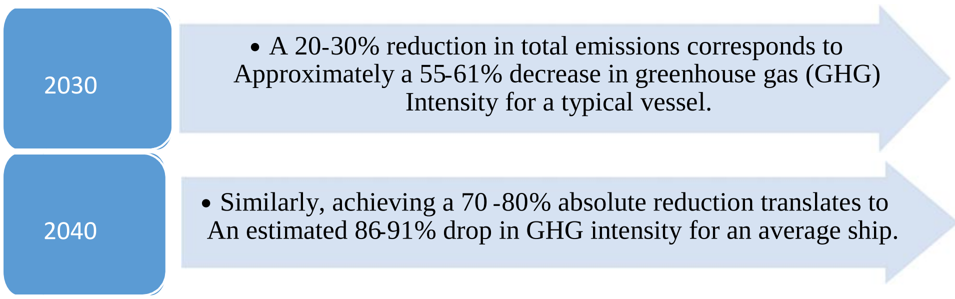

Figure 1: Two objectives of reducing GHG emission**s** *[10]*

Table 1: Comparison of 2018 vs. 2023 IMO GHG Strategy [10]

Category	2018 Initial GHG Strategy	2023 Revised GHG Strategy
Absolute Emission Reduction	2050: At least -50%	2030: -20% with an aim for -30% 2040: -70% with an aim for -80% ~2050: -100%
Emission Intensity	2030: at least -40% 2050: at least -70%	2030: at least -40%
Fuel Uptake Target	Not specified	2030: 5% with a goal of reaching 10%
Just and Equitable Transition	Not included	Included
Policy Measures	Lists potential short-term, midterm, and long-term measures	Commits to implementing mid-term measures by 2025, including technical and economic actions
Scope	Tank-to-wake carbon emissions	Well-to-wake GHG emissions

4.3 Existing technologies in the maritime industry aimed at reducing emissions

The International Maritime Organization (IMO) has amended the de-carbonization targets for shipping. The revised strategy specifies a 20% decrease in emissions by 2030, based on 2008 levels, and aims for net-zero emissions by 2050. Given the expected shortage of carbon-neutral fuels, it is essential to explore all de-carbonization options to achieve this goal. This constitutes a premise of DNV's "Maritime Forecast to 2050" research, which analyses the potential and challenges of the energy transition, focusing specifically on future ship energy. Innovative fuels and technology advancements are particularly crucial in this pathway for achieving de-carbonization. "The implementation and advancement of novel technologies are crucial for meeting emission reduction objectives in the maritime sector, which is challenging to decarbonize due to its inherent characteristics: significant energy consumption and extensive distances". [12]

- Solid oxide fuel cells are an extremely intriguing alternative for the business since they have the ability to convert fuels like ammonia, LNG, methanol, and hydrogen into electricity with a great potential for energy efficiency.
- Although there are many obstacles in the way, the development of liquefied hydrogen technology may eventually lead to the use and storage of this energy vector in the maritime industry.
- DNV claims that for some ships, wind-assisted propulsion has already resulted in yearly fuel savings of 5% to 9%, with the possibility of reaching 25%.
- Onboard Carbon Capture (OCC): This technology is interesting from an economic standpoint, "It's possible that as the globe switches to sustainable fuels, dwindling demand would cause fossil fuels to lose market value. In order to achieve net-zero, this technology may now be commercially feasible by combining fossil fuel and biofuel." The study notes that because this scenario depends on the ongoing creation of new prospections, it is unpredictable.
- Utilizing nuclear energy: "It appears like a really sensible technology, but social pressure might prevent its advancement or uptake, thus it could have a challenging future. The international nature of marine trade, which complicates the equipment's operation and may result in a lack of control in international waters, is another negative feature. "Technologically speaking, however, it is an excellent solution utilizing technologies that have been developed since 2000 (NPP gen IV). Naturally, before this kind of vessel is widely adopted, the International Atomic Energy Agency and the IMO will need to work closely together to ensure its safety". [12]

4.4 Case Studies

4.4.1 United Kingdom

Enacting legislation with the goal of becoming the first major economy to stop contributing to global warming by 2050, the United Kingdom has accomplished a major milestone. In order to reach net zero emissions by the year 2050, the United Kingdom must meet the new target, which requires it to attain a state where all GHG emissions are balanced by removals or reductions. The United Kingdom Department for Transport's Maritime 2050, Clean Maritime Plan, and Transport De-Carbonization Plan all express the nation's aspiration to establish a prominent position in the de-carbonization of the shipping industry. This endeavour is motivated by the acknowledgment of the substantial economic and societal benefits that are associated with such a transition. UK's proposal to further reduce marine emissions in the United

Kingdom is to progressively cease the sale of new, non-zero emission domestic maritime vessels. Increases in vessel efficiency and the utilization of electricity and zero-carbon fuels, especially ammonia produced from low-carbon hydrogen, have been considered as mitigation strategies to supplant fossil fuels. Consequently, United Kingdom will commence the process of incorporating its share of global maritime emissions into its objective of achieving net zero greenhouse gas emissions by 2050 in 2033. United Kingdom's ambition and commitment to addressing pressing issues are evident in the Plan clearly, which is at a critical juncture in the marine industry's growth. Additionally, numerous domestic policy initiatives have been implemented since the year (in addition to the measures previously mentioned). [13]

4.4.2 Malaysia

The 12th Malaysia Plan (12 MP), which emphasizes clean, green, and sustainable growth as a means of achieving a low-carbon, climate-resilient economy, lays out a roadmap for Malaysia to reach net-zero emissions by 2050. The phase-out of coal-fired electricity, the promotion of circular economy principles, and the prioritization of sustainable urban development are important projects. The administration wants to maintain the amount of forest cover while reducing dependency on fuels and establishing a carbon price system. However, there are several obstacles that Malaysia's maritime industry must overcome in order to comply with global de-carbonization objectives. These include insufficient funding, infrastructure, legislative frameworks, and stakeholder participation. The government is encouraged to enact strong policy commitments, carbon pricing, and non-tax-based incentives to boost maritime de-carbonization. Additionally, research on zero-emission fuels and technologies, such as E-Hydrogen, E-Ammonia, and other fuels produced from renewable energy sources, should be funded. To guarantee the maritime industry's shift to a low-carbon future, cooperation between the public and commercial sectors is necessary for this complete approach. [14]

4.5 Maritime Technical Challenges

Technically, switching to an energy system with net-zero carbon emissions will need significant investments in the development of new technologies. Among the now available and reasonably priced renewable energy technologies are solar, wind, and geothermal ones. They must, however, make significant infrastructure and energy storage technological investments if it is to ensure a consistent flow of electricity. Furthermore, needed are innovative technologies like carbon capture and storage (CCS) and green hydrogen generation to decarbonize industrial operations that provide difficulty for electrification. [15]

Renewable energy sources like the sun and wind don't always produce power when it's needed since they are intermittent. Scalable and effective energy storage systems are required to maintain supply and demand balance. Current battery technologies, such as lithium-ion, have limitations with regard to cost, energy density, and scalability. Some alternative storage technologies that are still in the early stages of study include advanced batteries and hydrogen storage.

The maritime industry must transition from heavy fuel oil (HFO) and marine diesel oil (MDO) to low or zero-emission fuels, including hydrogen, ammonia, biofuels, and methanol. Ammonia and hydrogen are both zero-emission fuels that show potential; however, they necessitate substantial improvements in onboard utilization, storage, and production technologies. In particular, hydrogen necessitates cryogenic temperatures or high-pressure containers for storage, whereas ammonia is toxic and necessitates gentle handling. Although biofuels can be used as drop-in replacements for conventional marine fuels, their production at a large scale raises concerns about sustainability, land use, and competition with food production. Methanol is more convenient to store and manage than conventional fuels, but it has a lower energy density, resulting in increased fuel consumption and storage requirements. New propulsion methods are required to reduce dependence on conventional marine engines and enhance energy efficiency. As a result of its low energy density and the requirement for regular recharging, battery-electric propulsion is not a viable option for extended marine journeys. On the other hand, it is useful for sailings that are quite short and for ferry services. Hydrogen fuel cells may partially clean up the environment, but putting them in big ships is still just an idea that is being tested. It's important to keep working to make fuel cells that are made to work in marine settings more affordable, effective, and long-lasting. Kites, rigid sails, and flattener rotors are technologies that have the potential to contribute to fuel conservation. However, they are not equipped with the capacity to operate as robust propulsion systems and are vulnerable to wind conditions.

In order to reach net-zero emissions, two strategies are needed: first, ships need to use less energy by using new systems and better ways to run their businesses. Improving the hydrodynamics and lowering the resistance of ship designs is a very hard and expensive process, especially when older boats need to be changed. There are systems that try to lower drag by adding a layer of air bubbles below the body. These systems should be thought about. Even so, a lot of technologies are still in the early stages of being widely used and need a lot more work. Optimizing routes with AI, implementing automated energy management systems, and installing high-tech monitoring systems can undeniably boost operational efficiency. This is the case even though it needs a big starting investment and to be easily connected to the maritime infrastructure that is already in place.

5. Conclusion

Reaching zero emissions by 2050 is a high goal with both enormous opportunities and difficult obstacles. However, despite the strong basis for development offered by economic opportunities, emerging technologies, modified international norms, and cooperative efforts, major obstacles still exist. Large capital costs, limited technology and infrastructure, complicated rules and regulations, unstable markets and economies, and social and environmental factors make it necessary for the whole world to work together, keep funding, and come up with new ideas. Marine diesel engines must be regulated because of the harmful pollutants they produce and the significant impact they have on the environment and human health. Emissions of carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM) are major worries because they have real effects.

The only way to solve this problem is to gather information and closely monitor every facet. The industry is steadfast in its resolve to cut emissions in spite of all obstacles. It will take government incentives, financial aid, successful case studies, and an emphasis on research and development to overcome technological, financial, and operational obstacles. A more ecologically friendly maritime industry is attainable by 2025 because harmful emissions must be addressed immediately through new technologies and policy changes.

6. Recommendations

i. To encourage shipping businesses to minimize greenhouse gas emissions, governments may explore carbon taxes or emissions trading. This aids industrial sustainability.

ii. Shippers should report greenhouse gas emissions. Data can measure progress, highlight areas for improvement, and hold firms responsible for their environmental impact.

iii. Governments, industry stakeholders, and the UN should align maritime industry actions with global sustainability frameworks. Attend international climate change conferences and agreements.

iv. Authorities and industry associations can promote shipping's environmental impact and greenhouse gas reduction. This boosts public support and green consumption.

v. Maintain engines and emission control systems to ensure they operate efficiently. This includes cleaning DPFs and monitoring SCR systems for urea injection.

vi. Explore alternative fuels, such as LNG (Liquefied Natural Gas), which produce fewer emissions than traditional marine diesel fuels.

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Hovercraft Technology for Transportation and Commercial Applications: A Comprehensive Review

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Abstract

This paper presents a comprehensive review of hovercraft technology, focusing on its principles, applications, and future potential. It explores the fundamental mechanics of hovercraft operation, their technological advancements, and their contributions to transportation, defense, and commercial sectors. The benefits and drawbacks of hovercraft are analyzed, considering factors such as efficiency, terrain adaptability, and environmental impact. A detailed cost and payload analysis is provided to assess economic viability, highlighting key cost drivers and considerations. Additionally, the paper examines the future prospects of hovercraft, including advancements that enhance their performance and versatility. With continuous technological progress, hovercrafts evolved into a more mainstream transportation solution, potentially replacing traditional vehicles in specific applications. Examined hovercraft applications; analyzed 287 topics, 92 relevant findings. The strong demonstration of [relevant topics, e.g., autonomous controlled hovercraft, innovative Skirt and hull design, advanced electric-powered propulsion system, reduced vibration and noise] opens up promising avenues for future research aimed at optimizing performance and efficiency, potentially paving the way for the widespread use of hovercraft in [relevant industries, e.g., transportation, logistics, environmental monitoring]. This study serves as a valuable resource for engineers, researchers, and policymakers seeking innovative amphibious transportation solutions and aims to inspire further advancements in this dynamic field.

Keywords: Hovercraft, Air-cushion vehicle (ACV); Transportation technology; Search and rescue; Environmental studies; Amphibious vehicles

1. Introduction

A hovercraft is known as an air-cushion vehicle (ACV) which represents a sensational junction of engineering innovation and versatile transportation abilities. Since its conceptual beginning in the early 18th century, the hovercraft has developed significantly, inspired by advancements in technology and a growing understanding of computational fluid dynamics. The first practical hovercraft, the SR.N1, developed in the 1950s by British engineer Christopher Cockerell, displayed the future of ACV technology to navigate smoothly over various terrains, including water, land, mud, and ice. This unique ability to hover above surfaces allows hovercrafts to operate in

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environments where traditional vehicles (car, bus, ship & airplane etc.) may struggle, making them valuable in various applications ranging from search and rescue operations to military training and environmental studies.

As global challenges such as climate change, urban bottleneck and the need for efficient transportation solutions enhance, the purpose of hovercraft technology is more noticeable than ever. This paper aims to explore the all-round applications of hovercrafts around the world, exploring their role in increasing connectivity, supporting emergency response efforts, and contributing to environmental conservation. By investigation into the principles that control hovercraft operation, as well as their historical development and modern implementations, this review seeks brighten the purpose of hovercrafts as a sustainable and adaptable mode of transportation for the future. Through a combination of existing literature and case studies, we aim to provide insights into the ongoing evolution of hovercraft technology and its implications for various sectors, ultimately advocating for its increased adoption in addressing contemporary transportation challenges**.**

1.1 The Birth of Hovercraft

The first design by Swedish designer Emmanuel Swedenborg in 1716.[1] In 1915 Austrian Dagobert Muller built the world first water effect.[1]In 1931 Finnish aero engineer Toivo J. Kaario began designing developed version of a vessel using an air cushion and built a prototype.[1]The concept of hovercraft can be traced back to the early 1900s, but it wasn't until the mid-20th century that serious development began. In the 1950s, Christopher Cockerell, a British engineer, conducted experiments that led to the creation of the SR.N1, the first practical hovercraft.[1]This groundbreaking vehicle demonstrated the potential of air-cushion technology for transportation over both land and water.

1.2 What is Hovercraft?

As noted in [2], [3], [4], [5], [6], [7], [8] ,hovercraft is a vehicle that flies like a plane, float like a boat, drive like a car. A hovercraft, also known as an air cushion vehicle or ACV, is a craft capable of travelling over grass, water, mud or ice and other surface.

Figure 1: Hovercraft[9]

1.3 Hovercraft Technology

Hovercraft technology is fascinating and versatile, combining elements of boats, planes, and helicopters. Hovercraft, also known as air-cushion vehicles (ACVs), use blowers to create a cushion of air beneath the hull. This cushion lifts the craft above the surface, allowing it to glide over water, land, mud, and even ice.

1.3.1 How Hovercraft Works

The consensus among experts like[10], [11], [12], [13], [14] is that:

1. **Lift Fans:** These fans blow air underneath the craft to create the air cushion.
2. **Propulsion Fans:** These fans push the craft forward, backward, or sideways.
3. **Skirt:** A flexible skirt around the base helps contain the air cushion, improving lift and stability.

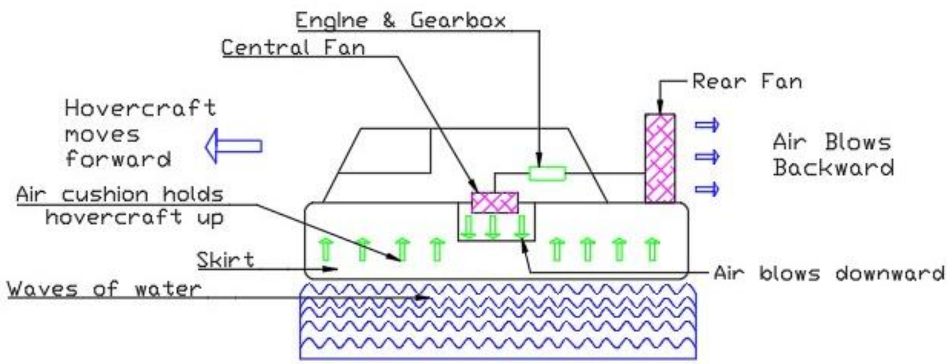


Figure 2: How hovercraft work (Drawn with AutoCAD for Visualization)

A central fan in the hovercraft forces air downwards, creating a cushion of air beneath the craft. This air cushion lifts the hovercraft, allowing it to glide over both land and water with reduced friction. A rear fan provides thrust, pushing the hovercraft forward. A flexible skirt helps to contain the air cushion.

1.3.2 What are the primary principles that govern the operation of hovercrafts?

Hovercrafts operate based on several fundamental principles, primarily derived from Newton’s Laws of Motion. The prevailing opinion among these experts [15], [16] that:

1. **Newton’s First Law (Inertia):** A hovercraft remains stationary or moves at a constant velocity unless acted upon by an external force.
2. **Newton’s Second Law (F = ma):** The force required to accelerate the hovercraft is proportional to its mass and the desired acceleration.
3. **Newton’s Third Law (Action and Reaction):** The downward thrust of air from the hovercraft’s fans creates an upward lift, allowing it to hover.

2. Method of Study

In this review paper, we collected and analyzed extensive data on hovercraft applications and technology. To ensure a comprehensive study, we examined various sources, including research papers, journal articles, conference proceedings, reports, books, book sections, websites, documents from online sources, and patents. A total of 287 topics were gathered from secondary data, of which 92 were relevant to the study, while 195 were deemed unrelated. We used 8 peer-reviewed journal articles and 6 conference proceedings. By using proper verification of data (academic research papers, journal articles, etc.), bias was minimized. Hovercraft technology is developing day by day; that's why there are so limited peer-reviewed academic research and journal articles on it. The method of study is shown in Table 1.

Table 1: Method of Study

Stage	Description	Number of Sources
1. Initial Data Collected	Total secondary data gathered	287
2. Relevance Screening	Rejected as unrelated data	195
3. Related Data	Sources deemed relevant to the topic	92
4. Source Type Breakdown	Breakdown of the 92 relevant sources by type:	
	Book	1
	Document From Website	1
	Patent	1
	Website	66
	Report	6
	Conference Proceeding	6
	Journal Article	8
	Book Section	3
5. Selected Data	Sources selected for the review paper	92

3. Application of Hovercraft

1. **Search and Rescue:** Multiple sources,[1], [17], [18], [19]including, concur that hovercrafts are a valuable tool for search and rescue operations.
2. **Environmental Studies:** As noted in [17], [18], [20]article and work, hovercrafts are frequently employed in environmental studies.
3. **Military:** Neoteric Hovercrafts used for military training.[1]
4. **Transportation**: Portsmouth to Ryde hovercraft (10 minutes), FastCat ferry (22 minutes).[17]
5. **Tourism:** Hovercraft services attracting tourists and locals.[21]
6. **Community Support:** Hovercraft services providing essential transportation links.[21]
7. **Icebreaking:** CCG using hovercrafts for icebreaking in Canadian waters.[1]
8. **Law Enforcement:** MNRP and CCG using hovercrafts for law enforcement and surveillance.[1]

9. **Disaster Relief:** MNRP using hovercrafts for mass evacuations during natural disasters.[1]
10. **Engineering Projects:** Mackley-ACE platforms used for offshore civil engineering tasks. [1]And also, hovercraft used for offshore platforms tasks.[22]
11. **Ferries:** Yukon Princess ferries operating across the Yukon River.[1]
12. **Overland Transportation:** Terracross HT-119 air cushion trailer used for overland transport.[1]
13. **Agriculture:** Pneumatic seeders on air cushion platforms used for planting in wet areas.[1] [23], [24]concur that hovercrafts are used for agriculture and also it is used for farming system.[25]
14. **Passenger Transportation:** The Solent is now the only place in Western Europe with a full passenger hovercraft service, operating between Southsea and Ryde.[26]
15. **Vehicle Transportation**: Hovercrafts are used for vehicle transportation.[17]
16. **Medical Evacuations:** Transporting patients from remote areas. [19]suggested a first-aid transportation by hovercraft in a disaster.
17. **Border Patrol:** Monitoring and securing borders.[1]
18. **Oil Spill Response:** Hovercrafts, as evidenced by multiple sources[27], [28], [29], [30], [31], [32]are indispensable assets in oil spill response and rapid deployment efforts. Their unique ability to operate over various terrains, including water, ice, and land, makes them ideal for containing and cleaning spills efficiently.
19. **Environmental Surveys**: Hovercrafts have proven to be indispensable for a variety of environmental research tasks. As evidenced by multiple studies[33], [34], [35] these versatile vehicles are particularly well-suited for environmental surveys and wildlife monitoring.
20. **Scientific Research:** Hovercrafts have emerged as a valuable tool for scientific research and accessing remote research sites. As demonstrated in multiple studies[36], [37], [38] these versatile vehicles offer unique advantages for researchers working in challenging environments.
21. **Arctic Operations:** Hovercrafts have proven to be indispensable for Arctic operations, particularly in navigating icy waters and frozen landscapes. As evidenced by numerous studies[1], [39], [40], [41], [42] these versatile vehicles offer unique advantages for researchers, explorers, and industry professionals working in this challenging environment.
22. **Fishing:** Hovercrafts have proven to be valuable assets for transporting fish and equipment in shallow waters and fishing operations. As highlighted by multiple

studies[43], [44], [45], [46], [47] these versatile vehicles offer unique advantages for aquatic transportation**.**

23. **Crime Prevention:** Patrolling and monitoring high-risk areas.[1]
24. **Recreational Racing:** Hovercraft racing events.[48], [49], [50]
25. **Forestry:** Hovercrafts have proven to be valuable assets for a variety of land-based activities, including accessing and viewing forest areas and supporting agriculture and farming. As demonstrated by multiple studies[51], [52] these versatile vehicles offer unique advantages for these applications.
26. **Mining:** Hovercrafts have proven to be indispensable for transporting personnel and equipment to mining sites, particularly in remote or challenging terrain. As evidenced by numerous studies[53], [54], [55], [56], [57], [58], [59], [60] these versatile vehicles offer unique advantages for mining operations.
27. **Construction:** Moving materials and workers to construction sites.[6]
28. **Event Support:** Providing logistics for large events.[61]
29. **Firefighting:** Hovercrafts have proven to be indispensable for accessing and fighting fires in remote areas. As demonstrated by multiple studies these [62], [63], [64], [65], [66]versatile vehicles offer unique advantages for firefighting operations.
30. **Flood Response**: Hovercrafts have proven to be invaluable assets for rescuing people and delivering supplies during floods. As evidenced by multiple studies[19], [67] these versatile vehicles offer unique advantages for disaster relief efforts**.**
31. **Coastal Surveillance:** Hovercrafts have proven to be indispensable for coastal surveillance and monitoring coastal areas for illegal activities. As demonstrated by multiple studies [68], [69], [70], [71], [72], [73], [74], [75], [76]these versatile vehicles offer unique advantages for coastal security.
32. **Marine Research:** Studying marine life and environments.[20], [40], [42]
33. **Cargo Transport**: Moving goods in areas with poor infrastructure. [61]
34. **Urban Mobility:** As demonstrated by multiple studies [17], [77], Providing transport in cities with water channels.
35. **Island Connectivity:** As evidenced by numerous studies [17], [78], [79], Connecting islands with the mainland.
36. **Wildlife Conservation:** Demonstrated by multiple studies[44], [51], [80],Protecting and monitoring wildlife habitats.
37. **Aquaculture:** Confirmed by copious studies[43], [45], [47] , Transporting fish and equipment in shallow waters.
38. **Dredging Support:** Assisting in dredging operations.[81]
39. **Patrol and Security:** Validated by multiple investigations[1], [18], [68], [69], [70], [71], [72], [73], [74], [75], [76] , Ensuring security in sensitive areas.

40. **Customs and Immigration:** Affirmed by a multitude of studies [1], [18], [68], [69], [70], [71], [72], [73], [74], [75], [76] , Monitoring and controlling borders.
41. **Emergency Services:** Indicated by numerous studies[19], [42], [62], [71], [82] , Providing rapid response in emergencies.
42. **Recreational Boating:** Validated by multiple investigations [48], [49], [50]Personal hovercraft for leisure.
43. **Education and Training:** Training personnel in hovercraft operation.[83], [84]

4. Benefits and drawbacks of Hovercraft in modern civilization

4.1 Benefits of hovercraft

Hovercrafts offer several benefits across various applications, including transportation, defense, and commercial sectors. Here are some key advantages:

1. Amphibious Capability

- Hovercrafts can travel over multiple surfaces, including water, land, mud, ice, and swampy terrain, making them highly versatile.

2. Reduced Friction and High Speed

- Since they hover above the surface on a cushion of air, there is minimal friction, allowing them to achieve higher speeds compared to traditional boats or land vehicles.

3. Accessibility to Remote Areas

- Hovercrafts can reach areas that are inaccessible to conventional vehicles, such as flood-prone regions, shallow waters, and marshlands.

4. Efficient Rescue and Emergency Operations

- Used in disaster relief and search-and-rescue missions, hovercrafts can navigate through difficult terrains like ice, flooded areas, or quicksand where other vehicles would struggle.

5. Military and Defense Applications

- Many defense forces use hovercrafts for amphibious landings, troop transport, and reconnaissance missions due to their ability to move across water and land seamlessly.

6. Fuel Efficiency and Lower Environmental Impact

- Hovercrafts consume less fuel compared to conventional boats or aircraft, and since they do not disturb the seabed or riverbeds, they have a lower ecological footprint.

7. Versatile Commercial Use

- Used in ferry services, tourism, and cargo transport, hovercrafts offer flexible solutions for crossing difficult terrains efficiently.

8. Minimal Infrastructure Requirements

- Unlike traditional boats or land vehicles that require harbors, roads, or rail tracks, hovercrafts can operate without dedicated infrastructure, reducing long-term costs.

9. Safer Travel in Hazardous Environments

- Hovercrafts can operate safely over ice, floodwaters, and areas with underwater debris, reducing the risk of accidents compared to conventional boats or land vehicles.

4.2 Drawbacks of Hovercraft

1.Does not perform well on roads:

- Although aircraft are designed to operate on a variety of surfaces, their aerodynamic suspension systems do not perform as well on paved roads as wheels.

2.Sensitivity to weather:

- Large waves, strong winds, and adverse sea conditions can significantly affect the stability and performance of hovercraft.

3.Noise pollution:

- The noise of older aircraft engines and ventilation systems was well known for noise pollution.

4.High operating and maintenance costs:

- Specialized components and complex hovercraft systems increase costs.

5.Limited passenger capacity:

- Hovercraft generally carries fewer passengers than conventional boats.

6.Specialized crew and training:

- A licensed captain and specialized training are required to operate the aircraft.

7.Specialized infrastructure:

- Hovercraft requires hovercraft docks for maintenance, refueling, and launching.

8.High costs associated with operating remotely:

- The technology systems involved would be very expensive if operated remotely.

9.Limited fuel power and range:

- The range of hovercraft is limited due to fuel consumption and design.

10. High construction costs:

- The cost of building a glider is much higher than the cost of building an aircraft of comparable size.
- The uses of hovercraft are limited, as they are best suited to coastal areas and certain types of terrain.

11.Single-handed travel:

- The design of the boat makes it ideal for short trips rather than long journeys.

5.Cost Analysis of Hovercraft

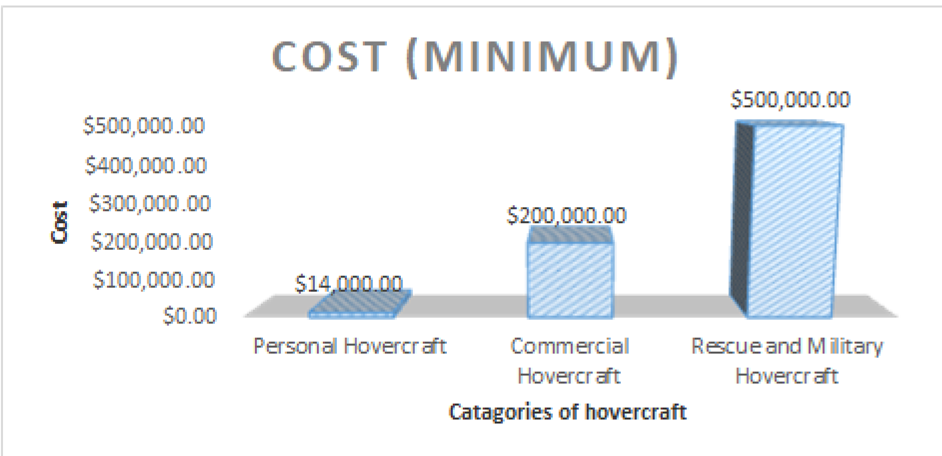


Figure 4: Minimum Cost for buying hovercraft[85], [86], [87], [88], [89], [90]

The graph represents the lowest possible prices for each hovercraft type. The graph clearly shows the significant cost difference between personal, commercial and rescue & military hovercraft. Rescue and military hovercraft are the most expensive, with a minimum cost of $500,000. Personal hovercraft is the most affordable, with a minimum cost of $14,000. Commercial hovercraft falls in the middle, with a minimum cost of $200,000.

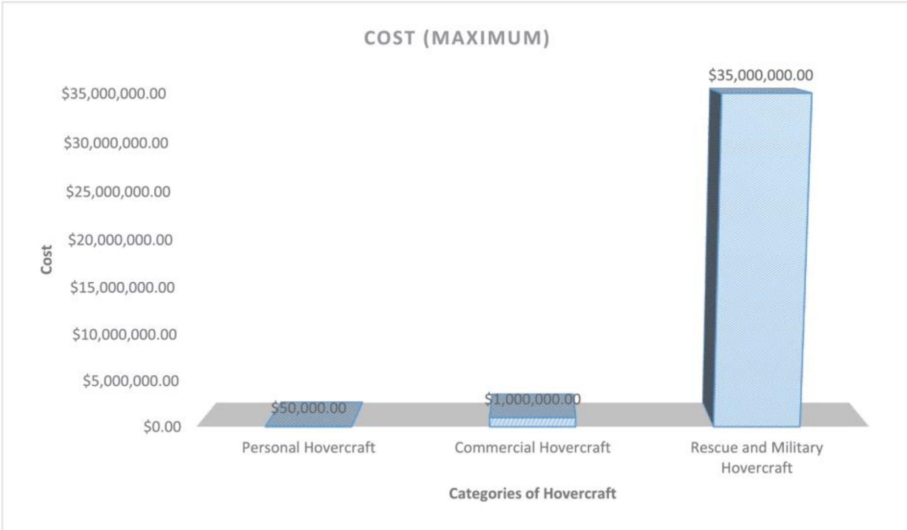
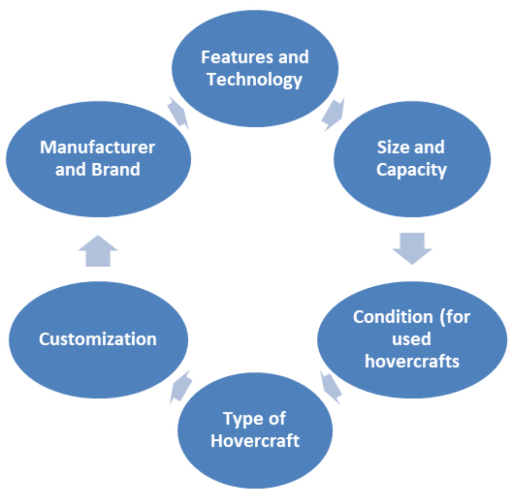


Figure 5: Maximum Cost for buying hovercraft [85], [86], [87], [88], [89], [90]

The graph represents the highest possible prices for each hovercraft type. The graph clearly shows the significant cost difference between personal, commercial, and rescue/military hovercraft at their maximum price points. Rescue and military hovercraft are the most expensive, with a maximum cost of $35,000,000. Personal hovercraft is the most affordable, with a maximum cost of $50,000. Commercial hovercraft falls in the middle, with a maximum cost of $3,000,000.

The cost of a hovercraft depends on several factors:



6. Passengers and Maximum Payload Capacity Analysis of Hovercraft

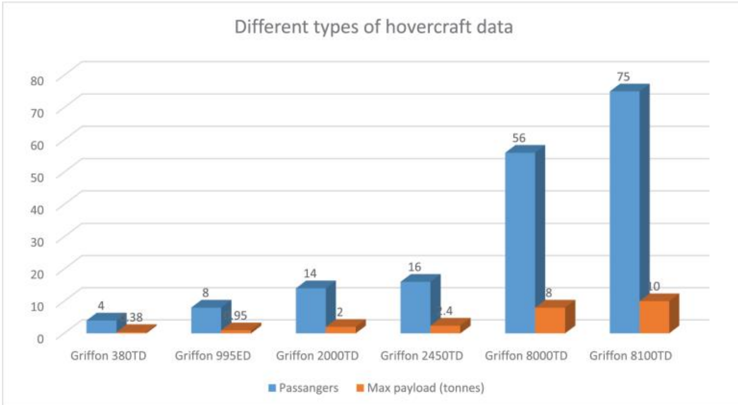
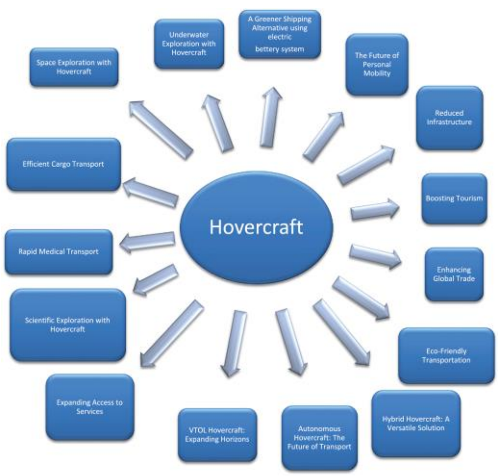


Figure 6: Different types of Hovercraft Passengers and Maximum Payload capacity[91], [92]

This graph provides a clear and concise overview of the passenger and payload capabilities of different Griffon hovercraft models, highlighting the significant differences between the smaller and larger models in the series. The Griffon 8000TD and 8100TD models show a very significant increase in both passenger and payload capacity compared to the earlier models. While passenger capacity generally increases with larger models, payload capacity doesn't always follow the same exact pattern. This suggests different design priorities for different models.

7.Future Prospects as A Multimodal Transportation



8.Conclusion

Hovercraft technology, a unique solution for transportation across diverse terrains, has evolved from its initial development to practical applications in modern fields such as search and rescue, military logistics, environmental research, and urban mobility. With the intensification of global challenges such as climate change and resource management, productivity and sustainability will be improved by technological advancements. Governments should invest in hovercraft for solving flood disaster quick response service, faster transportations from cox's bazar to Saint Martine route in Bangladesh, alternative of ferries for fast transportation in Bangladesh, solving loading and unloading problems in maritime port where draft is so low and making cargo transportations more quickly, using it our seashore areas and sunderbans for costal surveillance etc.

This paper underscores the importance of continued research and development in hovercraft technology, advocating for its broader adoption as a viable transportation solution. By leveraging the unique capabilities of hovercrafts, we can address contemporary transportation challenges and contribute to a more connected and sustainable future. As we look ahead, the potential for innovation in hovercraft design and application remains vast, promising exciting developments in the years to come.

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Artificial Intelligence Applications in Structural Health Monitoring of Offshore Wind Turbines

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Abstract

Offshore wind turbines adopted Structural Health Monitoring (SHM) systems are relatively new if hybridized with Artificial Intelligence (AI) and Machine Learning algorithms. In this paper, we talk about several approaches, describe examples, consider the issues, and suggest further research avenues. In this paper, we describe how AI and ML can improve the performance, reliability, and cost-effectiveness of the SHM through predictive maintenance, real time anomaly detection, and the automatic analysis of data. Several teams, such as neural networks, support vector machines, and ensemble learning methods, are researched in relation to their application concerning offshore turbine monitoring. The paper also addresses problems of implementation – the quality of data availability, cybersecurity, and integration with existing IT-solutions, and it defines future research lines. Through the development of SHM by intelligent algorithms, this study seeks to help resolve more resilient and sustainable offshore wind infrastructure.

Keywords: offshore wind turbines, AI, ML, renewable energy, SHM, RNN, LSTM

1. Introduction

Offshore wind turbines are important for wind energy resources as an important source of producing electricity. however, it is complex structures in very harsh working environments, thus call for precise Structural Health Monitoring (SHM) for effective protection. Traditional SHM methods have trouble even with sensor data in large volumes and high complexity. Many conventional SHM strategies prove to be inefficient when it comes to treating the quantity of data as well as intricate patterns necessary for supervision. With the help of AI and ML, new opportunities for improvement of SHM systems appear. The adoption of AI and machine learning for SHM systems has therefore been realized as the appropriate fix for the offshore wind turbines' keeping up and productivity. The monitoring systems using different sensors give an enormous amount of data, which can be processed with the help of machine learning algorithms, such as supervised and unsupervised learning to make Predictive Maintenance and Fault Detection possible.

Nomenclature

SHM = Structural Health Monitoring

AI = Artificial Intelligence

ML = Machine Learning

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RNN = Recurrent Neural Networks

LSTM = Long Short-Term Memory networks

1.1 Making artificial intelligence usable in the structural health monitoring of offshore wind turbines

Based on Artificial Intelligence techniques applied to structural fatigue load modeling and optimization, contemporary large-scale, and floating wind turbines may be more prepared for operational difficulties and stressors [1]. For instance, the advancement of a CNN-t-SNE-based neural network model that automatically identifies damages in mooring equipment of the floating wind turbine platforms gives a glimpse of what AI has in prospect in the advancement of structural health assessment and maintenance planning [1]. Moreover, it is evident that the health condition monitoring of offshore wind turbines using SVRs or other pattern recognition techniques such as K-nearest neighbors (KNN) algorithms for the small load behavior has shown better performance when compared with linear regression techniques [2]. These AI algorithms also enhance the outcome of extrapolation in structural health monitoring not only that they also give solutions to problems associated with measurement noise sensitivity in the operation of offshore wind turbines [2]. Due to the development of predictive maintenance and the controls research work which is still ongoing, the best combination of machine learning approaches and the best-set features to apply on the Offshore wind turbines may have a tremendous impact on the advanced Structural Health Monitoring practice of the Offshore Wind turbines to enhance the performance and durability of the Offshore wind energy systems in the future [2].

1.2 Using machine learning in target analytics of the data that are gathered from structural health monitoring systems

Li and Choung have employed the Multi-Layer Perceptron (MLP) networks to predict fatigue damages in mooring lines of floating offshore wind turbine platforms and the choice of MLP does not seem to be quite irrational in this case [2]. In addition, the highlighted integration of machine learning with the complex physics-based signal processing methods by Helsen et al enables one to develop dual solutions that incorporate real observations with the fundamental equations of physics to produce a more holistic picture of the turbine's behavior [2]. These models that combine machine learning with physics-based models not only improve the measures of prediction for structural behavior, fatigue, and performance but also convert the models into high-fidelity ones that are capable of being updated in response to new conditions of operation [2]. Moreover, artificial neural networks including the MLP network structure have been used for fault diagnosis of different parts of the wind turbine system proving the effectiveness of such techniques in realizing structural health monitoring systems [2]. The same study by Trizoglou et al. also demonstrated how the XGBoost ensemble model had higher accuracy and faster training time over LSTM deep learning neural networks in identifying faults in offshore wind turbines and thus the importance of ML in the topic [2]. All these uses of machine learning from basic regression to a classification model prove the flexibility of these frameworks for analyzing data obtained from structural health monitoring systems, especially in wind energy systems [3].

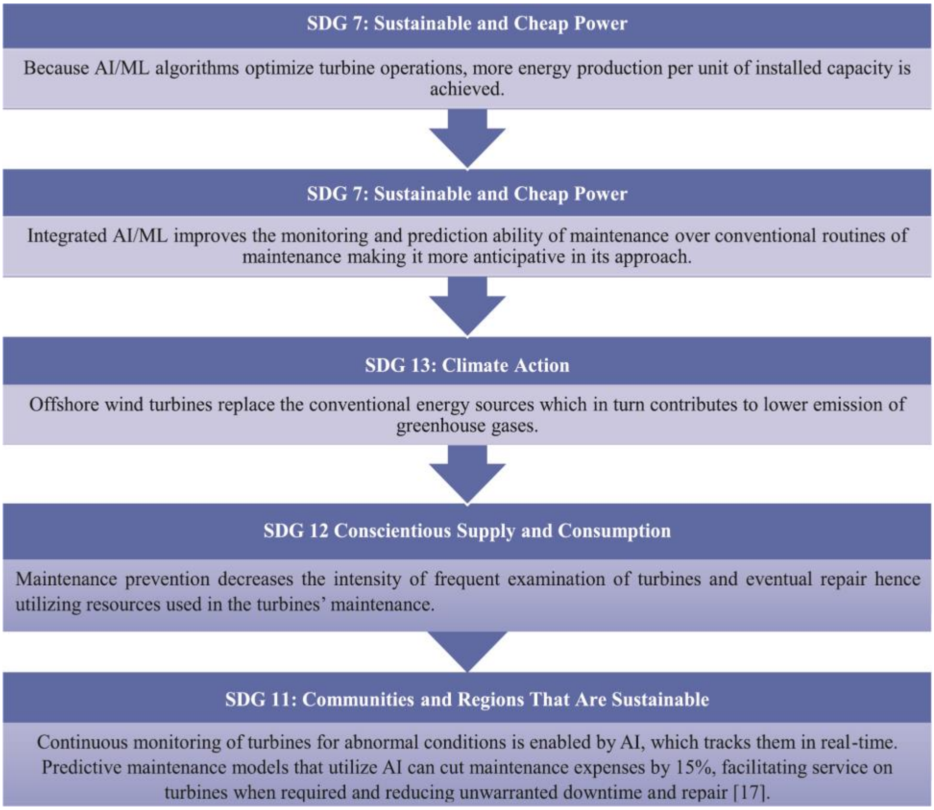
1.3 SHM Importance in Offshore Wind Turbine

In order to enhance the lifetime of the Offshore Wind Turbines, it is vital to implement the schedule maintenance and predict the failure times which can be done through structural health monitoring. Such structures are exposed to numerous attacks by unfriendly sea conditions; consequently, monitoring of these structures is crucial in order to assess their efficiency continuously.

Analyzing finances:

- **Offshore Wind Capacity Worldwide by 2023:** 35 GW of installed capacity; yearly growth rate: 19 percent
- **Investment Trends:** More than half of the total offshore wind investments made in 2023 were made in Europe, with 78% of the total investment. The Asia-Pacific investments were improved by 31 percent in the previous year.
- **Maintenance Costs:** $150, 000 is an approximate number that is required as an annual maintenance expenditure for each turbine. The reductions that have been known to be associated with predictive maintenance include a 15% reduction in maintenance costs and a 20% of downtime.
- **Adoption of AI/ML:** offshore wind operators, by 2023, 65 percent will be using AI/ML in a function like Predictive maintenance.

A number of the Goals for Sustainable Development (SDGs), particularly those pertaining to renewable power, creation, business, and structures, are greatly aided by the integration of artificial intelligence and machine learning (AI/ML) techniques in structural health monitoring (SHM) systems for offshore wind turbines. It is an in-depth study of the project's alignment with the SDGs:



1. 4 How AI & ML can Support Structural Health Monitoring

Data Handling and Analysis

Another area of importance of AI and ML in SHM is in test data processing and analysis of large amounts of experimental data. Offshore wind turbines have many sensors that regularly monitor various characteristics including vibration, strain, temperature, and wind speed. The relative quantity of data may be overwhelming for the conventional analytical approaches. Since, manually sorting this type of data and finding patterns and correlations that might not be easily distinguishable, AI and ML algorithms can easily do this. In fact, there are methods such as clustering and dimensionality reduction that assist in the understanding of such data, especially because they offer a better understanding of the health of the turbine.

Wireless data transmission systems, such as LoRa RF sensors and SDI-12 digital data loggers, enable the continuous collection and transmission of real-time data across large wind farms [18]. The SDI-12 interface allows for integrating multiple sensors into a single data stream, which is then transmitted to a central server via GSM/GPRS modems [18].

Anomaly Detection

Inclinometers like the EAN-52M vertical in-place system measure subsurface lateral movements, which are crucial for understanding the effects of environmental factors on turbine stability [18]. Structural problems or failures can often be defined by distortions in the data. Some of the supervised learning models include autoencoders, isolation forests, and others since they are trained to detect normal operating conditions and any anomalies in those conditions. Anomalies can be explained as a break from normal vibration, unanticipated changes to measured strain, or shifts in temperature values. Thus, the identification of such anomalies can be done early in operation hence avoiding situations where minor anomalies lead to major failure cases.

Predictive Maintenance

One of the greatest benefits of AI and ML to SHM is the use of predictive maintenance. While, in the reactive maintenance approach, a failure is only corrected once it is detected, in predictive maintenance, failure is predicted and prevented before occurring. RNN and LSTM networks used in the machine learning algorithms read data that has been recorded in the past and develop conditions for future scenarios as well as likely failures. The result of increased reliability is that it also has minimized the periods of time needed in maintenance hence increasing readiness levels making it efficient and cost-effective.

Adaptive Monitoring

In the use of machine learning algorithms, the sensitivity of the anomaly in a certain system can be regulated depending on the prevailing weather conditions or the operational loads. Adaptive monitoring makes it possible for the SHM system to continue performing optimally notwithstanding the changing situations and makes the monitoring process more reliable and more robust. To reveal trends in sensor data, especially in vibration signs that could indicate structural damage, we can train AI models that use Convolutional Neural Networks (CNNs). A new study applied CNNs to manage the integrity of offshore wind turbines, diagnosing anomalies in vibration data with a 95% success rate. Early detection enables the ability to take corrective measures before devastating failures can happen.

1. 5 Environmental Impact

Positive Environmental Impacts:

1. **Reduced Greenhouse Gas Emissions:** Offshore wind energy is thus an exemplary renewable energy source that replaces conventional electricity generated from fossil fuels thus reducing the emission of greenhouse gases. With the help of advanced AI & ML-based SHM systems for offshore wind turbines, the probability of high reliability and less wastage is achieved which in turn reduces the impact on the environment for energy production.

2. **Conservation of Natural Resources:** Implementations of AI/ML make it possible for machines to predict when they need repair and thus the period

between checks and maintenance is longer. This optimization also results in the conservation of resources such as materials and energies used in maintenance and consequently conserves natural resources.

3. **Protection of Marine Ecosystems:** Once established, its direct effects on the marine environment can be said to be almost negligible as compared to the effects of the conventional sources of energy for example; fossil energy sources. Application of AI/ML to SHM systems in wind turbines enables conservation of structures hence diminishing chances of investigations or failures that might be fatal to marine creatures.

4. **Enhanced Energy Efficiency:** AI/ML algorithms enhance the efficiency of turbines and decide the right time and process to maintain and repair these turbines, hence reducing energy losses due to non-operation or inefficient running. Such efficiency helps conserve energy in the overall energy system and cuts down the need for more unsavory forms of energy production.

Potential Negative Environmental Impacts:

1. **Construction and Installation Phase:** Potential environmental issues associated with offshore wind farm construction and installation include; Offshore wind farms pose impacts on certain aspects of the immediate environment in the form of noise pollution, habitat alteration and slightly affecting the marine biology in the process of installation of the structures.
2. **End-of-Life Considerations:** Despite the long life that offshore wind turbines can have, their operation entails the removal of the turbines at the end of their life and this process should not harm the environment. Disposal or recycling of the turbine components should also be done in a way that would allow reduction or eradication of pollution of the environment and disruption of habitats.
3. **Visual and Aesthetic Impact:** Offshore wind farms can result in visual effects that change the 'look' of the coast and reconcile these effects with the perception that they are displeasing to some. Such issues can be addressed through the use of mitigation measures such as proper siting of facilities in vulnerable areas as well as engaging stakeholders.

Mitigation Strategies:

The following tactics may be taken into consideration in order to minimize potential harmful environmental effects and maximize favorable outcomes:

- **EIAs, or environmental impact assessments:** Before starting a project, do comprehensive EIAs to find and reduce any possible environmental hazards and effects.
- **Technological Innovations:** Further studies in AI/ML of improved environmental monitoring and environmental impact reduction can therefore enhance the general environmental performance of offshore wind energy systems.

- **Stakeholder Engagement:** Consult stakeholders such as the local communities, environmental pressure groups, and regulatory agencies in the decision-making process on the projects to meet their concerns.
- **Adaptive Management:** To prepare oil and gas firms to adapt to environmental changes within the lifecycle of offshore wind projects, M2: Use adaptive management practices to track and manage environmental changes across the stages of offshore wind projects.

2. Literature Review

Nowadays, CM of rotating machines constitutes the most prosperous application of SHM Technology in terms of profitability, reliability and level of development [20]. The failure identification process is based on pattern recognition related to displacement, velocity or acceleration time histories, commonly located at one point on the housing or shafts of the machinery during standard-operating conditions and start-up or shut-down transients [19]. Commercial software integrated with measurement hardware is marketed to help the user systematically apply this technology to the operating equipment [22]. A good example of this is the US Navy's Integrated Condition Assessment System [23]. The aerospace sector started studying the use of vibration-based Damage Identification during the late 70 s and early 80 s in conjunction with the development of the space shuttle programs [22]. That effort carried out on other applications that are being investigated for the National Aeronautics and Space Administration's Space Station [21]. Some of the most widely used technologies in this field are: fastener monitoring [24], blade tip clearance [25], and fatigue monitoring [29]. The Civil Engineering community has researched on vibration-based Damage Identification of bridges and buildings since the 80 s [26,27]. This research is currently being applied to offshore structures due to the similarities across industries. During the 70 s and 80 s, the Oil and Gas industry carried out extensive research to develop vibration-based Damage Identification Techniques for offshore platforms [28]. Related to this technique, one of the research objectives was the detection of near-failing drilling equipment and the prevention of expensive oil pumps from becoming inoperable [30]. Unfortunately, most efforts were not successful, as this problem is fundamentally different to that of the rotating machines due to the impossibility of predicting where damage will occur and the structure's inaccessibility for data acquisition purposes [20].

Traditional SHM systems entail the use of physical sensors that are followed by analysis of data that is done manually. These methods are quite inadequate especially due to their inefficiency in handling large datasets that may be required from time to time. The conventional approach comprises visual testing, ultrasonic testing, and vibration testing, despite their effectiveness, they are slow, intensive, and require many resources. These methods also need so much human input and they are also so much susceptible to some errors and this is why there is a need to go for higher methods.

Predictive Maintenance with AI/ML:

Predictive maintenance permits the early recognition of structural defects and failures, giving operators the ability to organize maintenance tasks ahead of a critical failure. As an example, LSTM (Long Short-Term Memory) networks have efficiently predicted the Remaining Useful Life (RUL) of different components found in wind turbines. Support Vector Machines (SVMs) are used in SHM classification tasks too, as another instance. SVMs have achieved particular success in finding damage in wind turbine blades, showing accuracy levels that far exceed the results obtained from traditional linear regression models. Roy et al. (2020) indicates that SVMs achieved a detection accuracy of 92% regarding anomalies in turbine performance, providing early warnings that lowered maintenance costs by as much as 15%.

3. Methodology

3. 1 Data Collection

The process of Data acquisition is the initial process towards implementing AI and ML in SHM systems. Highly sensitive sensors such as accelerometers, strain gauges, and fiber optic sensors produce data of high resolution that is vital when monitoring. Their placement also needs to be well thought out, so as to obtain key structural data with little or no impact on the surrounding environment of the sensors and reduced maintenance.

3. 2 Data Preprocessing

Several sets of raw data come from the sensors and for most of them, they require data cleaning and preprocessing. This step entails data cleaning or data pre-processing which includes; the de-noising process, normalization, and data with missing values. Preprocessing is very important in order to control the data quality and compliance with the feeding sources for AI and ML. Some of the most popular methods of preparation include; filtering, interpolation as well and statistical normalization. Appropriate preprocessing helps in increasing the possibilities of the models learning from the data to give the appropriate results.

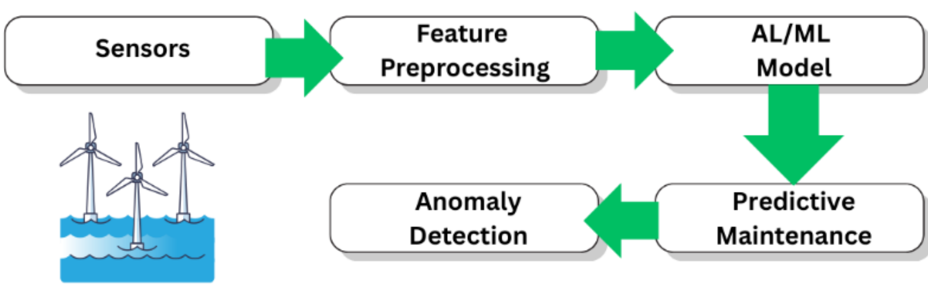


Figure 1: AI/ML Working process

3. 3 Feature Extraction

Feature engineering deals with assessing and selecting which aspect or characteristics of the preprocessed data will be of measurement in the training of ML models. Some examples include; Principal Component Analysis; PCA and Fast Fourier Transform; and FFT. PCA is useful in a way that it can simplify the amount of data and at the same time incorporates vital information to the operations and algorithms of ML models. Discrete Fourier Transform more commonly called FFTs are used to convert time signals to the frequency domain that helps in identifying periodic behavior or faults.

3. 4 Model Training

These extracted feature vectors are then used to train the up till now described ML models. SVMs are good for classification, neural networks go well with patterns, and random forests are good to go against overfitting. The specific selection of an algorithm will, therefore, depend on the kind of data to be analyzed as well as the requirements of the SHM goals to be achieved.

3. 5 Model Validation and Testing

To assess the trained model's performance, different datasets are employed and solely used for validation and testing purposes. It is important not to overfit, techniques such as cross-validation are therefore used to avoid this. This means splitting the data into training and testing sets in a number of times and taking the mean of the outcomes. This has become self-explanatory that the models should generalize well, to return good results when tested on unknown data.

3. 6 Deployment

The models so developed are then integrated into the SHM system for actual monitoring and prediction of the structures. The system is designed to gather data, analyze it, and make future forecasts of structural failures based on the models. It is the process of ensuring that the models are a part of the SHM system and hardware to collect and consolidate data together with creating warning procedures for anomalous behavior. This makes the system always be on the lookout for other conditions and periodically trains the models in order to improve the performance of the system.

3. 7 Structural Dynamics

- **Equations of Motion**: The equations that define the structural response of wind turbines depending on different kinds of loads (e.g., wind and waves) are basic. The assessment of the structural responses of wind turbine components due to the environmental loads becomes essential by considering the dynamic characteristics of said components. It is possible to use AI/ML approaches to assess data gathered from sensors that measure these responses, making it possible to make real-time evaluations of structures' health status and possible failure.

Fatigue Analysis

- **Miner's Rule:** This rule is used in the assessment of the total fatigue damage accumulated on components subjected to repeated loading cycles. It is important because of cyclic stressing resulting from wind and wave loading on the wind turbines. By analyzing big data such as operational conditions and structures, it is possible to predict the fatigue life and minimize the number of failures for their maintenance or repair.

$$\sum_{i=1}^{n} \frac{ti}{Ti}$$

where t_i is the time spent at stress level i, and T_i is the endurance limit at stress level i.

Vibration Theory

- **Natural Frequencies:** It highlights the natural frequencies of wind turbine blades and structures which are the fundamental aspects in determining the dynamic characteristic of wind turbines or vulnerability to resonance. Artificial intelligence and machine learning algorithms can identify shifts in natural frequencies using captured vibrations from sensors and thus alarming structural damage or deterioration. This is a proactive approach that strengthens SHM capacities by allowing for early identification of the developing issues that may soon become critical.

$F_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$; where f_n is the natural frequency, K is the stiffness, and M is the mass.

Aerodynamics and Fluid Dynamics

- **Aerodynamic Loads:** It is also important to know how wind acts on the blades of the turbine in order to evaluate the structural condition they are in. AI/ML-based algorithms can use real-time wind speed data and other relevant turbine parameters in order to forecast the forces of aerodynamics. This information enhances the operations of turbines, efficiency of energy, and reduction of fatigue on the structures.

  $F_{aero} = \frac{1}{2}\rho v^2 CA$

  where ρ is air density, v is wind speed, C is the lift coefficient, and A is the area.

How physics theory can be combined with AI and/or ML?

- **Enhanced Predictive Maintenance:** By integrating physics-based models including structural dynamics and aerodynamics, the SHM systems use AI/ML models for accurate prognosis of health and performance of turbines. Through integration, it becomes possible to employ predictive maintenance strategies that help in operating at lower costs and little or no time of stoppage.

- **Data-Driven Decision Making**: Physics theories are the basic concepts on which the working of wind turbines is explained and AI/ML uses large volumes of data and learns from past experiences. It therefore allows the operators to be in a position to make good choices on when to service any part of the structure or when to implement new strategies of operation.

3.8 Performance Evaluation

The performance of the presented AI and ML-integrated SHM system was assessed in terms of accuracy, effectiveness, and dependability. There is evidence of enhanced anomaly detection and failure prediction in the developed system than the conventional SHM techniques. Neural network analysis made it possible to identify and monitor changes in structural behavior that may be missed when using other methods. A significance of the system was the real-time analysis of data, which made it quite easier to discover incongruities that may lead to problems, and avert them.

Advantage from Integration of AL & ML

Table 1: Traditional vs AI/ML based SHM

Feature	Traditional SHM	AL/ML Based SHM
Data Handling	Manual, Limited	Automated, Measurable
Real Time Monitoring	No	Yes
Cost Efficiency	Low	High
Accuracy	Very low	Very High
Predictive Capability	Low	Very High

4. Challenges

4.1 Data Quality and Quantity

This, in essence, means that training data play a critical role in determining the accuracy of AI and ML models. If the collected data is not complete or noisy this will lead to the development of a wrong model and therefore wrong predictions will be made. To guarantee the quality of collected data, calibration of sensors is needed and data pre-processing could be a part of the data collection process.

4.2 Model Complexity

That's why simple models are the best to work with because it takes a lot of computational power and knowledge to create and maintain complex models in AI. There are certain kinds of nets, for example, neural nets that need specific hardware, like GPUs, for training. At the same time, the elaborated structure of these models complicates their analysis, which creates issues with their validation and debugging.

How to make models simplified without being unrealistic is a major research question, therefore.

4.3 Integration with Existing Systems

The integration of AI and ML with conventional systems of SHM could be problematic in many ways because not all systems are compatible and one needs specific knowledge for this kind of integration. Standard bearers of such systems may lack some of the sophisticated data processing features, hence requiring an overhaul or updating. Analyzing and integrating these domains need a lot of planning and good cooperation between the domain experts as well as the AI/ML experts.

4. 4 Cybersecurity Risks

Currently, the AI and ML systems have certain weaknesses in terms of security and the effectiveness of SHM may significantly be affected in the event of a cyber threat. Security of data and the models they have built also become another critical question – how to prevent data from being intercepted in its transfer and storage, as well as how to prevent AI/ML models from changing? While implementing approaches for strengthening the security of SHM systems, it is important to implement strict security measures and periodically upgrade the security settings.

5. Future Work

5. 1 Advanced ML Algorithms

Thus, future research can be carried out to create better algorithms of ML where the data in question will be more complex and the discrimination can help to predict more accurate results. It is believed that deep learning, reinforcement learning, as well as transfer learning, are the ways to improve SHM systems. Ways of melding site and/or app models based on the strengths of different algorithms can equally lead to better results.

5. 2 Integration with IoT

The inclusion of AI and ML in the system can improve the functions of SHM systems through the collection of IoT data and analysis of collected data in real-time. From the present IoT devices, real-time surveillance and uninterrupted data transfer can be made to enable the AI/ML models. In a similar way, using the multiple-edge computational units can enhance the effectiveness and interactive nature of the SHM systems.

5. 3 Edge Computing

Its implementation in SHM systems eliminates the problems of high latency and the need for large bandwidth since the data processing occurs at the edge. This approach keeps the computations running in real-time and minimizes dependence on centralized computing facilities. The realization of edge computing hence requires stable hardware and software solutions capable of functioning offshore.

5. 4 Enhanced Cybersecurity Measures

Nonetheless, proper cybersecurity should be implemented to ensure safe operations of such systems as AI and ML-based SHM systems are also vulnerable to cyber-attacks. The security of SHM systems can be improved through the use of measures such as encryption, intrusion detection systems, and secure communication protocols. Security which is a dynamic process needs to be updated frequently due to changes in threat and risk patterns.

5.5 API and Middleware Development: Essential here is the creation of API-layer and middleware-layer solutions that would enable the integration of the new systems with the older ones. These integration tools can actually serve as Middleware between these technologies and help in the transfer of data as well as maintaining synchronization between the various systems.

5.6 Model Simplification: Some of the steps to potentially decrease the model complexity include; Diminishing the size of features for example by performing feature reduction like Principal Component Analysis (PCA), or applying low complicated machine learning algorithms like decision trees or linear regression when needed.

5.7 Data Augmentation: Borrowing synthetic data generation and simulation models can go a long way in mitigating this problem of lack of real data. When a number of operational conditions, weather effects, and structural failures are modeled, it becomes possible to generate a vast amount of data.

5.8 AI-Driven Cybersecurity: AI and ML algorithms themselves can be utilized for the purpose of network traffic analysis and to identify any irregularity/ threat in real-time. Algorithms can also predict future cyber threats and come up with ways of preventing such threats from materializing.

***5.9 Robust Encryption*:** All necessary data are transmitted between turbines, sensors, and other systems based on AI through the use of end-to-end encrypted data links to minimize the risk of cyberattacks. Such measures as AES-256 or TLS can be applied to provide data integrity.

5.10 Explainable AI (XAI): Introducing explicable AI models enables the engineers and operators to comprehend how and why the models tend to perform specified decisions. This makes the users develop confidence in the models hence enhancing their use for real-time monitoring.

***5.11 Hybrid Models*:** The integration of physics-based models with AI/ ML provides the best of both worlds in terms of complexity as well as interpretability. Such models are a little less opaque as they incorporate conventional engineering concepts complemented by AI/ML findings.

Summarized Techniques Used in SHM by AI-ML

Table 2: AL/ML Techniques for SHM

Technique	Application	Benefits
LSTM	Predictive maintenance	Better RUL estimation
SVM	Error Classification	Better detection accuracy
Random Forest	Anomaly Detection	Robustness to noise
CNN	Damage Finding	Feature automation

6. Discussion

Many discourses demonstrate that the application of AI and ML techniques in analyzing and monitoring SHM of offshore wind turbines provides numerous advantages including improved precision, real-time tracking, and comparatively low Annual Maintenance Costs. However, there are issues that still need to be solved like data quality issues, the issue of a complex model, and the issue of cyber security. ML research needs to be continued in the future to improve the existing ML algorithms, incorporate IoT, and emphasize edge computing and the security of ML systems. All the said challenges can however be conquered by the help of AI and ML, making a dramatic difference in the SHM systems and overall advancement of offshore wind energy in relation to sustainable development goals.

Seas and oceans account for approximately two-thirds of the earth's surface, current offshore turbines can only function in water depths of up to 98 ft; extension of this to 164 ft meters is possible but anything beyond this is difficult since turbines have to be anchored to the sea bed. Almost 80% of the globalization maritime area is beyond the scope of the utilization of fixed turbines Floating arrays are deemed to be a viable option as pointed out by the International Energy Agency IEA, if only 1-2% of the area which is considered good for wind power development worldwide would be covered then that is enough to supply more electricity to the world market. Some of the prime locations for the exploitation of offshore wind power include the North Sea in Europe, the East China Sea, the Gulf of Mexico in the USA, and the coastline of India. Given that seventy percent of the Earth's surface is covered in water, the scope for offshore wind energy is large and all the more so as technology improves.

7. Conclusion

The research paper focuses on the opportunities for the use of AI technologies in cooperation with structural fatigue load modeling and optimization to enhance the climatic and operational resistance of large-scale and floating wind turbines. This evolution in the industry relies on condition-based rather than calendar-based or time-based maintenance based on system condition information for decision-making in offshore wind turbine maintenance. The work thus establishes the effectiveness of algorithms such as the K-nearest neighbors (KNN) algorithm in the monitoring of the health of offshore wind turbines, more so in cases involving small loads, as against traditional methods like the linear regression method. In addition, the paper stresses the appropriateness of machine learning techniques to employ predictive functionality for failure recognition and to determine and apply correct maintenance tactics. On this account, the creation of a CNN-t-SNE-based neural network model for the automatic identification of damages in mooring equipment of floating wind turbine platforms reveals AI's ability to revolutionize structural health analysis and maintenance techniques.

Via Artificial Intelligence and machine learning, offshore wind farms shall be capable of fine-tuning operational strategies, as well as engineering system stability and adaptability and increasing energy generation thus increasing its general performance and reliability. However, it also opens the discussion by recognizing the financial reality and the goals of energy productivity when implementing contextual AI and machine learning in achieving the maintenance practices of offshore wind farms. New scholars will first focus on the further developments in AI and machine learning; second, the developments in constraints that have been found in current research; and third embrace, sustainable improvements of offshore wind turbine maintenance practices.

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Life Cycle Assessment of Steel in Bangladesh's Ship Recycling Industry

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Abstract

In Bangladesh the ship recycling industry plays a centric role in supplying scrap metal for domestic steel production specifically rebar (reinforcing bars) which is used in construction. This study is an examination of the lifecycle process of steel within the ship recycling sector in Bangladesh considering its environmental and economic implication. Lifecycle assessment methodology is adopted in the research in which steel production from recycled ship materials surrounding stages from ship transportation to pull apart in Chittagong and successive processing in re-rolling mills and light engineering workshops in Dhaka are studied. The discoveries recommend that producing secondary rebar from ship-derived scrap crucially reduces energy depletion and greenhouse gas emissions compared to primary rebar production. However, some processes particularly re-rolling activities contribute significantly to environmental degradation also focus on areas for development to amplify sustainability within the industry. Some of the issues point out in the study include lack of worker safety, risky disposal of hazardous wastes and need of cleaner technologies and more stringent regulations. It recommends some of the changes such as the use of energy efficient technology, promotion of safety and tighter controls on environmental factors to maximize on sustainability. The results support the role of the industry in the economy of Bangladesh and supply of steel, nationalize the environmental hotspots and pathways for sustainable ship recycling development.

Keywords: Rebar; scrap metal; steel; re-rolling; lifecycle; Bangladesh; industry

1. Introduction

Ship recycling industry in Bangladesh has become an important element of steel supply chain and economy in the country. It is taking a lead in the production to cater to the local demand of the construction materials particularly the rebar. The industry produces and helps to directly employ anywhere between 20,000 and 40,000 people yearly providing it with about US $770 million or so in output, each year. Additionally, over a million more are benefiting indirectly through related industries such as rolling mills, oxygen plants, equipment trading and local services. Since Bangladesh does not have any iron ore, recycling of such end-of-life ships is a great source of raw steel. Consequently, 50-60% of steel used in re-rolling mills are coming from shipbreaking yards and about 60-70% of the country's rebar and steel products are relying on this recycled input. The process begins when obsolete ships after 20-30 years of service are

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brought to coastal yards where they are dismantled using manual labor and basic tools. Afterwards, the extracted steel is transported to re-rolling mills in cities like Dhaka for cleaning, melting and reformation into new construction materials. This industry drives economic growth and supports the livelihoods of thousands especially in poverty-prone coastal regions. It also assists to save energy and less emission of greenhouse gases as opposed to primary manufacture of steel. The sector is however affected by great challenges such as environmental pollution caused by hazardous wastes, poor safety standards of the workers and necessity of more stringent laws and environmentally friendly technologies to guarantee long term sustainability. The environmental concern of life cycle of steel from ship recycling in Bangladesh need to be examined in this study with a view of establishing major processes causing ecological deterioration and recommending improvements that could be made. [1][2]

Figure.1: A glimpse of ship-breaking industry in Bangladesh [3]

2. Literature Review

2.1 Ship breaking and Steel Extraction

When ships reach near the end of their service life (20-30 years) are sold to ship breaking yards in Bangladesh. These decommissioned ships are sailed at high tide and beached over flat muddy lands. All gear and equipment are removed from the ships. Using gas torches, cranes and manual labors, the ships are dismantled. Materials such as wood, plastics, insulation and machinery are separated from the ship's structure. Steel elements like plates, beams and pipes are extracted for reuse. Lastly non-usable parts are discarded or sometimes sold as scrap and usable steel is sent to re-rolling mills. [4]

2.2 Steps of Processing and Refining of Recycled Steel

2.2.1 Sorting and Transportation

Recycled steel is kept in reserve into plates, rods, beams and pipes and transferred to re-rolling mills. [5]

2.2.2 Cleaning and Treatment

Rust, paint, and oil residue are pulled out from the surface. [5]

2.2.3 Melting and Re-rolling

Steel is melted in electric arc furnaces or induction furnaces and re-formed into building materials. [5]

2.2.4 Cooling and Storage

End products (rebar, sheets, structural steel) are cooled and warehoused for delivery. [5]

2.3 Case studies on Ship breaking and Steel Recycling in Bangladesh

2.3.1 Case Study 1: Chittagong Ship breaking – Environmental Degradation & Resilience

Chittagong is the largest ship breaking hub of Bangladesh and the biggest in the entire country. It has been a ship breaking site of retired ships for long haul but ecological risks are still a real issue. In 2023, an oil tanker dismantled led to dangerous oil spill contamination that contaminated beaches surrounding that locality excessively, which caused the death of marine life and widespread water pollution. The Bangladesh Department of Environment penalized the culpable shipbreaking yard but clean-up was limited due to the absence of advanced treatment facilities. The case highlighted the ongoing danger of hazardous waste dumping in the industry. [6] Transforming the ship-breaking industry into a green and sustainable sector has been a major challenge. Entrepreneurs in the ship-breaking industry have invested heavily in developing green-certified yards but they are now experiencing financial difficulties. To remain competitive and meet international standards, Bangladesh is working to convert all ship recycling yards into green yards by 2025 in accordance with the Hong Kong International Convention. [7]

Figure.2: Chittagong Ship-breaking industry [8]

2.3.2 Case Study 2: Steel Recycling in Bangladesh's Re-Rolling Mills

About 150 of re-rolling mills crowded in Dhaka and Chittagong, Bangladesh's steel recycling industry is crucial to meet the country's construction demand. But, these are resulting into high rates of carbon emission. [1] Recently, one of the highest-rated re-rolling mills namely the Meghna Re-Rolling & Steel Mills Limited (MRSL) has moved from coal-burning furnaces to Electric Arc Furnaces. It has cut down its CO_2 emission by 30%. This facility is estimated to produce 1.5 million tonnes of steel annually using 100% recycled scrap. [9] But, there are challenges comprising of frequent power outages and the use of imported electricity which is still based on fossil fuels. This case accentuates the need for huge investment in renewable and reusable resources in order to amplify sustainability in Bangladesh's steel recycling sector.

Figure.3: Steel Re-rolling Industry of Bangladesh [10]

3. Research Gap

Despite of the economic and environmental benefits of steel recycling out of ships, there exist big loopholes in different respects. Such as-

a. Safety and health standards of workers with high level of accidents and intoxication.
b. Proper handling of hazardous waste and pollutant during ship breaking and re-rolling activities.
c. Use of new and modern technology which is energy efficient and environment friendly both in shipbreaking and steel processing.
d. All-out implementation of regulative and green standards in the industry.

4. Research Question

How can the lifecycle of steel in the ship recycling industry in Bangladesh be optimized to minimize environmental and health impacts while maintaining economic benefits and sustainability?

5. Methodology

This paper is an individual desk study. The research work provides a crystal clear idea about the life cycle of steel in the Bangladesh ship recycling industry. The paper also portrays the challenges that can put forward a difference in the overall arena. This is a theoretical paper and a sound combination of existing thoughts and new ideas. Research works conducted by experts helped the authors to look into the overall scenery. The life cycle of steel in the Bangladesh ship recycling industry is cradle-to-grave, and the procedure starts in the purchase of scrapped ships, which are primarily imported from foreign waters. Beached ships are manually dismantled by a labor-intensive method where steel components are cut, segregated and shipped to re-rolling mills. The recovered steel is smelted, cleaned and reshaped into rods, beams and sheets that are traded in the domestic manufacturing and construction industry. While the practice maintains the country's steel demand, it poses environmentally deteriorating consequences due to improper disposal of waste as well as contamination by harmful chemicals like asbestos, oil residues, and heavy metals. Despite efforts to improve sustainability, challenges remain in implementing eco-friendly shipbreaking practices and ensuring worker safety.

6. Analysis

6.1 Safety Problems

Lack of labour safety is one of the major concerns of present ship recycling industry in Bangladesh. Labours are generally unskilled and sometimes they do not have even any basic training for this risky job like ship recycling. Plates are carried away by group of labours without knowing the weight of the plate. Sometimes, heavy plate weight as well as very sloppy and muddy ground makes the plate carrying job very risky. While cutting at height in the main deck or upper deck, lack of special safety measure like erection of scaffolding, wearing safety belts etc. has been noticed. As a result, falling from the height is a very common accident in Bangladesh. It is also observed that worker is assigned to work below others particularly where there is a danger of tools, equipment and cut sections or any other loose work item falling from the upper work location. As a result, accident due to falling of heavy object is very common. While cutting plate, no care is taken about removing coating and usually plates are cut with coating. While working in confined space, due to lack of enough safety measure like measurement device, safety suite etc. serious accident occurs. Many minor accidents like cutting due to sharp edge, bruising etc. have not been reported. Lack of appropriate emergency response, rescue and first aid is also common in ship breaking industry in Bangladesh. Winch/ pully / crane etc are not tested periodically and so there is no way of ascertaining their capacity. This is risking occupational safety of the involved workers. [11]

6.2 Health Problems

Although ship breaking is one of the most hazardous activities of any maritime industry, but most of the workers in ship breaking yards in Bangladesh have no basic knowledge about the impact of ship scrapping on health. As a result, particular hazard exposure especially generated by asbestos, PCBs, heavy metals and chemicals causes serious health problems of the worker dealing with ship breaking industry. Asbestos is very risky substance. The workers dismantle asbestos materials without knowing the consequences of inhaling such materials. They went to their living space without taking shower thus risking others persons who live with him. Exposure of poisonous paints like Tributylin (TBT) causes serious health problem in ship breaking workers in Bangladesh. Most of the cutter has to work in very intense light of cutting torches. Though, they use goggles, but these PPEs are sometimes not up to mark for heavy duty works like ship breaking activities. Thus, workers complain of facing problems like eye redness, tearing, burning sensation, blurring of vision and conjunctivitis etc after long working hour. Some workers complain of impairment of hearing after working in the harsh environment of ship breaking industry where excessive noise is present. [11]

6.3 Environmental Problems

Poor practice of present ship breaking industry generates huge environmental pollution in the coastal area of Bangladesh. For example, cutting operation is generally advanced from forward to aft end slice by slice. While slicing the ship, little care is taken about the contained inside the double bottom or pipe. This action paves the way to release bilge, ballast water into the sea. Sometimes, the slice is pulled near to the yard for further cutting. Limited environment protection is a major concern of ship-recycling industry in Bangladesh. Sound management of asbestos, PCBs, ODS, heavy metals etc. is virtually non-existent. Due to lack of appropriate procedure and trained worker, asbestos containing material causes atmospheric pollution by forming carcinogenic powder. Practice of stripping the electrical cables off their insulation by burning is another source of environmental pollution as it produces highly toxic gases such as dioxins, polychromatic hydrocarbons, etc. Disassembling of air conditioning and refrigeration systems can also result in the release of Chloro-Floro-Carbon (CFC) series chemicals that are hazardous to the ozone layer. Some shipboard fire extinguishing systems is also the source of such gases. Engine, pumps, compressors, motors etc which contain oils, oily substance should be stored on impermeable surface with shaded storage area. But, in case of ship recycling industry in Bangladesh, equipment is stored in open space and thus soil is contaminated due to mixing of oil with soil. One of major advantages of presently practicing beaching method by Bangladeshi yards is that it is a natural process where instead of installing expensive and heavy infrastructure for pulling and docking the ship, huge labour forces are used. Beaching method is preferred by local ship breakers because of presence of huge pools of cheap labour. At the same time, they must focus on improving environment friendly approach to be competitive & sustainable in world market in coming years too. [11]

7. Results and Discussions

7.1 Environmental Benefits

Re-rolling operations causes low CO_2 emission compared to producing virgin steel. Among all the categories, the main process of steel manufacturing particularly the pig iron production stage has more environmental impacts. The steelmaking phase of the main production causes approximately 85.3% of human health damage of which pig iron production alone is responsible for 75% of this impact. [6]

7.2 Regional Comparison of Steel Life Cycle in Ship Recycling Industry: Bangladesh vs. India vs. Pakistan

Ship recycling in South Asia constitutes a significant phase of the steel life cycle as ships are dismantled and their steel is reutilized in construction, manufacturing, and infrastructure. Bangladesh, India and Pakistan are the pioneers of this business but regulatory policies, efficiency, and environmental regulations affect the processing and reusing of steel.

7.2.1 Steel Life Cycle in Bangladesh

Bangladesh is the leading ship recycler country recording approximately 37.2% of total global ship recycling tonnage during the 12 months up to January 2023. Bangladesh's ship recycling industry is primarily located in the Sitakunda area (Bhatiary to Kumira), along the coastal strip north of Chittagong city on the Bay of Bengal. The industry generates approximately US $770 million annually and provides a crucial steel source representing 50-60% of the feed for domestic steel-making. This particular sector provides direct employment to more than 40,000 workers, with indirect support to over a million jobs in allied industries. Four units in Bangladesh have obtained voluntary Statements of Compliance with the Hong Kong Convention, giving confidence of eco-friendly recycling operations. [12]

However, the industry experienced a substantial decrease in activity processing only 144 ships and totalling 968,000 gross tons (GT). This marks the lowest level of scrap ship imports since 2005, a sharp decline from the 2.73 million GT processed in 2021. [13]

7.2.2 Steel Life Cycle in India

India's ship recycling industry is primarily located in Alang, Gujarat which is housing approximately 135 shipbreaking yards with a combined capacity of about 4.5 million light displacement tonnage (LDT) annually. The government has been actively upgrading the quality of these yards, and 90% of Alang yards are now compliant with Hong Kong Convention standards. However, of the recovered steel, only 25% is melting scrap, used for the production of crude steel, and the balance 75% is remanufactured into value-added products. In order to ensure maximum contribution from ship recycling to India's scrap requirements, targeted interventions in the shape of investment in advanced processing technologies are essential.[14] In the fiscal year 2023-2024 (FY24), the Alang-Sosiya region beached 125 ships for recycling and translated it into a light displacement tonnage (LDT) of 944,069.25. This marked the lowest LDT in the last two decades reflects a downturn in ship recycling activities in India. [15]

7.2.3 Steel Life Cycle in Pakistan

Pakistan's ship recycling industry is concentrated in Gadani, with 40 yards processing a capacity of 3.7 million GT. The industry is a valuable source of raw material and employment. Gadani yards have been upgrading their environmental and safety standards, as part of a regional move to increase industry standards. [16] The industry employs approximately 20,000 to 25,000 individuals directly with an additional 200,000 to 250,000 jobs indirectly linked to the sector. Annually, it contributes around Rs14-15 billion in taxes and supplies millions of tons of steel to various industries across Pakistan accounting for 20% of the nation's total steel supply. [17]

Aspect	**Bangladesh**	**India**	**Pakistan**
Annual Ship Recycling Share	40-50% (Largest globally)	30-35%	15-20%
Major Shipbreaking Hub	Chittagong	Alang	Gadani
Worker Safety	Poor (High injury rates, lack of PPE)	Moderate (Better than BD)	Poor (Similar to BD)
Environmental Compliance	Weak (Toxic waste mismanagement)	Better (Some yards HKC-certified)	Weak (Pollution, oil spills)
CO_2 Emissions from Steel Recycling	Lower (More manual cutting, less energy-intensive)	Higher (More automation)	Similar to BD
Adoption of Green Ship Recycling	Low (Few eco-friendly yards)	Highest (Many certified yards)	Low (Few regulations)
Government Regulations	Weak enforcement	Stronger enforcement	Moderate enforcement

Table.1: Comparative Analysis of Ship Recycling Practices in Bangladesh, India and Pakistan. [18][19][20]

Environmental and Economic Impact			
Factor	**Bangladesh**	**India**	**Pakistan**
Environmental Impact	High pollution, weak enforcement	Moderate pollution, better regulation	High pollution, weakest enforcement
Worker Safety	Poor, but improving	Better due to regulations	Worst, frequent accidents
Steel Efficiency	Moderate, mostly re-rolling	Higher efficiency with EAF and re-rolling	Low efficiency, mostly re-rolling
Economic Role	50% of construction steel comes from ship recycling	Stronger industry integration with steelmaking	Weaker industry linkages

Table.2: Comparative Analysis of Environmental and Economic Impacts in the Ship Recycling Industries of Bangladesh, India, and Pakistan [21][22][23]

7.3 Future improvement and Sustainable solution

7.3.1 Short-Term Solutions

a. Improvement in Cutting Practices

In order to improve cutting practices alternative cutting technologies that have lower emissions must be adapted because it can efficiently reduce health risks and environmental harm.

b. Use of Personal Protective Equipment

Awareness among the workers to use safety equipment should be raised. Workers should use appropriate protective equipment when performing cutting operations can reduce human health risks associated with air pollutants.

c. Energy Efficiency in Rerolling Mills

Energy-efficient technologies and practices must be utilized in re-rolling mills. Consequently, it can also reduce the environmental damage caused by secondary steel production.

d. Stricter Waste Management Laws

Safe disposal of oil sludge, paint residues, and asbestos must be practiced

e. Reforms in Safety of Workers

There are some steps which can be followed such as enforce of mandatory PPE, training, and medical cover.

f. Green Ship breaking Incentives

Grant tax relief to yards adopting green recycling techniques is a mandatory attempt should be taken. [2]

7.4 Long-Term Sustainable Solutions

a. Invest in Dry-Dock Ship breaking

By using advanced technologies oil spills and sea pollution can be reduced.

b. Optimize Renewable Energy Use in Steel Recycling

In near future re-rolling mills can be converted to solar/wind energy. [2]

c. Enhanced Global Cooperation

Farther steps should be taken to collaborate with IMO (International Maritime Organization) and EU regulations for ethically recycling. [2]

d. Public-Private Partnerships (PPP)

Bangladesh should take initiate to Invest in green steel technology. [2]

8. Conclusions and Recommendations

The most precious source of steel in Bangladesh is ship-recycled steel. But, shipbreaking in Bangladesh causes considerable damage to environment and has safety risk to shipmen. Bangladesh has greater deal of opportunities compared to neighbouring countries. But, it lags behind in regulation enforcement and sustainability. By investing in green technologies and enhanced worker protections with regulation, Bangladesh can continue to dominate ship recycling industry while reducing its environmental degradation. As ship recycling sector of Bangladesh offers significant environmental benefits by providing scrap steel for secondary processing which lead to substantial energy savings and reduction in greenhouse gas emissions over primary steel production. Nevertheless, certain operations namely re-rolling operations and ship cutting activities are the key reasons for environmental damage. Lastly maintaining improvement in these sectors through technical improvements and enhanced occupational safety practices is of critical importance for enhancing the sustainability of this sector.

In order to increase sustainability, Bangladesh ought to:

- **a.** Develop and implement a centralized hazardous waste treatment, storage and disposal facility near shipbreaking yards to properly handle toxic waste and prevent soil and water pollution as planned under the SENSREC project.
- **b.** Institutionalize and expand of the occupation health and safety training of the workers especially about the safety measures in recognizing hazards, the techniques of dismantling objects and using PPE as well as being prepared in case of an emergency that has the international support of organizations such as IMO and ILO.
- **c.** Facilitate public-private partnerships to finance and implement green infrastructure upgrades including dry-dock shipbreaking facilities, advanced wastewater treatment and air pollution control systems to minimize environmental degradations.
- **d.** Promote activity to raise awareness among both workers and local communities on the health hazards of shipbreaking and steel recycling and the behavioral changes necessary to limit the exposure to hazardous substance.
- **e.** Encourage innovation and research into circular economy designs including the use of shipping steel parts and plates by simply reusing them rather than melting them down to further cut down the energy required and reduce the lifecycle of materials.

Consecutive improvement in these sectors will allow Bangladesh to remain the leader in ship recycling with a minimal impact on the environment and enhanced sustainability of the industry.

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Notes for the Contributors

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