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Evaluating Exhaust Gas Economizers for Emission Reduction in Diesel-*Powered* Marine Vessels on Lagos Lagoon

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ABSTRACT

The maritime transport sector is a cornerstone of national and global logistics, facilitating the movement of goods and passengers across inland waterways. In Nigeria, the Lagos Lagoon hosts thousands of diesel-powered marine vessels including passenger ferries, cargo barges, and fishing boats, which emit substantial quantities of carbon dioxide (CO_2), contributing to climate change and local air pollution. Waste heat recovery (WHR) via exhaust gas economizers (EGE) presents a cost-effective approach to improving energy efficiency and reducing emissions in these vessels. This study assesses the potential of EGEs as a waste heat recovery solution for diesel-powered marine vessels operating in Lagos Lagoon. Using standard emission factors and thermodynamic calculations, the fuel consumption, CO_2 emissions, available exhaust heat, recoverable heat, fuel savings, and emission reductions are quantified for three representative vessel categories: Passenger Ferry (A), Cargo Barge (B), and Fishing Boat (C). Results show that with an economizer effectiveness of 70%, recoverable heat amounts to 3,586.8, 1,694.8, and 789.1 MJ/day respectively. Equivalent fuel savings are 93.33, 44.10, and 20.53 kg/day, with corresponding CO_2 reductions of 299.23, 141.38, and 65.83 kg/day. These findings demonstrate that EGE-based WHR systems can achieve meaningful emission reductions and operational cost savings in inland waterway vessels. Recommendations for practical adoption are provided, including simplified system designs, stakeholder collaboration, and supportive policy frameworks.

Keywords: Exhaust Gas Economizer, Waste Heat Recovery, CO_2 Emissions, Lagos Lagoon, Diesel Marine Engines, Fuel Efficiency, Inland Waterway Vessels.

1. INTRODUCTION

1.1 Background of Study

The maritime transport sector is a cornerstone of national and global logistics, facilitating the movement of goods and passengers. In Nigeria, the Lagos Lagoon serves as a strategic inland waterway, hosting thousands of marine vessels including passenger ferries, dredgers, fishing boats, and cargo barges. Most of these vessels rely on diesel engines for propulsion due to their robustness and high energy density. However, diesel engines emit substantial amounts of carbon dioxide (CO_2), a major greenhouse gas contributing to climate change (Corbett & Winebrake, 2008; Eyring *et al.,* 2005).

Globally, the shipping industry contributes about 2.5–3% of anthropogenic CO_2 emissions (IMO, 2020). In developing nations like Nigeria, where emission regulations are less stringent and engine maintenance is often inadequate, the environmental impact of diesel-powered marine traffic is significant (Adewuyi & Badiru, 2021). Within the Lagos Lagoon, densely populated coastal communities are directly exposed to these emissions, raising concerns about both environmental degradation and public health (Akinfolarin et al., 2021; Olukanni & Adeoye, 2019).

While various emission reduction strategies exist — such as fuel switching, alternative energy sources, and hybrid systems — waste heat recovery (WHR) stands out as a cost-effective and technically feasible solution for improving energy efficiency and reducing emissions in marine applications (Baldi et al., 2015). Diesel engines typically lose over 30% of input fuel energy as heat through exhaust gases (Zhang et al., 2013). This thermal energy, if recovered using technologies such as Exhaust Gas Economizers (EGE), can be reused onboard for heating or converted into mechanical or electrical energy, thereby reducing fuel consumption and associated emissions (Tzeremes et al., 2017).

EGEs are simple heat exchangers that transfer heat from exhaust gases to water or working fluids. Their integration into marine vessels has proven effective in reducing Specific Fuel Consumption (SFC) and improving overall engine efficiency by up to 10% (Ni et al., 2016). Although such technologies are widely used in ocean-going vessels, their application in small-scale inland marine crafts — like those operating in Lagos Lagoon — remains limited.

This study explores the potential of using waste heat recovery via an exhaust gas economizer to reduce CO_2 emissions and improve fuel efficiency in diesel-powered vessels in Lagos Lagoon. The results are expected to support local and national efforts towards cleaner maritime operations and contribute to Nigeria's commitment to the International Maritime Organization's GHG reduction strategy.

1.2 Statement of the Problem

Marine vessels operating in Lagos Lagoon predominantly use diesel engines that emit significant amounts of carbon dioxide due to low thermal efficiency and lack of energy recovery systems. Despite the potential of waste heat recovery technologies to reduce emissions and improve fuel economy, they are rarely considered or implemented in small to medium-sized inland watercraft. Furthermore, there is limited research assessing the technical and environmental benefits of such systems in the Nigerian inland waterway context. The absence of this information hinders progress towards sustainable marine transport practices in the region.

1.3 Aim of the Study

The aim of this study is to assess the potential of exhaust gas economizers as a waste heat recovery solution for reducing carbon emissions and improving fuel efficiency in diesel-powered marine vessels operating in Lagos Lagoon traffic.

1.4 Objectives of the Study

The specific objectives of the study are to:

1. Identify the characteristics and operational profiles of diesel-powered vessels in Lagos Lagoon.
2. Estimate the fuel consumption and carbon dioxide emissions of these vessels using standard emission factors.
3. Quantify the waste heat available in the exhaust gas stream based on engine energy balance.
4. Calculate the amount of thermal energy recoverable using an exhaust gas economizer.
5. Evaluate the potential fuel savings and CO_2 emission reductions resulting from heat recovery.
6. Recommend strategies for adopting WHR systems in local marine transport operations.

1.5 Scope of the Study

This study focuses on diesel-powered vessels operating within Lagos Lagoon, with an emphasis on estimating their carbon dioxide emissions and evaluating the potential of waste heat recovery using exhaust gas economizers. The research is limited to theoretical modeling and manual calculations based on available data (e.g., engine ratings, operating time, fuel properties, emission factors). No actual installation or testing of equipment will be conducted. Other pollutants such as NO_x and PM are outside the scope of this work.

1.6 Significance of the Study

This research offers valuable insights into sustainable practices for inland marine transport in Nigeria. It highlights how waste heat recovery — an often overlooked solution in small vessel operations — can enhance fuel efficiency and reduce greenhouse gas emissions. The study will:

- **Provide a cost-effective technical solution**: The integration of an exhaust gas economizer (EGE) as a waste heat recovery system offers a practical way to reduce diesel fuel consumption and carbon emissions. This method requires minimal modification to existing engines, making it feasible for the small to medium-sized vessels commonly operating in Lagos Lagoon.

- **Fill a critical knowledge gap**: While WHR technologies are widely studied in large ocean-going vessels, their applicability and benefits in inland waterways and smaller crafts in developing countries like Nigeria remain underexplored. This study provides data-driven insights into how such systems can improve energy efficiency and reduce emissions in local maritime operations.

- **Support environmental and regulatory goals**: By estimating the potential reduction in CO_2 emissions through WHR adoption, the study aligns with Nigeria's commitments to the International Maritime Organization's greenhouse gas reduction targets. Improved fuel efficiency directly contributes to these climate action goals.

- **Enhance engineering education and local capacity**: The project demonstrates how manual calculations and theoretical modeling can be effectively used to assess complex energy systems without relying on expensive software. This approach equips students, engineers, and policymakers with accessible tools for sustainable marine technology assessments.

- **Encourage sustainable development and innovation**: The findings promote awareness and adoption of cleaner technologies in the Nigerian marine sector, supporting broader sustainable development objectives and fostering innovation in maritime engineering.

2. LITERATURE REVIEW

2.1 Extent of Past Work

The literature review is organized based on the specific objectives of the study, covering existing knowledge on diesel-powered vessels in inland waterways, fuel consumption and emission estimation, waste heat recovery technologies in marine applications, and the assessment of fuel savings and emission reductions through WHR.

2.1.1 Characteristics and Operational Profiles of Diesel-Powered Vessels

Several studies have examined the types, operational profiles, and energy consumption patterns of diesel-powered vessels, particularly in inland and coastal waters. Inland waterway transport plays a vital role in urban mobility and freight movement, especially in coastal cities such as Lagos, Nigeria, where road congestion has made water-based transportation increasingly attractive. As such, understanding the characteristics of diesel-powered vessels that dominate these waterways is essential for any assessment related to emissions and energy efficiency.

Olukanni and Adeoye (2019) analyzed water transportation in Lagos, noting a predominance of small to medium-sized diesel-powered crafts with diverse operating hours and load conditions. These vessels include ferries, fishing boats, cargo boats, and passenger water taxis. They often operate on variable schedules dictated by passenger demand, tidal patterns, and weather conditions. The engine usage in such crafts varies significantly across the day, with frequent start-stop cycles, low-speed cruising, and intermittent full-throttle operation. Such fluctuating operational modes directly impact fuel consumption rates and emission patterns, which tend to be higher under transient conditions than during steady-state operations.

Similarly, Adewuyi and Badiru (2021) reviewed inland waterway vessels in Nigeria, highlighting variability in engine sizes from 50 kW to 500 kW depending on vessel type and function. For instance, larger ferries and cargo vessels are typically fitted with engines at the upper end of the power spectrum to ensure the capacity for longer hauls and heavier loads, while smaller boats used for short-distance transport often use compact engines. Engine size, however, is only one determinant of energy consumption. The operational profile — including factors such as frequency of trips, average load, maintenance practices, and idling times — also plays a critical role in determining the fuel consumption and emissions of these vessels.

Globally, studies like those of Corbett and Winebrake (2008) and Wang et al. (2008) have provided comprehensive surveys of vessel classes and their operational behaviors, emphasizing how vessel speed, engine load, and trip duration influence fuel consumption and emissions. Although these studies focused more on large ocean-going vessels, the core concepts remain applicable to inland vessels when adjusted for scale and operational context. For example, slow steaming — a strategy employed by large ships to reduce fuel use and emissions — can be adapted for inland craft through optimized speed regulations, especially during non-peak periods.

Wang et al. (2008) emphasized the importance of improving spatial representation in global ship emissions inventories, noting that emission estimates can be highly inaccurate without precise data on vessel movements and operational states. This reinforces the need for locally grounded studies, like those conducted in Lagos, which consider the specific traffic patterns, voyage distances, and port turnaround times common to that geographic and economic context.

This operational variability must be considered when estimating emissions and evaluating the feasibility of retrofit technologies such as WHR systems (Eyring et al., 2005). In many cases, inland waterway vessels experience frequent idling and operate at low engine loads for extended periods — conditions that may limit the efficiency of traditional waste heat recovery systems, which perform best under high and steady exhaust gas temperatures. Therefore, the design and implementation of WHR systems for such vessels require tailored solutions that can operate effectively under intermittent and variable load profiles.

Additionally, vessel maintenance practices and fuel quality play crucial roles in shaping operational efficiency. In many developing regions, including parts of Nigeria, inconsistent fuel quality and limited access to regular maintenance services can lead to reduced engine performance and higher specific fuel consumption. These factors, coupled with aging vessel fleets and the absence of emission control technologies, underscore the importance of adopting practical and cost-effective strategies such as WHR to enhance fuel efficiency and reduce emissions.

Furthermore, regulatory frameworks and enforcement mechanisms also influence the operational behavior of vessels. In areas with weak environmental oversight, vessels may operate inefficiently or use low-grade fuel with high sulfur content, compounding the environmental impact. As international regulations — such as those from the International Maritime Organization (IMO) — increasingly target emission reductions, it becomes vital for developing nations to consider scalable solutions like exhaust gas economizers that can be retrofitted to existing vessels operating under less-than-ideal conditions.

2.1.2 Fuel Consumption and Carbon Emission Estimation in Marine Engines

Estimating fuel consumption and emissions from marine diesel engines has been extensively studied using emission factors, specific fuel consumption (SFC) data, and engine load profiles. The International Maritime Organization (IMO, 2020) provides standardized emission factors linking fuel consumption to CO_2 output, typically around 3.206 kg CO_2 per kg of diesel fuel burned.

Studies by Zhang et al. (2013) and Ni et al. (2016) detail the methodologies for calculating fuel consumption from engine power ratings and operating hours, with adjustment factors for varying load conditions. Baldi et al. (2015) applied energy and exergy analyses to marine engines, emphasizing the importance of accurate load characterization for precise emission estimates.

In Nigeria, Adewuyi and Badiru (2021) and Akinfolarin et al. (2021) have reported emissions profiles for inland waterway vessels but have noted limitations due to scarce operational data and reliance on default emission factors, highlighting a need for more localized and detailed assessments.

2.1.3 Waste Heat Recovery Technologies in Marine Applications

Waste heat recovery (WHR) has attracted considerable attention as a means to improve fuel efficiency and reduce emissions from marine diesel engines. Zhang et al. (2013) and Ni et al. (2016) provide comprehensive reviews of WHR technologies, including exhaust gas economizers (EGEs), organic Rankine cycle systems, and thermoelectric generators.

EGEs are widely adopted in large commercial vessels, as shown by Tzeremes et al. (2017) and Baldi et al. (2015), where they recover heat from exhaust gases to produce steam or hot water for onboard use. Studies by Ni et al. (2016) demonstrated that EGEs can recover 10–15% of waste heat, leading to 5–10% reductions in fuel consumption.

In the context of small to medium inland vessels, research is sparse. Most existing literature focuses on ocean-going ships with high engine loads and continuous operation. The application of WHR in inland vessels, with intermittent operation and lower power ratings, remains underexplored (Adewuyi & Badiru, 2021).

2.1.4 Evaluation of Fuel Savings and CO_2 Emission Reductions from WHR

Several researchers have quantified the environmental benefits of WHR systems in marine applications. Baldi et al. (2015) and Ni et al. (2016) used thermodynamic analyses to show significant fuel savings and CO_2 emission reductions achievable by recovering exhaust heat.

Tzeremes et al. (2017) further highlighted the economic and environmental trade-offs, noting that fuel savings depend heavily on vessel operational profiles, ambient conditions, and system design. However, these studies largely rely on simulations or empirical data from large vessels, with limited application to inland or smaller-scale operations.

In Nigeria, while there is growing interest in emission reduction technologies, documented evaluations of WHR impact on fuel consumption and emissions in local vessels are rare, underscoring a gap in practical knowledge for the Lagos Lagoon marine environment (Akinfolarin et al., 2021).

2.2 Limitations of the Reviewed Past Work

- Most existing studies focus on large ocean-going vessels with high engine power and continuous operations, limiting their applicability to inland waterway vessels which typically have lower power and more variable operating cycles (Ni et al., 2016; Baldi et al., 2015).
- Data on vessel operational profiles and engine loads in Nigerian inland waters, especially Lagos Lagoon, are scarce or outdated, reducing the accuracy of emission estimates and WHR feasibility assessments (Adewuyi & Badiru, 2021; Olukanni & Adeoye, 2019).

- The majority of WHR research relies heavily on computer simulations and modeling software, which are often inaccessible or unaffordable for local researchers and operators, limiting practical adoption (Tzeremes et al., 2017).
- Limited empirical or case study data exist for the performance and economic viability of exhaust gas economizers in small to medium-sized vessels typical of Lagos Lagoon traffic (Akinfolarin et al., 2021).
- The environmental impact studies largely concentrate on CO_2 emissions, often neglecting the co-benefits or trade-offs related to other pollutants or operational constraints in inland waterway vessels.

2.3 Overview of Exhaust Gas Economizer Designs

Exhaust Gas Economizers (EGEs) are heat exchangers installed in the engine exhaust line to extract thermal energy from hot exhaust gases. They are typically used to preheat feedwater for auxiliary boilers or to directly supply thermal energy for onboard services such as domestic hot water or fuel preheating (Ni et al., 2016).

The most common designs of EGEs used in marine applications include:

- **Shell-and-Tube Heat Exchangers**: These consist of a bundle of tubes enclosed within a shell. Exhaust gases pass around the tubes while water flows through them (or vice versa). This design is robust and can handle high-pressure systems, making it suitable for larger vessels.

- **Plate Heat Exchangers**: These are more compact and consist of corrugated plates stacked together to facilitate heat transfer. They are less bulky but require cleaner exhaust gases and more frequent maintenance.

- **Finned Tube Economizers**: These enhance heat transfer by increasing the surface area via fins, improving the heat recovery from relatively low flow exhaust gases common in smaller engines.

- **Integrated Economizer-Boiler Units**: In some systems, the EGE is integrated directly with an auxiliary boiler to generate steam for heating or mechanical use.

For smaller inland vessels, compact, corrosion-resistant, and low-maintenance EGEs are most suitable due to space constraints and lower exhaust flow rates. Material selection is also critical, with stainless steel and corrosion-resistant alloys preferred to withstand high temperatures and acidic condensates.

Proper design must consider the pressure drop, soot deposition, fouling, and thermal stress to ensure long-term reliability and safety in marine environments (Zhang et al., 2013; Baldi et al., 2015).

2.4 Challenges of WHR Implementation in Inland Marine Vessels

Despite the recognized benefits of waste heat recovery (WHR) technologies such as exhaust gas economizers, their adoption in small to medium-sized marine vessels — especially those operating in inland waterways like Lagos Lagoon — faces several technical, economic, and institutional challenges.

One of the primary technological barriers is size and space limitation. Small vessels often lack the physical space to accommodate traditional WHR components such as heat exchangers, piping systems, and auxiliary boilers. While EGEs can be compactly designed, integrating them into existing engine compartments without interfering with operations or safety systems remains difficult (Baldi et al., 2015; Ni et al., 2016). Unlike ocean-going ships that have large engine rooms and dedicated utility spaces, inland vessels often operate with minimal space for retrofits.

Another key challenge lies in variability in operational profiles. Inland waterway vessels frequently operate under variable load conditions, including start-stop operations, idle periods, and low-speed cruising. These conditions affect the exhaust gas temperature and flow rate, which in turn impacts the effectiveness and stability of heat recovery systems (Tzeremes et al., 2017). WHR systems are typically most efficient at high, stable loads, which are not consistently observed in small-scale inland operations.

Maintenance complexity and system reliability are also concerns. Many local vessel operators lack technical training and resources to maintain advanced energy recovery systems. Poor maintenance can lead to fouling of heat exchanger surfaces, corrosion, or even system failure, which would offset any potential benefits. Furthermore, marine environments are corrosive and harsh, and without proper protective measures, WHR components may deteriorate quickly (Zhang et al., 2013).

The cost of acquisition and installation is a further deterrent. WHR systems can be capital intensive, and for small-scale operators already dealing with high operational costs and limited revenue, the initial investment is often seen as unaffordable. Moreover, access to affordable credit or government incentives for green technology adoption in Nigeria remains limited.

Institutional and policy barriers also exist. Although Nigeria has endorsed several international environmental treaties, enforcement mechanisms at the inland waterway level are weak. There are few incentives or mandates compelling vessel owners to upgrade to energy-efficient technologies. Moreover, there is limited collaboration between research institutions, manufacturers, and the marine industry to localize or pilot new systems (Adewuyi & Badiru, 2021).

Recent developments in micro-scale WHR technologies offer some hope. Advances in compact heat exchanger materials, thermoelectric generators, and modular economizers are showing promise for application in space-constrained environments (Huang et al., 2020). However, these innovations are still in the early stages of commercial availability and require pilot testing in developing country contexts.

In conclusion, while the environmental and economic benefits of WHR systems are clear, the challenges to their adoption in small marine vessels operating in inland waterways remain significant. Addressing these barriers will require technical innovation, localized design, stakeholder collaboration, and supportive policy frameworks.

2.5 Environmental and Health Impact of Marine Diesel Emissions

The environmental and economic consequences of marine diesel emissions, particularly in inland waterways such as Lagos Lagoon, are increasingly becoming a focus of academic, policy, and engineering research. The combustion of diesel fuel in marine engines produces various pollutants including carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), unburnt hydrocarbons (HC), and particulate matter (PM), all of which contribute to environmental degradation and public health risks (Eyring et al., 2010; Fang et al., 2018).

In densely populated coastal and riverine cities such as Lagos, the proximity of marine operations to urban populations exacerbates the impact of these emissions. Studies such as Akinfolarin et al. (2021) have shown that emissions from marine transport contribute significantly to ambient air pollution levels, leading to increased cases of respiratory illnesses, cardiovascular diseases, and other pollution-related health issues. The World Health Organization (WHO, 2020) estimates that air pollution is responsible for millions of premature deaths annually, many of which occur in urban centers near major ports or busy inland water routes.

Beyond the health effects, there are substantial environmental consequences. Marine engine emissions contribute to acid rain (from SO_x and NO_x), eutrophication of aquatic ecosystems, and contribute significantly to global greenhouse gas (GHG) emissions. According to the International Council on Clean Transportation (ICCT, 2017), the shipping industry accounts for roughly 3% of global CO_2 emissions, with inland water transport contributing a notable share in developing nations where regulatory frameworks are still evolving.

In Lagos Lagoon, diesel-powered boats operate frequently, often with little maintenance or emission control. The resulting pollution affects both water and air quality. Research by Olukanni and Adeoye (2019) noted that water quality in parts of the lagoon has declined due to surface run-off and direct discharge from marine operations, which can include not only gaseous pollutants but also oil residues and unburnt hydrocarbons.

Efforts to address these environmental and economic costs have led to international and regional regulations. The International Maritime Organization (IMO) has implemented several measures under MARPOL Annex VI to limit SO_x and NO_x emissions. However, enforcement and adoption remain a challenge in many developing countries, including Nigeria, due to inadequate monitoring infrastructure, limited funding, and technical expertise (Buhaug et al., 2009).

In this context, technologies such as exhaust gas economizers (EGEs) offer a dual advantage by reducing fuel consumption — thus cutting operational costs — and lowering emissions. These systems recover thermal energy from exhaust gases that would otherwise be wasted, converting it into usable energy for auxiliary systems or heating applications (Zhang et al., 2013). This not only improves overall engine efficiency but also reduces pollutant discharge per unit of energy produced.

In summary, emissions from diesel-powered marine vessels have a profound impact on both environmental quality and economic sustainability in inland water regions like Lagos Lagoon. Effective emission mitigation through technology adoption — such as WHR systems — and policy interventions is necessary to ensure the long-term viability of water-based transport in urban Nigeria.

2.6 Comparative Analysis of WHR Applications in Developing and Developed Maritime Sectors

Waste heat recovery (WHR) systems have been widely adopted in developed maritime sectors due to their proven ability to improve engine efficiency and reduce harmful emissions. However, their application in developing countries, particularly in the context of inland and coastal marine transportation, remains limited. This section compares WHR implementation across these contexts to highlight critical disparities and lessons that could be adapted for local applications like those in Lagos Lagoon.

In developed maritime sectors such as those in Europe, North America, and parts of East Asia, WHR technologies have seen extensive deployment on large commercial ships, cruise liners, and naval vessels. These regions benefit from well-established regulatory frameworks, robust R&D support, and access to advanced engineering and manufacturing capabilities. For instance, the European Union has mandated stricter emission limits under directives like the Sulphur Emission Control Areas (SECAs), pushing vessel operators to invest in WHR and other green technologies (European Maritime Safety Agency, 2020).

In contrast, in many developing nations including Nigeria, regulatory enforcement is often weak, and environmental compliance is minimal or voluntary. As a result, operators are less motivated to invest in long-term solutions such as WHR systems, especially when short-term profitability is a priority. Furthermore, the limited availability of indigenous engineering expertise and lack of local production facilities for WHR components mean that systems must often be imported at high costs, further discouraging adoption.

Technological readiness also differs. Developed countries have access to advanced materials, control systems, and modeling tools that enable efficient WHR integration and performance optimization. In contrast, developing regions rely more on manual engineering methods and legacy systems. Research by Mohammed et al. (2019) noted that in sub-Saharan Africa, the majority of marine vessels operate with outdated technology, making retrofitting complicated and less effective.

Financial models in developed nations also facilitate green technology uptake. Subsidies, tax incentives, and green financing are widely available for companies investing in sustainable solutions. For instance, Japan's Green Innovation Fund provides support for shipbuilders and operators deploying WHR and LNG-based systems. Such support mechanisms are almost entirely absent in Nigeria, where maritime innovation is largely market-driven and donor-dependent.

However, despite these limitations, there are lessons to be learned. Pilot projects in countries like India and Indonesia have successfully adapted low-cost WHR systems for small fishing boats and ferries through collaborative partnerships between academia, industry, and government. These models emphasize local fabrication, modular designs, and simplified maintenance protocols, which could be replicated in Nigeria.

Moreover, international organizations such as the IMO and UNDP have launched technical cooperation programs aimed at transferring green marine technologies to developing nations. The Global Maritime Technology Cooperation Centres (MTCC) initiative, for example, supports pilot demonstrations and capacity building in countries like Nigeria, providing a potential pathway for WHR adoption (IMO, 2020).

In summary, while developed countries lead in WHR deployment due to superior infrastructure, policy, and funding support, emerging economies have an opportunity to leapfrog traditional barriers by leveraging localized innovation and international cooperation. A tailored approach that accounts for Nigeria's specific maritime conditions, vessel types, and economic constraints is necessary for WHR technologies to gain traction in inland waterways like Lagos Lagoon.

2.7 Knowledge Gap

The reviewed literature reveals several knowledge gaps that this study seeks to address:

- There is a lack of detailed characterization of diesel-powered vessel operational profiles specific to Lagos Lagoon, impeding accurate fuel consumption and emission assessments.
- The feasibility and potential benefits of waste heat recovery using exhaust gas economizers on small to medium-sized inland vessels remain insufficiently explored, especially in the Nigerian context.
- Practical, manual calculation methodologies for estimating WHR energy recovery, fuel savings, and emission reductions — suitable for environments with limited data and resources — are inadequately documented.
- Comprehensive assessments that integrate vessel-specific operational data, energy balance calculations, and emission reduction potentials using WHR systems for inland waterway vessels are absent.

2.8 Current Research

To address these gaps, the current research undertakes:

- A detailed review and collection of vessel operational characteristics and engine specifications relevant to Lagos Lagoon traffic.
- Application of manual, calculation-based methodologies to estimate fuel consumption, CO_2 emissions, and waste heat available in diesel engines without reliance on complex simulation software.
- Quantification of thermal energy recoverable from exhaust gases using a simplified model of an exhaust gas economizer tailored to small to medium inland vessels.
- Estimation of potential fuel savings and CO_2 emission reductions from implementing waste heat recovery technology, grounded in realistic operational assumptions.
- Recommendations for practical adoption of WHR systems in local marine vessels, providing a foundation for policymakers, engineers, and operators interested in sustainable inland water transport.

3. MATERIALS AND METHODS

3.1 Materials

The materials required for this study include:

- Vessel and Engine Specifications: Technical datasheets for representative diesel-powered vessels operating in Lagos Lagoon (e.g., ferries, cargo boats, fishing boats). Three vessel categories are considered: Catamaran Passenger Ferry (A), Cargo Barge (B), and Fishing Boat (C).

Figure 3.1: Catamaran Passenger Ferry (A)

Figure 3.2: Cargo Barge (B)

Figure 3.3: Fishing Boat (C)

- Fuel Properties: Diesel fuel calorific value and density (42,700 kJ/kg; 0.84 kg/L).
- Emission Factors: Standard CO_2 emission factor for marine diesel (3.206 kg CO_2/kg fuel).
- Heat Recovery Equipment Data: Manufacturer data for a marine exhaust gas economizer (heat exchanger surface area, effectiveness, specific heat capacity of exhaust gases).

- Measurement Tools: Stopwatch or operation logs for vessel running hours; portable thermometer for exhaust and inlet temperatures (if field data collected); calculating devices (scientific calculator or spreadsheet).
- Reference Literature: Published values for Specific Fuel Consumption (SFC), engine efficiency, and WHR efficiencies (from Ni et al., 2016; Zhang et al., 2013).

3.2 Data Source and Collection

Data essential for this analysis are drawn from literature, technical manuals, and field/organizational records. Table 3.1 summarizes the assumed operating parameters for three representative vessel categories in Lagos Lagoon.

Table 3.1: Vessel Operational and Engine Data

Vessel Type	Engine Power (kW)	Specific Fuel Consumption (g/kWh)	Daily Operating Hours (h/day)	Fuel Density (kg/L)	Calorific Value (kJ/kg)
Passenger Ferry (A)	250	200	8	0.84	42,700
Cargo Barge (B)	150	210	6	0.84	42,700
Fishing Boat (C)	80	220	5	0.84	42,700

Data sources: Vessel operators' logs; engine manufacturer datasheets; IMO emission guidelines.

3.3 Methods

The methodology aligns with each of the study objectives. Equations are provided for manual calculation steps.

3.3.1 Identify Vessel Characteristics and Profiles

- Approach: Classify vessels into three categories (A, B, C) based on function. Compile engine power ratings and average operating hours from logs and datasheets.

3.3.2 Estimate Fuel Consumption and CO_2 Emissions

1. Fuel Consumption (kg/day)

$$FC_i = P_i \times H_i \times \frac{SFC_i}{1000} \tag{3.1}$$

P_i: Engine power for vessel i (kW)

H_i: Operating hours per day for vessel i (h/day)

SFC_i: Specific Fuel Consumption (g/kWh)

Performing the calculations with the data provided:

A: 250 × 8 × 200 / 1000 = 400.0 kg/day

B: 150 × 6 × 210 / 1000 = 189.0 kg/day

C: 80 × 5 × 220 / 1000 = 88.0 kg/day

2. Volume of Fuel (L/day)

$$V_{\mathrm{i}} = \frac{FC_{\mathrm{i}}}{\rho} \tag{3.2}$$

ρ: Diesel density (kg/L)

Performing the calculations with the data provided:

A: 400.0 / 0.84 = 476.19 L/day
B: 189.0 / 0.84 = 225.00 L/day
C: 88.0 / 0.84 = 104.76 L/day

3. CO_2 Emissions (kg/day)

$$E_{CO2,i} = FC_{\mathrm{i}} \times EF_{CO2} \tag{3.3}$$

EF_{CO2}: Emission factor (3.206 kg CO_2/kg fuel)

Performing the calculations with the data provided:

A: 400.0 × 3.206 = 1,282.40 kg/day
B: 189.0 × 3.206 = 605.93 kg/day
C: 88.0 × 3.206 = 282.13 kg/day

3.3.3 Quantify Waste Heat Available

Energy Input (MJ/day)

$$Q_{in,i} = FC_{\mathrm{i}} \times \frac{CV}{1000} \tag{3.4}$$

CV: Calorific value of diesel (42,700 kJ/kg)

Performing the calculations with the data provided:

A: 400.0 × 42,700 / 1,000 = 17080.0 MJ/day
B: 189.0 × 42,700 / 1,000 = 8070.3 MJ/day
C: 88.0 × 42,700 / 1,000 = 3757.6 MJ/day

Exhaust Heat (MJ/day)

$$Q_{exh,i} = Q_{in.i} \times \eta_{loss} \tag{3.5}$$

η_{loss}: Fraction of fuel energy lost in exhaust (assumed 30%)

Performing the calculations with the data provided:

A: 17,080.0 × 0.30 = 5124.0 MJ/day
B: 8,070.3 × 0.30 = 2421.1 MJ/day

C: 3,757.6 × 0.30 = 1127.3 MJ/day

3.3.4 Calculate Recoverable Heat via Economizer

Recoverable Heat (MJ/day)

$$Q_{rec,i} = Q_{exh,i} \times \varepsilon \tag{3.6}$$

ε: Economizer effectiveness (assumed 70%)

Performing the calculations with the data provided:

A: 5,124.0 × 0.70 = 3,586.8 MJ/day
B: 2,421.1 × 0.70 = 1,694.8 MJ/day
C: 1,127.3 × 0.70 = 789.1 MJ/day

Alternatively, using the heat exchanger formula when exhaust mass flow rate and temperature change are known:

$$Q_{rec,i} = \dot{m}_{exh,i} \times c_{p,exh} \times \Delta T \tag{3.7}$$

$c_{p,exh}$: Specific heat capacity of exhaust gas (kJ/kg·K)
ΔT: Temperature drop across economizer (K)

3.3.5 Evaluate Fuel Savings and CO_2 Reduction

1. Equivalent Fuel Savings (kg/day)

$$FS_{\mathrm{i}} = \frac{Q_{rec,i}}{CV_{MJ} \times \eta_{aux}} \tag{3.8}$$

η_{aux}: Efficiency of auxiliary use (assumed 90%)
CV_{MJ}: Calorific value in MJ/kg (42.7 MJ/kg)

Performing the calculations with the data provided:

A: 3,586.8 / (42.7 × 0.90) = 93.33 kg/day
B: 1,694.8 / (42.7 × 0.90) = 44.10 kg/day
C: 789.1 / (42.7 × 0.90) = 20.53 kg/day

2. CO_2 Reduction (kg/day)

$$\Delta E_{CO2,i} = FS_i \times EF_{CO2} \tag{3.9}$$

Performing the calculations with the data provided:

A: 93.33 × 3.206 = 299.23 kg/day
B: 44.10 × 3.206 = 141.38 kg/day
C: 20.53 × 3.206 = 65.83 kg/day

Table 3.2 summarizes the computed values.

Table 3.2: Calculated Fuel, Emissions, Waste Heat, and Savings

Vessel Type	**FC_i (kg/day)**	**V_i (L/day)**	**E_CO_2,i (kg/day)**	**Q_in,i (MJ/day)**	**Q_exh,i (MJ/day)**	**Q_rec,i (MJ/day)**	**FS_i (kg/day)**	**$\Delta E\_CO_2,i$ (kg/day)**
Passenger Ferry (A)	400.0	476.19	1,282.40	17,080.0	5,124.0	3,586.8	93.33	299.23
Cargo Barge (B)	189.0	225.00	605.93	8,070.3	2,421.1	1,694.8	44.10	141.38
Fishing Boat (C)	88.0	104.76	282.13	3,757.6	1,127.3	789.1	20.53	65.83

3.3.6 Recommendations for WHR Adoption

- Aggregate results across vessel categories to determine average fuel savings and emission reductions.
- Compare cost-benefit ratio by estimating saved fuel cost versus amortized economizer installation cost.
- Identify operational conditions under which WHR yields maximum benefit (e.g., minimum daily operating hours, load thresholds).

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