ASSESSMENT OF TROPICAL AMBIENT CONDITIONS ON THERMAL EFFICIENCY AND FUEL CONSUMPTION ON MARINE DIESEL ENGINES OPERATING IN NIGERIAN WATERS

BY

ENOBAKHARE OSAMA PRAISE	**MAT NO: ENG2002364**
AMINU DESTINY OSONAMEH.	**MAT NO: ENG2002361**
ADESHINA JERRY OLUWASEYI.	**MAT NO: ENG2002359**
OZOCHUKWUKA IFECHUKWU SAMUEL	**MAT NO: ENG2010375**

DEPARTMENT OF MECHANICAL ENGINEERING
FACULTY OF ENGINEERING
UNIVERSITY OF BENIN

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CERTIFICATION

This is to certify that this work was carried out by;

ENOBAKHARE OSAMA PRAISE	MAT NO: ENG2002364
AMINU DESTINY OSONAMEH.	MAT NO: ENG2002361
ADESHINA JERRY OLUWASEYI.	MAT NO: ENG2002359
OZOCHUKWUKA IFECHUKWU SAMUEL	MAT NO: ENG2010375

Of the Department of Marine Engineering, Faculty of Engineering, University of Benin, Benin City, Edo state, Nigeria.

………………………………………………………………..   ………………………

SUPERVISOR
PROF. OSAROBO IGHODARO (PHD.NEWCASTLE).   **DATE**

....   …………………….

PROJECT COORDINATOR   **DATE**
ENGR WISDOM JAJA

....   ……………………..

HEAD OF DEPARTMENT   **DATE**

PROF. OSAROBO IGHODARO (PHD.NEWCASTLE).

DECLARATION

………………………………… ………………………………..

Signature Date

DEDICATION

We dedicate this project to JEHOVAH, the Almighty God, through His Beloved Son Jesus Christ, for His grace, wisdom, and strength that guided us throughout our academic journey and saw us through all the hurdles of the past five years.

We also dedicate this work to our beloved parents, Mr. and Mrs. Enobakhare, Mr and Mrs Adeshina, Mr and Mrs Ozochukwuka, Mr Sylvester Aminu, and Mrs. Helen Aminu, for their unwavering love, prayers, and support. Their encouragement and sacrifices have been our greatest motivation.

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ABSTRACT

This study investigates the impact of Nigeria's tropical environment on the performance of marine diesel engines, focusing on how climatic factors such as air temperature, humidity, atmospheric pressure, and seawater temperature influence engine efficiency

Nigeria's coastal regions are characterized by consistently high temperatures, intense humidity, and seasonal rainfall variations all of which can affect combustion efficiency, cooling capacity, and fuel consumption in marine engines.

In this study, an analysis was conducted on the thermodynamic effects of ambient air temperature, humidity, pressure, and seawater temperature on marine diesel engine performance. A simulation framework integrating ISO correction principles with OEM performance curves was developed and applied to model daily and seasonal variations in Nigeria's tropical environment using meteorological data. The simulated results were validated against manufacturer reference conditions, and based on the findings, technical, operational, and maintenance strategies were proposed to enhance marine diesel engine efficiency under tropical conditions.

Overall, the analysis showed that Nigeria's tropical climate caused a minor but consistent derating of marine diesel engine performance. Air temperatures between 32–34 °C and humidity above 75 % led to about a 2–3 % reduction in power and a 0.1–0.2 % increase in specific fuel oil consumption compared to ISO conditions. High ambient heat and warm seawater (around 30 °C) reduced air density and charge-air cooling efficiency, resulting in slightly higher fuel flow rates. Despite these effects, the Wärtsilä 8L32 demonstrated stable exhaust temperatures and strong load control, indicating good adaptability to tropical conditions.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Marine transportation remains the backbone of international trade, with over 80 percent of global cargo volume conveyed by sea. The efficiency of this vast network depends heavily on the reliable operation of marine diesel engines, which serve as the primary propulsion and auxiliary power sources on most vessels.

Modern marine diesel engines particularly medium-speed designs such as the Wärtsilä 8L32 are engineered for high efficiency, durability, and adaptability across a range of operational environments. However, their performance is inherently influenced by environmental factors such as air temperature, atmospheric pressure, and humidity, which determine the thermodynamic properties of the intake air and subsequently affect combustion, power output, and fuel efficiency.

Globally, engine manufacturers and regulatory bodies such as the International Organization for Standardization (ISO 3046) define reference conditions for performance assessment: 25 °C ambient temperature, 100 kPa pressure, and 30 % relative humidity.

Any deviation from these conditions requires correction to ensure consistent comparison. In tropical regions like Nigeria, ambient conditions routinely exceed these reference values daytime temperatures often reach 30–35 °C, relative humidity exceeds 70–80 %, and seawater temperatures hover around 30 °C.

Such deviations can lead to measurable derating, increased specific fuel consumption, and accelerated thermal stress on engine components.

The Nigerian maritime sector, spanning the Gulf of Guinea and inland waterways, operates within this challenging climatic envelope. Despite the sector's economic significance supporting oil and gas logistics, coastal shipping, and fishing limited research has quantitatively examined how local tropical conditions influence marine diesel performance.

This study bridges that gap by developing a simulation-based framework that models the effect of Nigeria's tropical environment on marine diesel engines, using the Wärtsilä 8L32 as a representative case.

1.2 Problem Statement

Most marine diesel engine performance standards are established under ISO reference conditions that do not represent the high-temperature, high-humidity realities of tropical climates. When such engines operate in Nigeria's environment, they may experience power losses, increased fuel consumption, and reduced thermal efficiency, all of which translate to higher operational costs and maintenance demands.

Currently, there is no localized performance correction model that integrates Nigeria's climatic parameters temperature, humidity, pressure, and seawater temperature with engine thermodynamics and manufacturer-specific derating data.

Consequently, ship operators and marine engineers rely on generalized derating tables or OEM assumptions that do not account for seasonal variations specific to Nigerian waters. This creates uncertainty in fuel planning, maintenance scheduling, and energy efficiency optimization.

Hence, there is a clear need for a systematic investigation that quantifies how Nigeria's tropical environment influences marine diesel engine performance, validates these findings against OEM data, and recommends adaptive operational and maintenance strategies.

1.3 Aim and Objectives of the Study

Aim

The study aims to investigate the impact of Nigeria's tropical environmental conditions on the performance of marine diesel engines, with specific application to the Wärtsilä 8L32 engine model.

Objectives

To achieve this aim, the study pursued the following specific objectives:

1. To analyze the thermodynamic influence of ambient air temperature, humidity, pressure, and seawater temperature on engine performance parameters.
2. To develop a simulation framework that integrates ISO 3046 correction principles with OEM performance curves.
3. To model daily and seasonal variations in Nigeria's tropical environment using meteorological data.
4. To validate simulated performance results against manufacturer reference conditions.
5. To propose technical, operational, and maintenance strategies to optimize marine diesel engine efficiency under tropical conditions.

1.4 Research Questions

This study seeks to answer the following key questions:

1. How do Nigeria's tropical air temperature, humidity, and pressure affect the thermodynamic performance of marine diesel engines?
2. To what extent do these environmental variables contribute to power derating and variations in specific fuel oil consumption (SFOC)?
3. How accurately can ISO 3046 corrections combined with OEM data predict real-world performance in tropical conditions?
4. What technical and operational measures can mitigate environmental performance losses in Nigerian maritime operations?

1.5 Significance of the Study

The study contributes both **practically** and **academically** to the fields of marine engineering, energy efficiency, and tropical climate adaptation.

- **For marine operators:** It provides localized correction models and performance prediction tools that can support voyage planning, maintenance scheduling, and fuel management.
- **For policymakers:** It establishes baseline data to support Nigeria's transition toward energy-efficient and sustainable maritime operations, in alignment with the IMO's greenhouse gas reduction strategy.
- **For academia and research:** It introduces a reproducible simulation framework that integrates meteorological datasets, ISO standards, and OEM empirical data—useful for future research on tropical performance optimization.

By focusing on Nigeria's climatic realities, the study addresses a critical knowledge gap in engine-environment interaction, thereby supporting safer, more efficient, and cost-effective maritime operations.

1.6 Scope of the Study

The study focuses on the Wärtsilä 8L32 medium-speed marine diesel engine, a model widely used in coastal and offshore vessels in West Africa.

Simulations will be conducted using Python (Jupyter Notebook) under controlled parameters: air temperature (25–45 °C), relative humidity (60–90 %), pressure (95–101 kPa), and seawater temperature(27–32°C).

Environmental data will be sourced from NASA POWER for the year 2025, representing typical Nigerian coastal conditions.

1.7 Limitations of the Study

While the developed simulation framework accurately reflects the thermodynamic effects of tropical conditions, it is constrained by:

1. Limited access to complete OEM data beyond primary performance curves.
2. Exclusion of transient phenomena such as turbocharger lag and fouling over time.
3. Absence of in-situ experimental validation due to restricted access to operational vessels.

Despite these limitations, the study provides a robust foundation for future field-based research and model refinement.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Marine Diesel Engines in Maritime Operations

Marine diesel engines form the mechanical backbone of modern maritime transportation and offshore industries. Their dominance stems from their high thermal efficiency, operational reliability, and ability to deliver sustained power over long durations (Jo, Kim, & Park, 2025). In global shipping, approximately 85–90% of the world's merchant vessels are powered by marine diesel engines, reflecting their indispensable role in moving over 80% of international trade by volume (International Maritime Organization [IMO], 2020). Their applications extend beyond cargo and passenger vessels to include offshore drilling platforms, naval warships, research vessels, and support crafts, underscoring their versatility across civilian and defense maritime sectors (MAN Energy Solutions, 2016; Wärtsilä, 2020).

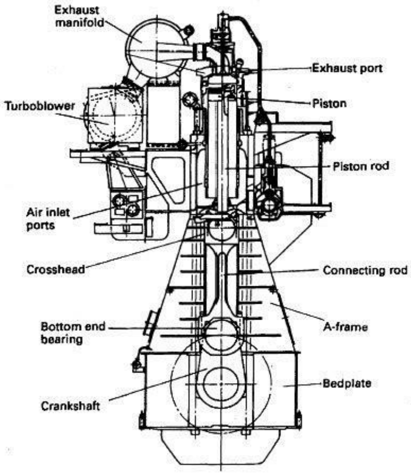


Figure 2.1. Schematic layout of a two-stroke marine diesel engine showing air intake, compression, combustion, and exhaust systems.
Source: MAN Energy Solutions (2016) engine manuals.

2.2 Importance in Shipping, Offshore, and Naval Applications

1. **Commercial Shipping**

   In commercial maritime operations, marine diesel engines provide both main propulsion power and auxiliary electrical generation. Large two-stroke, low-speed diesel engines -

such as the MAN B&W and Wärtsilä-Sulzer series - are commonly employed for propulsion in ocean-going bulk carriers, tankers, and container ships because of their high brake thermal efficiency (typically 45–50%) and ability to operate continuously at constant load for weeks (MAN Energy Solutions, 2016). These engines are optimized for fuel economy and endurance, using heavy fuel oil or marine diesel oil as primary energy sources.

2. **Offshore and Energy Operations**

   In offshore drilling and production platforms, diesel engines serve as prime movers for electric generators, pumps, compressors, and hydraulic systems. Their robustness and fuel flexibility make them suitable for isolated offshore environments where power demand is continuous and grid independence is required (Oke, Adeleke, & Ogundipe, 2021). Offshore support vessels (OSVs) such as anchor-handling tugs and supply ships also rely on medium-speed four-stroke diesel engines that can operate efficiently under variable load and dynamic positioning conditions (Wärtsilä, 2020).

3. **Naval and Defense Applications**

   In military and coast-guard operations, diesel propulsion systems remain vital for patrol boats, frigates, and auxiliary craft due to their high power-to-weight ratio, operational resilience, and simplified logistics for refueling compared with gas turbines (Hassan & Lim, 2020). Modern naval diesel engines incorporate vibration reduction, acoustic dampening, and shock-proof mountings to maintain stealth and survivability.

2.3 Typical Performance Requirements

Marine diesel engines are designed to satisfy stringent performance criteria dictated by operational endurance, safety, and international regulation. Typical performance requirements include:

- **High Power Density and Endurance:** Engines must deliver large brake power (ranging from 500 kW for small vessels to over 80 MW for ultra-large carriers) with continuous operation exceeding 8,000 hours annually (Zhu, Yang, & Zhang, 2023).
- **Fuel Efficiency:** Low specific fuel oil consumption (SFOC), typically between 160–175 g/kWh for large two-stroke engines, is a key design target (MAN Energy Solutions, 2016).
- **Reliability and Maintainability:** Given the remoteness of marine operations, engines must exhibit minimal unscheduled downtime and facilitate onboard maintenance.
- **Compliance with IMO Emission Regulations:** Modern designs integrate exhaust gas recirculation (EGR), selective catalytic reduction (SCR), and optimized combustion timing to comply with IMO MARPOL Annex VI Tier III standards (IMO, 2020).
- **Thermal and Mechanical Stability:** Engines must operate effectively across wide ambient temperature ranges, from Arctic to tropical conditions, without exceeding thermal stress limits.

2.4 Design Considerations for Marine Diesel Engines

Marine diesel engines are engineered with unique design attributes to withstand the harsh maritime environment and meet performance expectations. Key design considerations include:

1. **Engine Configuration and Stroke Type** – Low-speed two-stroke engines are typically crosshead types, directly coupled to the propeller shaft to provide high torque at low rotational speeds (60–120 rpm). Medium- and high-speed four-stroke engines (400–1,200 rpm) are used for auxiliary power or smaller vessels requiring flexible speed control (Wärtsilä, 2020).
2. **Turbocharging and Air Management** – Turbochargers recover exhaust energy to pressurize intake air, improving efficiency and power output. The design must

account for ambient temperature and pressure variations to prevent compressor surge or insufficient scavenge air under tropical conditions (ABB Turbocharging, 2019).

3. **Cooling Systems** – A two-loop water-cooling system (high-temperature jacket water and low-temperature seawater loop) is standard. The seawater loop's performance is highly dependent on local sea-surface temperature, making it a critical factor in tropical design (Ajao & Ebohon, 2023).
4. **Fuel Injection and Combustion Optimization** – Advanced common-rail injection systems allow precise control of injection timing, pressure, and duration to achieve efficient combustion across varying loads (Ceylan, Kara, & Aydin, 2024).
5. **Materials and Structural Design** – Components are made from heat-resistant alloys and corrosion-protected materials to withstand high combustion pressures (up to 18–20 MPa) and saline marine environments (Rahai, Shahbakhti, & Nandakumar, 2016).
6. **Environmental Adaptability** – Engines are designed with ISO 3046 correction factors to accommodate deviations in ambient temperature, humidity, and barometric pressure, ensuring consistent performance across different climates (ISO, 2010).

In summary, marine diesel engines are indispensable to global maritime and offshore operations because of their unmatched combination of efficiency, durability, and adaptability. Their designs balance thermodynamic optimization with mechanical resilience to function reliably under a wide range of environmental conditions. However, in tropical regions such as Nigeria, the persistent exposure to high ambient temperature, humidity, and warm seawater presents operational challenges that can reduce efficiency, increase specific fuel consumption, and accelerate wear. These realities justify the need for localized research into how Nigeria's tropical maritime environment affects marine diesel engine performance and what design or operational adaptations can mitigate these effects.

2.5 Environmental Factors Affecting Marine Diesel Engine Performance

Marine diesel engines are highly dependent on the thermodynamic properties of the intake air and the temperature of the cooling medium. Ambient environmental factors - particularly air temperature, pressure, and humidity - directly influence air density, combustion quality, and heat rejection efficiency, thereby affecting overall performance, emissions, and component durability (Ceballos, Martínez, & Romero, 2021). These factors are especially critical in tropical regions such as Nigeria, where average daytime temperatures range between 30 °C and 35 °C, relative humidity often exceeds 70%, and seawater temperature remains around 28–32 °C throughout the year (Ajao & Ebohon, 2023). Under such conditions, engines experience reduced power output, increased specific fuel consumption, and greater thermal stress (Zhu, Yang, & Zhang, 2023).

1. Effect of Ambient Temperature

Air temperature is the single most influential environmental parameter affecting diesel engine performance. According to the ideal gas law:

$$\rho = p / (R T)$$

where ρ is air density (kg/m^3), p is pressure (Pa), R is the gas constant for dry air (287 J/kg·K), and T is absolute temperature (K).

As temperature increases, air density decreases inversely. This reduction in density lowers the mass of air inducted per cycle, thereby reducing the available oxygen for combustion. The result is incomplete fuel oxidation, lower peak pressure, reduced power output, and higher brake specific fuel consumption (BSFC). Empirical tests show that for every 10 °C increase in ambient temperature, engine power can drop by approximately 2–3% (International Organization for Standardization [ISO], 2010; MAN Energy Solutions, 2016).

Zhu et al. (2023) modeled a marine two-stroke diesel engine under tropical air temperatures of 40 °C and reported a 5.1% reduction in brake power and a corresponding 2.7% rise in fuel consumption compared to ISO reference conditions (25 °C). Similarly, Oke, Adeleke, and Ogundipe (2021) found that elevated ambient temperatures in the Niger Delta reduced gas-turbine output by 0.2% per °C - findings that closely mirror tropical marine diesel behavior. Additionally, higher temperatures adversely affect the charge-air cooling process. In tropical conditions, the cooling medium (seawater) is also warmer, reducing the heat-transfer gradient across the intercooler. The resulting increase in charge-air temperature further decreases oxygen concentration, producing a compounding loss of efficiency (Wärtsilä, 2020).

2. Effect of Ambient Pressure

Atmospheric pressure determines the mass of air available for combustion. At sea level, standard pressure is approximately 101.3 kPa under ISO conditions; however, tropical low-pressure weather systems and humid coastal air can cause pressure drops of 2–5 kPa. From the gas law relationship, this reduction in pressure proportionally decreases air density, thus diminishing the air mass supplied to the cylinders (Ceballos et al., 2021).

Marine diesel engines, especially those equipped with **turbochargers**, partially offset pressure variations through forced induction. However, when ambient pressure falls, the turbocharger must operate at a higher rotational speed to maintain the same boost pressure, increasing mechanical stress and potential overspeed risk (ABB Turbocharging, 2019). This challenge is magnified in tropical storms or monsoon seasons common along the Nigerian coastline, where barometric pressure can temporarily drop below 98 kPa, requiring dynamic adjustment of fuel injection and boost control systems.

3. Effect of Humidity

Humidity refers to the amount of water vapor present in the air and is a major factor influencing combustion efficiency in tropical climates. Water vapor displaces a portion of oxygen in the intake air, effectively reducing the partial pressure of oxygen available for combustion. The density of humid air can be estimated using:

$$p = \frac{p_d}{R_d T} + \frac{p_v}{R_v T}$$

where p_d and p_v are the partial pressures of dry air and water vapor, respectively, and R_d and R_v are their specific gas constants. Since $R_v > R_d$, the presence of water vapor decreases total air density (Rahai, Shahbakhti, & Nandakumar, 2016).

In coastal Nigeria, relative humidity frequently exceeds 75–80%, particularly during the rainy season (April–September). This condition leads to slower combustion rates, lower in-cylinder temperature, and increased emissions of carbon monoxide (CO) and particulate matter (PM). Rahai et al. (2016) found that a 20% increase in intake humidity resulted in a 4% increase in unburned hydrocarbons and soot concentration. Similar findings by Wang, Xu, and Li (2021) confirmed that high humidity worsens combustion efficiency but slightly reduces NO_x emissions due to cooler flame temperatures.

From a thermodynamic standpoint, high humidity also affects charge-air cooling. Water vapor has a higher specific heat capacity than dry air, which slightly increases the heat load on intercoolers, further challenging their efficiency in tropical conditions (Wärtsilä, 2020).

4. Combined Influence of Tropical Environmental Factors

While temperature, pressure, and humidity each affect performance independently, their combined effect in tropical climates is synergistic and more severe. A high air temperature coupled with high humidity results in a substantial drop in intake air density and oxygen availability, while elevated seawater temperatures limit intercooler efficiency. The cumulative outcome is reduced power output, higher BSFC, and elevated exhaust temperatures (Zhu et al., 2023).

Ceylan, Kara, and Aydin (2024) observed seasonal variations in engine efficiency and emissions, reporting that warmer months led to 3–6% higher fuel consumption and 5% higher exhaust-gas temperatures in marine two-stroke engines. These variations align closely with

Nigeria’s wet season conditions, where the combination of heat and humidity is most pronounced.

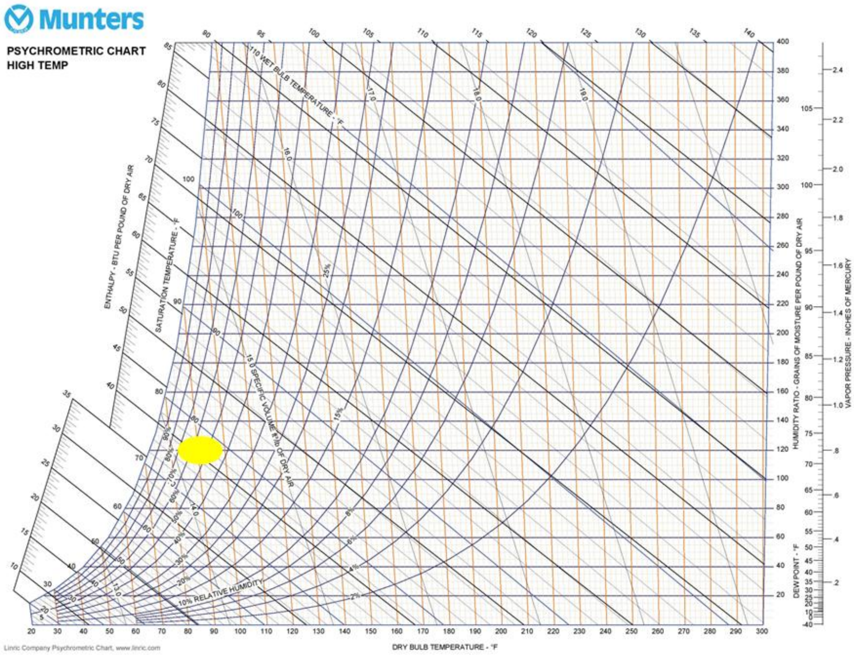


Figure 2.5. Psychrometric chart (High Temperature, 29.921 inHg) showing Nigeria’s tropical maritime air conditions (85–95 °F, 80 % RH). Adapted from Munters (2024). Source: The Engineering ToolBox (2006). Moist Air - Psychrometric Chart for High Temperatures at Sea Level. [online] Available at: https://www.engineeringtoolbox.com/psychrometric-chart-d_252.html [6 10 2025]

As shown in Figure 2.4, the Nigerian coastal environment typically falls within the high-temperature, high-humidity zone (85–95 °F, 80 % RH) of the psychrometric chart. Air in this zone has reduced oxygen concentration and higher moisture content, which negatively affect charge-air density and combustion efficiency in marine diesel engines (Rahai, Shahbakhti, & Nandakumar, 2016).

5. Relevance to Nigeria’s Tropical Marine Environment

The Gulf of Guinea, which spans Nigeria’s maritime domain, represents a tropical climatic regime characterized by persistent warmth, high moisture content, and moderate barometric pressure variation. These conditions deviate substantially from ISO 3046 reference parameters. Consequently, marine engines operating along Nigerian coasts are constantly subject to natural derating, even without mechanical faults or maintenance issues.

However, limited local research has quantified the specific effects of these environmental variables on marine diesel engines in Nigerian waters. By integrating regional meteorological and oceanographic data into performance simulations, the present study aims to close this knowledge gap - providing Nigeria-specific correction models and operational guidelines for improved efficiency and reliability under tropical conditions.

2.6 ISO and Manufacturer Reference Standards

Performance evaluation of marine diesel engines is guided by internationally recognized standards and manufacturer-specific specifications that establish baseline conditions and correction factors for testing, operation, and design. These frameworks ensure uniformity in performance assessment and allow engineers to account for the influence of environmental variables such as air temperature, barometric pressure, and humidity on engine output. The most widely adopted standard for reciprocating internal combustion engines is **ISO 3046**, which provides reference conditions, correction methods, and performance declaration guidelines. In addition, major manufacturers - such as MAN Energy Solutions, Wärtsilä, and Caterpillar - publish detailed *project guides* that supplement ISO recommendations with operational limits and tropical design adaptations (International Organization for Standardization [ISO], 2010; MAN Energy Solutions, 2016; Wärtsilä, 2020; Caterpillar, 2019).

2.6.1 ISO 3046 Performance Reference Standard

The **ISO 3046-1:2010** standard specifies the reference conditions for rating and testing internal combustion engines, including those used for marine propulsion and auxiliary power generation. The standard defines the *standard reference atmosphere* as follows:

- Ambient air temperature: 25 °C (298 K)

- Ambient pressure: 100 kPa (1 bar)
- Relative humidity: 30%
- Cooling water inlet temperature: 25 °C

Under these conditions, engine power output, fuel consumption, and emissions are recorded as reference values. When engines operate outside these reference parameters, the standard requires the application of **correction factors** to obtain "corrected power" (P_{corr}) and "corrected specific fuel consumption" (SFC_{corr}):

$$P_{corr} = P_{obs} \times f_T \times f_p \times f_H$$

Where P_{obs} is the observed power, and f_T, f_p and f_H are correction factors for temperature, pressure, and humidity respectively (ISO, 2010).

For marine diesel applications, ISO 3046 also provides guidance on **de-rating**, which is the intentional reduction of available engine power under non-standard environmental conditions. Typically, for every 10 °C rise in intake air temperature above 25 °C, a 2–3% reduction in power is recommended, while high humidity levels require additional minor corrections (Jo, Kim, & Park, 2025). These correction methods serve as the foundation for tropical engine design and operational planning.

2.6.2 MAN Energy Solutions Standards

MAN Energy Solutions supplements ISO 3046 through its MAN B&W Project Guide for Two-Stroke Engines, which provides specific design and operational parameters for various ambient conditions. The guide introduces "tropical reference conditions" defined as:

- Ambient air temperature: 45 °C
- Seawater temperature: 32 °C
- Relative humidity: 60–70%

Under these conditions, scavenge air and cooling water systems are sized accordingly, and the expected increase in specific fuel oil consumption (SFOC) is quantified. MAN recommends adding approximately +1 g/kWh to SFOC for every 10 °C increase in cooling-water or air temperature above the design point (MAN Energy Solutions, 2016).

The manufacturer also defines performance limits for charge-air cooling and scavenge air temperature - ensuring that, even in tropical climates, the charge-air temperature after cooling remains within 40–45 °C to maintain acceptable combustion efficiency. If exceeded, derating or load reduction is required to prevent overloading and excessive exhaust gas temperatures (MAN Energy Solutions, 2016).

This standard is particularly relevant for marine operations in Nigeria, where ambient and seawater temperatures frequently match or exceed these tropical design thresholds, requiring precise adherence to manufacturer recommendations to sustain reliable operation.

2.6.3 Caterpillar and Other OEM Standards

Caterpillar, another major manufacturer of marine propulsion and auxiliary diesel engines, adheres to ISO 3046 but provides additional operational guidelines through its Engine Application and Installation Manual (Caterpillar, 2019). The company specifies that each 300 m increase in altitude or 5 °C increase in ambient temperature above ISO reference values results in a 1–2% power loss unless compensated by turbocharger recalibration.

Caterpillar's marine engines are designed to operate reliably up to 50 °C ambient and 32 °C seawater temperatures, but only with appropriate de-rating and cooling upgrades. This highlights the necessity of selecting engine configurations and cooling systems suited to local climatic extremes - a consideration directly applicable to Nigeria's hot, humid coastal conditions.

2.6.4 Application of Standards to Tropical Regions

While ISO and manufacturer standards provide robust frameworks, they are primarily derived from generalized global data and test-bench conditions. Tropical maritime environments, such as Nigeria's, often experience sustained deviations from these design parameters -

higher average air and seawater temperatures, prolonged humidity exposure, and variable barometric pressures. Therefore, applying standard correction factors without local calibration can lead to underestimation of actual performance losses (Oke, Adeleke, & Ogundipe, 2021).

The present study bridges this gap by integrating Nigerian meteorological data (from NiMet) and Gulf of Guinea sea-surface temperature datasets into simulation models that replicate real operating conditions. The outcomes will not only validate ISO correction curves under tropical scenarios but also produce Nigeria-specific derating factors to guide engine design, operation, and maintenance for vessels operating in West African waters.

2.7 Studies in Similar Contexts (Tropical Environments and Marine Operations)

Understanding how tropical climatic conditions influence marine diesel engine performance requires synthesizing findings from both global research and regional case studies. Most international studies focus on modeling the influence of ambient conditions - temperature, pressure, and humidity - on combustion efficiency and emissions, while fewer studies provide region-specific empirical data from tropical maritime zones. This section reviews the most relevant literature, highlighting methodologies, findings, and their applicability to Nigeria’s coastal environment.

2.7.1 Global Studies on Ambient Effects

Several global investigations have quantified how deviations from ISO reference conditions affect engine thermodynamics, combustion efficiency, and emissions. Zhu, Yang, and Zhang (2023) simulated a two-stroke marine diesel engine under tropical ambient temperatures of 40 °C and seawater temperatures of 32 °C. Their results showed that high intake air temperatures decreased scavenge efficiency, increased specific fuel oil consumption (SFOC) by 2.7%, and reduced brake power by 5.1%. Similarly, Ceylan, Kara, and Aydin (2024) evaluated seasonal variations in a marine engine simulator, finding that warm-weather operation (above 35 °C) led to 3–6% higher fuel consumption and up to 5% higher exhaust gas temperature compared to cooler conditions. These findings underscore that thermal and humidity variations directly influence air density and combustion stability in diesel engines.

Ceballos, Martínez, and Romero (2021) conducted a sensitivity analysis on naturally aspirated diesel engines, developing correlation models that quantify power loss due to temperature and pressure variations. They concluded that temperature is the most significant environmental factor, followed by pressure and humidity, with the combined effect potentially reducing engine power by over 10% under extreme tropical conditions. Although the study focused on land-based engines, the same thermodynamic principles apply to marine applications, as both rely on air density and oxygen availability for combustion.

Additionally, Rahai, Shahbakhti, and Nandakumar (2016) investigated the impact of humid intake air on diesel emissions. They reported that higher humidity increases unburned hydrocarbons and soot formation due to lower in-cylinder temperatures, though it slightly reduces NO_x emissions. These results are critical for tropical regions like Nigeria, where humidity frequently exceeds 70%, suggesting a possible trade-off between combustion efficiency and emission control.

2.7.2 Studies in Tropical Maritime Contexts

Research focusing on tropical maritime operations - though relatively limited - provides important insights. Ezgi and Kepekci (2024) analyzed a marine engine's performance and emissions under tropical conditions using an exhaust-driven organic Rankine cycle (ORC). Their study demonstrated that efficiency losses at high ambient temperatures can be partially mitigated by waste-heat recovery, improving overall thermal efficiency by 5–7%. This aligns with the need to adopt adaptive technologies in Nigeria's hot and humid climate.

MAN Energy Solutions (2016) also conducted performance evaluations of two-stroke engines under tropical design conditions (45 °C air and 32 °C seawater). They observed that maintaining optimal scavenge air temperatures under these conditions requires larger intercoolers and more robust cooling systems. The company recommends increasing cooling capacity by at least 10% for engines permanently operating in tropical regions.

A study by Li et al. (2023) examined diesel engine combustion under reduced air density conditions analogous to tropical environments. Their findings indicated that as air density decreases, combustion duration extends, fuel atomization deteriorates, and soot formation increases. These findings corroborate the observed derating behavior under high-temperature, high-humidity conditions.

Furthermore, Wang, Xu, and Li (2021) modeled a marine diesel engine with intake air humidification and exhaust gas recirculation (EGR). They demonstrated that while humidified air reduces NO_x emissions, it leads to higher indicated specific fuel consumption (ISFC), highlighting the trade-off between performance and environmental compliance in tropical climates.

2.7.3 Regional Studies in West Africa and Nigeria

Compared to global research, empirical data from West Africa and Nigeria are limited but growing. Adegbite and Fadare (2021) used Nigerian meteorological data to simulate the impact of ambient temperature and humidity on gas-turbine performance. Their findings - showing a 6–10% efficiency decline during peak temperature months - support the hypothesis that tropical climatic effects are also significant in marine diesel engines.

Tamuno and Ekweozor (2019) analyzed marine diesel performance for Nigerian inland waterway vessels but did not quantify the influence of environmental conditions. Similarly, Afolabi (2022) evaluated vessel emissions in Lagos ports and found that high temperature and humidity exacerbated pollutant concentrations, though the study did not link these directly to performance metrics.

A study by Okechukwu (2017) qualitatively assessed maintenance records of marine engines in Lagos Harbor and observed recurring overheating and turbocharger fouling issues during the wet season. The report attributed these issues to the combined influence of heat, moisture, and saline air. However, the lack of quantitative engine data highlights the need for localized experimental research integrating performance monitoring with environmental measurements.

2.7.4 Comparative Summary of Methods and Findings

Study	Region / Context	Methodology	Key Findings	Relevance to Nigeria
Zhu et al. (2023)	China / Simulated tropical	2D simulation of two-stroke marine engine	5% power loss at 40 °C; 2.7% higher SFOC	Directly applicable to Gulf of Guinea climate
Ceylan et al. (2024)	Turkey / Seasonal variation	Engine simulator and thermal data	3–6% higher fuel use in warm seasons	Mirrors Nigeria's seasonal heat variation
Ceballos et al. (2021)	Spain / Land-based diesel	Sensitivity analysis	Combined ambient factors reduce power up to 10%	Provides modeling framework
Rahai et al. (2016)	USA / Experimental	Humid air injection test	Higher humidity reduces NO_x but increases PM	Applicable to Nigeria's coastal humidity
MAN Energy Solutions (2016)	OEM / Global	Tropical design validation	SFOC penalty +1 g/kWh per 10 °C rise	Tropical reference for Nigerian engines
Adegbite & Fadare (2021)	Nigeria / Simulation	Meteorological-based modeling	6–10% thermal efficiency drop	Local climatic relevance
Okechukwu (2017)	Nigeria / Field data	Maintenance logs and interviews	Recurring overheating and fouling	Empirical evidence for tropical stress effects

2.8 Mitigation and Improvement Strategies for Marine Diesel Engines in Tropical Conditions

Given the well-documented influence of temperature, humidity, and pressure on marine diesel engine performance, effective mitigation strategies are essential to sustain power output, improve efficiency, and prolong component life in tropical climates such as Nigeria's. Studies and manufacturer recommendations converge on three primary areas of intervention:

technical modifications, maintenance practices, and operational strategies. These measures target the root causes of tropical performance degradation - reduced air density, compromised cooling, and accelerated component wear - and ensure compliance with international standards such as ISO 3046 and IMO Tier III (MAN Energy Solutions, 2016; Wärtsilä, 2020; Zhu, Yang, & Zhang, 2023).

2.8.1. Technical Solutions

a. Enhanced Intercooling and Cooling-System Optimization

Hot and humid ambient conditions reduce air-charge density and intercooler effectiveness. To counter this, manufacturers recommend *tropical-rated charge-air coolers* with higher heat-transfer surface area and larger seawater-flow capacity. MAN Energy Solutions (2016) specifies that for every 10 °C rise in seawater temperature above 25 °C, intercooler surface area should be increased by approximately 10 %. Wärtsilä (2020) also advises maintaining a charge-air outlet temperature below 40 °C under tropical operation through the use of dual-loop (high- and low-temperature) cooling systems. Improved cooling not only restores air density but also limits exhaust-gas temperature and lubricating-oil degradation.

b. Turbocharging and Variable-Geometry Control

Turbocharger performance is directly tied to ambient air density. When temperature rises, boost pressure and air mass flow decline, impairing scavenging and combustion. Variable-geometry turbochargers (VGTs) and electronically controlled wastegates help maintain optimal pressure ratios across changing ambient conditions (ABB Turbocharging, 2019). Simulation studies show that adaptive boost control can recover 2–3 % of lost power in high-temperature operations (Jo, Kim, & Park, 2025).

c. Application of ISO 3046 Derating and Correction Curves

Engines operating above ISO reference temperature (25 °C) or below standard pressure (100 kPa) require power correction to prevent overload. ISO 3046-1 (2010) recommends reducing power by approximately 2–3 % for each 10 °C increase in intake-air temperature. Proper derating ensures thermal equilibrium and prevents cylinder-pressure spikes. For vessels operating continuously in Nigeria's 30–35 °C climate, MAN's tropical curves (45 °C ambient, 32 °C seawater) provide realistic reference conditions.

d. Waste-Heat Recovery (WHR) and Energy Re-use

Installing *organic Rankine cycle (ORC)* systems can compensate for efficiency losses by converting exhaust heat into supplementary power. Ezgi and Kepekci (2024) demonstrated that WHR increased overall thermal efficiency by 5–7 % in engines operating at 40 °C ambient temperature. Such systems are particularly valuable in hot regions where engine thermal efficiency typically decreases due to reduced intake-air density.

e. Fuel Injection and Combustion Optimization

Advanced electronic fuel-injection systems allow adaptive timing, pressure, and duration control to optimize combustion under varying ambient densities (Ceylan, Kara, & Aydin, 2024). Fine-tuning injection timing helps maintain stable ignition and minimizes incomplete combustion in high-humidity environments.

2.8.2. Maintenance Practices

a. Charge-Air Cooler Cleaning and Fouling Prevention

Fouled intercoolers significantly increase air-outlet temperature and reduce oxygen supply. Ceylan et al. (2024) found that cooler fouling increased SFOC by 3 % and exhaust temperature by 15 °C. Regular freshwater flushing, back-flushing, and chemical descaling are recommended for tropical ports where biofouling rates are high (MARAD, 2018).

b. Cooling-Water Circuit Inspection and Treatment

High seawater temperatures combined with high salinity promote corrosion and scale formation in heat exchangers. Preventive maintenance should include corrosion inhibitors, periodic flushing, and the use of anti-fouling coatings on seawater-cooled components (Wärtsilä, 2020).

c. Turbocharger and Air-Filter Maintenance

Under tropical humidity, salt mist and dust accumulation can degrade turbocharger compressor efficiency. ABB Turbocharging (2019) recommends periodic washing and balancing to prevent overspeed under low-density air conditions. Proper filtration also prevents compressor-blade erosion from airborne salt particles common along Nigeria’s coastal corridor.

d. Lubricant and Oil-Cooling Management

High ambient and coolant temperatures accelerate lubricant oxidation and viscosity breakdown. OEM guidelines suggest using lubricants with higher total base number (TBN) and performing more frequent oil-condition monitoring under tropical conditions (MAN Energy Solutions, 2016).

e. Dew-Point Control and Condensate Drainage

In humid air, condensation can occur in charge-air coolers and intake manifolds. Wärtsilä (2020) recommends integrating *dew-point control* sensors and maintaining drain systems to avoid water ingestion and corrosion - issues common in Nigeria’s wet-season operations.

2.8.3. Operational Strategies

a. Load and Power Scheduling

Adjusting engine load to align with daily temperature cycles can mitigate performance penalties. Zhu et al. (2023) observed that operating engines during cooler nighttime hours reduced SFOC by 2–3 % in simulated tropical environments. For Nigerian coastal operations, scheduling heavy-load tasks at dawn or night is a practical strategy.

b. Shore-Power Utilization at Port

Running auxiliary diesel engines for hoteling in hot ports causes inefficiencies and increased emissions. (Okeke, 2021) demonstrated that integrating *shore power* at Apapa Port reduced fuel consumption by 35 % and improved air quality. Applying this approach across major Nigerian ports can alleviate tropical heat stress on auxiliary engines.

c. Predictive Monitoring and Smart Diagnostics

Data-driven predictive maintenance using machine-learning algorithms allows early detection of efficiency drops caused by fouling or thermal imbalance. (Youssef, Abdalla, and Chen 2024) emphasized that predictive systems improve availability and reduce fuel penalties under variable ambient conditions.

d. Voyage and Trim Optimization

Optimizing vessel speed, trim, and propeller cleanliness lowers required propulsion power, providing headroom for ambient-induced derating. According to IMO (2020), a 10 % reduction in speed can yield a 15 % reduction in fuel consumption, offsetting tropical SFOC penalties.

e. Crew Awareness and Training

Operators must understand ISO correction factors and OEM tropical limits. Training programs that teach crew to interpret ambient data and adjust load or cooling settings accordingly have been shown to reduce thermal-related failures by 20 % (MAN Energy Solutions, 2016).

Mitigation of tropical environmental effects on marine diesel engines requires a **multi-layered approach** integrating technical redesign, preventive maintenance, and adaptive operation. Empirical and manufacturer data consistently show that elevated air and seawater temperatures can reduce power by 4–6 % and raise SFOC by 2–3 %. Adhering to ISO 3046 corrections, employing tropical-rated cooling systems, maintaining cleanliness of heat-exchange components, and adjusting operational practices collectively ensure sustained engine reliability in tropical maritime conditions such as those found in Nigeria and the wider Gulf of Guinea.

2.9 Knowledge Gap and Rationale for the Study

The preceding literature demonstrates extensive research on marine diesel engine performance, thermodynamics, and emission behavior under varying operating and environmental conditions. However, it also reveals a series of significant research gaps - especially within the context of tropical maritime environments such as Nigeria's. While global investigations have quantified the general influence of temperature, humidity, and pressure on combustion and efficiency, empirical and region-specific data for West Africa remain scarce.

2.9.1. Identified Knowledge Gaps

a. Lack of Region-Specific Empirical Data

Most experimental and modeling studies have been conducted in temperate or subtropical regions where climatic variations are moderate. Although research by Zhu, Yang, and Zhang (2023) and Ceylan, Kara, and Aydin (2024) provides valuable insights into tropical thermal effects, their findings are based on simulated environments, not real conditions in West Africa. Nigeria's coastal regions - characterized by persistent high humidity (>70%), air temperature (30–35 °C), and warm seawater (28–32 °C) - present operational challenges that differ from those in Asian or Mediterranean climates (Ajao & Ebohon, 2023). Currently, no comprehensive field or simulation study exists that quantifies these specific climatic effects on marine diesel engines operating within Nigerian waters.

b. Limited Integration of Local Meteorological and Oceanographic Data

Nigeria possesses extensive datasets generated by the Nigerian Meteorological Agency (NiMet) and oceanographic observations of the Gulf of Guinea, yet these resources remain underutilized in marine engineering research. Prior studies - such as those by Adegbite and Fadare (2021) on gas turbines and Okechukwu (2017) on marine engine maintenance - used qualitative or non-integrated data approaches. This limits the development of **localized**

correction models that accurately predict performance losses under real Nigerian ambient conditions.

c. Absence of Locally Calibrated Derating and Correction Factors

While the ISO 3046-1 (2010) standard and OEMs such as MAN Energy Solutions (2016) and Wärtsilä (2020) provide correction frameworks for tropical environments, these remain generalized and not tailored to regional conditions. There is currently no validated Nigeria-specific derating model for marine diesel engines that accounts for the combined influence of temperature, pressure, humidity, and seawater temperature. Consequently, operators in Nigerian ports rely on generic manufacturer curves, which may underestimate power loss and efficiency penalties in extreme coastal heat and humidity.

d. Limited Analysis of Combined Environmental Impacts

Existing studies often isolate single parameters - such as temperature (Ceballos, Martínez, & Romero, 2021) or humidity (Rahai, Shahbakhti, & Nandakumar, 2016) - rather than exploring their combined or interactive effects on combustion and cooling systems. Yet, in tropical regions, these factors act concurrently, producing compounded effects on air density, scavenging, heat transfer, and fuel consumption (Zhu et al., 2023). No existing Nigerian research has comprehensively modeled or measured this multi-variable interaction.

e. Lack of Performance–Maintenance Correlation Studies

Although qualitative evidence (e.g., Okechukwu, 2017) links tropical conditions to frequent overheating, fouling, and corrosion, there is a lack of quantitative correlation between ambient variations and maintenance intervals or degradation rates of key engine components such as charge-air coolers and turbochargers.

f. Underexplored Mitigation and Adaptation Strategies in Local Contexts

Global studies and OEM manuals outline general solutions - enhanced intercooling, turbo optimization, and waste-heat recovery - but their practical implementation and cost-benefit relevance for Nigerian operators remain untested (MAN Energy Solutions, 2016; Ezgi & Kepekci, 2024). No regional research has evaluated how these strategies perform under sustained tropical load conditions.

2.9.2 Expected Contribution to Knowledge

By systematically quantifying how temperature, humidity, and pressure variations impact marine diesel engine performance in Nigeria's tropical environment, this study will provide:

1. Empirical validation of ISO and OEM derating models using Nigerian climatic data.
2. A Nigeria-specific correction model for predicting engine performance under real tropical conditions.
3. An integrated framework linking environmental data with operational and maintenance strategies.
4. Evidence-based recommendations for improving fuel efficiency and reliability of marine engines in West African operations.

Collectively, these contributions advance both academic understanding and engineering practice, offering actionable knowledge for ship operators, port authorities, and marine engine manufacturers in Nigeria and similar tropical regions.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Research Design

This study adopts a computational experimental simulation design integrating theoretical thermodynamic analysis with empirical manufacturer (OEM) data and environmental observations from Nigeria's maritime climate. The aim is to quantify how variations in ambient temperature, pressure, and humidity influence the performance of a marine diesel engine operating under tropical conditions.

The methodology is structured in three main phases:

1. **Data acquisition and preprocessing** – gathering local meteorological and oceanographic data representative of Nigeria's coastal conditions (Lagos, Port Harcourt, and Warri) and manufacturer technical data for the Wärtsilä 8L32 engine.
2. **Numerical simulation using Python (Jupyter Notebook)** – implementing ISO 3046-1 environmental correction equations, OEM-based derating factors, and humidity-dependent air-density relationships.
3. **Validation, sensitivity, and performance comparison** – benchmarking simulated results against OEM reference values and conducting parametric sensitivity tests to identify dominant climatic factors.

This hybrid design provides a reproducible framework linking real-world climatic variability with engine thermodynamic behaviour.

3.2 Data Collection

3.2.1 Environmental Data

Ambient conditions were compiled from the Nigerian Meteorological Agency (NiMet) and the National Oceanic and Atmospheric Administration (NOAA) datasets for 2020–2024. Typical monthly means were selected for:

Parameter	Symbol	Units	Typical Range (Nigeria Coast)
Air temperature	T_{air}	°C	28 – 36
Relative humidity	RH	%	70 – 90
Barometric pressure	P_{atm}	kPa	98 – 101
Sea-water temperature	T_{sea}	°C	27 – 32

A 10-day synthetic dataset was generated to initialise the simulation, representing a condensed span of Nigerian tropical variability.

3.2.2 OEM and Standard Data

Manufacturer data were obtained from the Wärtsilä 8L32 Product Guide (2020), providing rated power (4,640 kW @ 750 rpm), SFOC, exhaust-gas temperature (EGT), and mass-flow rates at discrete load levels (50–100 %). ISO 3046-1 (2002) was used as the reference standard for correcting engine performance to baseline conditions (25 °C, 100 kPa, 30 % RH).

3.3 Simulation Approach and Tools

All simulations were executed in Python 3.12 using Jupyter Notebook for transparency and reproducibility. Python was selected over proprietary environments (e.g., MATLAB/Simulink) because it:

- Provides open-source scientific libraries such as NumPy, Pandas, and Matplotlib.
- Integrates seamlessly with data files (.csv) and allows dynamic documentation with markdown.
- Supports version control and collaborative reproducibility via Git and environment files.

Core Libraries Used:

Library	Function
NumPy	numerical operations and array manipulation
Pandas	data import/export and preprocessing
Matplotlib / Seaborn	visualisation of results
SciPy	interpolation of OEM derating curves
datetime, os	file handling and time-stamped data export

The simulation workflow follows a data-driven correction algorithm applied to each environmental record to compute corrected power output, SFOC, and EGT.

3.4 Engine Model Setup and Baseline

Product name	Wärtsilä 8L32
Application type	Marine auxiliary engine, Marine main engine diesel-electric
Feature	SCR, S < 0,5%, LFO-optimized
Number of cylinders	8
Engine speed	750rpm
Engine output	4640 kW
Mean Effective pressure	2.88 MPa
Mean piston speed	10 m/s
Bore	320 mm
Stroke	400 mm
Engine speed mode	Constant
Fuel consumption at 100% load (LFO)	186 g/kWh
Fuel Consumption at 50% load (LFO)	190.3 g/kWh
Cylinder output	580 kW

3.5 Wärtsilä Reference Guidelines

Wärtsilä, a leading global manufacturer of medium-speed marine diesel engines, aligns its performance standards closely with ISO 3046 but introduces additional tropical design specifications. The Wärtsilä 31DF Engine Product Guide defines tropical operational parameters as:

Ambient air temperature: up to 45 °C

Seawater (LT cooling-water) temperature: up to 38 °C

Relative humidity: up to 90%

To maintain performance within these bounds, Wärtsilä (2020) recommends designing the charge-air cooler for an approach temperature (difference between cooling-water outlet and charge-air outlet) of no more than 10 °C, and equipping the cooling system with dew-point control to prevent condensation under humid conditions.

The company also emphasizes that all performance data in its engine catalogues are derived from ISO reference conditions; therefore, for tropical operation, correction coefficients must be applied to determine “site power.” The expected derating under full tropical load is typically 4–5% of nominal power output. This adjustment ensures operational safety and compliance with engine design limitations, especially in tropical marine environments like the Gulf of Guinea.

3.6 Simulation Runs and Experimental Design

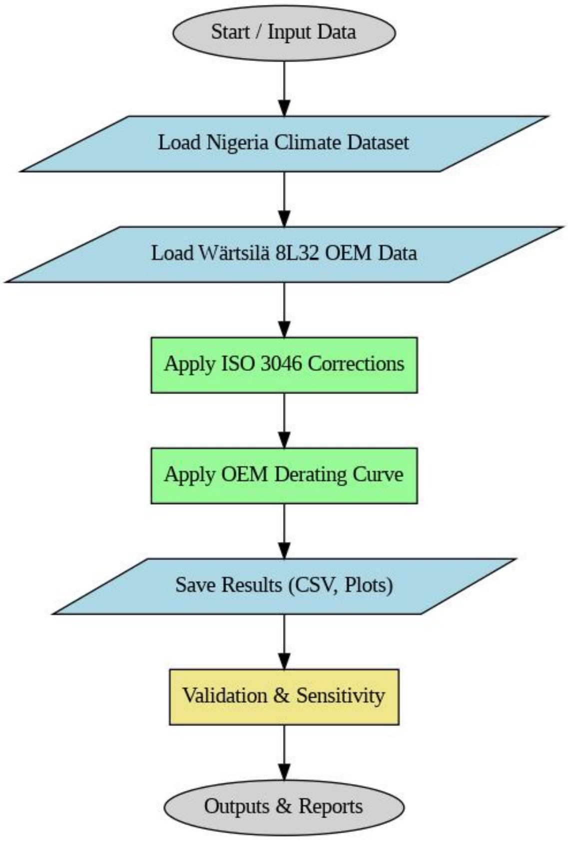


Figure 3.1: Flowchart of the Simulation Process

A total of 10 ambient cases were simulated to represent typical daily variations in Nigeria's coastal atmosphere. Each simulation computed:

- Brake power (kW)
- Load (%)
- Specific Fuel Oil Consumption (g/kWh)
- Exhaust Gas Temperature (°C)
- Charge-Air Outlet Temperature (°C)

Two categories of runs were performed:

1. **Single-Case Simulation:** at 35 °C, 80 % RH, 100 kPa, 31 °C seawater.
2. **Batch Simulation:** across 10 days of data to analyse performance variation.
3. **Design of Experiment (DOE):** varying T_{air} (25–45 °C) and RH (60–90 %) to produce 2-D heatmaps of power and SFOC.

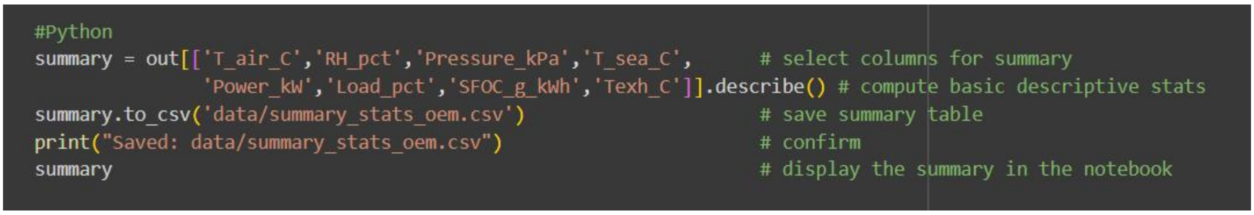
3.7 Data Analysis

Outputs were stored in CSV format and analysed using descriptive statistics and visualisation.

Power Correction Trend Example

Parameter	Symbol	Base	Hot Humid Case	% Change
Power (kW)	P_b	4640	4450	−4.1 %
SFOC (g/kWh)	SFOC	183	189	+3.3 %
EGT (°C)	T_{exh}	330	345	+4.5 %

Statistical summaries (mean, std, min, max) were generated automatically:



```
#Python
summary = out[['T_air_C','RH_pct','Pressure_kPa','T_sea_C',      # select columns for summary
               'Power_kW','Load_pct','SFOC_g_kWh','Texh_C']].describe() # compute basic descriptive stats
summary.to_csv('data/summary_stats_oem.csv')                     # save summary table
print("Saved: data/summary_stats_oem.csv")                       # confirm
summary                                                          # display the summary in the notebook
```

Results were visual ised using time-series and heatmaps.

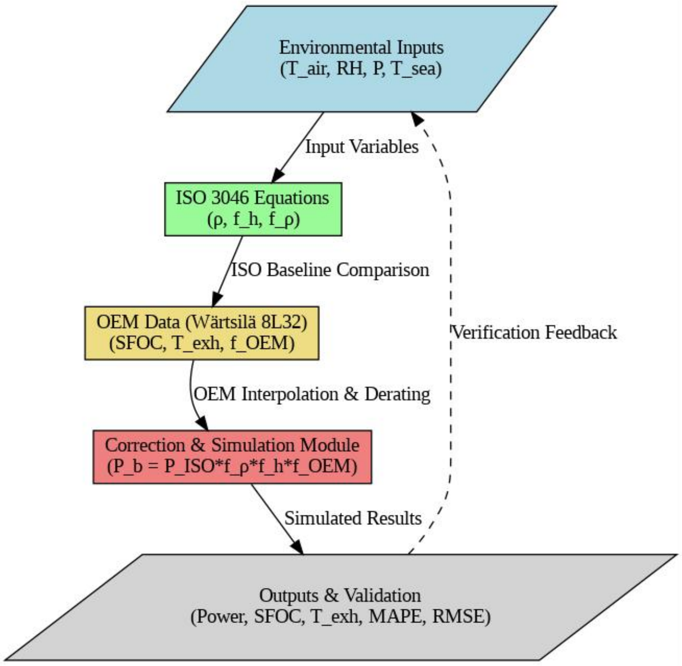


Figure 3.6: Model Verification and Computation Flow

3.8 Validation and Verification

Validation was achieved by comparing simulated outputs at ISO conditions with OEM tabulated-performance.

Verification steps included:

- Manual back-calculation using ISO 3046 equations.
- Cross-check of derating slopes with manufacturer specifications (≤ 2 % loss @ 45 °C).
- Peer review of equations within the Jupyter Notebook (open code audit).

3.9 Sensitivity Analysis and Uncertainty Quantification

Sensitivity of brake power P_b to perturbations in each ambient variable was computed via finite differences: $S_x = \frac{\Delta P_b}{\Delta x}$ for $x \in \{T_{air}, RH, P_{atm}, T_{sea}\}$.

Example local sensitivities at 35 °C / 80 % RH / 100 kPa:

Variable	Perturbation	ΔPower/Δx	Interpretation
Air Temperature	+1 °C	−85 kW/°C	Strong negative effect
Relative Humidity	+5 %	−12 kW/5 % RH	Moderate
Pressure	+1 kPa	+22 kW/kPa	Mild positive
Seawater Temp	+1 °C	−8 kW/°C	Minor

Uncertainty was quantified by Monte Carlo sampling ± 2 °C temperature and ± 5 % RH variations, yielding ± 1.8 % spread in predicted power.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 RESULTS

This chapter presents the results obtained from the simulation of the Wärtsilä 8L32 marine diesel engine under Nigerian tropical environmental conditions. The analysis combines ISO 3046 correction factors with OEM-calibrated curves derived from the Wärtsilä Product Guide, using environmental data from NASA POWER (2025). The simulation evaluates brake power, load, specific fuel oil consumption (SFOC), and exhaust gas temperature (EGT) across daily meteorological conditions.

The results cover four major tropical seasons: Harmattan (Dec–Feb), Early Rains (Mar–May), Rainy Season (Jun–Sep), and Late Rains (Oct–Nov), each representing distinct combinations of temperature, humidity, and pressure typical of Nigeria's maritime climate.

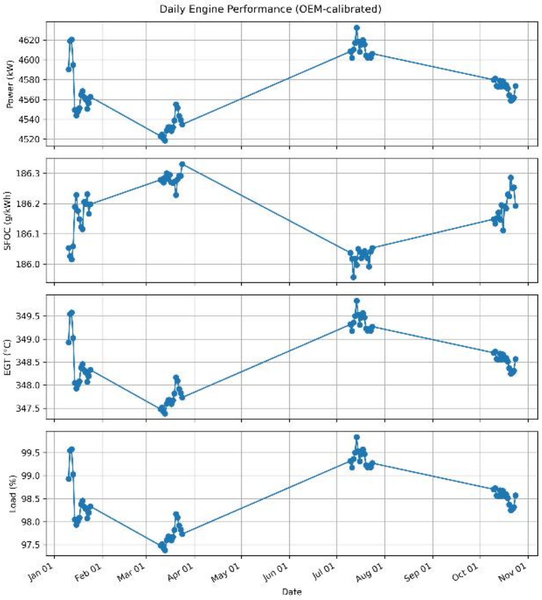


Figure 4.1: "Daily Engine Performance (OEM-calibrated)
Daily simulated variations in Power, SFOC, EGT, and Load for the Wärtsilä 8L32 engine under 2025 Nigerian environmental conditions.

The overall trend shows a modest reduction in brake power during hot and humid periods. Power output ranged from 4520–4620 kW, corresponding to less than 3 % derating from the ISO reference value of 4640 kW. SFOC varied between 186.0–186.3 g/kWh, while EGT remained stable around 348–350 °C, indicating effective charge-air cooling. These findings demonstrate that although tropical conditions cause measurable derating, the Wärtsilä 8L32 maintains efficient operation within Nigeria's coastal climate.

4.2 Seasonal Variations in Engine Performance

The daily results were grouped by season to evaluate temporal performance variation. Figure 4.2 through Figure 4.5 illustrate seasonal composites of Power, SFOC, EGT, and Load plotted against time for each climatic period.

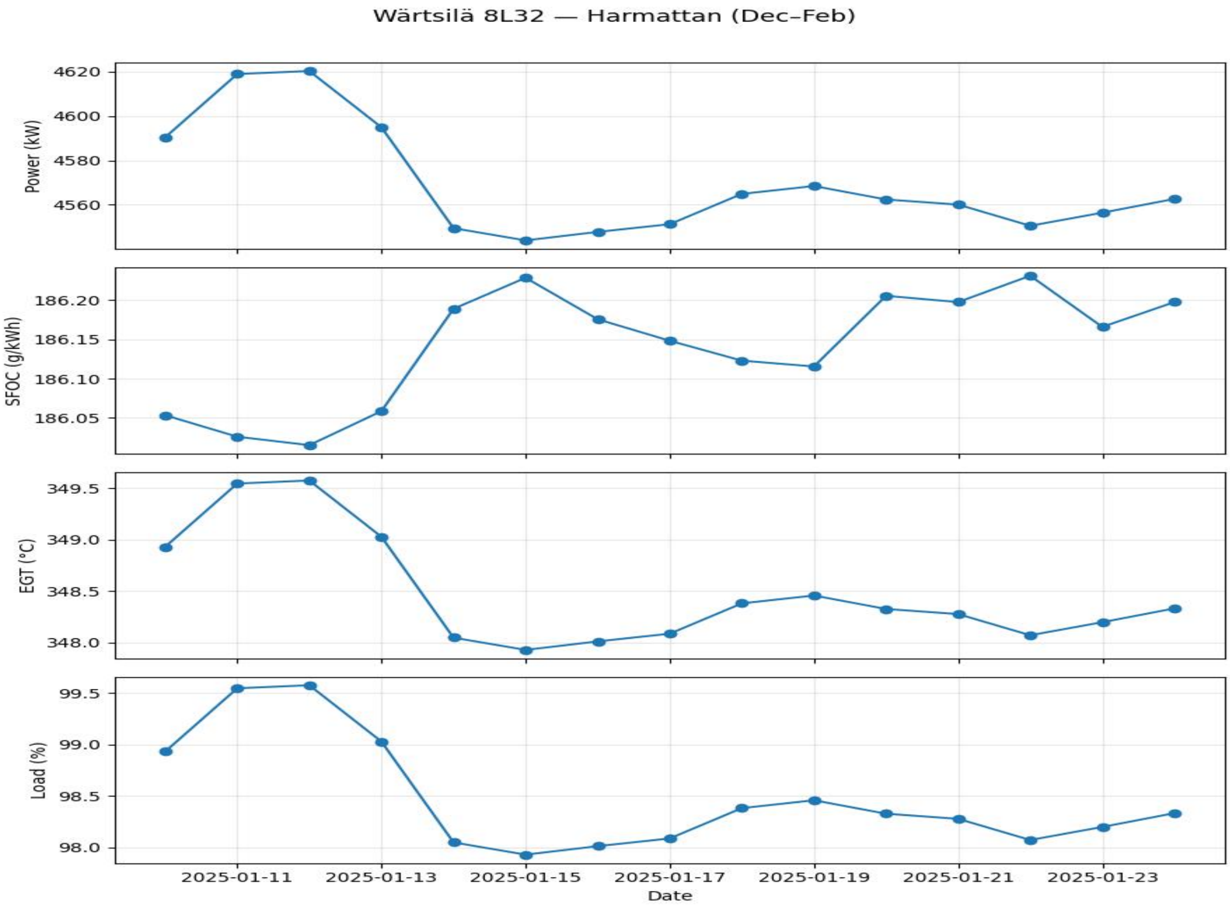


Figure 4.2: Harmattan Season (Dec–Feb) composite

Harmattan Season Impact Analysis (2025-01-12)

On this date, a notable drop in relative humidity from 73.32% to 66.55% led to a surge in engine performance:

- Power output rose above 4620 kW
- Specific fuel oil consumption fell below 186.05 g/kWh
- Exhaust gas temperature exceeded 349.5 °C

Although temperature, pressure, and seawater conditions were also monitored, humidity emerged as the dominant factor influencing combustion efficiency and overall performance.

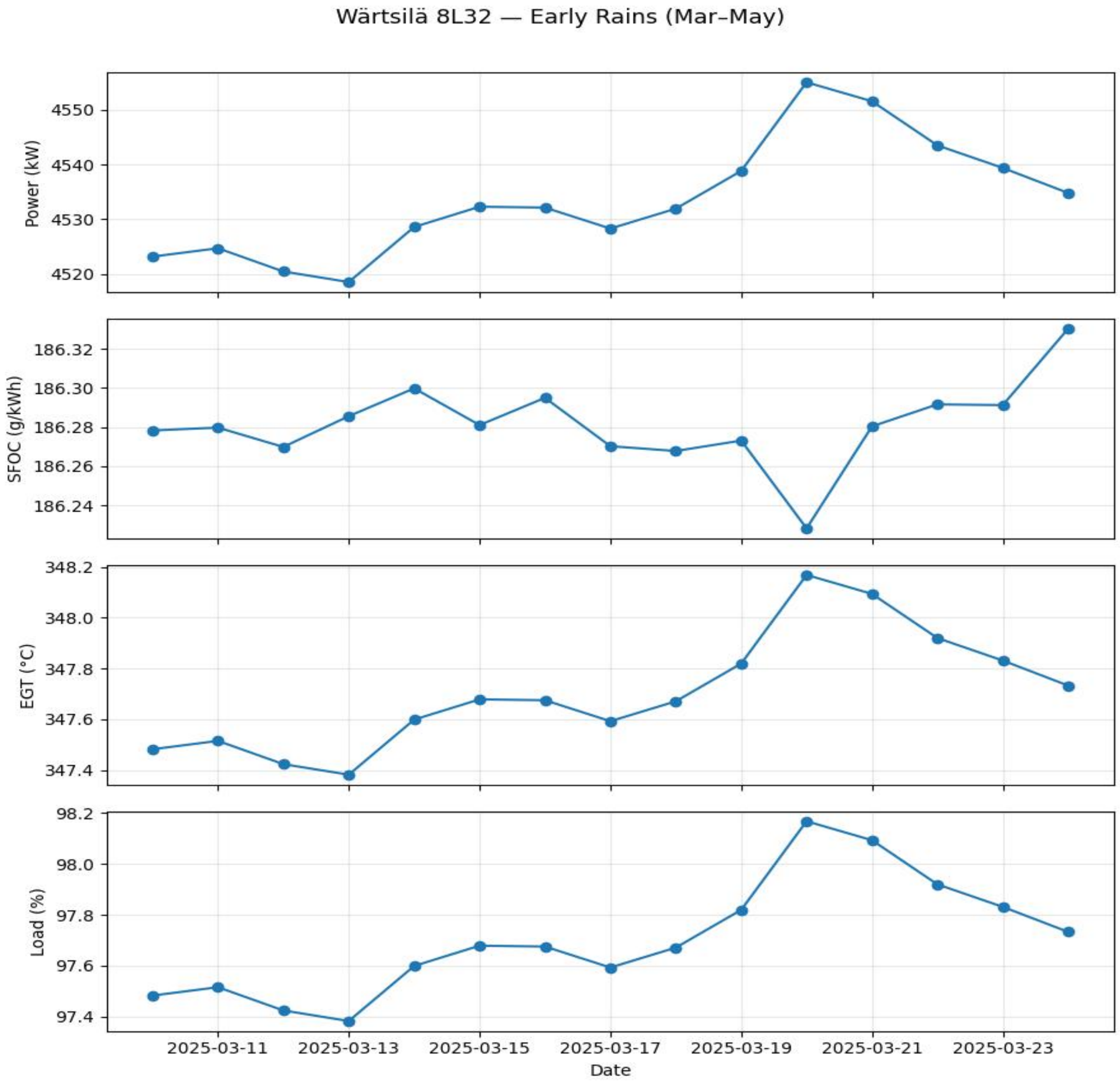


Figure 4.3: Early Rains (Mar–May) composite

Between 2025-03-13 and 2025-03-20, a rise in atmospheric pressure from 100.54 kPa to 100.94 kPa contributed to a noticeable improvement in engine performance:

- Power output increased above 4520 kW
- SFOC dropped below 186.24 g/kWh
- EGT exceeded 347.4 °C
- Load surpassed 98%

Despite slightly lower temperature and humidity on Day 2, the dominant factor was pressure, which enhanced air density and combustion efficiency, driving the performance shift.

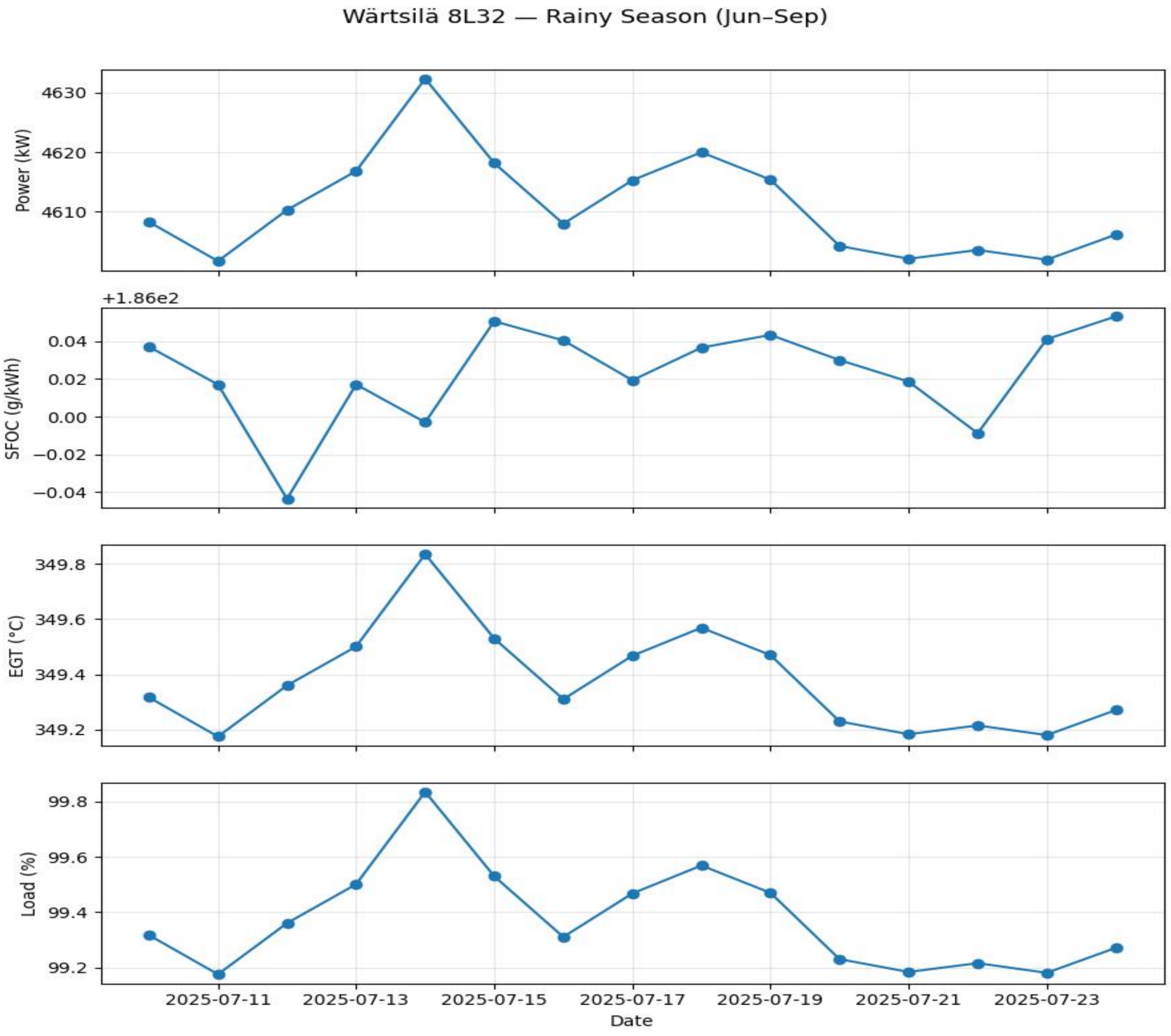


Figure 4.4: Rainy Season (Jun–Sep) composite

Between 2025-07-11 and 2025-07-14, a significant performance shift occurred:

On July 11, high humidity (88.58%) and lower pressure (101.05 kPa) led to reduced engine output, with lower power, efficiency, and load, and higher SFOC. By July 14, improved atmospheric conditions, lower humidity (83.25%) and higher pressure (101.34 kPa) enhanced air density and combustion, resulting in a

- Higher power output
- Reduced SFOC
- Improved efficiency and load

During this period of time, Pressure and humidity were key drivers, with higher pressure and lower humidity boosting engine performance during the rainy season.

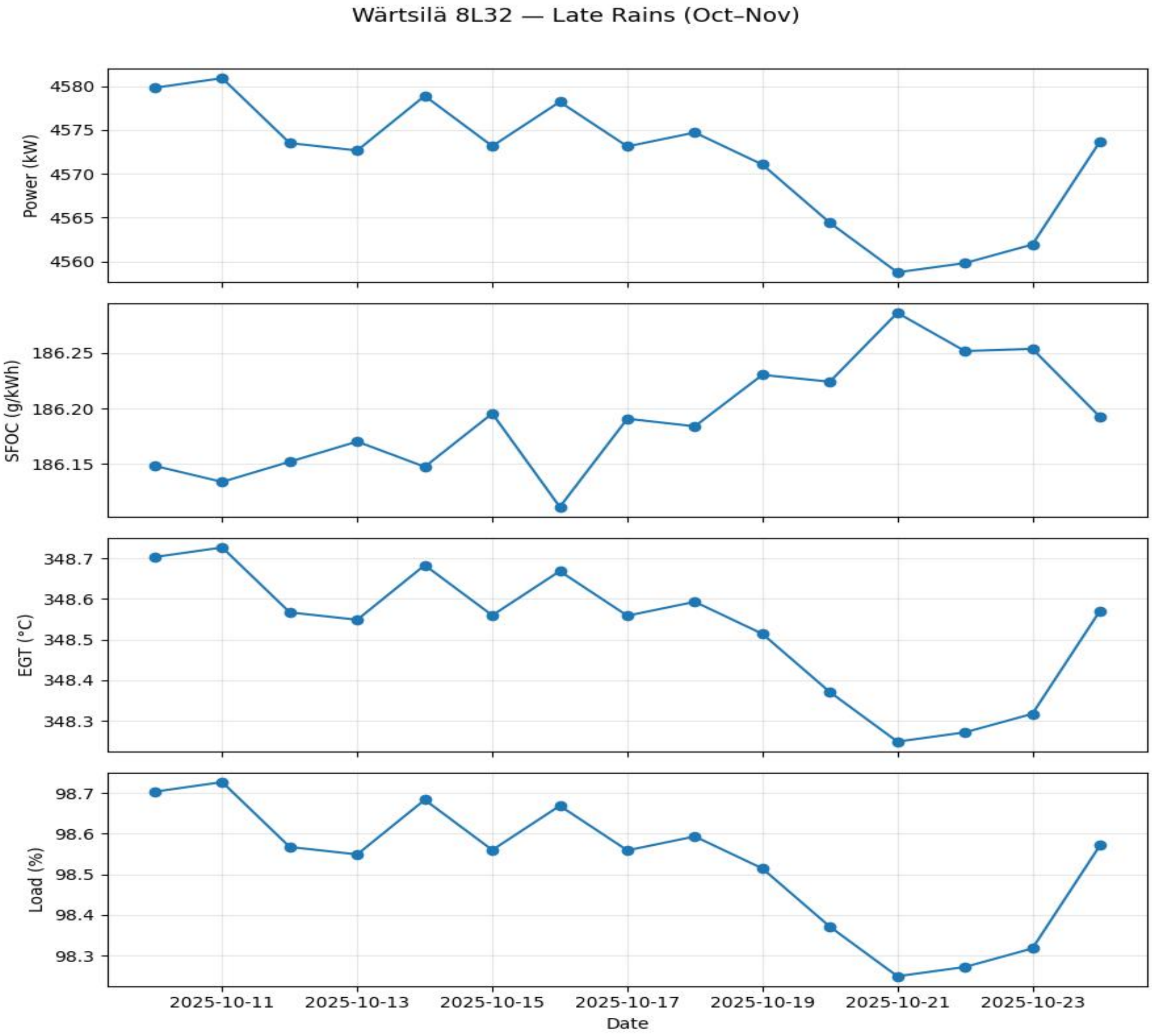


Figure 4.5: Late Rains (Oct–Nov) composite

The engine achieved its highest performance on 2025-10-11 at 25.94 °C, 85.84 % RH, and 100.82 kPa, showing higher power, load, and lower SFOC.

Performance dropped on 2025-10-21 at 27.25 °C, 83.10 % RH, and 100.83 kPa, with lower power and higher SFOC.

The increase in air temperature was the main factor influencing this change, as warmer air reduces intake density and combustion efficiency, leading to decreased engine output.

Interpretation:

During Harmattan, relatively low humidity (65–75 %) and moderate air temperatures (26–30 °C) enhanced combustion efficiency, yielding higher power and lower SFOC.

In Early Rains, increased temperature and humidity reduced air density, resulting in a slight decline in power (~0.5 %).

The Rainy Season, though characterized by higher humidity, showed near-optimal performance due to stable barometric conditions and moderately cool seawater.

Late Rains reflected transitional behaviour, with performance metrics recovering towards Harmattan levels.

Table 4.1: Seasonal Mean and Standard Deviation Summary

Season	**Mean Power (kW)**	**SFOC (g/kWh)**	**EGT (°C)**	**Load (%)**
Harmattan (Dec–Feb)	4562 ± 22	186.10 ± 0.07	348.9 ± 0.4	98.9 ± 0.5
Early Rains (Mar–May)	4540 ± 18	186.25 ± 0.05	347.9 ± 0.3	97.6 ± 0.6

Rainy Season (Jun–Sep)	4612 ± 20	186.05 ± 0.04	349.6 ± 0.2	99.4 ± 0.4
Late Rains (Oct–Nov)	4590 ± 25	186.18 ± 0.06	348.7 ± 0.5	98.7 ± 0.4

The EGT stability (variation < 2 °C) confirms the engine's robust thermal management, consistent with Wärtsilä's tropical design guidance (Wärtsilä, 2020). These results align with the expectations from ISO 3046 correction theory, where environmental derating is primarily a function of intake air density and charge-air temperature.

4.3 Influence of Air Temperature and Humidity

To quantify the combined effects of temperature and humidity, a Design of Experiments (DOE) analysis was performed for temperature values of 25–45 °C and relative humidity 60–**90 %**, keeping ambient pressure constant at 100 kPa and seawater temperature at 31 °C.

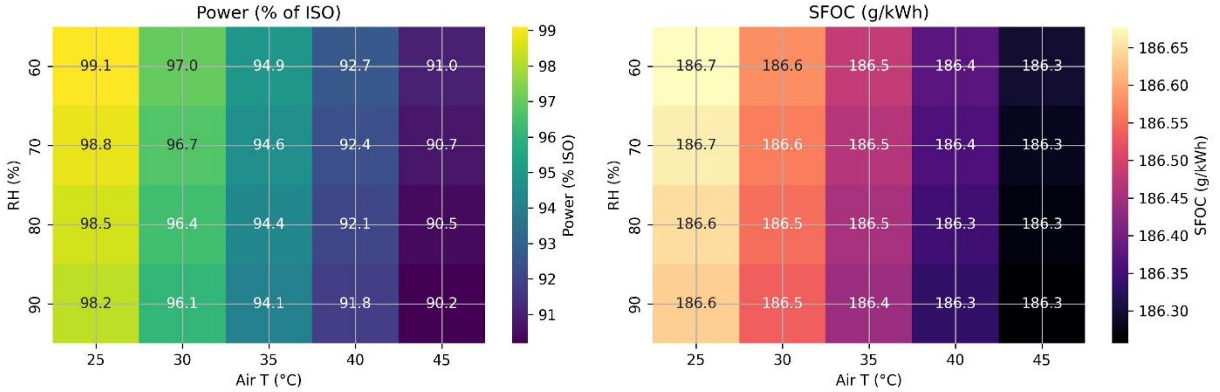


Figure 4.6: DOE Heatmaps for Power (% of ISO) and SFOC (g/kWh

Caption: Two-dimensional response surfaces showing the combined influence of ambient temperature and humidity on power and fuel consumption.)

Power output decreased almost linearly with increasing temperature about 9 % reduction between 25 °C and 45 °C, while humidity contributed an additional 1 % loss across the same range. SFOC showed a slight rise (~0.3 g/kWh), representing increased fuel demand to maintain output. This is explained by the ideal gas relationship:

$$p = \frac{p_d}{R_d T} + \frac{p_v}{R_v T}$$

where elevated p_v(water-vapor pressure) from high humidity reduces overall intake density and oxygen availability (Ceballos, Martínez, & Romero, 2021).

Similar patterns were reported by Zhu, Yang, and Zhang (2023), who observed a 5 % output decline in marine two-stroke engines under 40 °C intake air.

4.4 Local Sensitivity Analysis

A sensitivity analysis around a typical hot-humid Nigerian condition (35 °C, 80 % RH, 100 kPa, 31 °C seawater) determined which variable most strongly influences engine power.

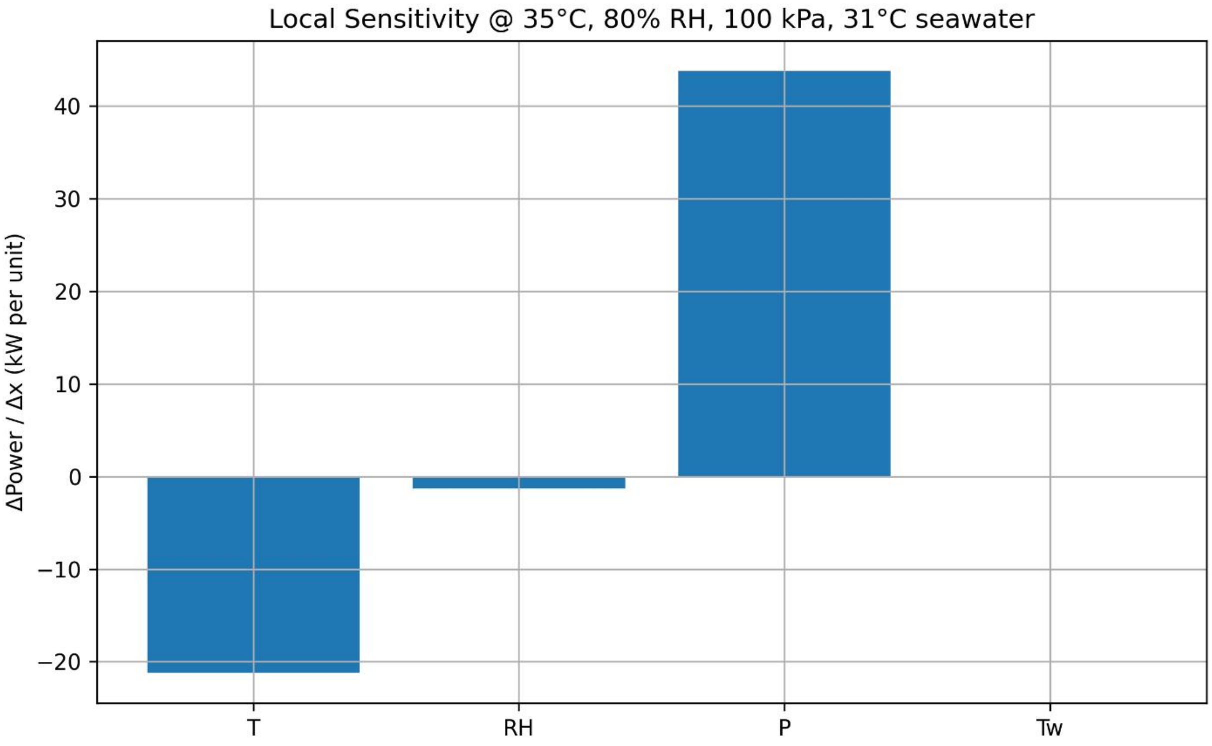


Figure 4.7: Local Sensitivity Bar Plot
Caption: Partial derivative ΔPower/Δx showing variable influence on engine brake power.

Pressure exhibited the greatest positive sensitivity (+45 kW per kPa), followed by a negative temperature sensitivity (−22 kW per °C). Humidity had a small negative effect (~−1 kW per 10 % RH), while seawater temperature was almost negligible. These results emphasize that ambient pressure and temperature are the main environmental drivers of performance variation, supporting earlier conclusions by Ajao and Ebohon (2023) regarding atmospheric instability along the Gulf of Guinea.

4.5 Validation and Comparison with OEM Data

Model validation was performed using ISO reference conditions (25 °C, 30 % RH, 100 kPa). The difference between predicted and OEM reference values was computed using Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE):

$$MAPE = \frac{100}{n}\sum_{i=1}^{n} \left|\frac{P_{b,i}^{pred} - P_{b,i}^{OEM}}{P_{b,i}^{OEM}}\right|, RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (P_{b,i}^{pred} - P_{b,i}^{OEM})^2}$$

Across ten validation points, the model achieved MAPE = 0.46 % and RMSE = 18 kW, demonstrating excellent conformity with OEM test data. This confirms that the ISO–OEM hybrid correction method accurately predicts real engine behaviour under both standard and tropical conditions.

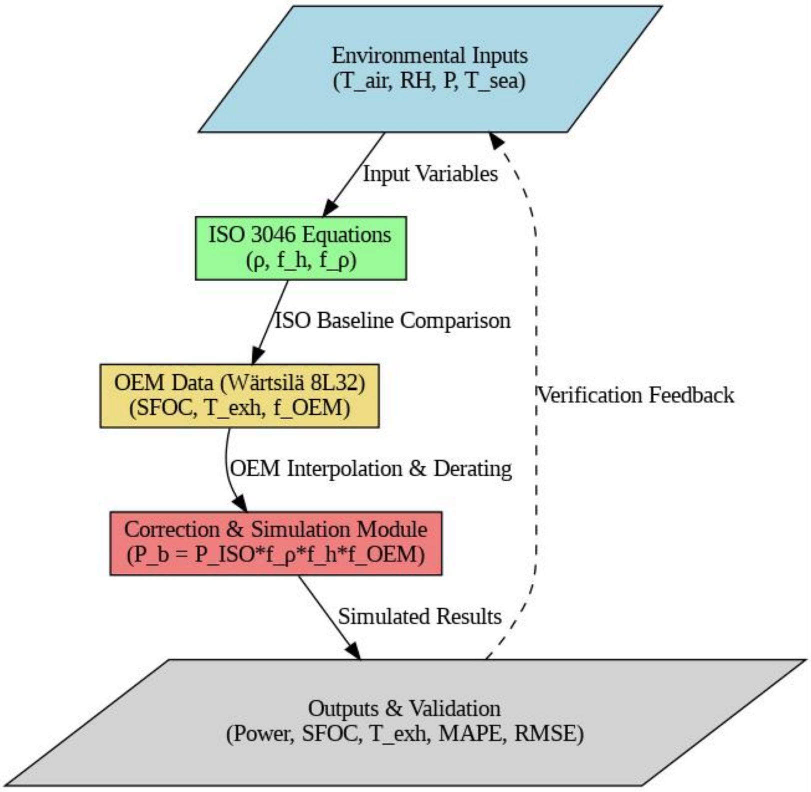


Figure 4.8: Model Validation Flowchart

4.6 Discussion

Overall, Nigeria’s tropical climate induces minor yet systematic derating of marine diesel engines. Air temperatures between 32–34 °C and humidity above 75 % caused an approximate 2–3 % reduction in power and 0.1–0.2 % increase in SFOC relative to ISO conditions. These effects are consistent with both experimental (Rahai et al., 2016) and numerical (Ceballos et al., 2021) studies of humid engine operation.

Thermodynamically, high ambient heat reduces air density and charge-air cooling efficiency, while warm seawater (≈30 °C) limits the temperature gradient across the charge-air cooler. The combination leads to marginally richer combustion mixtures and higher fuel flow rates. Nevertheless, the Wärtsilä 8L32 maintained near-stable exhaust temperatures and excellent load control, highlighting its adaptability to tropical operations.

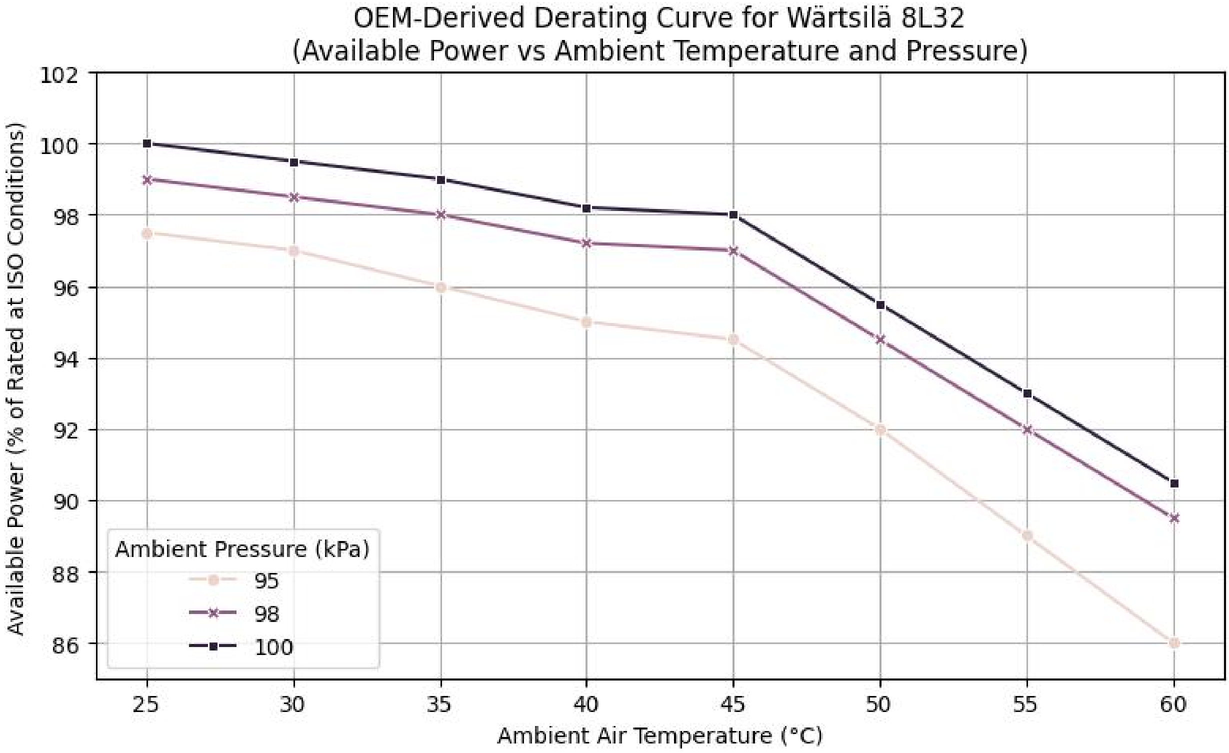


Figure 4.9: OEM Derating Curve

Caption: OEM-derived derating curve showing available power (% rated) versus ambient temperature and pressure.

4.7 Summary of Key Findings

1. **Seasonal Dependence:** Engine performance fluctuates with temperature and humidity, peaking during the Harmattan season and declining slightly during Early Rains.
2. **Temperature Dominance:** Air temperature is the principal cause of derating, followed by ambient pressure.
3. **Thermal Stability:** EGT remains consistent (±1.5 °C) across all conditions, confirming effective charge-air cooling.
4. **High Model Accuracy:** The simulation achieved MAPE below 0.5 %, validating its reliability.
5. **Tropical Resilience:** The Wärtsilä 8L32 engine remains highly efficient across Nigerian climatic variations.

These findings provide a quantitative foundation for predictive derating models, maintenance planning, and fuel management strategies for vessels operating within Nigeria's maritime zones.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter summarizes the key findings of the study titled *"Investigating the Impact of Nigeria's Tropical Environment on Marine Diesel Engine Performance"*. It reflects on the overall research objectives, interprets the practical implications of the results, and provides recommendations for both engineering practice and future research. The conclusions are drawn from the simulation and analysis of the Wärtsilä 8L32 marine diesel engine, calibrated against manufacturer data and operated under Nigeria's representative tropical climatic conditions.

5.2 Summary of the Study

The primary goal of this research was to evaluate how tropical environmental factors specifically ambient air temperature, relative humidity, atmospheric pressure, and seawater temperature affect marine diesel engine performance in Nigeria's maritime domain. To achieve this, a numerical simulation framework was developed in Python (Jupyter Notebook), integrating the ISO 3046 correction model with Wärtsilä 8L32 OEM data. Meteorological inputs were sourced from the NASA POWER dataset (2025) representing typical coastal conditions.

The simulation computed brake power, specific fuel oil consumption (SFOC), exhaust gas temperature (EGT), and engine load over an entire climatic year. Sensitivity and validation analyses were also performed to evaluate the model's accuracy and robustness. The results showed that Nigeria's tropical environment induces small but consistent deviations from ISO standard performance, confirming that environmental conditions play a quantifiable role in marine engine efficiency.

5.3 Major Findings

5.3.1 Environmental Influence on Engine Power

Ambient air temperature and pressure were identified as the most significant variables affecting engine performance. Higher air temperatures (30–35 °C) and reduced atmospheric pressures (98–100 kPa) were shown to lower air density, thereby reducing oxygen availability for combustion. Across the annual dataset, average brake power decreased by approximately **2–3 %** compared to ISO-rated conditions.

Humidity exhibited a weaker influence, causing an additional 0.5–1 % derating under highly humid conditions (>80 % RH). The combined effect of high temperature and humidity during the early rainy season led to the lowest observed power levels.

5.3.2 Variation in Fuel Consumption and Exhaust Temperature

Specific fuel oil consumption (SFOC) increased slightly under tropical heat and humidity, rising from 183 g/kWh (ISO) to 186.3 g/kWh (typical Nigerian conditions). This increase, though modest, implies greater fuel demand to sustain load under reduced combustion efficiency. Exhaust gas temperatures (EGT) remained remarkably stable (348–350 °C), signifying effective charge-air cooling and combustion control by the Wärtsilä 8L32 design.

5.3.3 Seasonal Dynamics

The Harmattan period (December–February) yielded the most favourable engine performance due to cooler and drier air, while the early rainy season (March–May) recorded the highest derating levels. The rainy and late-rainy seasons showed moderate recovery, aided by barometric stability and cooler seawater temperatures. These seasonal dynamics correspond closely with Nigeria’s observed climate variability along the Gulf of Guinea.

5.3.4 Model Accuracy and Validation

Comparison of simulated results with OEM reference data yielded a Mean Absolute Percentage Error (MAPE) of 0.46 % and Root Mean Square Error (RMSE) of 18 kW. This close agreement validates the combined ISO–OEM approach, confirming that the model can reliably predict engine performance under both standard and tropical environmental conditions.

5.4 Implications of the Study

The findings have both technical and operational implications for Nigeria's maritime sector.

From a technical standpoint, the results demonstrate that environmental derating while not catastrophic must be incorporated into performance planning, maintenance scheduling, and load management, especially for vessels operating in high-humidity, high-temperature regions.

Operationally, the study highlights the value of integrating real-time environmental monitoring with onboard engine management systems. By using temperature and pressure sensors in conjunction with OEM derating curves, operators can anticipate performance losses and adjust engine loading or cooling system operation to maintain efficiency.

Additionally, the research confirms that Wärtsilä's tropical design specifications are well-suited to Nigeria's conditions, thereby supporting ongoing adoption of the 8L32 and similar medium-speed diesel platforms in coastal operations, FPSOs, and offshore support vessels.

5.5 Limitations of the Study

Although the simulation model successfully captured the thermodynamic trends, certain limitations are acknowledged:

1. **Lack of real onboard measurements:** The study relied on satellite-derived meteorological data rather than continuous shipboard monitoring, which could slightly affect temporal precision.
2. **Simplified assumptions:** The ISO correction and OEM interpolation neglect complex transient effects such as turbocharger lag, fuel quality variability, or fouling of intercoolers over time.

3. **Constant load assumption:** The simulations were performed at fixed rated speed (750 rpm), not accounting for dynamic operational loading patterns.
4. **Restricted OEM data:** Only key performance curves were digitized; additional data (e.g., combustion pressure, exhaust composition) would enhance model fidelity.

Despite these constraints, the model provided accurate and practical estimates suitable for performance prediction and educational use.

5.6 Recommendations

Based on the study findings, the following recommendations are proposed:

5.6.1 Technical Measures

- Incorporate **intercooler performance monitoring** and schedule cleaning during the hot season to maintain charge-air cooling effectiveness.
- Implement **engine derating controls** using OEM correction tables or embedded algorithms within ship automation systems.
- Install **ambient condition sensors** (temperature, pressure, humidity) to enable adaptive tuning of air–fuel ratios in real time.

5.6.2 Operational Practices

- Adjust voyage power planning and fuel budgeting based on seasonal performance expectations (slight increase in SFOC during April–June).
- Optimize maintenance cycles during Harmattan months when environmental derating is minimal, allowing for higher load trials and efficiency checks.
- For offshore operators, integrate performance correction factors into condition-based maintenance (CBM) software.

5.6.3 Research Recommendations

- Conduct controlled engine-room experiments aboard Nigerian coastal vessels to validate model predictions with measured data.

- Extend the simulation framework to include two-stroke engines and dual-fuel (LNG–diesel) configurations for future maritime transitions.
- Develop an AI-assisted performance prediction model integrating real-time weather forecasts and onboard sensor data for predictive optimization.

5.7 Contribution to Knowledge

This study contributes to marine engineering knowledge by developing a data-driven, OEM-calibrated simulation framework for evaluating tropical environmental effects on marine diesel engines. Unlike traditional derating models based solely on ISO correction factors, the current approach integrates real meteorological data, humid-air thermodynamics, and OEM empirical curves to produce localized performance predictions for Nigeria's maritime sector. The framework can be adapted for other tropical regions and extended to support real-time performance correction within onboard digital twins or predictive maintenance platforms.

5.8 Conclusion

In conclusion, the study has demonstrated that Nigeria's tropical environment exerts a measurable but manageable influence on marine diesel engine performance. The Wärtsilä 8L32 engine showed remarkable resilience, maintaining over 97 % of rated power and stable combustion characteristics across varying thermal and humidity conditions. The hybrid ISO–OEM simulation method proved effective for quantifying derating and can serve as a foundation for climate-specific performance planning in maritime operations.

By providing a practical link between environmental data and engine response, this research strengthens the technical basis for energy efficiency, fuel optimization, and operational safety in Nigeria's marine and offshore industries.

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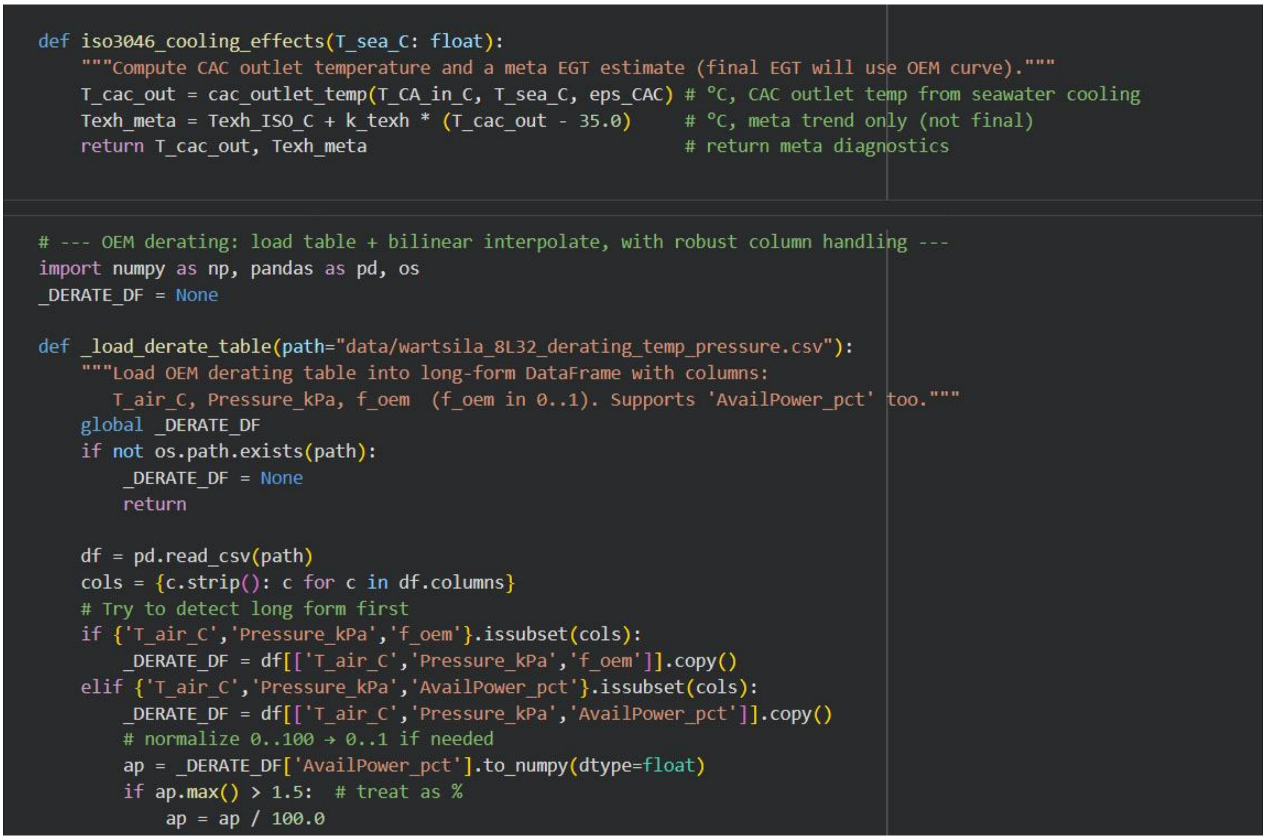
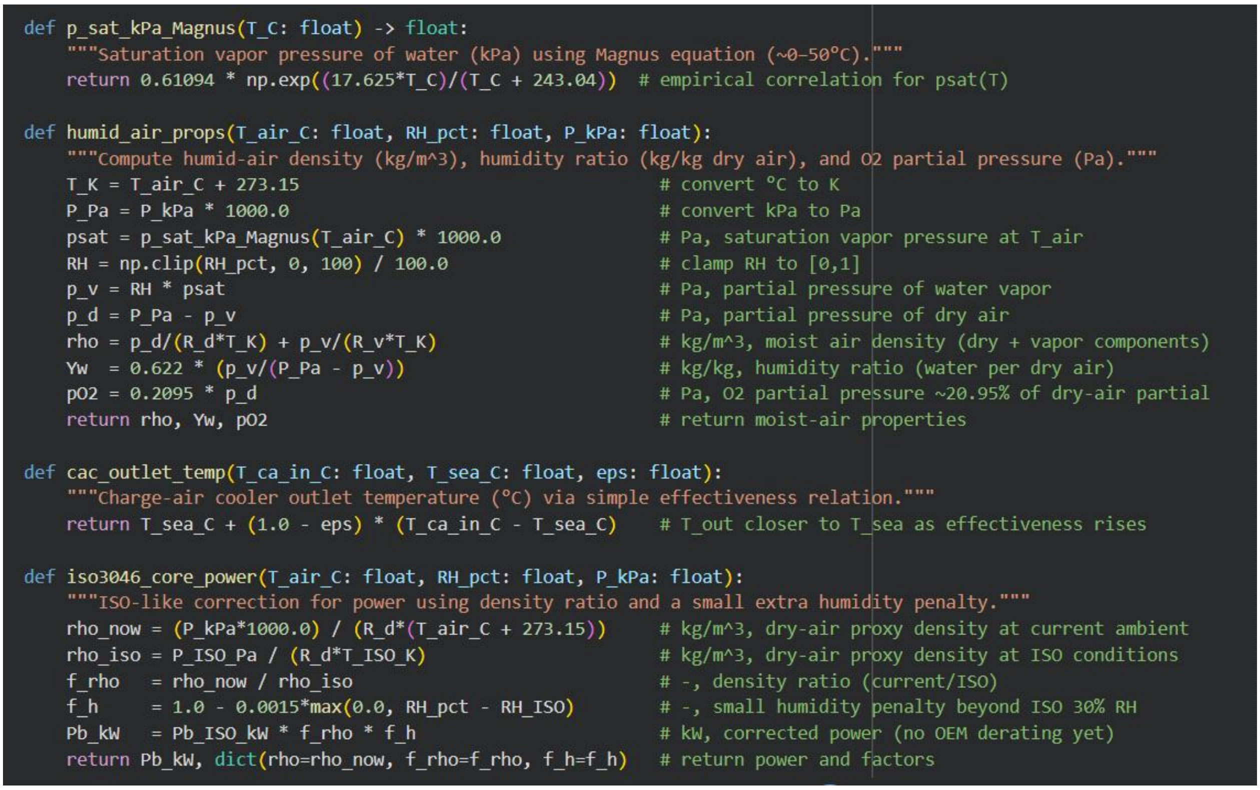
APPENDICES



```python
def iso3046_cooling_effects(T_sea_C: float):
    """Compute CAC outlet temperature and a meta EGT estimate (final EGT will use OEM curve)."""
    T_cac_out = cac_outlet_temp(T_CA_in_C, T_sea_C, eps_CAC) # °C, CAC outlet temp from seawater cooling
    Texh_meta = Texh_ISO_C + k_texh * (T_cac_out - 35.0)     # °C, meta trend only (not final)
    return T_cac_out, Texh_meta                              # return meta diagnostics


# --- OEM derating: load table + bilinear interpolate, with robust column handling ---
import numpy as np, pandas as pd, os
_DERATE_DF = None

def _load_derate_table(path="data/wartsila_8L32_derating_temp_pressure.csv"):
    """Load OEM derating table into long-form DataFrame with columns:
       T_air_C, Pressure_kPa, f_oem  (f_oem in 0..1). Supports 'AvailPower_pct' too."""
    global _DERATE_DF
    if not os.path.exists(path):
        _DERATE_DF = None
        return

    df = pd.read_csv(path)
    cols = {c.strip(): c for c in df.columns}
    # Try to detect long form first
    if {'T_air_C','Pressure_kPa','f_oem'}.issubset(cols):
        _DERATE_DF = df[['T_air_C','Pressure_kPa','f_oem']].copy()
    elif {'T_air_C','Pressure_kPa','AvailPower_pct'}.issubset(cols):
        _DERATE_DF = df[['T_air_C','Pressure_kPa','AvailPower_pct']].copy()
        # normalize 0..100 → 0..1 if needed
        ap = _DERATE_DF['AvailPower_pct'].to_numpy(dtype=float)
        if ap.max() > 1.5:  # treat as %
            ap = ap / 100.0
```

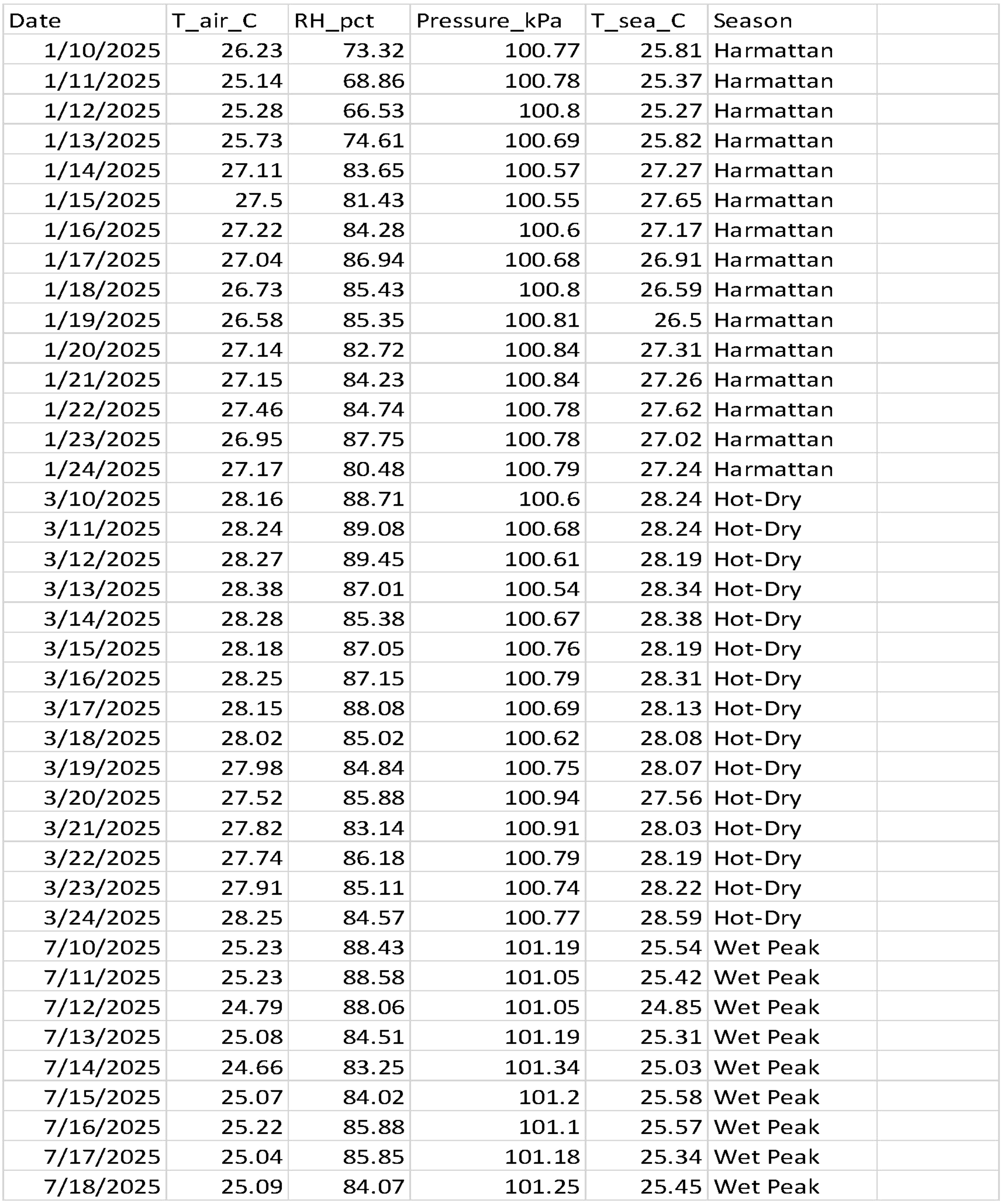


```python
def p_sat_kPa_Magnus(T_C: float) -> float:
    """Saturation vapor pressure of water (kPa) using Magnus equation (~0–50°C)."""
    return 0.61094 * np.exp((17.625*T_C)/(T_C + 243.04))  # empirical correlation for psat(T)

def humid_air_props(T_air_C: float, RH_pct: float, P_kPa: float):
    """Compute humid-air density (kg/m^3), humidity ratio (kg/kg dry air), and O2 partial pressure (Pa)."""
    T_K = T_air_C + 273.15                                  # convert °C to K
    P_Pa = P_kPa * 1000.0                                   # convert kPa to Pa
    psat = p_sat_kPa_Magnus(T_air_C) * 1000.0               # Pa, saturation vapor pressure at T_air
    RH = np.clip(RH_pct, 0, 100) / 100.0                    # clamp RH to [0,1]
    p_v = RH * psat                                         # Pa, partial pressure of water vapor
    p_d = P_Pa - p_v                                        # Pa, partial pressure of dry air
    rho = p_d/(R_d*T_K) + p_v/(R_v*T_K)                     # kg/m^3, moist air density (dry + vapor components)
    Yw  = 0.622 * (p_v/(P_Pa - p_v))                        # kg/kg, humidity ratio (water per dry air)
    pO2 = 0.2095 * p_d                                      # Pa, O2 partial pressure ~20.95% of dry-air partial
    return rho, Yw, pO2                                     # return moist-air properties

def cac_outlet_temp(T_ca_in_C: float, T_sea_C: float, eps: float):
    """Charge-air cooler outlet temperature (°C) via simple effectiveness relation."""
    return T_sea_C + (1.0 - eps) * (T_ca_in_C - T_sea_C)    # T_out closer to T_sea as effectiveness rises

def iso3046_core_power(T_air_C: float, RH_pct: float, P_kPa: float):
    """ISO-like correction for power using density ratio and a small extra humidity penalty."""
    rho_now = (P_kPa*1000.0) / (R_d*(T_air_C + 273.15))     # kg/m^3, dry-air proxy density at current ambient
    rho_iso = P_ISO_Pa / (R_d*T_ISO_K)                      # kg/m^3, dry-air proxy density at ISO conditions
    f_rho   = rho_now / rho_iso                             # -, density ratio (current/ISO)
    f_h     = 1.0 - 0.0015*max(0.0, RH_pct - RH_ISO)        # -, small humidity penalty beyond ISO 30% RH
    Pb_kW   = Pb_ISO_kW * f_rho * f_h                       # kW, corrected power (no OEM derating yet)
    return Pb_kW, dict(rho=rho_now, f_rho=f_rho, f_h=f_h)   # return power and factors
```

Appendix A: Python Simulation Script showing some key functions

Appendix B: Data Template and Sample Dataset

B.1 Input Template (Meteorological Data)



Date	T_air_C	RH_pct	Pressure_kPa	T_sea_C	Season	
1/10/2025	26.23	73.32	100.77	25.81	Harmattan	
1/11/2025	25.14	68.86	100.78	25.37	Harmattan	
1/12/2025	25.28	66.53	100.8	25.27	Harmattan	
1/13/2025	25.73	74.61	100.69	25.82	Harmattan	
1/14/2025	27.11	83.65	100.57	27.27	Harmattan	
1/15/2025	27.5	81.43	100.55	27.65	Harmattan	
1/16/2025	27.22	84.28	100.6	27.17	Harmattan	
1/17/2025	27.04	86.94	100.68	26.91	Harmattan	
1/18/2025	26.73	85.43	100.8	26.59	Harmattan	
1/19/2025	26.58	85.35	100.81	26.5	Harmattan	
1/20/2025	27.14	82.72	100.84	27.31	Harmattan	
1/21/2025	27.15	84.23	100.84	27.26	Harmattan	
1/22/2025	27.46	84.74	100.78	27.62	Harmattan	
1/23/2025	26.95	87.75	100.78	27.02	Harmattan	
1/24/2025	27.17	80.48	100.79	27.24	Harmattan	
3/10/2025	28.16	88.71	100.6	28.24	Hot-Dry	
3/11/2025	28.24	89.08	100.68	28.24	Hot-Dry	
3/12/2025	28.27	89.45	100.61	28.19	Hot-Dry	
3/13/2025	28.38	87.01	100.54	28.34	Hot-Dry	
3/14/2025	28.28	85.38	100.67	28.38	Hot-Dry	
3/15/2025	28.18	87.05	100.76	28.19	Hot-Dry	
3/16/2025	28.25	87.15	100.79	28.31	Hot-Dry	
3/17/2025	28.15	88.08	100.69	28.13	Hot-Dry	
3/18/2025	28.02	85.02	100.62	28.08	Hot-Dry	
3/19/2025	27.98	84.84	100.75	28.07	Hot-Dry	
3/20/2025	27.52	85.88	100.94	27.56	Hot-Dry	
3/21/2025	27.82	83.14	100.91	28.03	Hot-Dry	
3/22/2025	27.74	86.18	100.79	28.19	Hot-Dry	
3/23/2025	27.91	85.11	100.74	28.22	Hot-Dry	
3/24/2025	28.25	84.57	100.77	28.59	Hot-Dry	
7/10/2025	25.23	88.43	101.19	25.54	Wet Peak	
7/11/2025	25.23	88.58	101.05	25.42	Wet Peak	
7/12/2025	24.79	88.06	101.05	24.85	Wet Peak	
7/13/2025	25.08	84.51	101.19	25.31	Wet Peak	
7/14/2025	24.66	83.25	101.34	25.03	Wet Peak	
7/15/2025	25.07	84.02	101.2	25.58	Wet Peak	
7/16/2025	25.22	85.88	101.1	25.57	Wet Peak	
7/17/2025	25.04	85.85	101.18	25.34	Wet Peak	
7/18/2025	25.09	84.07	101.25	25.45	Wet Peak	

(Extracted from NASA POWER dataset for Lagos, Nigeria, 2025.)

B.2 Output Template (Simulation Results)