UNIVERSITY OF PIRAEUS

DEPARTMENT OF MARITIME STUDIES

HELLENIC NAVAL ACADEMY

DEPARTMENT OF NAVAL SCIENCES

INTERINSTITUTIONAL POSTGRADUATE PROGRAM IN MARINE SCIENCE AND TECHNOLOGY MANAGEMENT

MSc Thesis

DESIGN OF MEASUREMENTS AND DATA PROCESSING FOR ENERGY AUDITS IN SHIPS

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Piraeus

September 2025

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The approval of the thesis by the Department of Maritime Studies of the University of Piraeus does not imply acceptance of the author's views.

Acknowledgements

This thesis was developed in the context of the postgraduate program in Marine Science and Technology Management. I would like to sincerely thank my supervisor, Professor Efthimios Pariotis, for his invaluable guidance, support, and continuous feedback throughout this process. I also extend my gratitude to the members of the Three-Member Examination Committee for their insightful comments and suggestions.

Abstract

This thesis investigates the methodologies and tools used to collect and process measurement data during shipboard energy audits. The study aims to provide a structured framework for engineers conducting such audits, focusing on the accuracy, reliability, and regulatory alignment of collected data. It begins by categorizing the main technical quantities monitored onboard and evaluates the most common measurement methodologies based on criteria such as accuracy, complexity, cost, and suitability for marine environments. A detailed review of instrumentation, ranging from flow meters and shaft power sensors to temperature and emissions analyzers, is presented, including comparative tables. The thesis then analyzes signal processing techniques and estimation uncertainty, outlining best practices for sampling, synchronization, and data treatment. The study concludes with a series of real-world case evaluations, highlighting strengths, limitations, and methodological alternatives. Findings emphasize that proper instrumentation selection, uncertainty quantification, and adherence to international standards (ISO 50001, ISO 50002, EN 16247-4, MARPOL Annex VI) are essential for producing valid and actionable audit results. This work serves as a practical guide for audit engineers seeking to optimize energy performance monitoring in maritime contexts.

Keywords: Energy Audit, Ship Efficiency, Measurement Methodology, Signal Processing, Uncertainty Evaluation

Περίληψη

Η παρούσα διπλωματική εργασία διερευνά τις μεθοδολογίες και τα εργαλεία που χρησιμοποιούνται για τη συλλογή και επεξεργασία δεδομένων μετρήσεων κατά τη διάρκεια ενεργειακών ελέγχων επί των πλοίων. Η μελέτη στοχεύει να παρέχει ένα δομημένο πλαίσιο για τους μηχανικούς που διεξάγουν τέτοιους ελέγχους, εστιάζοντας στην ακρίβεια, την αξιοπιστία και την ευθυγράμμιση των συλλεγόμενων δεδομένων με τους διεθνείς κανονισμούς. Αρχικά κατηγοριοποιούνται οι κύριες τεχνικές ποσότητες που παρακολουθούνται επί του πλοίου και αξιολογούνται οι πιο συνηθισμένες μεθοδολογίες μέτρησης με βάση κριτήρια όπως η ακρίβεια, η πολυπλοκότητα, το κόστος και η καταλληλόλητα για θαλάσσια περιβάλλοντα. Παρουσιάζεται μια λεπτομερής ανασκόπηση των οργάνων, που κυμαίνονται από μετρητές ροής και αισθητήρες ισχύος άξονα έως αναλυτές θερμοκρασίας και εκπομπών, συμπεριλαμβανομένων συγκριτικών πινάκων. Στη συνέχεια, η διατριβή αναλύει τις τεχνικές επεξεργασίας σήματος και την αβεβαιότητα εκτίμησης, περιγράφοντας τις βέλτιστες πρακτικές για τη δειγματοληψία, τον συγχρονισμό και την επεξεργασία δεδομένων. Η μελέτη ολοκληρώνεται με μια σειρά αξιολογήσεων πραγματικών περιπτώσεων, επισημαίνοντας τα δυνατά σημεία, τους περιορισμούς και τις μεθοδολογικές εναλλακτικές λύσεις. Τα ευρήματα τονίζουν ότι η σωστή επιλογή οργάνων, η ποσοτικοποίηση της αβεβαιότητας και η τήρηση των διεθνών προτύπων (ISO 50001, ISO 50002, EN 16247-4, Παράρτημα VI της MARPOL) είναι απαραίτητα για την παραγωγή έγκυρων και εφαρμόσιμων αποτελεσμάτων ελέγχου. Αυτή η εργασία χρησιμεύει ως πρακτικός οδηγός για τους μηχανικούς ελέγχου που επιδιώκουν να βελτιστοποιήσουν την παρακολούθηση της ενεργειακής απόδοσης σε ναυτιλιακά περιβάλλοντα.

Λέξεις-κλειδιά: Ενεργειακός Έλεγχος, Απόδοση Πλοίου, Μεθοδολογία Μέτρησης, Επεξεργασία Σήματος, Αξιολόγηση Αβεβαιότητας

Table of Contents

Table of Images

Tables

1. Introduction

1.1 Background

Maritime transport accounts for over 80% of the international trade by volume, underscoring its role as an essential component of the global economy. Even though its efficiency in mass cargo transportation is undeniable, the sector contributes significantly to global greenhouse gas (GHG) emissions and energy consumption. Maritime trade is responsible for approximately 3% of all global GHG emissions. It may seem a relatively low share, but it is comparable to that of entire countries. Indicatively, if the sector were a country, it would rank as 6th-7th largest GHG emitter on a global scale.(Christensen and Fahnestock, 2025) In 2024 alone, CO2 emissions from only container ships set a record high of about 240 million tons, a 14% increase year over year, largely driven by longer voyages. Despite improvements in energy intensity (approximately 10% gains since 2016), absolute emissions continue to rise due to growth in shipping volume. (Mao *et al.*, 2025)

To address these growing environmental challenges, the International Maritime Organization (IMO) has progressively developed a regulatory framework aimed at decarbonizing maritime transport. The regulatory effort began in 2003 with Assembly Resolution A.963(23), which introduced the control of GHG emissions from ships. It was significantly advanced in 2011 with the adoption of Resolution MEPC.203(62), which incorporated technical and operational measures for energy efficiency into MARPOL Annex VI. In 2018, the Initial GHG Strategy (MEPC.304(72)) (Maritime Organization, 2018) set clear targets; a 40% reduction in carbon intensity by 2030 and a 70% reduction by 2050, with the ultimate goal of full decarbonization within this century. The revised 2023 GHG Strategy (MEPC 80) (International Maritime Organization, 2023) reinforced these commitments by setting a firm objective of achieving net-zero GHG emissions from international shipping by 2050. It also established an interim target for at least 5% (ideally 10%) of energy used in international shipping to come from zero or near-zero GHG fuels by 2030.

To operationalize these regulatory targets, the IMO has introduced several mandatory instruments focused on monitoring and improving ship-level energy performance. These include the Energy Efficiency Design Index (EEDI) for new ships, the Energy Efficiency Existing Ship Index (EEXI) for existing vessels and the Ship Energy Efficiency Management Plan (SEEMP), which outlines measures for improving operational performance. In addition, the Energy Efficiency Operational Indicator (EEOI) was developed to monitor carbon intensity during operations and support performance benchmarking.

In this context, improving energy performance on ships has become both a regulatory obligation and an operational priority. Enhancing energy efficiency is directly linked to emissions reduction, as lower fuel consumption leads to proportionally lower CO_2 emissions, the primary source of GHGs in maritime transport. Therefore, energy efficiency measures not only support compliance with international targets but also contribute to cost savings and environmental responsibility. To achieve these objectives, energy audits are employed as systematic processes to assess onboard energy use, identify inefficiencies and recommend corrective actions. These audits form the foundation for developing targeted improvement strategies and ensuring alignment with evolving international standards.

However, the application of energy audits in the shipboard environment presents distinct challenges that limit the effectiveness of standardized methodologies. Variability in sea conditions, limited onboard instrumentation, restricted physical space and inconsistent availability of data often set back the optimal collection and analysis of energy-related information. Furthermore, several critical parameters may not be directly measurable under real-world operating conditions, necessitating the use of indirect assessment techniques based on empirical models, proxy indicators, or estimated correlations. These practical limitations highlight the need for tailored audit approaches that can adapt to the complexities of maritime operations while still delivering reliable insights into energy performance.

1.2 Motivation and purpose

This thesis, entitled "Design of Measurements and Data Processing for Energy Audits in Ships," is driven by the need to enhance the accuracy, reliability and technical robustness of energy audits conducted in the maritime sector. Its primary objective is to systematically document the tools, techniques and methodologies employed in the collection, processing and interpretation of energy-related data during onboard audits, with the ultimate aim of supporting sound, well-substantiated conclusions.

Recognizing the practical constraints inherent to the shipboard environment, this study places particular emphasis on the evaluation and adaptation of measurement methodologies in light of their underlying operating principles, technical characteristics, cost-effectiveness and suitability for maritime applications. Furthermore, it underscores the importance of applying appropriate sampling protocols, signal conditioning techniques and uncertainty estimation procedures to ensure the integrity and reliability of audit outcomes. In doing so, the thesis contributes to the development of more effective and context-aware auditing practices that can support regulatory compliance, performance optimization and environmental sustainability in the shipping industry.

1.3 Objectives

Building upon the motivation and scope outlined above, this thesis sets out the following specific objectives:

1. To identify and systematically categorize the fundamental physical quantities typically measured

during shipboard energy audits.

2. To describe standard measurement methodologies employed in practice or, where such standards are lacking, to propose the most suitable techniques based on operational constraints and audit requirements.
3. To critically evaluate these methodologies in terms of reliability, implementation complexity, required instrumentation, cost and expected accuracy, thereby offering practical guidance for selecting the most appropriate approach in each context.
4. To catalogue the primary measuring instruments used in maritime energy audits, compile their key technical specifications into comparative tables and assess their applicability and resilience within the shipboard environment.
5. To examine the complete data processing workflow, encompassing sampling procedures, signal conditioning, estimation methods and the evaluation of measurement uncertainty, with an emphasis on ensuring the robustness of audit results.
6. To present and analyze representative case studies or real-world applications drawn from academic literature and available data sources, assessing the effectiveness of applied methodologies and identifying possible alternative approaches.

2. Categorization of Quantities Measured During Energy Audits in Ships

2.1 Introduction

Conducting an effective energy audit onboard a vessel necessitates a structured, methodical approach to the identification, acquisition and interpretation of energy-related data. These measurements encompass a wide range of shipboard systems and operational conditions, forming the foundation for evaluating the vessel's energy balance, emissions footprint and overall performance efficiency. Accurate and well-organized data collection is critical not only for internal performance assessments but also for ensuring compliance with international regulatory frameworks such as MARPOL Annex VI, the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), and the Energy Efficiency Operational Indicator (EEOI). (Maritime Organization, 2013, 2022a, 2022b)

A key aspect of ensuring audit quality lies in the proper classification of the measured quantities. This allows the audit to remain comprehensive, targeted and consistent with the regulatory objectives and operational realities of maritime energy management.

This chapter provides a detailed categorization of the quantities typically measured during an energy audit, structured by relevant ship systems (e.g. propulsion, auxiliary, HVAC), physical domains (e.g. thermal, electrical, mechanical) and operational contexts (e.g. steady-state vs. transient conditions, voyage phase). In addition to raw measurements, it includes derived performance indicators, temporal and spatial considerations affecting data quality and the regulatory and methodological frameworks that shape the scope and priorities of data collection activities. (BSI, 2013, 2018; CEN, 2022)

2.2 Categorization by Ship System

A logical and widely adopted method for organizing energy-related measurements is by grouping them according to the vessel's main energy-consuming systems. Each shipboard system (whether related to propulsion, auxiliary operations, thermal management, or hotel services) has unique functional characteristics and specific energy demands. As such, each one requires a tailored set of measurement parameters to accurately assess its energy performance, identify inefficiencies and support targeted optimization strategies.

By categorizing data based on these systems, the audit process becomes more manageable, structured and aligned with the ship's actual energy distribution. This approach also ensures that all significant consumers of fuel and electrical energy are accounted for, facilitating comprehensive energy profiling and enabling system-level diagnostics. Furthermore, it supports the identification of interdependencies between systems, such as the influence of auxiliary engine load on cooling or HVAC demands and allows for more meaningful benchmarking and comparison across vessels or voyages.

The following table outlines the primary ship systems typically included in an energy audit, along with representative quantities commonly measured for each:

Ship System	Typical Measured Quantities
Main Propulsion	- Shaft torque and power - Engine revolutions per minute (RPM) - Fuel flow rate - Engine load - Exhaust gas temperature
Auxiliary Engines	- Electrical output (kW) - Fuel consumption - Load factor - Exhaust gas temperature
Boilers and Steam	- Fuel input rate - Steam production flow (kg/h) - Steam pressure - Flue gas temperature - Insulation heat losses
Cooling Systems	- Inlet and outlet temperatures - Seawater/freshwater flow rates - Pump motor power consumption
Fuel Service System	- Fuel temperature - Viscosity - Flow rate - Delivery pressure
Compressed Air System	- System pressure - Air flow rate - Detection and quantification of leaks
HVAC Systems	- Compressor power load - Airflow rates (m^3/h) - Ambient and conditioned space temperatures - CO_2 concentration levels
Lighting & Hotel Loads	- Electrical power consumption (kWh) - Illumination levels (lux) - Occupancy patterns - Usage duration
Electrical System	- Voltage - Current - Frequency - Power factor - Harmonic distortion - Total energy consumption (kWh)

Table 1: Typical Measured Quantities in Energy Audits by Ship System(Iordanidis et al.*, 2010)*

This system-based classification not only ensures full coverage of all key energy-consuming subsystems onboard but also provides a foundation for prioritizing data collection efforts, designing instrumentation layouts and selecting appropriate measurement and logging equipment. Moreover, this approach facilitates the alignment of audit practices with the performance indicators required under regulatory frameworks such as the EEDI, EEXI and SEEMP, and it supports continuous monitoring efforts that can feed into automated performance management and decision-support systems. (Marantis, 2012; Johnson, 2014; GHGES MARINE SOLUTIONS, 2016)

2.3 Categorization by Physical Domain

Beyond system-based classification, a complementary and technically insightful approach is to group measured quantities according to their physical domain, by the type of physical property they represent and their role in energy transfer, conversion, and consumption onboard the vessel. This categorization enables a more close-up understanding of shipboard processes by identifying the nature of energy flows and losses in electrical, mechanical, thermal, and fluid systems, as well as emissions and operational performance. (Marantis, 2012; GHGES MARINE SOLUTIONS, 2016)

This section organizes typical energy audit measurements into distinct physical categories, explaining their significance and relevance to performance evaluation, regulatory compliance, and energy efficiency optimization.

2.3.1 Electrical Quantities

Typical Measurements:

- Voltage (V), Current (A)
- Active, Reactive and Apparent Power (kW, kVAR, kVA)
- Power Factor (cosφ), Frequency (Hz)
- Energy Consumption (kWh), Load Profiles, Harmonics(Hasanbeigi and Price, 2010; Rosenqvist *et al.*, 2012)

Electrical parameters are fundamental for assessing the performance and quality of the onboard power distribution system. They support the evaluation of energy efficiency in electrically powered equipment, the identification of load imbalances and overloading conditions and the detection of poor power factor or harmonic distortions that may affect system reliability or lead to energy losses.

2.3.2 Mechanical Quantities

Typical Measurements:

- Torque (Nm), Rotational Speed (RPM), Shaft Power
- Static and Differential Pressure (bar or psi)
- Motor Load, Mechanical Vibrations(Iliopoulos, 2018)

Mechanical measurements are essential for evaluating propulsion systems, auxiliary machinery and various rotating components. These parameters enable performance diagnostics, early fault detection and optimization of machinery operation. For instance, shaft power is a key input for calculating propulsion efficiency and fuel-specific performance indicators.

2.3.3 Thermal Quantities

Typical Measurements:

- Exhaust Gas, Steam, and Cooling Water Temperatures
- Heat Transfer Rate (e.g. $Q=m\cdot cp\cdot\Delta T$)
- Surface and Ambient Temperatures (including infrared thermal imaging)(Ministry of Environment, 2017)

Thermal parameters are crucial for understanding heat generation, dissipation and recovery within the ship’s energy systems. Monitoring thermal losses helps identify opportunities for insulation improvements and waste heat recovery, thereby increasing the overall thermal efficiency of steam, engine and HVAC systems.

2.3.4 Fuel-Related Quantities

Typical Measurements:

- Fuel Flow Rate (kg/h or L/h)
- Fuel Temperature, Viscosity, and Calorific Value
- Specific Fuel Oil Consumption (SFOC)(Marantis, 2012)

Fuel-related data directly impact both operating cost and environmental performance. These measurements are key for calculating energy and emissions-related KPIs such as EEOI and EEXI. Fuel properties also influence combustion quality and engine performance, making them essential for both monitoring and optimization.

2.3.5 Fluid Flow Parameters

Typical Measurements:

- Flow Rates of Water, Steam, Lubricants, and Air
- Air Velocity in Ventilation Ducts(Marantis, 2012)

Accurate flow measurements are necessary for evaluating pump and fan efficiency, assessing thermal and ventilation system performance and ensuring proper operation of heat exchangers, cooling loops and compressed air systems. Inefficiencies in flow management can lead to energy waste or compromised system functionality.

2.3.6 Emissions Parameters

Typical Measurements:

- Exhaust Gas Composition: CO_2, NOx, SOx, O_2
- Exhaust Mass Flow Rate (kg/h), Particulate Matter(Hasanbeigi and Price, 2010)

Emissions data are critical for demonstrating compliance with environmental regulations under MARPOL Annex VI and other emission control frameworks. These parameters are also useful for calculating carbon intensity and fuel-specific emissions factors, contributing to the verification of EEXI and EEOI targets.

2.3.7 Environmental & Comfort Parameters

Typical Measurements:

- Ambient Conditions: Temperature, Humidity, Wind, Wave Height
- Indoor Conditions: CO_2 Concentration, Illumination (lux), Air Velocity(CRES, 2000)

Environmental and comfort parameters provide context for energy demand patterns, especially in HVAC and lighting systems. Measuring indoor air quality and ambient conditions supports the optimization of comfort systems without unnecessary energy use, aligning operational needs with energy efficiency objectives.

2.3.8 Operational Parameters

Typical Measurements:

- Ship Speed, Draft, Trim
- Voyage Distance and Duration
- Cargo Load, Engine Operating Hours(Marantis, 2012)

Operational data are essential for contextualizing energy consumption and enabling normalization of performance metrics. These values serve as input for calculating specific consumption indices and allow for fair comparisons between voyages, ships, or operational modes. They also provide baseline input for voyage planning and simulation tools.

Grouping measured variables by physical domain not only aids in selecting appropriate sensors and instrumentation but also supports a deeper understanding of energy transformations occurring throughout the ship’s systems. This classification forms the technical backbone for advanced energy modeling, diagnostics and targeted efficiency improvements.

2.4 Derived Energy Performance Indicators

In addition to directly measured quantities, a comprehensive energy audit requires the calculation of derived energy performance indicators, metrics that combine multiple measurements to quantify efficiency, emissions intensity, or operational characteristics. These indicators play a critical role in interpreting raw data, benchmarking ship performance, tracking trends over time and ensuring compliance with international regulatory frameworks such as the EEXI, EEOI and SEEMP. (Maritime Organization, 2013; BSI, 2018; IACS, 2022)

Derived indicators enable auditors to move beyond isolated readings and evaluate how effectively energy is being transformed, distributed and utilized onboard. They also support comparisons across different vessels, voyages and operational conditions, making them indispensable for performance monitoring and decision-making.

The table below summarizes several key derived indicators commonly used in ship energy audits, along with their typical formulations and practical applications:

Indicator	**Formula / Purpose**
Specific Fuel Oil Consumption (SFOC) (g/kWh)	$\text{SFOC} = \text{Fuel Flow Rate (g/h)} / \text{Power Output (kW)}$ Assesses engine fuel efficiency by expressing the amount of fuel required per unit of power produced(Wahyudi *et al.*, 2020)
Shaft Power (kW)	$P = 2 \cdot \pi \cdot N \cdot T / 60$ Calculates the mechanical power transmitted by the propulsion shaft, using torque (T) and rotational speed (N, in RPM) Essential for propulsion performance analysis(Katsanis, 2024)
Energy Efficiency Operational Indicator (EEOI) (gCO_2 / (ton·nm))	$\text{EEOI} = \text{Total CO}_2\text{ Emissions} / \text{Cargo Transported} \times \text{Distance Travelled}$ Measures voyage-based carbon intensity Used for benchmarking and regulatory reporting(Chakarvarti, 2011)
Thermal Efficiency	$Q = m \cdot cp \cdot \Delta T$ Represents the heat transfer rate in thermal systems (e.g. boilers, heat exchangers), based on mass flow, specific heat capacity, and temperature difference
Energy Intensity (EnPI)	Examples: kWh per nautical mile, per ton of cargo, or per operating hour Useful for trend analysis, diagnostics, and performance comparison across different conditions or voyages
Load Profiles	Time-series analysis of power consumption Identifies patterns such as peak demand, idle periods, and baseload consumption Useful for optimizing load management and detecting anomalies

Table 2: Key Derived Indicators Used in Ship Energy Audits

Derived indicators bridge the gap between raw measurements and actionable insights. Their correct calculation depends on the availability of high-quality input data, as well as an understanding of system interactions and operational contexts. In energy audits, these metrics serve not only as diagnostic tools but also as compliance instruments and performance benchmarks for continuous improvement.

2.5 Temporal and Logging Considerations

The effectiveness of an energy audit is not solely determined by the type of data collected but also by the temporal resolution, duration and synchronization of measurements. Different shipboard systems operate on varying time scales and under fluctuating conditions, which means that the data acquisition strategy must be carefully adapted to suit the dynamics and characteristics of each system. Inadequate logging practices may lead to incomplete datasets, misinterpretations, or missed inefficiencies.

Three primary data acquisition modes are commonly used during ship energy audits:

i. Spot Measurements: These are instantaneous readings obtained using handheld or portable instruments, such as multimeters, anemometers, or thermal cameras. Spot checks are useful for assessing static conditions, verifying sensor accuracy, or supplementing automated measurements. However, they lack the temporal depth needed for trend analysis or dynamic system evaluation.

ii. Continuous Logging: For systems with time-varying behavior, such as propulsion, HVAC and electrical distribution, continuous data logging is essential. Logging periods typically range from 24 to 72 hours, allowing for the capture of variations across different operational modes (e.g. maneuvering, cruising, idle periods). This approach supports load profiling, transient response analysis and energy balance calculations.

iii. Sampling Rate Considerations: The choice of sampling frequency must reflect the response speed and variability of the measured quantity:

   - 1 Hz (once per second) is generally appropriate for fast-changing signals such as electrical current, power output, or frequency.
   - Every 10–60 seconds is sufficient for slower-changing parameters such as temperatures, flow rates, or pressure levels in thermal and hydraulic systems. Incorrect sampling rates can result in undersampling or data overload, both of which hinder meaningful analysis.

A well-designed logging strategy, tailored to system-specific dynamics and supported by appropriate instrumentation, is a critical enabler of high-quality energy audits. It ensures completeness, coherence and comparability of the data, ultimately supporting more reliable conclusions and more effective energy performance improvement measures.(PRS SA, 2025)

2.6 Operational Conditions and Audit Constraints

For energy audits to yield meaningful and actionable insights, measured data must be interpreted within the context of the vessel's operational conditions. The performance of shipboard systems and by extension, their energy consumption, can vary significantly depending on voyage status, environmental influences and onboard procedures. Consequently, energy-related measurements must be carefully contextualized to reflect realistic operating profiles and to ensure that conclusions drawn from the audit are both accurate and applicable.

Several key factors influence the quality, relevance and feasibility of data collection during an onboard energy audit:(Wakeford, 2006; Smith *et al.*, 2013)

- Operational State:
  The energy profile of a vessel is heavily dependent on its operational mode. Measurements taken at sea (e.g. during cruising, maneuvering, or dynamic positioning) will differ significantly from those taken at port, where auxiliary systems, cargo handling equipment, and hotel loads may dominate energy usage. Additionally, systems may operate under part-load or full-load conditions and these variations must be clearly documented during data acquisition, as they affect both efficiency and emissions. Ensuring a representative spread of operational scenarios improves the robustness of performance indicators.
- Environmental Influences:
  External conditions such as wind speed, wave height, ambient temperature and seawater temperature can impact propulsion resistance, cooling system demand and HVAC loads. These variables can distort energy usage patterns and must therefore be recorded alongside technical measurements. Including such environmental data enables normalization and comparative analysis across voyages or vessel types and it supports the application of weather correction factors when calculating energy efficiency metrics.
- Instrumentation Limitations:
  Practical constraints often arise from the physical configuration of the vessel and the capabilities of measurement instruments. Challenges may include restricted access to key measurement points (e.g. engine room pipelines, exhaust stacks), excessive vibration that compromises sensor stability and instrument drift or calibration errors. These issues must be anticipated and addressed through appropriate instrument selection, secure mounting solutions and regular calibration procedures. Where direct measurement is not possible, validated estimation methods or proxy indicators should be used with proper documentation of associated uncertainties.
- Crew Involvement:
  The successful execution of an onboard energy audit often depends on the active participation of the vessel's crew. Crew members are essential for facilitating access to systems, enabling temporary test configurations, operating equipment during performance checks and validating recorded data based on operational logs. Their collaboration enhances

the quality of data and helps ensure that measurements reflect actual working conditions. In some cases, training or briefings may be required to ensure that all personnel involved understand the audit's purpose, procedures and expected outcomes.

In summary, conducting a technically sound and context-aware energy audit requires auditors to recognize and manage the inherent constraints of the shipboard environment. This includes adapting data collection strategies to operating conditions, accounting for external variables, overcoming technical limitations and engaging human resources onboard. These considerations are fundamental to ensuring that the audit results are not only reliable but also relevant for energy optimization and regulatory compliance efforts.

2.7 Regulatory and Standards Context

The planning and execution of shipboard energy audits must be firmly anchored in the regulatory frameworks and technical standards that govern energy efficiency, emissions control and audit practices. These frameworks not only define key performance indicators and compliance obligations but also provide methodological guidance on how energy-related data should be measured, processed and reported. Alignment with these instruments ensures that the audit findings are valid, verifiable and applicable for both regulatory and operational purposes.

The following are the principal international regulations and standards relevant to maritime energy auditing:

- IMO MARPOL Annex VI - Prevention of Air Pollution from Ships:
  This regulation establishes mandatory limits for NO_x, SO_x and CO_2 emissions and provides verification requirements for emissions control measures. Audits must include emissions-related measurements and documentation that support compliance with emission reduction targets, including for ships operating within Emission Control Areas (ECAs). MARPOL Annex VI is also the foundation for the Energy Efficiency-related instruments described below.
- Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI):
  These performance-based measures are used to assess the energy efficiency of new and existing ships, respectively. Both rely on accurate data regarding fuel consumption, shaft power, engine and propeller characteristics and emissions. Energy audits contribute to verifying compliance and evaluating the effectiveness of design and retrofit interventions intended to improve energy performance.
- Ship Energy Efficiency Management Plan (SEEMP) - Part I & II:
  SEEMP Part I focuses on ship-specific energy management practices and operational efficiency strategies, while Part II (for vessels subject to the IMO Data Collection System)

mandates annual reporting of fuel consumption and transport work. Energy audits help assess the effectiveness of implemented SEEMP measures and support the development of evidence-based improvement plans and fuel-saving initiatives.

- ISO 50001 / ISO 50002 –-Energy Management Systems and Audits:
  These international standards provide a structured approach to establishing, implementing, maintaining and improving energy management systems (EnMS). ISO 50001 outlines the general principles of energy management, while ISO 50002 offers detailed guidance on how to plan and conduct energy audits. Though not shipping-specific, these standards provide valuable methodologies for audit preparation, data analysis and continuous improvement and are especially relevant for shipping companies pursuing fleet-wide energy optimization.

- EN 16247-4 - Energy Audits: Part 4 - Transport:
  As a European standard specifically addressing transport sector audits, EN 16247-4 offers additional context and procedural recommendations for conducting energy audits on mobile systems, including maritime vessels. It complements ISO 50002 by addressing sector-specific challenges such as variable operating conditions, load dependency and mobile asset constraints.

Incorporating these regulatory and standardization frameworks into the audit process enhances the credibility, comparability and compliance readiness of the results. It ensures that measurement protocols, data granularity and performance indicators are fully aligned with both legal obligations and best practices in energy management. As shipping continues to face mounting pressure for decarbonization and energy transparency, alignment with these frameworks becomes increasingly essential for operational, commercial and environmental success.

2.8 Summary

This chapter has provided a structured and comprehensive categorization of the key quantities commonly measured during shipboard energy audits. The classification was developed across multiple dimensions, including ship system, physical domain, operational context and regulatory relevance, to reflect the complexity and interconnectedness of maritime energy consumption.

The parameters included were selected based on several core criteria:

- Their direct influence on fuel consumption, energy efficiency and pollutant emissions, which are central to the energy and environmental performance of vessels.

- Their critical role in satisfying international regulations and performance indicators, such as those defined by IMO instruments (e.g. EEDI, EEXI, EEOI, SEEMP) and energy management standards (e.g. ISO 50001, EN 16247-4).

- Their practical feasibility for accurate and reliable measurement under real-world shipboard conditions, acknowledging the technical constraints and environmental variability inherent in maritime operations.

Additionally, the chapter emphasized the importance of data logging strategies, temporal resolution, operational context and audit constraints, all of which must be carefully considered to ensure the integrity and usefulness of the collected data.

3. Standard Methodology for Measuring Quantities During Ship Energy Audits

3.1 Introduction

This chapter presents a structured overview of the standard methodologies and widely accepted procedures used to measure critical quantities during shipboard energy audits. The focus is placed specifically on the practical execution of measurements, addressing how data are acquired under real operating conditions through established practices grounded in international guidelines, industry norms and audit-specific protocols.

Rather than discussing the selection of what to measure, this chapter concentrates on how measurements are carried out. Key aspects include instrument setup, operational procedures, data logging strategies and measurement timing in relation to audit phases such as baseline assessment, testing and performance verification.

Each measurement methodology is outlined in terms of:

- Step-by-step execution, including required preconditions, system stabilization and measurement duration
- Data handling requirements, such as sampling frequency, synchronization and integrity checks
- Relevance to specific audit stages, ensuring alignment between methodology and intended diagnostic or compliance purpose.

The objective is to establish a robust and repeatable foundation for collecting high-quality, consistent, and audit-relevant data across different vessels and operational contexts. This framework will serve as the basis for instrumentation selection and data processing and interpretation.

3.2 Applicable Standards and Frameworks

The methodologies used for measuring key quantities during ship energy audits must be consistent with established international standards and regulatory frameworks. These references provide structured guidance on the planning, execution and validation of measurements, ensuring that the audit process is technically sound, transparent and aligned with both compliance requirements and best practices in energy management.

The following standards and regulatory instruments are particularly relevant to shipboard energy measurement methodologies:

- ISO 50002:2014 - Energy Audits: Requirements with Guidance for Use
  This international standard defines the general structure of the energy audit process, including how measurement plans should be designed and how data should be collected,

validated and interpreted. It emphasizes the importance of defining clear objectives, identifying significant energy uses and applying suitable verification techniques. ISO 50002 also outlines roles, responsibilities and recommended measurement durations, making it a key reference for ensuring methodological rigidity during onboard audits. (BSI, 2013)

- ISO 50001:2018 - Energy Management Systems: Requirements with Guidance for Use
  ISO 50001 provides a comprehensive framework for establishing, implementing and maintaining an energy management system (EnMS). While not audit-specific, it underscores the importance of continuous energy performance monitoring, instrument calibration, documentation control and corrective action. In the context of ship energy audits, it supports the integration of measurement practices into a broader strategy of continuous improvement and operational accountability.(BSI, 2018)
- EN 16247-4 - Energy Audits: Part 4: Transport
  This European standard complements ISO 50002 by providing sector-specific guidance for energy audits in transport applications, including maritime operations. It includes practical recommendations on how to categorize measurement activities based on operational modes (e.g. at-sea vs. at-port), how to account for environmental influences and how to normalize data for meaningful comparisons. EN 16247-4 is especially valuable for auditors working in mobile and variable operating environments.(CEN, 2022)
- IMO Guidelines - SEEMP, EEOI, EEXI
  Several guidelines issued by the International Maritime Organization (IMO) establish performance and reporting requirements for energy efficiency and emissions compliance. The Ship Energy Efficiency Management Plan (SEEMP) outlines operational best practices and fuel-saving measures, including the need for performance monitoring. The Energy Efficiency Operational Indicator (EEOI) provides a voyage-based carbon intensity metric, requiring reliable fuel, cargo and distance measurements. The Energy Efficiency Existing Ship Index (EEXI) framework includes detailed technical survey and certification requirements, supported by accurate measurements of shaft power, engine specifications and design parameters. Together, these IMO instruments shape the core measurement expectations for regulatory compliance and energy performance tracking.(Maritime Organization, 2022b, 2022c)

Adhering to these standards ensures that measurement methodologies used during audits are not only consistent across vessels and audit teams but also aligned with global expectations for transparency, comparability and continual improvement. In the sections that follow, individual methodologies for each physical and system domain will be described within this normative context.

3.3 Detailed Methodologies by Measurement Domain

This section presents the core methodologies used for measuring the primary energy-related quantities during ship energy audits, categorized by physical domain. Each method is described step by step, outlining the tools involved, execution procedures, and relevance to audit objectives such as regulatory compliance, performance benchmarking, and diagnostics. Where applicable, reference is made to international standards, technical literature, or real-world audit documentation.

3.3.1 Fuel Consumption

Accurate fuel consumption measurement is fundamental for assessing energy efficiency, calculating emissions and complying with IMO indicators such as the EEOI and EEXI. Three common methods are employed and are described below.

3.3.1.1 Tank Sounding with Temperature Correction

1. Measure the depth of fuel in the tank using a calibrated sounding tape.
2. Convert the raw reading into volume using a tank calibration table specific to the vessel.
3. Apply temperature correction using onboard measurements and fuel density tables to account for volume expansion or contraction.
4. Convert corrected volume to mass based on temperature-dependent fuel density.
5. Determine daily consumption by calculating the difference between initial and final tank levels over a defined period (e.g. per voyage or per day).
6. Record and store the data in a fuel consumption logbook for use in performance indices such as EEOI. (Lovins *et al.*, 2001; GHGES MARINE SOLUTIONS, 2016)

3.3.1.2 Mass Flow Metering (Coriolis or Positive Displacement Flow Meters)

1. Install the flow meter in the fuel supply or return line of the engine.
2. Capture real-time continuous flow measurements (typically in kg/h or L/h) using a dedicated logging system.
3. Ensure proper calibration of the meter according to manufacturer specifications.
4. Synchronize fuel flow readings with engine RPM and operational phase (e.g. maneuvering, cruising) for accurate contextual analysis.
5. Export daily or voyage-level aggregate data for reporting and cross-verification. (GHGES MARINE SOLUTIONS, 2016; TÜV SÜD National Engineering Laboratory, 2019)

3.3.1.3 Logbook Cross-Validation

1. Collect bunker delivery notes, fuel requisition logs and daily engine room reports.
2. Compare reported consumption figures with tank level readings and flow meter data to detect inconsistencies.
3. Reconcile deviations using operational knowledge of fuel transfers, leakages, or calibration drift. (Iliopoulos, 2018)

3.3.2 Electrical Load Measurements

Electrical measurements are essential for analyzing the efficiency and stability of shipboard power systems.

3.3.2.1 Spot Measurements (Clamp Meter)

1. Place a clamp meter on the live conductor of the circuit or equipment under examination (e.g. generator output, switchboard feeder).
2. Record instantaneous current and voltage.
3. Calculate power factor or estimate power output if required.
4. Use as a rapid diagnostic or baseline assessment tool. (Rosenqvist *et al.*, 2012; Maritime Organization, 2016)

3.3.2.2 Logging via 3-Phase Power Analyzers

1. Connect the analyzer to the main switchboard or generator terminals.
2. Configure sampling rates (e.g. 1 Hz) and log duration (typically 24–72 hours).
3. Record real-time RMS voltage, current, active/reactive/apparent power and harmonic distortion.
4. Analyze load profiles by system category (e.g. lighting, HVAC, auxiliaries) to identify baseloads and peak demand. (Ministry of Environment, 2017; BSI, 2018)

3.3.3 Thermal Measurements

Thermal measurements are critical for quantifying heat losses, evaluating heat exchanger performance and assessing boiler efficiency.

3.3.3.1 Thermocouples and Resistance Temperature Detectors (RTDs)

1. Install sensors at key thermal exchange points (e.g. exhaust outlets, steam lines, cooling water circuits).

2. Use a data acquisition system (DAQ) or handheld thermometer to capture readings.
3. Measure temperature differentials across heat exchangers and calculate heat transfer using: $Q=m\cdot cp\cdot\Delta T$
4. Log readings for trend analysis and efficiency benchmarking. (Hasanbeigi and Price, 2010; GHGES MARINE SOLUTIONS, 2016)

3.3.3.2 Infrared Thermography

1. Scan surfaces such as thermal insulation, electrical panels, or exhaust systems with an IR camera
2. Calibrate for material emissivity and ambient conditions
3. Identify thermal anomalies indicative of insulation failures, heat leaks, or equipment overheating. (Iliopoulos, 2018)

3.3.4 Mechanical Parameters

Mechanical metrics support the evaluation of propulsion and auxiliary machinery performance.

3.3.4.1 Shaft Torque and RPM Monitoring

1. Install telemetry-based torque sensors or strain gauges on the propulsion shaft
2. Use a tachometer to measure shaft rotational speed (RPM)
3. Calculate shaft power using: $P=2\cdot\pi\cdot N\cdot T/60$
4. Record data under various operational states for performance mapping. (Hydrus Engineering Ltd., 2015)

3.3.4.2 Derived Engine Performance (Without Torque Sensors)

1. Measure fuel consumption and engine load
2. Apply manufacturer-supplied Specific Fuel Oil Consumption (SFOC) curves
3. Estimate shaft power indirectly, suitable for vessels lacking torque instrumentation. (Langou, 2019)

3.3.5 Emissions Monitoring

Emissions measurement is essential for MARPOL Annex VI compliance and performance metrics like EEOI.

3.3.5.1 Portable Flue Gas Analyzer

1. Insert the analyzer probe into the engine exhaust stack or duct
2. Allow the device to warm up and stabilize
3. Measure gas concentrations: CO_2, NO_x, SO_x, O_2, along with exhaust temperature and flow velocity
4. Calibrate the instrument using reference gases before each measurement campaign
5. Record emissions under representative load conditions. (Hasanbeigi and Price, 2010)

3.3.6 HVAC and Indoor Conditions

Indoor environment monitoring supports HVAC system performance assessment and crew comfort standards.

3.3.6.1 CO_2, Temperature and Humidity Spot Logging

1. Place portable sensors in accommodation or control areas
2. Record environmental parameters during active occupancy and rest periods
3. Compare results with indoor air quality and comfort standards (e.g. ISO 7730) (Johnson, 2014)

3.3.6.2 Airflow Measurement (Anemometer)

1. Use a vane-type or hot-wire anemometer to measure air velocity at duct outlets or diffusers
2. Calculate volumetric airflow to evaluate fan efficiency and detect imbalances in distribution. (Hasanbeigi and Price, 2010)

3.3.7 Operational Parameters

Operational data provides essential context for interpreting energy use and normalizing performance metrics.

3.3.7.1 AIS, GPS and Noon Report Data

1. Extract vessel speed, heading and distance travelled from AIS or GPS logs
2. Combine with cargo manifests and draft data to determine transport work (ton·nm)
3. Normalize energy and fuel consumption using this data for EEOI or other voyage-based metrics. (Smith *et al.*, 2013)

Each of these methodologies contributes to building a complete and reliable energy performance profile of the vessel. Selection among them depends on instrumentation availability, system characteristics and the objectives of the specific audit.

3.4 Logging, Sampling and Data Handling

Accurate data acquisition is fundamental to any energy audit. The way measurements are logged and processed directly affects the reliability of derived performance indicators and the interpretability of audit results. This section outlines the principles and best practices for data logging, sampling and handling during shipboard energy audits.

3.4.1 Spot checks

Spot measurements refer to short-term, instantaneous readings typically carried out using handheld instruments. These are particularly useful for:

- Diagnostic assessments (e.g. detecting abnormal temperature spikes or current draw)
- Quick validation of instrument calibration
- One-time inspections of rarely accessed systems

While spot checks are limited in temporal scope, they offer high flexibility and are often the only practical method in areas with restricted access or safety concerns.

3.4.2 Continuous Logging

For systems that are dynamic or have a significant impact on overall energy performance, such as propulsion, HVAC, or power generation, continuous logging is essential. The duration typically ranges from 24 to 72 hours and must cover a representative set of operational conditions (e.g. maneuvering, cruising and hotel load at port).

Continuous data logging allows:

- Identification of trends and anomalies
- Load profile creation
- Peak demand and baseload differentiation
- Calculation of KPIs like Energy Intensity (kWh/nm) or Specific Fuel Oil Consumption (SFOC)

According to ISO 50002, this practice is indispensable for validating energy-saving opportunities and quantifying system behavior under actual operational scenarios.(BSI, 2013)

3.4.3 Sampling Rates

Sampling frequency must be tailored to the response characteristics of each system:

- Electrical Systems: A high sampling rate of 1 Hz (one sample per second) is recommended for capturing fast-changing electrical loads and transients, particularly in generators and switchboards.
- Thermal, Flow and Comfort Measurements: These systems exhibit slower changes, so sampling intervals of 10 to 60 seconds are generally sufficient. For example, monitoring boiler outlet temperature or cabin air quality does not require high-frequency data but must still be logged consistently to detect drift or inefficiencies.

The selected rate must ensure the resolution is fine enough to detect changes while minimizing unnecessary data storage burdens.

3.4.4 Synchronization

When measurements are collected from different subsystems (e.g. fuel flow, engine RPM, GPS position), temporal synchronization is critical for accurate cross-referencing and KPI derivation.

Recommended strategies include:

- Centralized Data Loggers: Multi-channel systems capable of synchronously recording inputs from various sensors
- Time-Stamp Alignment: In cases where multiple instruments are used, all devices should be synchronized to a common time base (e.g. shipboard server time or GPS-based time stamps)

Proper synchronization enables reliable correlation between inputs and outputs (e.g. fuel consumption vs. shaft power), thus allowing for valid computation of efficiency metrics like EEOI or thermal efficiency. Lack of synchronization can lead to significant errors, particularly when operational phases shift frequently. (Ghaforian Masodzadeh, 2018)

In summary, the effectiveness of an energy audit relies not only on what is measured, but also on how it is measured, how often and how accurately the data from various sources are aligned. Proper logging and sampling practices ensure the fidelity of all subsequent analysis, trend identification and performance evaluations.

3.5 Calibration and Quality Control

Ensuring the accuracy and reliability of measured data is essential in the context of ship energy audits. The integrity of any derived conclusions, such as efficiency trends, compliance assessments, or proposed energy-saving measures, depends heavily on the quality and credibility of the underlying measurements. This section outlines the standard practices for calibration, cross-validation and uncertainty estimation.

3.5.1 Calibration Schedules

All measurement instruments used during the audit should undergo regular calibration, in accordance with international standards such as ISO 50002. These calibrations must be:

- Scheduled periodically, following manufacturer guidelines or regulatory minimums
- Documented with traceable calibration certificates
- Verified onboard using quick-reference test procedures where possible

This is particularly important for sensors involved in continuous logging or compliance-relevant parameters (e.g. fuel flow meters, gas analyzers, torque sensors). Instruments out of calibration can introduce systemic bias into the dataset, undermining the audit's credibility.

3.5.2 Cross-Validation Techniques

To strengthen the reliability of key figures and detect potential anomalies, redundant measurements and mass-energy balance checks should be employed where feasible:

- For instance, fuel consumption measured via tank sounding can be compared with mass flow meter readings and engine logbook records
- Electrical energy input can be cross-checked against mechanical output and fuel usage to assess conversion losses

Such triangulation methods help in validating critical data points and provide a built-in quality check mechanism, as suggested by the Industrial Energy Audit Guidebook. (Hasanbeigi and Price, 2010)

3.5.3 Error Estimation and Uncertainty Analysis

All audit reports should include uncertainty estimates for calculated KPIs, particularly those used in regulatory compliance or investment planning. This involves:

- Determining measurement error margins based on instrument specifications and calibration data
- Propagating uncertainty through formulas used for derived indicators (e.g. EEOI, shaft power)
- Reporting confidence intervals where applicable

By quantifying uncertainty, the audit gains transparency and enables stakeholders to make better-informed decisions regarding energy efficiency measures or system modifications.

3.6 Calibration and Quality Control

This chapter has presented a detailed overview of standard methodologies for measuring energy-related quantities onboard ships, structured by domain and aligned with international best practices. The key elements of this methodology include:

- Procedure-specific measurement protocols for fuel use, electrical loads, thermal systems, emissions and operational variables
- Standardized logging and sampling strategies, ensuring temporal resolution and data integrity
- Calibration and quality control routines, that guarantee data reliability and audit credibility

Together, these methodologies form a solid foundation for conducting robust, traceable and regulation-compliant energy audits. They allow auditors to generate actionable insights, compute accurate KPIs and support continuous improvement initiatives as per ISO and IMO frameworks.

The next chapter will build upon these practices by evaluating each methodology based on ease of implementation, required equipment, operational constraints and relevance to audit objectives.

4. Evaluation of Measurement Methodologies in Ship Energy Audits

4.1 Introduction

Accurate, consistent and context-appropriate measurement methodologies are essential for the successful execution of ship energy audits. As outlined in the previous chapter, a wide array of techniques exists for capturing critical energy-related data onboard vessels. However, the selection of the most suitable method for each application is not straightforward and depends on a combination of technical, operational and regulatory considerations.

This chapter presents a structured evaluation of those methodologies, applying a set of key criteria tailored to the maritime environment. These criteria are designed to support informed decision-making by engineers and energy auditors when selecting measurement approaches for different shipboard systems and audit objectives. The evaluation framework includes:

- Reliability of the method: The degree to which the measurement technique produces consistent and repeatable results under varying operational conditions, such as sea state, engine load, and ambient temperature. Reliable methods are essential for comparative assessments, long-term monitoring, and performance benchmarking.
- Level of difficulty in application: The practical feasibility of implementing each method onboard, considering constraints such as limited access, system downtime requirements, and installation complexity. Ease of deployment is especially important in retrofitting contexts and during audits conducted under time constraints.
- Requirements for equipment and specialized knowledge: The level of technical sophistication required, both in terms of hardware (e.g. sensors, data acquisition systems) and personnel skills. This criterion accounts for the availability of trained crew or auditing staff capable of configuring, operating and interpreting measurement instruments.
- Acquisition and operating cost of equipment: Includes not only the initial investment in equipment but also the associated costs of calibration, maintenance, replacement parts and data management over time. Cost-effectiveness must be assessed in relation to the expected value of the data and its relevance to audit objectives.
- Measurement accuracy for energy audit purposes: The extent to which the measurement captures the true value of the quantity of interest, with adequate precision and resolution. High accuracy is particularly important for compliance with international regulatory frameworks and the calculation of performance indicators such as the Energy Efficiency Operational Indicator (EEOI) and the Energy Efficiency Existing Ship Index (EEXI).

The overarching goal of this chapter is to offer a robust and actionable decision-support tool for auditors and engineers. By systematically comparing the strengths and limitations of each method, this evaluation helps align technical performance with ship-specific constraints, available resources and the demands of international standards, including MARPOL Annex VI, ISO 50002 and SEEMP Parts I & II. (Hasanbeigi and Price, 2010; BNERI, 2015).

4.2 Evaluation Criteria and Classification Scheme

To facilitate an objective and comparative assessment of the methodologies described in Chapter 3, this section introduces a structured classification scheme based on six evaluation criteria. Each measurement method is rated qualitatively across these dimensions to reflect its practical suitability and technical merit in ship energy audit applications.

Criterion	Rating Scale
Reliability	Low / Moderate / High
Application Difficulty	Easy / Moderate / Difficult
Equipment Requirement	Basic / Intermediate / Advanced
Specialized Knowledge	Low / Medium / High
Equipment Cost	Low / Medium / High
Measurement Accuracy	Low / Medium / High

Table 3: Evaluation criteria of Measurement Methodologies

Each of these criteria is defined as follows:

- Reliability: The likelihood that repeated measurements under consistent operational conditions will yield consistent results. This is essential for benchmarking, monitoring trends and verifying improvements over time.
- Application Difficulty: The complexity of implementing the method onboard, considering factors such as accessibility of the measurement point, interference with ship operations and the need for vessel downtime or modifications.
- Equipment Requirement: A classification of the technical sophistication and logistical footprint of the instruments involved. Basic methods may require only handheld devices, while advanced methods may involve fixed sensors, data acquisition systems and integration with onboard automation systems.
- Specialized Knowledge: The level of expertise required for proper deployment, operation, and interpretation of results. This includes familiarity with measurement principles, calibration procedures and troubleshooting techniques.
- Equipment Cost: A general indication of the financial resources needed for procurement, installation and operation of the instruments. This includes capital expenses, consumables, maintenance, and potential upgrades.
- Measurement Accuracy: The ability of the method to produce results that are close to the true value of the quantity being measured. High-accuracy methods are often essential when data are used for calculating regulatory performance indicators or for optimizing energy

usage with fine granularity.

Importantly, these ratings are not absolute but are intended to guide selection based on contextual interpretation. For example, a method rated “Moderate” in complexity might still be preferred if its accuracy and compliance benefits are substantial. Similarly, costlier systems may be justified when supporting long-term monitoring or mandatory reporting under frameworks like SEEMP Part II, EEXI, or ISO 50001.

Moreover, the evaluation recognizes the unique challenges of shipboard environments, such as vibration, space constraints, marine exposure and limited crew availability. These constraints often influence the feasibility and sustainability of implementing certain methodologies in practice.(Hasanbeigi and Price, 2010; Marantis, 2012)

In the next section, these criteria will be applied to a range of measurement methods, grouped by energy domain, providing a comparative overview of their advantages and limitations.

4.3 Comparative Evaluation by Measurement Type

This section presents a structured and comparative evaluation of the principal measurement methodologies employed in ship energy audits. The objective is to assist engineers and auditors in selecting the most appropriate approach for each measured quantity, taking into account both technical performance and practical implementation challenges specific to maritime environments.

Each methodology is evaluated across six key criteria, reliability, application difficulty, equipment requirements, required expertise, cost and accuracy. Together, these criteria offer a balanced framework for analyzing measurement techniques, not just in terms of theoretical capability, but in terms of real-world performance under the operational and environmental constraints of maritime audits.

The following comparative tables provide a concise overview of each method's performance profile, offering immediate insights into the strengths and trade-offs associated with each approach. These tables serve as a decision-making tool, especially when selecting between manual versus automated techniques, or temporary versus permanently installed systems.

4.3.1 Fuel Consumption

Method	Reliability	Difficulty	Equipment	Knowledge	Cost	Accuracy
Tank Sounding	Moderate	Moderate	Basic	Medium	Low	Medium
Mass Flow Metering	High	Easy	Advanced	Low	High	High
Logbook Validation	Moderate	Easy	Basic	Medium	Low	Low

Table 4: Evaluation of Fuel Consumption Measurement Methods

Tank sounding remains a standard method on older vessels or where instrumentation budgets are limited. However, its accuracy is heavily influenced by tank geometry, temperature gradients and human error during sounding. Correcting fuel density and temperature is essential for reasonable accuracy. (GHGES MARINE SOLUTIONS, 2016)

Mass flow meters (especially Coriolis types) deliver real-time, high-precision data and support direct integration with monitoring systems. Despite their cost and complexity, they are increasingly required under SEEMP Part II and EEXI protocols.

Logbook validation is useful for sanity checks and trend analysis, but lacks precision and should not be used as the sole method for high-stakes audits.

4.3.2 Electrical Load Monitoring

Method	Reliability	Difficulty	Equipment	Knowledge	Cost	Accuracy
Clamp Meter (Spot)	Moderate	Easy	Basic	Low	Low	Medium
Power Analyzer Logging	High	Moderate	Advanced	Medium	Medium	High

Table 5: Evaluation of Electrical Load Monitoring Methods

Clamp meters are highly portable and non-intrusive, making them ideal for rapid diagnostics. However, they provide only snapshot data and cannot detect time-based load fluctuations or harmonics.

Power analyzers, especially three-phase models, enable detailed logging of current, voltage, power factor, and frequency variations over time. These are critical for uncovering operational inefficiencies and peak demand issues (Marantis, 2012).

4.3.3 Thermal Systems

Method	Reliability	Difficulty	Equipment	Knowledge	Cost	Accuracy
RTDs / Thermocouples	High	Easy	Intermediate	Low	Medium	High
IR Thermography	High	Moderate	Advanced	Medium	High	Medium

Table 6: Evaluation of Thermal Systems Monitoring Methods

Contact sensors such as RTDs and thermocouples are preferred for embedded monitoring of steady-state systems (e.g. heat exchangers, exhaust streams), offering high accuracy and low maintenance.

IR thermography excels during inspections or walk-through audits, especially for identifying insulation faults or overheated components. However, it is sensitive to emissivity errors and surface conditions (Iliopoulos, 2018).

4.3.4 Mechanical Power

Method	Reliability	Difficulty	Equipment	Knowledge	Cost	Accuracy
Torque & RPM Sensors	High	Moderate	Advanced	Medium	High	High
SFOC-Based Power Estimation	Moderate	Easy	Basic	Medium	Low	Medium

Table 7: Evaluation of Mechanical Power Measurement Methods

Direct shaft power measurement using torque and RPM sensors is indispensable for EEXI verification and accurate propulsion efficiency analysis. While precise, retrofitting these systems on older vessels can be invasive and costly.

In such cases, power estimation through fuel consumption (SFOC curves) and engine maps is a reasonable fallback, provided the assumptions and interpolation models are carefully validated (Langou, 2019)

4.3.5 Exhaust Emissions

Method	Reliability	Difficulty	Equipment	Knowledge	Cost	Accuracy
Flue Gas Analyzer	High	Moderate	Advanced	High	High	High

Table 8: Evaluation of Exhaust Emissions Measurement Method

Portable gas analyzers are essential for measuring SO_x, NO_x, and CO_2, as required under MARPOL Annex VI. Proper calibration and competent operation are mandatory to ensure accuracy. Frequent recalibration and consumables (e.g. filters, sensors) contribute to lifecycle cost (Johnson et al., 2013).

4.3.6 HVAC / Indoor Comfort

Method	Reliability	Difficulty	Equipment	Knowledge	Cost	Accuracy
CO_2 / Temp / RH Loggers	High	Easy	Basic	Low	Low	High
Anemometers	Moderate	Easy	Basic	Low	Low	Medium

Table 9: Evaluation of Indoor Air Quality Measurement Methods

Monitoring indoor air quality supports crew wellbeing and HVAC efficiency. CO_2 levels, relative humidity and temperature data help detect poor ventilation or over-conditioning. Anemometers are useful for analyzing air distribution and flow balance in cabins and engine rooms (Hasanbeigi & Price, 2010).

4.3.7 Operational Parameters

Method	Reliability	Difficulty	Equipment	Knowledge	Cost	Accuracy
AIS / Noon Reports	High	Easy	Basic	Low	Low	Medium

Table 10: Evaluation of Operational Parameters Collection

Bridge logs and AIS data provide critical inputs for calculating voyage-specific indicators like EEOI. While easy to collect, data consistency, time alignment and completeness must be ensured during audits. These data sources are foundational for contextualizing fuel consumption and transport work (Smith et al., 2013).

4.4 Summary and Recommendations

This section consolidates the main insights derived from the comparative evaluation of measurement methodologies, offering actionable guidance for selecting appropriate techniques in ship energy audits. These recommendations aim to balance technical performance with feasibility in real-world maritime environments.

- For high-priority and high-accuracy applications, such as propulsion monitoring and emissions measurement, auditors should prioritize automated, real-time and direct measurement technologies. These approaches offer superior precision, traceability and temporal resolution, qualities essential for meeting international compliance demands and supporting data-driven performance optimization.
- Manual or low-cost methodologies, including tank sounding, clamp meters, or logbook analysis, remain valuable under specific conditions. Their simplicity, affordability and ease of deployment make them suitable for preliminary diagnostics, older vessels without integrated monitoring systems, or audits conducted under tight budget or time constraints.
- Indirect or derived methods, such as SFOC-based power estimation or cross-validation using logbooks, can serve as viable alternatives when real-time instrumentation is not feasible. While these methods offer reduced granularity and higher uncertainty, they are often the only practical option for retrofits or cases with limited access, especially if paired with robust uncertainty quantification.
- Combining complementary techniques enhances diagnostic accuracy. For instance, pairing RTD sensors with infrared thermography improves thermal system evaluation by capturing both embedded process data and surface-level anomalies, thereby supporting maintenance planning and energy optimization more holistically.

- Usability and crew familiarity are critical. Even the most sophisticated systems yield limited value without proper training. Measurement approaches must therefore be matched not only to the technical requirements of the audit, but also to the ship's human resource profile (considering whether crew or audit staff possess the skills to install, operate and interpret the system effectively).

To support informed and context-sensitive selection of methodologies, audit engineers should align measurement strategies with the following:

- The energy significance of the system under evaluation (e.g. propulsion, HVAC, auxiliaries)
- The regulatory or certification framework governing the audit (e.g. SEEMP Part II, EEXI, ISO 50002)
- The budgetary and operational constraints of the ship (e.g. drydock availability, retrofitting limitations)
- The required accuracy and resolution, particularly where audit results inform compliance calculations or performance benchmarking

In addition, adherence to established standards ensures both methodological soundness and audit credibility. Selection and implementation of measurement systems should consider:

- ISO 50002 - General guidelines for energy audits
- EN 16247-4 - Sector-specific guidance for transport and maritime audits
- IMO frameworks, including SEEMP Parts I & II, EEDI and EEXI, which define reporting and efficiency standards for vessels

These recommendations are not prescriptive but are intended to support rational decision-making by adapting to each vessel’s unique profile. The qualitative classification and evaluation criteria presented in Sections 4.1 and 4.2, spanning reliability, difficulty, equipment needs, expertise, cost and accuracy, form the foundation for this guidance. By integrating these criteria into a structured evaluation process, auditors can devise measurement plans that are both technically sound and practically feasible, ultimately enhancing audit impact and compliance readiness.

5. Instruments for Energy Audits: Comparative Evaluation

5.1 Introduction

The effectiveness of an energy audit onboard a ship is closely linked to the selection, proper deployment and performance of the measurement instruments used. These instruments not only facilitate the acquisition of key operational parameters, but also determine the accuracy, reliability and interpretability of the collected data, factors that are crucial for identifying inefficiencies and formulating targeted energy-saving recommendations.

This chapter builds on the comparative evaluation framework established in Chapter 4 and offers a systematic overview of the most commonly used measurement instruments in ship energy audits. Each instrument is discussed in terms of measurement accuracy, cost-effectiveness, robustness under marine environmental conditions and maintenance or calibration demands, all of which are essential considerations for successful and sustainable auditing practices.

The analysis is supported by technical references drawn from national and international best practices, including the Greek Ministry of Environment and Energy Guide for Energy Inspections (ΥΠΕΚΑ) (Ministry of Environment, 2017), the Industrial Energy Audit Guidebook (Hasanbeigi and Price, 2010), regulatory documents such as the SEEMP Appendix (Bureau Veritas, 2012) and practical audit reports, notably the one conducted on the MV Explorer (GHGES MARINE SOLUTIONS, 2016). These sources provide a robust foundation for assessing instrumentation in the real-world context of maritime operations, where factors such as vibration, humidity, corrosion, space constraints and limited crew availability often challenge the applicability of otherwise standard measurement tools.

5.2 Instrumentation Categories for Shipboard Energy Audits

5.2.1 Fuel Flow Measurement

Fuel consumption is a central parameter in maritime energy audits, directly influencing energy efficiency indicators such as EEOI (Energy Efficiency Operational Indicator) and EEXI (Energy Efficiency Existing Ship Index). The choice of instrumentation for fuel flow measurement must account for multiple operational constraints, including system accessibility, measurement resolution, data acquisition requirements and environmental resilience.

Various instrument types are available for measuring fuel consumption, each with distinct advantages, limitations and degrees of suitability for onboard deployment. The table below categorizes the main technologies employed, alongside a summary of their accuracy and applicability in ship energy audits:

Method	Instrument	Accuracy	Suitability	Notes
Manual	Tank Sounding & Temperature Correction	Medium	High	Widely used in legacy systems Vulnerable to inaccuracies due to ship motion and fluid sloshing(Lovins *et al.*, 2001)

Direct	Coriolis Flow Meter (e.g. Siemens)	Very High (±0.1%)	High	Real-time, mass-based measurements Reliable for continuous auditing; periodic calibration required(Hasanbeigi and Price, 2010)
Clamp-on	Ultrasonic Flow Meter	High	Medium	Non-invasive installation Sensitive to pipe layout (straight runs); generally used for retrofit audits(Hasanbeigi and Price, 2010)
Differential	Orifice Plate, Venturi Tube	Medium	Medium	Established in older systems; susceptible to fouling; pressure-drop based; moderate installation cost(Hasanbeigi and Price, 2010)

Table 11: Categorization of Fuel Flow Measurement Technologies

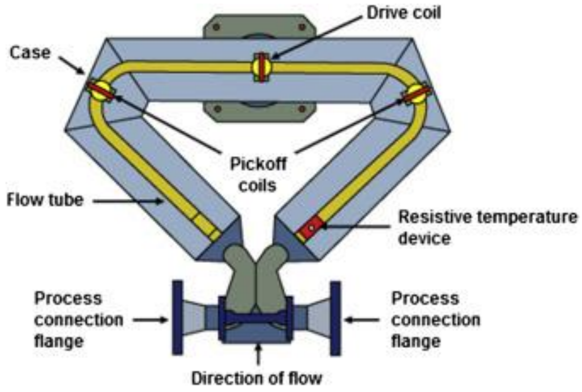

Image 1: Coriolis Flow Meter

In addition to these core instruments, integrated tank gauging systems employing radar and pressure transducers are increasingly found in newer vessel designs. These systems offer continuous volume tracking and are often interfaced with bunker reconciliation platforms for verifying fuel inventory and consumption during voyages. While they contain no moving parts and are therefore less prone to mechanical failure, their accuracy can be adversely affected by pitching, rolling and fuel stratification due to thermal gradients, especially during rough sea conditions. (Lovins et al., 2001)

Overall, the selection of fuel flow measurement instruments must balance precision, practicality and cost. While mass flow meters (e.g. Coriolis type) provide unmatched accuracy and real-time integration, their installation may be challenging on older vessels. In contrast, tank sounding remains prevalent due to its simplicity and low cost but requires manual intervention and introduces a higher margin of error. Hybrid approaches, such as using ultrasonic meters during temporary audits or combining tank level data with onboard automation logs, may offer a viable compromise in certain contexts.

5.2.2 Electrical Measurements

Accurately measuring electrical power generation and consumption is essential for assessing the energy efficiency of auxiliary systems such as pumps, HVAC units, lighting and hotel loads. (Rosenqvist et al., 2012) These systems often operate continuously during voyages and port stays, contributing significantly to overall fuel usage and energy performance metrics like the Energy Efficiency Operational Indicator (EEOI).

The following table summarizes commonly used electrical instruments in shipboard energy audits:

Type	Instrument	Accuracy	Portability	Remarks
Power Analysis	3-Phase Clamp Power Analyzer (Fluke 1735)	±0.5-1%	High	True RMS Captures power factor, harmonics, transients, and imbalance issues(Hasanbeigi and Price, 2010; Iliopoulos, 2018)
Load Profiling	Clamp Meter & Logger	±1-2%	High	Ideal for temporal load variation analysis Supports demand-side evaluation(Wakeford, 2006; Rosenqvist *et al.*, 2012)
Generator Health	Megger Insulation Tester	--	Medium	Used for insulation resistance testing Critical for preventive maintenance
Integrated Meters	Shipboard Switchboard Meters	High	Low	Permanently installed Offer continuous readings but depend on periodic calibration and maintenance routines

Table 12: Categorization of Electrical Measurement Technologies

3-phase power analyzers such as the Fluke 1735 are preferred for in-depth diagnostics. They can identify power quality issues like harmonics and voltage imbalances, which may affect motor and drive efficiency. They are particularly valuable during walkthrough audits or when evaluating system upgrades.

Image 2: 3-Phase Analyzer Fluke 1735

Clamp meters with logging capabilities are suitable for longer-term load profiling and are easy to deploy without interrupting operations. These tools help identify peak demands, idle loads, or oversized equipment.

Image 3: Clamp meter Fluke 345

Megger testers are used more selectively, mainly for electrical integrity checks on generators and critical machinery. Although not energy-specific, they support the identification of faults that could lead to inefficiencies or safety hazards.

While fixed switchboard meters are present on most commercial vessels, auditors must ensure their accuracy through calibration records. They provide useful baseline data, but portable instruments are often required for audit-grade measurements and comparative validation.

5.2.3 Mechanical Power and Shaft Monitoring

Accurate measurement of mechanical power, particularly shaft torque and rotational speed (RPM), is crucial in propulsion system audits, as it directly affects energy efficiency indices like EEXI and fuel benchmarking.

Parameter	Instrument	Example	Comment
Shaft Power	Shaft Power Meter	Kyma ShaftPower	Measures torque, RPM and thrust in real time Vital for propulsion audits(Iliopoulos, 2018)
RPM	Tachometer/Stroboscope	Extech 461995	Offers spot checks for rotational speed Useful for verification purposes(Wakeford, 2006; Hasanbeigi and Price, 2010; Iliopoulos, 2018)
Load Simulation	Dynamometer	--	Used mainly in shore-based trials Not practical for onboard deployment(Ministry of Environment, 2017)
SFOC Estimation	Derived Methods	--	Estimate brake power using fuel consumption, torque and RPM data(Iliopoulos, 2018)

Table 13: Categorization of Mechanical Power and Shaft Monitoring Technologies

Shaft power meters provide the most direct and regulation-compliant readings, while tachometers offer simple but useful validation. Dynamometers are not used in routine audits onboard but serve in controlled engine tests. Derived methods can be useful where direct sensors are absent, though they rely on several assumptions and introduce uncertainty.

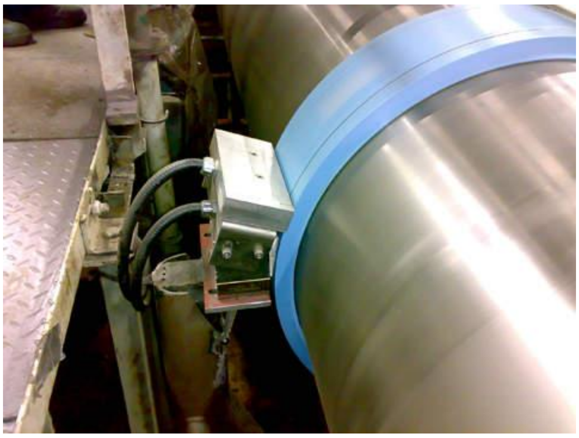

Image 4: Kyma Shaft Power Meter

Image 5: Tachometer

5.2.4 Temperature Monitoring

Monitoring temperature across various ship systems provides critical insights into thermal losses, equipment inefficiencies and HVAC performance. Both surface and embedded sensors are employed depending on the application.

Type	Instrument	Notes
Surface	IR Thermography (e.g. FLIR Systems - ThermaCAM E45, FLUKE IR 566, FLIR C2)	Enables non-contact diagnostics of insulation faults, electrical panels and heat leaks in piping or equipment casings(CRES, 2000; Hasanbeigi and Price, 2010; GHGES MARINE SOLUTIONS, 2016; Iliopoulos, 2018)
Embedded	RTDs / Thermocouples (Pt100, Type K)	High-accuracy sensors ideal for long-term monitoring of exhausts, engines and heat exchangers(CRES, 2000; Hasanbeigi and Price, 2010; GHGES MARINE SOLUTIONS, 2016)
Ambient	Digital Thermometers	Used for general air temperature tracking in accommodation or engine rooms, supporting HVAC tuning and comfort assessment

Table 14: Categorization of Temperature Monitoring Technologies

IR thermography is particularly valuable for walk-through inspections, while RTDs and thermocouples are preferred for automated logging and integration with shipboard monitoring systems.

Image 6: IR Thermometer

5.2.5 Exhaust Gas and Combustion Analysis

Emission analysis plays a pivotal role in ensuring compliance with environmental regulations such as SEEMP, MARPOL Annex VI and IMO DCS. These measurements help verify fuel quality, engine tuning and overall combustion efficiency.

Gas	Analyzer Type	Comments
CO, NOx, SOx, O_2	Portable Exhaust Analyzer (e.g. KANE 900 Plus)	Provides real-time data on key pollutants and combustion efficiency Portable and suitable for periodic inspections(Hasanbeigi and Price, 2010; GHGES MARINE SOLUTIONS, 2016; Iliopoulos, 2018)
Smoke	Optical Smoke Meter	Assesses particulate levels Often integrated into multifunction analyzers(CRES, 2000)
-	CEMS (Continuous Emissions Monitoring Systems)	Installed on some regulated vessels Provides continuous data but involves high costs and maintenance effort

Table 15: Categorization of Exhaust Gas and Combustion Analysis Technologies

Portable analyzers are commonly used during audits due to their flexibility, while CEMS are typically mandated on vessels with specific operational profiles or regulatory obligations.

Image 7: Portable Gas Emission Analyzer

5.2.6 Other Common Measurements

In addition to fuel, power and emissions monitoring, ship energy audits benefit from a range of auxiliary instruments that support broader diagnostics. These tools help assess the performance of lighting systems, ventilation, HVAC efficiency and mechanical integrity, areas often linked to indirect energy consumption and preventive maintenance.

Parameter	Instrument	Use Case
Light Level	Lux Meter (e.g. FLUKE 922 KIT)	Evaluates lighting system efficiency and adequacy in workspaces or cabins(CRES, 2000; Schneider Electric SPA et al, 2007; Ministry of Environment, 2017; Iliopoulos, 2018)
Pressure	Differential Manometer	Measures pressure drops across filters and ducts in HVAC systems(CRES, 2000)
Humidity	Digital Hygrometer (e.g. LT Lutron HT-3006HA)	Monitors relative humidity for crew comfort and IAQ analysis(CRES, 2000; Iliopoulos, 2018)
Vibration	Vibrometer / FFT Analyzer	Detects imbalance or misalignment in motors, pumps and other rotating machinery for condition-based maintenance(Ministry of Environment, 2017)
Air Velocity	Hot-Wire / Vane Anemometer	Quantifies airflow in ducts or work zones to assess HVAC performance(CRES, 2000)

Table 16: Categorization of Other Common Measurements Technologies

Such instruments contribute to a more holistic audit, allowing engineers to detect hidden inefficiencies or early signs of component degradation that may impact energy performance indirectly.

Image 8: Lux Meter

Image 9: Hugrometer

5.3 Comparative Instrumentation Table

This consolidated table offers a practical comparison of key instrumentation used in shipboard energy audits, synthesizing information on accuracy, cost, marine applicability, maintenance needs and typical use cases. It serves as a quick-reference guide for selecting tools based on audit goals, system criticality and onboard constraints.

Instrument	Accuracy	Cost	Marine Suitability	Maintenance	Application Notes
Kyma ShaftPower	Very High	High	Excellent	Medium	Full shaft power audit Widely adopted in SEEMP frameworks
Coriolis Flow Meter	Very High	High	Excellent	Medium	Best-in-class for real-time mass fuel flow Requires periodic recalibration
Ultrasonic Flow Meter	High	Medium	Medium	Low	Non-intrusive Suited for retrofits or temporary campaigns
Clamp Power Analyzer	High	Medium	High	Low	Used for harmonic analysis, transient recording and electrical diagnostics
RTD Sensor	Very High	Medium	High	Low	Stable, precise monitoring of engine, exhaust, or heat exchanger temperatures
IR Camera	Medium	Medium	Medium	Low	Effective for inspections of thermal insulation, motors and switchboards
Portable Gas Analyzer	High	High	Medium	Medium–High	Key for MARPOL and SEEMP compliance Multi-gas capabilities
CEMS	Very High	Very High	High	High	Continuous Emissions Monitoring System Essential for regulated fleets

Clamp Meter	Medium	Low	Good	Low	Quick and portable for spot checks on electrical loads
Thermocouple (K-type)	Medium	Low	High	Low	Durable for high-temperature measurements, such as exhaust ducts
Tachometer	High	Low	High	Low	Measures RPM of shafts, pumps and fans Useful for validation or diagnostics

Table 17: Comparative Instrumentation Table

This overview supports audit engineers in aligning instrument selection with measurement goals, technical requirements and lifecycle considerations, while maintaining compliance with international standards and operational feasibility.

5.4 Signal Conditioning and Estimation Accuracy

In shipboard environments, raw sensor outputs are subject to a range of disturbances that may degrade measurement fidelity. Electrical noise, thermal drift, electromagnetic interference and sampling artifacts can all compromise data quality if left unaddressed. To ensure data reliability and maintain confidence in energy-related Key Performance Indicators (KPIs), appropriate signal conditioning is essential.

Best practices include:

- Filtering and Shielding: Low-pass filters should be applied to reduce high-frequency noise and signal cables must be properly shielded to prevent electromagnetic coupling with nearby equipment and power lines.(Maritime Organization, 2016)
- Time Synchronization: Signals originating from different subsystems, such as electrical power meters and flow sensors, must be time-aligned to permit coherent analysis, especially for calculating energy balances and conversion efficiencies.
- Pre-deployment Calibration: Sensors must be calibrated using certified reference instruments or calibration rigs under known operating conditions.(Bureau Veritas, 2012; Maritime Organization, 2016)
- Uncertainty Propagation: Estimation of overall uncertainty should be performed by analytically propagating the individual error margins of each sensor component, especially in derived metrics.(Lovins *et al.*, 2001)

For instance, calculated fuel consumption based on the product of mass flow rate and lower heating value (LHV) can exhibit cumulative errors between 2% and 5%. These propagate directly into KPIs such as Specific Fuel Oil Consumption (SFOC), potentially misleading audit conclusions if not properly accounted for.

5.5 Instrument Selection Guidelines

The selection of instrumentation for a maritime energy audit must consider both technical suitability and practical deployment constraints. The following guidelines help align instrumentation choices with audit goals, ship characteristics and operational realities:

- Audit Duration: For short-term or diagnostic audits, portable and non-intrusive tools, such as clamp-on meters, ultrasonic flow sensors and handheld IR cameras, offer rapid deployment and minimal disruption.
- Accuracy vs. Cost Trade-off: High-precision devices like Coriolis flowmeters or shaft power meters represent a significant investment but are indispensable for EEXI compliance or long-term monitoring where regulatory traceability is required.
- Retrofitting Compatibility: Older vessels with limited instrumentation or automation systems benefit from clamp-on, battery-powered, or magnetic-mount sensors that require minimal physical integration.
- Environmental Resilience: Devices exposed to vibration, humidity and salt-laden air must be ruggedized. Selecting equipment with appropriate IP ratings and vibration resistance ensures measurement stability over time.
- System Integration: Where shipboard automation systems are available, preference should be given to instruments capable of interfacing with existing data buses, enabling centralized logging and analysis.

These considerations help ensure that selected instruments provide relevant, accurate, and actionable data under the often-variable conditions of shipboard operation.(CRES, 2000; Lovins *et al.*, 2001; Hasanbeigi and Price, 2010)

5.6 Summary and Recommendations

This chapter provided a structured overview of measurement instruments commonly used in ship energy audits. Instruments were categorized by function (e.g. fuel, power, temperature, emissions), evaluated across key performance criteria and assessed for their suitability in maritime environments. The goal was to offer a practical reference for selecting measurement tools that align with specific audit scopes, ship types and regulatory requirements.

Key recommendations include:

- Fuel–Power Correlation: Deploy Coriolis flowmeters and shaft power meters for high-confidence tracking of propulsion efficiency and EEOI-related KPIs.

- System Profiling: Use clamp-type analyzers for electric load analysis and RTDs or thermocouples for long-term temperature monitoring in engines and heat exchangers.
- Supplementary Diagnostics: Apply infrared thermography for surface inspection and portable gas analyzers for verifying combustion quality and emissions compliance.
- Audit Transparency: Maintain a clear record of instrument calibration, configuration and estimated uncertainty in all reporting outputs to ensure repeatability and traceability.

With these tools and practices, audit teams can acquire high-resolution operational data, identify inefficiencies and propose targeted energy-saving actions.

6. Signal Processing and Estimation Accuracy in Ship Energy Audits

6.1 Introduction

The effectiveness of shipboard energy audits depends not only on the appropriate selection of measurement instruments as discussed in the previous chapter, but also on the way data are processed, refined and interpreted. Signal processing is essential for transforming raw sensor outputs (often affected by environmental noise, fluctuations and sensor drift) into reliable, meaningful engineering values. Equally important is the rigorous estimation of measurement accuracy, which ensures that key performance indicators (KPIs), such as Specific Fuel Oil Consumption (SFOC), Energy Efficiency Operational Indicator (EEOI) and Energy Efficiency Existing Ship Index (EEXI), are both scientifically valid and compliant with regulatory requirements.

These two complementary processes, signal integrity and accuracy quantification, form the backbone of audit reliability. Without them, conclusions regarding energy performance and efficiency improvements would lack credibility and traceability. Therefore, all procedures must adhere to internationally recognized standards, including ISO 50001 (for energy monitoring and performance tracking), ISO 50002 and EN 16247-4 (for structured energy audits and reporting) and MARPOL Annex VI, which mandates the documentation and verification of emissions and energy efficiency indices.

This chapter presents the foundational techniques for signal acquisition, filtering, synchronization and uncertainty estimation. Together, these practices ensure high-confidence data interpretation and support decision-making for operational improvements, regulatory compliance and sustainable performance in shipboard energy audits.

6.2 Sampling Methods and Synchronization

Accurate and well-coordinated sampling is a cornerstone of reliable data collection in ship energy audits. When multiple sensors or instruments, such as mass flow meters, power analyzers, tachometers, or thermal sensors, operate concurrently, it is essential to ensure that data streams are both temporally aligned and sampled at appropriate rates.(GHGES MARINE SOLUTIONS, 2016) Failure to do so may lead to mismatched datasets and flawed conclusions, particularly when calculating derived indicators such as Specific Fuel Oil Consumption (SFOC) or real-time energy efficiency metrics.

Key considerations include:

- Sampling Rate Selection: The frequency at which measurements are captured must be tailored to the dynamic behavior of each parameter. For instance, power analyzers typically operate at 1-10 Hz to effectively capture variations in electrical load, whereas vibration sensors used for condition monitoring may require sampling rates in the range of hundreds to thousands of Hz (e.g. up to 1 kHz) to detect high-frequency oscillations.(Hasanbeigi and Price, 2010)

- Aliasing Prevention: To avoid distortion caused by undersampling, analog anti-aliasing filters must be implemented before signal digitization. These filters eliminate high-frequency components that could otherwise corrupt the integrity of the sampled data.
- Time Synchronization: Aligning timestamps across different data acquisition systems is vital when conducting correlation-based analysis, such as comparing shaft power with fuel flow to compute instantaneous SFOC. This can be achieved using GPS-based timing modules or Network Time Protocol (NTP) synchronization, depending on system architecture and audit scope.
- Regulatory and Standardization Requirements: According to ISO 50002, the planning and execution of energy audits must explicitly address sampling frequency, duration and synchronization. Measurements must reflect representative operating conditions and ensure temporal coherence across subsystems to support valid energy performance assessments. (BSI, 2013)

Effective synchronization not only enhances the validity of derived indicators but also enables advanced analytics, including power-fuel-efficiency mapping, load profile analysis and multi-parameter anomaly detection.

6.3 Signal Conditioning Techniques

Sensor data acquired onboard ships are often affected by various forms of distortion due to harsh operational environments, electromagnetic interference and mechanical vibrations. Without appropriate signal conditioning, such raw measurements may introduce significant errors into performance assessments and energy efficiency calculations.

To ensure the usability and accuracy of these data streams, several conditioning techniques are routinely applied:

- Noise Filtering: Low-pass digital filters are widely employed to attenuate high-frequency noise superimposed on sensor outputs. This is particularly relevant in electrical measurements (e.g. voltage, current) and temperature sensing where signal fluctuations can mask actual trends.(Kester, Bryant and Buxton, 2006)
- Sensor Calibration: Accurate readings depend on proper calibration before and when feasible, after each audit. Calibration must be traceable to national or international standards, as emphasized in ISO 50001 for energy performance monitoring. For systems falling under EEXI compliance, calibration procedures are often formally recorded in technical documentation submitted to regulatory authorities.(IMO, 2022)

- Signal Conversion and Scaling: Analog sensor outputs (commonly 4-20 mA or 0-10 V) must be converted into engineering units through high-resolution analog-to-digital converters (ADCs) and appropriate scaling functions based on manufacturer specifications. Typical ADC resolutions range from 12 to 24 bits, enabling precise conversion even for small signal variations.(Kester, Bryant and Buxton, 2006)
- Outlier Detection and Filtering: Statistical methods, such as moving averages and the 3-sigma rule, are used to detect and suppress outliers. These techniques help identify erroneous readings caused by transient faults, operator intervention, or sensor degradation during long-term measurements.(Lovins *et al.*, 2001)
- Redundancy and Differential Measurements: Applying redundant sensors on critical parameters or using differential readings (e.g. inlet vs. outlet temperatures in heat exchangers) adds an extra layer of validation. Discrepancies between parallel measurements can signal sensor drift, degradation, or improper placement, allowing corrective action before final data analysis.

By integrating these signal conditioning practices into the audit workflow, engineers enhance the reliability of measured values and ensure that performance metrics are both traceable and robust against environmental disturbances.

6.4 Data Processing and Derived Quantities

In ship energy audits, many key performance indicators are not measured directly but are instead calculated from multiple raw data streams. The accuracy and usefulness of these derived quantities depend heavily on the quality, synchronization and pre-processing of the underlying measurements.

- Specific Fuel Oil Consumption (SFOC): SFOC is one of the most critical metrics in propulsion analysis and benchmarking. Its calculation requires temporally aligned data from both the shaft power measurement system and the fuel flow meter. Even slight desynchronization can lead to significant errors in the computed value, particularly during transient engine operation.(IMO, 2022)
- Energy Balance and Thermal Efficiency: For systems involving heat exchange (e.g. cooling water circuits, exhaust gas boilers), energy balances are computed by combining flow rates with temperature differentials and power inputs. These calculations reveal energy losses or conversion inefficiencies, forming the basis for technical improvement recommendations.(IMO, 2016)
- Electrical Load Profiles: Raw voltage and current data are often processed into load profiles using rolling averages or peak demand detection. These profiles help identify load cycles, oversized equipment and potential opportunities for energy savings in auxiliary systems.

- Regulatory Compliance Indicators: International frameworks such as MARPOL Annex VI require the computation of indices like the Energy Efficiency Existing Ship Index (EEXI) and the Energy Efficiency Operational Indicator (EEOI). These indicators are derived from measured parameters and are only valid when based on consistent, calibrated and traceable data sources.

Accurate computation of derived quantities is essential not only for audit reporting and decision-making but also for demonstrating compliance with energy efficiency standards and international maritime regulations.

6.5 Estimation of Measurement Uncertainty

In the context of ship energy audits, the credibility of calculated performance indicators such as Specific Fuel Oil Consumption (SFOC), Energy Efficiency Operational Indicator (EEOI), or energy balance metrics hinges not only on the accuracy of individual measurements but also on the proper quantification of overall uncertainty. No measurement or derived value can be considered complete unless accompanied by a well-defined error margin that reflects the limitations of the instruments and the calculation method.

6.5.1 Instrument-Level Accuracy

Every sensor or measuring device contributes a nominal uncertainty based on its physical principles, calibration status and environmental sensitivity. Some indicative uncertainty levels commonly encountered in maritime audits include:

- Coriolis Flow Meters: ±0.1-0.5% of reading
- Ultrasonic Flow Meters: ±1-2%, depending on pipe conditions and flow profile
- Shaft Power Meters: ±1-3%, including effects from misalignment, sensor placement and signal noise
- RTDs (Resistance Temperature Detectors): ±0.1-0.3°C, depending on class and installation

These values typically derive from manufacturer specifications and certified calibration reports.

6.5.2 Combined Uncertainty and Error Propagation

When measurements are used in combination to calculate a performance indicator, the overall uncertainty must account for the interaction between variables. This is done using the law of propagation of uncertainty, commonly implemented through the Root Sum Square (RSS) method.(Taylor and Kuyatt, 1994)

For example, if SFOC is calculated from a mass flow meter with ±1.0% uncertainty and a shaft power meter with ±2.0%, the combined uncertainty of the resulting SFOC will be approximately ±2.2%, assuming uncorrelated variables.

6.5.3 Type A and Type B Uncertainty Contributions

- Type A uncertainty arises from statistical analysis of repeated measurements under the same conditions. This includes standard deviation, confidence intervals, or variability across audit periods.
- Type B uncertainty encompasses systematic sources, such as calibration errors, drift, resolution limits and external environmental influences.

Combining both types into a unified uncertainty value allows auditors to evaluate the confidence level associated with each metric and make decisions accordingly.

6.5.4 Standards and Reporting Requirements

International standards such as ISO 50002 and EN 16247-4 explicitly require that all reported audit results be accompanied by documented uncertainty assessments. These assessments must include:

- Identification of all significant error sources
- Explanation of the estimation method
- Reference to calibration procedures and traceable standards
- Presentation of uncertainty in both absolute and relative terms

These requirements are also aligned with MARPOL Annex VI and its associated metrics (e.g. EEXI and EEOI), which emphasize traceability and reliability in reporting. Without such documentation, audit results may lack the robustness necessary for regulatory acceptance or effective benchmarking.(Von Knorring, 2019)

6.6 Practical Considerations and Best Practices

Beyond methodological accuracy, the practical implementation of energy audits at sea requires careful attention to data integrity, operational feasibility and traceability. The following best practices enhance the robustness of the audit process and increase confidence in the resulting performance indicators:

- Employ Redundant Measurements: For key variables such as fuel flow rate or temperature differentials (ΔT), the use of multiple sensors or parallel data channels can help detect drift, instrument failure, or transient anomalies. This redundancy is particularly important in mission-critical subsystems like propulsion and main engine cooling circuits.
- Cross-Validation with Manual Logs: Automated measurement systems should be periodically cross-checked against manual entries (e.g. engine room logbooks) to ensure plausibility and detect calibration drift or logging errors. This practice serves as a sanity check, especially in audits conducted over multiple operational phases.(Von Knorring, 2019)

- Data Structuring and Traceability: Collected data should be stored in structured, timestamped and version-controlled formats such as CSV or JSON. This allows for traceability of data provenance and reproducibility of audit outcomes, which are key requirements under standards like ISO 50002 and MARPOL audit practices.
- Maintain Full Transformation Records: All processing steps, from raw sensor signals to final performance indicators, must be well-documented. This includes filtering algorithms, calibration coefficients, unit conversions and time alignment procedures. Full transparency in the data processing chain enables verification and supports audit credibility.
- Automate Plausibility Checks: When possible, integrate automatic validation routines that flag values outside expected operational ranges or identify inconsistent behavior across sensor arrays. These checks can catch instrumentation errors early and reduce post-processing overhead.(Ghaforian Masodzadeh, 2018)

By applying these principles, auditors can safeguard the integrity of measured data and the validity of the derived insights, supporting data-driven decision-making and compliance with international audit frameworks.

6.7 Summary

Signal processing is not merely a technical formality but a foundational component of regulatory compliance in ship energy audits. Accurate sampling, proper filtering, time synchronization and thorough uncertainty estimation collectively determine the credibility and traceability of all derived performance indicators, such as Specific Fuel Oil Consumption (SFOC), Energy Efficiency Operational Indicator (EEOI) and thermal system balances.

These procedures transform raw sensor data into validated, audit-ready information that supports informed decision-making and operational optimization. Furthermore, they align closely with international standards, including MARPOL Annex VI, ISO 50001 and 50002 and EN 16247-4, which explicitly or implicitly require precision, traceability and transparency in the processing and reporting of energy performance data.

By integrating the methodologies presented in this chapter, energy audits can move beyond diagnostic snapshots to become robust tools for continuous improvement and regulatory accountability.

7. Case Applications and Evaluation of Measurement Methodologies in Ship Energy Audits

7.1 Introduction

This chapter presents real-world examples of how key technical quantities are measured on board ships, using case studies from the literature and actual energy audit reports. These examples help illustrate how the measurement techniques described in earlier chapters are applied in practice. For each case, the method used and its effectiveness are assessed, as well as how well current standards and requirements are met. Special attention is given to the reliability of the collected data, the degree to which it aligns with international regulations like ISO 50002 and MARPOL Annex VI and whether alternative measurement approaches could have offered better results in terms of accuracy, cost, or ease of use. The goal is to connect theory with practice and highlight the strengths and possible limitations of different measurement strategies in real shipboard environments.

7.2 Case Study: MV Explorer Energy Audit

The MV Explorer energy audit serves as a representative example of how advanced measurement instrumentation can be applied in practice to evaluate ship performance. The audit focused on quantifying propulsion efficiency and onboard energy usage through real-time monitoring of fuel consumption, shaft power and electrical load profiles.(GHGES MARINE SOLUTIONS, 2016)

7.2.1 Methodology Used

In the MV Explorer energy audit, torque and RPM sensors were installed on the main propulsion shaft to dynamically calculate shaft power. Fuel consumption was recorded using a Coriolis mass flow meter, chosen for its high accuracy and its ability to operate continuously under real-world conditions. All measurement data were synchronized via a central data acquisition system that employed GPS-based timestamping to ensure temporal coherence between all monitored parameters.

7.2.2 Evaluation

One of the audit's key strengths was the use of high-precision instrumentation. The Coriolis flow meter, for example, operated within a typical uncertainty range of ±0.1-0.5%, contributing to high-quality data acquisition. Additionally, the 1 Hz sampling rate allowed for real-time and accurate calculation of Specific Fuel Oil Consumption (SFOC), even under variable operational conditions. However, a notable weakness in the setup was the manual logging of calibration records, which introduced potential for human error and compromised the traceability of the measurements.

As for possible improvements, integrating a secondary (redundant) flow meter would have enabled cross-verification of readings and earlier detection of potential sensor faults. Furthermore, automating the calibration record-keeping process and aligning it with ISO 17025-certified documentation would have significantly enhanced the audit's credibility and ensured full traceability in line with regulatory expectations.

This case illustrates both the potential and the challenges of high-resolution energy audits in operational vessels, emphasizing the importance of synchronization, traceability and redundancy in measurement methodologies.

7.3 Case Study: Australian Fishing Vessel Fleet Audit

An energy audit was carried out across a fleet of 16 Australian fishing vessels with the aim of establishing standardized methods for evaluating onboard energy efficiency. The primary objective was to develop consistent, practical protocols that could be applied across similar small-scale maritime operations.(Wakeford, 2006)

7.3.1 Methodology Used

Fuel consumption data was manually extracted from the vessels' daily logbooks and then corrected using spot measurements taken during operation. Power output was not directly measured, but it was estimated indirectly using shaft speed readings and torque values derived from manufacturer-provided performance curves. For auxiliary systems, measurements such as temperature and electrical loads were obtained using portable power analyzers and temperature sensors.

7.3.2 Evaluation

The primary strength of this approach lay in its practicality and affordability, which made it well-suited to small commercial fleets. The integration of existing operational logs with targeted manual measurements helped improve the completeness of the dataset without requiring major retrofitting or costly instrumentation. However, the absence of direct torque measurements introduced a significant degree of uncertainty into the power estimates. This limitation reduced the accuracy of derived indicators like the Specific Fuel Oil Consumption (SFOC), which relies on reliable power data.

To enhance the methodology, the use of inline shaft power meters or torque sensors based on strain-gauge technology could have provided more accurate real-time power measurements. Additionally, incorporating GPS modules compliant with NMEA standards for timestamping would have improved the synchronization of data across parameters, further enhancing the reliability and interpretability of the results.

7.4 Methodological Comparison: Shipboard Survey (CG59)

The CG59 shipboard survey involved an energy efficiency assessment conducted across a diverse group of vessels, with the goal of applying a unified auditing methodology. This effort aimed to gather comparable performance data across ship types using standardized templates and common key performance indicators (KPIs).(Lovins *et al.*, 2001)

7.4.1 Methodology Used

The survey focused on collecting values for KPIs such as Specific Fuel Oil Consumption (SFOC), Energy Efficiency Operational Indicator (EEOI) and auxiliary load factors. Measurements were obtained using a combination of clamp-on power meters, portable data loggers and entries from vessel logbooks. Each vessel followed a common data collection template to support consistency in reporting and to ensure that similar operational parameters were assessed across the fleet.

7.4.2 Evaluation

The greatest strength of this methodology was the consistency it offered. By using a shared framework, the audit enabled reliable comparisons between vessels, helping to identify general trends and fleet-wide improvement opportunities. However, one significant weakness was the variation in measurement quality. Some vessels used calibrated and reliable sensors, while others relied on older or unverified tools. This inconsistency led to discrepancies in the data and reduced the reliability of cross-vessel comparisons.

To address these challenges, future surveys could benefit from the use of standardized sensor kits featuring pre-calibrated instruments. These could be complemented by automated logging systems capable of detecting and flagging anomalies or sensor drift. Such improvements would enhance measurement traceability and reduce the uncertainty associated with inconsistent instrumentation.

7.5 Advanced Approach: SEMSA Self-Assessment System

The Ship Energy Management Self-Assessment (SEMSA) system represents an advanced methodology for onboard energy audits. Unlike traditional audit frameworks based on periodic assessments, SEMSA implements a continuous self-monitoring platform designed to support real-time energy performance tracking. The system is aligned with ISO 50001 principles and targets operational improvements through constant feedback.(Ghaforian Masodzadeh, 2018)

7.5.1 Methodology Used

SEMSA integrates a digital dashboard that continuously collects and displays data from propulsion and auxiliary systems. It includes built-in thresholds for key performance metrics and automatically issues alerts when deviations from expected values occur. The platform is configured to interface with ISO 50001 compliant monitoring plans, allowing for structured performance management and alignment with recognized energy management standards.

7.5.2 Evaluation

One of the key advantages of the SEMSA approach is its ability to detect performance anomalies in real time, which allows ship operators to take corrective actions without waiting for scheduled audits. This supports a culture of continuous improvement and audit readiness. The system also helps streamline reporting processes by organizing performance data into structured outputs.

However, the effectiveness of SEMSA depends heavily on the initial setup. The cost of installing sensors and configuring the dashboard can be significant, especially for older vessels. Moreover, successful operation requires that crew members are familiar with the system’s interface and can respond appropriately to alerts and diagnostics.

To enhance its reliability and complement its real-time monitoring capabilities, SEMSA can be paired with scheduled manual audits. These periodic checks not only help validate the system’s automated outputs but also provide deeper diagnostic insight, especially in complex operational scenarios where human evaluation remains essential.

7.6 Comparative Assessment of Methodologies

Case	Instrumentation	Sampling & Sync	Estimation Accuracy	Regulatory Alignment	Reliability Rating
MV Explorer	High-grade sensors (Coriolis, Torque)	GPS-based sync	High	MARPOL Annex VI, ISO 50002	High
Australian Vessels	Manual & estimated	Manual logging	Moderate to low	Partial (SEEMP logs)	Medium
CG59 Survey	Mixed portable tools	Shared template	Variable	ISO 50002-inspired	Medium
SEMSA	Automated platform	Fully integrated	High (continuous)	ISO 50001, SEMSA	High

Table 18: Comparative Assessment of Methodologies in Real Case Studies

7.7 Conclusion

The case studies presented in this chapter highlight the wide range of methods used in ship energy audits, from simple manual data collection to fully integrated digital systems. Based on the findings of this thesis, several key conclusions can be drawn:

- Reliable performance indicators depend heavily on proper data synchronization and clear traceability
- In many audits, especially those relying on manual methods, the systematic estimation of measurement uncertainty is often overlooked
- Calibration procedures and sensor redundancy stand out as major factors that distinguish basic setups from more robust and dependable ones

Overall, the most effective strategy seems to be a hybrid model that combines scheduled expert-driven audits with continuous onboard monitoring solutions like SEMSA. This combination offers a practical path toward improving audit quality while remaining consistent with international energy management standards.

8. Conclusions, Recommendations, and Future Work

8.1 Conclusions

This thesis presented a comprehensive analysis of the tools, methodologies, and procedures involved in conducting energy audits in the maritime sector, with a focus on ensuring the accuracy, reliability, and applicability of measurement-based conclusions in real shipboard conditions.

The key conclusions from the research are summarized below:

- Measurement Integrity Is Foundational: The accuracy and reliability of any energy audit are directly tied to the suitability and calibration of the instruments used. The comparative evaluation presented in chapter 5 shows that while high-precision instruments such as Coriolis flow meters and power analyzers offer clear advantages, their use must be contextualized within operational constraints such as cost, installation feasibility, and environmental robustness.
- Signal Processing Enables Trustworthy KPIs: As highlighted in chapter 6, signal processing, including sampling, conditioning, and uncertainty estimation, is indispensable for translating raw measurements into meaningful and traceable Key Performance Indicators (KPIs). Errors introduced through poor synchronization, sensor drift, or inadequate filtering can significantly compromise the validity of indicators such as Specific Fuel Oil Consumption (SFOC) or Energy Efficiency Operational Indicator (EEOI).
- Real-world Applications Validate Methodological Findings: Chapter 7 demonstrated, through literature-derived case studies, that the methodologies proposed in earlier chapters are consistent with actual audit implementations. It was shown that successful audits combine calibrated instruments, synchronized data collection, and post-processing with documented uncertainty estimation. Notably, even simplified approaches (e.g. using tank sounding or manual logbooks) can yield acceptable results when enhanced with procedural rigor and error analysis.
- Regulatory Alignment Is Achievable: The methodologies presented in this thesis align with the requirements of MARPOL Annex VI (particularly for EEXI and EEOI), ISO 50001 (energy management systems), ISO 50002 (energy audits), and EN 16247-4 (audits in the transport sector). These frameworks either explicitly or implicitly demand traceable, documented, and verifiable measurement and processing practices.

In conclusion, a hybrid audit strategy, combining robust measurement instruments with well-documented sampling and signal processing workflows, offers a viable and scalable solution for ship energy auditing across a range of operational contexts and vessel types.

8.2 Recommendations

Building upon the conclusions drawn above, several practical recommendations can be made to guide maritime professionals, auditors, and ship operators in strengthening the quality and regulatory compliance of their energy audits:

1. Prioritize Instrument Suitability: Selection of instruments should not be based solely on accuracy specifications but must consider factors such as environmental suitability (vibration, humidity), ease of installation, and cost-effectiveness.
2. Standardize Calibration Protocols: All measurement instruments must be calibrated before deployment using certified procedures, and recalibration intervals must be defined based on operating conditions and manufacturer guidelines.
3. Implement Synchronized Data Logging Systems: Where possible, adopt centralized data logging platforms with GPS or NTP time synchronization to ensure consistent timestamps across all sensors.
4. Apply Real-time Filtering and Validation: Use digital filters and automated plausibility checks onboard to detect and correct anomalies in real time, minimizing the risk of corrupt data reaching the analysis stage.
5. Document All Processing Steps: From raw data acquisition to KPI reporting, each transformation (e.g. filtering, scaling, alignment) must be fully documented. This ensures audit traceability and supports verification by third parties or regulators.
6. Incorporate Uncertainty Estimation: Each reported value, particularly derived KPIsmust be accompanied by uncertainty analysis using methods such as the root sum square (RSS) approach. This is not only good practice but often required under ISO and MARPOL guidelines.

These recommendations aim to bridge the gap between technical audit methodology and operational best practices, ensuring that the tools and techniques explored throughout the thesis can be readily implemented in real-world contexts.

8.3 Future Work

While the current research provides a solid foundation for energy auditing practices in shipping, several areas remain open for further exploration. Future work may aim to expand, automate, or enhance the current methodologies in the following directions:

1. Integration of Machine Learning in Audit Data Analysis: The use of AI and machine learning for anomaly detection, predictive maintenance, and dynamic optimization of KPIs remains underexplored in ship energy audits.

2. Development of Lightweight Audit Frameworks for Small Vessels: Many audit methodologies assume large vessels with extensive instrumentation. There is a need to adapt tools and procedures for smaller ships operating with limited onboard systems.
3. Expansion of Real-Time Monitoring Systems: Future studies should examine the integration of continuous monitoring platforms (e.g. SEMSA) with ship management systems to enable automatic compliance verification and energy optimization feedback loops.
4. Lifecycle Assessment (LCA) Integration: Future audit methodologies may benefit from incorporating full lifecycle energy and emission metrics, aligning ship performance monitoring with broader environmental impact assessments.
5. Pilot Testing of Proposed Methods: Finally, the methodologies and recommendations outlined in this thesis should be field-tested in a live shipboard environment. Such pilots would offer valuable validation and highlight any implementation challenges not foreseen during the theoretical analysis.

These forward-looking efforts could serve to further consolidate the role of energy audits not just as regulatory checklists, but as dynamic tools for performance optimization, environmental stewardship, and digital transformation within the maritime sector.

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