Energy efficiency technology benefit-tracking procedures

Table of Contents

01 Introduction to vessel energy efficiency technologies and the split-incentive dilemma

Improving the energy efficiency of vessels is a necessary step towards a sustainable decarbonization of shipping. Increased energy efficiency also offers cost savings through lower operational expenses, along with reduced emissions of greenhouse gases (GHGs) and pollutants.

Looking at the bigger picture, reducing the world fleet's energy demand leads to a much greater decrease in resource demand upstream in the energy production chain.[1] Studies from the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) indicate an approximate 4:1 ratio of renewable energy required for green fuel production to delivered energy on board vessels, as illustrated in Figure 1.[2]

Environmental and industry advantages of improved energy efficiency include reductions in:

| Fuel consumption | GHG emissions | Energy demand for fuel production | Cost for the energy transition |

These advantages contribute to a more sustainable and economically viable maritime industry.

Figure 1: Energy losses in the fuel production chain from energy required for e-fuel production to energy delivered on board.

Renewable energy generated for the production of e-fuels

Available energy on board from e-fuels

Delivered energy on board for propulsion and electrical needs

~-50%

~-50%
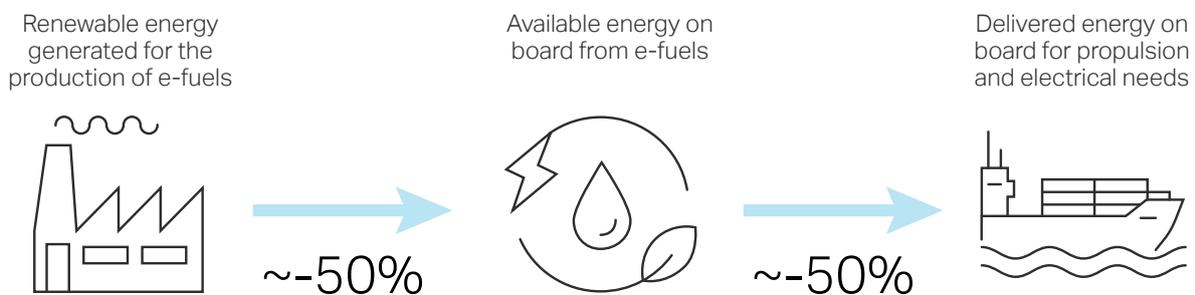
One way of improving the energy efficiency of existing vessels is by retrofitting **energy efficiency technologies (EETs).** In this document, EETs are changes to a physical aspect or control systems of a vessel made with the intention of reducing the energy required for propulsion. Examples of implementing EETs include:

- Fitting a new bulbous bow to the vessel
- Replacing the vessel's propellers
- Applying a low-friction (i.e., foul release) coating to the hull during dry docking
- Implementing engine control software to optimize fuel consumption
- Installing suction sails for wind-assisted propulsion

The aim of retrofitting EETs on existing vessels is to immediately reduce the vessel fuel consumption and energy demand, which leads to reduced demands on both conventional and alternative fuel production, and a reduction in GHG emissions. It should also bring a positive net cash flow to the fuel bill owner and be a positive business case in an asset's lifetime.

A large part of the global fleet is not owned and operated by the same company but is instead operated through time-chartering agreements. In these agreements, the charterer normally pays for the fuel. This may cause a split-incentive problem: the charterer benefits from fuel savings achieved through retrofitting EETs, while the shipowner normally bears the cost of the retrofit — an investment which is not necessarily reflected in the vessel's charter-market value. As a result, shipowners often lack a strong financial incentive to invest in EETs. Additionally, perceived risks related to the operation of the technology, return on investment, variation in fuel prices, and other factors may result in misaligned interests.

Sharing the benefits and costs of implementing EETs at the individual contract level may help align the interests of owners and charterers, thereby reducing barriers to implementing EETs. To enable cost-benefit sharing, the parties need a method for quantifying the benefits of EETs: specifically, reduced fuel consumption, energy demand, and GHG emissions.

1.1   Purpose of this technical guide

This guide provides the MMMCZCS's recommended best-practice procedures for tracking the benefits of EETs retrofitted to existing vessels to reduce propulsion power requirements. The procedures include calculating fuel savings with a sufficient level of confidence and transparency to support each party's own commercial decision-making on cost-benefit sharing.

The methodologies for evaluating the performance improvement are based on either: 1) operational data obtained before and after the EET retrofit, or 2) in-service trials of the technology, if it can be switched on and off and is not intended for continuous use.

The procedures use the vessels' performance monitoring data and performance evaluation principles found in industry-acknowledged standards and procedures for vessel performance monitoring and evaluation, as well as other relevant industry publications.

The technical guide is intended for use on monohull cargo vessels with conventional propulsion trains, i.e., the engine drives the propeller shaft(s) directly through mechanical connections such as gearboxes and clutches.

The guide can be adapted to other vessel types with other types of energy generation solutions and EETs, provided there is an understanding of the principles upon which these standard methods are based.

The guide only covers the technical evaluation of the fuel savings as determined by vessel performance monitoring activities. The scope of this guide does not include how fuel and emissions savings are distributed between parties, as such arrangements should be determined independently by the parties involved in any cost-benefit sharing agreement.

1.2   Target audience of this technical guide

This guide presents methods for evaluating fuel savings based on data analysis and engineering principles of vessel resistance and propulsion. The procedures described are intended for readers with a technical background in vessel performance monitoring and evaluation, e.g., vessel technical managers, vessel performance system providers, and performance verification service providers.

The performance evaluation does not require special data analysis software, machine learning or AI-based systems, or similar tools. The performance data can be sufficiently filtered and processed using standard spreadsheet functionalities, relatively simple computer programs, and scripts.

This guide will primarily benefit shipowners and charterers who want to de-risk their investment in a retrofit of EETs through independently negotiated cost-benefit sharing agreements, and where the benefits' justification must be based on attained performance improvements. Shipowners or charterers can also benefit directly from the application of these standardized methods if they plan to implement EETs outside of the context of a cost-benefit sharing agreement.

Additionally, stakeholders involved in discussions about performance evaluation of retrofitted EETs, such as shipowners, cargo owners, and original equipment manufacturers, can also benefit from the procedures in this guide for evaluating fuel savings.

1.3   Classification of EETs and the structure of this technical guide

EETs can be split into two general categories:

-   **EETs designed for continuous operation without the possibility of switching between 'on' and 'off' modes.** Typical examples include retrofitted propellers, propeller ducts, propeller boss cap fins, a re-designed bulbous bow, application of new hull coatings, and other fixed or static modifications of the vessel.
-   **EETs that are not designed for continuous operation and can be switched between 'on' and 'off' modes.** Typical examples of this technology are shaft generators, auxiliary engine economizers, wind-assisted propulsion systems (WAPS), and air lubrication systems (ALS).

Based on this categorization, the guide has two main procedures for tracking the benefits of EETs:

-   Continuous monitoring procedure for EETs in continuous use (Section 2)
-   In-service testing procedure for EETs that can be switched on and off and are not intended for continuous use (Section 3)

The main difference between the two procedures is that the benefit of the technology operating continuously is defined by comparing vessel performance before and after the retrofit. For EETs that can be switched on and off, the benefit is defined by comparing vessel performance with the technology on versus off.

Both procedures can be applied for EETs which can be switched on and off, and they should show similar results when considering the percentage of time the EET is active. Furthermore, it may also be necessary to compare performances before and after the retrofit to determine the passive energy demand of the EET, e.g., added wind resistance of sails mounted on deck when folded down.

Both procedures require collecting and filtering performance data, encountered weather conditions, and relevant ship technical data, as described in Sections 2.1 to 2.4. The vessel's operating profile must also be considered, i.e., the distribution of operating drafts, trims, and speeds, when calculating the benefits of a particular EET.

Both procedures therefore recommend periodic reviews of performance gains in terms of fuel consumption reduction, GHG emissions reduction, and financial savings. This will allow tracking of the EET benefit while considering variations in operational profile. This aspect is discussed in Section 4.

The methodologies in this guide are demonstrated by applying these to historical performance data and EET retrofit projects carried out by project partners of MMMCZCS, and presented as case studies in Section 5. These case studies demonstrate the robustness of the proposed methodologies, the value of data quality, data availability and alignment with governing assumptions, and the performance of EETs implemented. The case studies use real data from measurement campaigns carried out on the vessels presented. All case-study data is anonymized and used with permission to illustrate the methodology.

Other figures in this report show data and curve fitting to data which is not measured but is representative of typical measurement data. These plots are included to illustrate concepts using values which are realistic for the quantities presented, but which are not from real measurements.

1.4 General considerations regarding application of the technical guide

Note that the benefit-tracking procedures presented may not be applicable to all EET retrofit projects. A vessel's energy demand, fuel consumption, and corresponding technical performance indicators depend on numerous factors related to the vessel's design characteristics, the specific EET, and the environmental conditions encountered.

The applicability of the benefit-tracking approaches outlined is limited by governing assumptions, as detailed in the appropriate reference, or as explicitly stated in this guide. These assumptions should not be disregarded, as it may significantly influence confidence in the results of a performance evaluation and become a basis for flawed decision-making.

To support a commercial benefit sharing agreement and to avoid disputes about energy savings, fuel savings, or financial savings, uncertainties related to the performance evaluation should be adequately assessed. The variable environmental factors include waves, sea currents, sea and air temperatures, and wind conditions, all of which can significantly impact the vessel's energy demand and fuel consumption while underway in a natural seaway.

Other vessel-related factors, such as degraded hull performance due to mechanical failure, or marine fouling of the hull and propeller as well as deteriorated efficiency of energy-producing machinery and its auxiliary systems, can also contribute significantly to increases in the power demand and fuel consumption. These vessel conditions exhibit inherent variability, introducing additional uncertainty.

Ultimately, the expertise of the performance verifier should be relied upon to assess the applicability of these guidelines considering the specific vessel, EET, data quality, and data availability. The intention of the procedures in this guide is to support the performance verifier as much as possible in making these assessments.

1.5   Use cases

The primary purpose of this guideline is to serve as an unbiased and fair basis for benefit tracking in terms of fuel consumption savings realized by retrofitting EETs to existing vessels. This should help reduce the commercial risk associated with implementing EETs by supporting independently negotiated cost-benefit sharing arrangements in EET retrofitting projects that may not be viable for a single party to pursue alone.

Other use cases for the methodologies include:

- Establishing baseline performance data for existing vessels to support speed-consumption guarantees in time-charter agreements, particularly after the implementation of an EET

- Assessing fuel savings and emissions reductions resulting from retrofitting EETs on existing vessels

- Assessing the performance of EETs that can be switched on and off on vessels, especially emerging technologies for which limited operational experience may be available

- Assessing the performance improvement due to dry docking and maintenance activities on the hull and propeller

- Monitoring performance changes during operation to help plan dry docking, hull and propeller cleaning, and other vessel maintenance activities

1.6   Definitions

This section describes the key terms and definitions used in this guide, which are not necessarily commonly used outside the field of vessel performance monitoring.

- **Added resistance:** The relative difference in percent between vessel resistances derived from measurements during operation and as determined by a reference vessel model.

- **Baseline period:** The timespan during which the performance of the vessel is measured before implementing an EET.

- **Benchmark period:** The timespan during which the performance of the vessel is measured after implementing an EET.

- **Cost-benefit sharing agreement:** A contractually binding agreement that aims to fairly distribute costs and financial savings from reduced fuel oil cost and/or avoided GHG emissions taxation derived from the performance monitoring of EETs retrofitted as part of the agreement. Such agreements are typically established directly between the involved parties based on mutually agreed terms.

- **Continuous performance monitoring:** Measuring and assessing the fuel consumption and emissions of the vessel continuously based on regular periodic reporting of measured quantities. This is typically done using noon reports and/or high-frequency automatic data measuring systems on board the vessel.

- **Conventional propulsion train:** A propulsion system consisting of one or more main engines connected to one or more propeller shafts through clutches and gearboxes, i.e., a direct mechanical propulsion system.

- **Energy efficiency technology (EET):** A technology implemented on board a vessel with the intention to improve the energy efficiency of the vessel. In this guide, 'EET' covers physical modifications to the vessel (e.g., bulbous bow replacements), maintenance activities (e.g., hull coating renewals, propeller polishing), and devices or systems implemented on board (e.g., propeller pitch control systems, WAPS, etc.), among other possible changes to the vessel. In general, the EET is assumed to influence the vessel performance by reducing the fuel consumption at a particular vessel operating condition.

- Data filtering: The process of removing measured data points from a data set so that the remaining data points can be used in further analysis.

- Data normalization: The process of changing the values of data points after filtering by removing the influence of varying factors across data points, so that all data is referenced to the same operating condition. This ensures that, for example, fuel consumption values from two measurements are comparable. Power at a given speed, draft, and trim should be referenced to the same operating conditions of the vessel, so that effects of wind, currents, and waves are removed.

- On/off technology: An EET that can be altered by the crew on board the vessel from a state where the EET is active and should have its intended effect on the performance of the vessel to a state where the EET is not active and should not have its intended effect on the performance of the vessel.

- Performance indicator: The quantity used to define the vessel performance. Within the context of this guide, fuel consumption is the performance indicator of the vessel while underway on a voyage, i.e., during sea passage.

- Reference model: A relation between the speed of the vessel and the vessel resistance, power, or fuel consumption at a given draft and trim. The reference model serves as the reference for determining the added resistance during the baseline and benchmark periods. The reference model performance curve usually comes from the vessel sea trials, self-propulsion model tests, or computational fluid dynamics (CFD) simulations and represents the ideal vessel performance.

- Static technology: An EET that cannot be altered from an active to an inactive state and is always affecting the energy efficiency and performance of the vessel, e.g., propeller boss cap fins, new hull paint, or coating system, etc.

- Vessel performance: The relation between the vessel speed and the performance indicator chosen (typically power or fuel consumption) to evaluate the quality of vessel operations. The performance is assessed for the entire range of operating conditions that the vessel encounters.

It is assumed that the reader has some understanding of the relation between vessel speed, resistance, power, energy, and fuel consumption. However, these terms are often improperly mixed and used interchangeably in the field of vessel performance monitoring. Therefore, it is worth pointing out the differences to avoid misunderstandings:

- Resistance is the force that the vessel must overcome to move in a desired direction at a constant speed.

- Power is the rate of work delivered, which depends on where it is assessed in the propulsion system.
  - Normally, we are interested in the rated power of the engine and the relative power (0% to 100%) at which it is running.
  - Brake power is the power delivered by the engine to the propulsion machinery, before any gears, clutches, or other transmission devices.
  - Shaft power or delivered shaft power is the power delivered to rotate the propeller when measured on the propeller shaft close to the propeller, after power transmission components and after delivering power to other devices, e.g., shaft generators.
  - Transmission efficiency is the ratio of shaft power to brake power.
  - Effective power is the power delivered after subtracting losses due to hydrodynamic effects of the rotating propeller behind a moving hull. The effective power is equal to the vessel resistance at a particular speed multiplied by the vessel speed.
  - Total propulsion efficiency is the ratio of effective power to engine power.
  - Power is normally reported using units of kilowatt (kW) or megawatt (MW).

- Energy is the total amount of work delivered by the propulsion system, which can be evaluated at different points in the propulsion system, i.e., at the propeller, at the beginning of the propeller shaft, etc. Energy is calculated by integrating power over time. Energy is typically reported in units of kilowatt hours (kWh) or gigawatt hours (GWh). Normally, we are only interested in the total energy output by the engine, because it is related to fuel consumption.

- Fuel consumption is the mass of fuel used by an internal combustion engine. For vessels, it is normally reported using the unit metric tonnes (mt).

- Specific fuel oil consumption (SFOC) is the mass of fuel used per unit of energy generated by the engine and is a characteristic of the particular engine. It is normally expressed as gram per kilowatt hour (g/kWh) as a function of relative engine power, i.e., in relation (0% to 100%) to maximum power. Brake power is normally reported in engine factory acceptance tests (FATs) together with the corresponding SFOC.

02 Continuous performance monitoring

This section provides guidance on methodologies for tracking the benefits of EETs that are retrofitted to an existing vessel and are always active. The benefit is defined as the fuel saving due to the use of the technology. Such technologies include redesigned propellers, a redesigned bulbous bow, propeller in-flow adjusting by stator fins, or other upgrades designed to continuously reduce the required propulsion power.

The continuous performance monitoring procedure is divided into seven steps, as illustrated in Figure 2:

1. Onboard data measurements and collection of vessel technical documentation
2. Data quality checks, cleaning, and filtering
3. Definition of reference models for performance evaluation
4. Data normalization to a reference operational condition
5. Evaluation of performance during baseline and benchmark periods
6. Calculation of performance improvements
7. Regular review of savings

The performance improvement is defined as the reduction in added resistance between the baseline period and the benchmark period. The added resistance is defined as the ratio of the reference model shaft power delivered in deep calm water conditions and operational measurements of delivered shaft power normalized to calm water conditions by correcting for wave, wind, and shallow water effects. The resulting fuel saving is therefore normalized and referenced to the calm water condition.

Note that the procedure for continuous performance monitoring uses propeller shaft power as reported in noon reports or measured by data collection systems on board the vessel. When a combination of EETs has been installed on board a vessel during a single dry docking, the estimated fuel saving is for the EET combination. Therefore, when a combination of EETs has been retrofitted at the same time, the continuous performance monitoring procedure outlined in Figure 2 cannot be used to isolate the effect of a single EET.
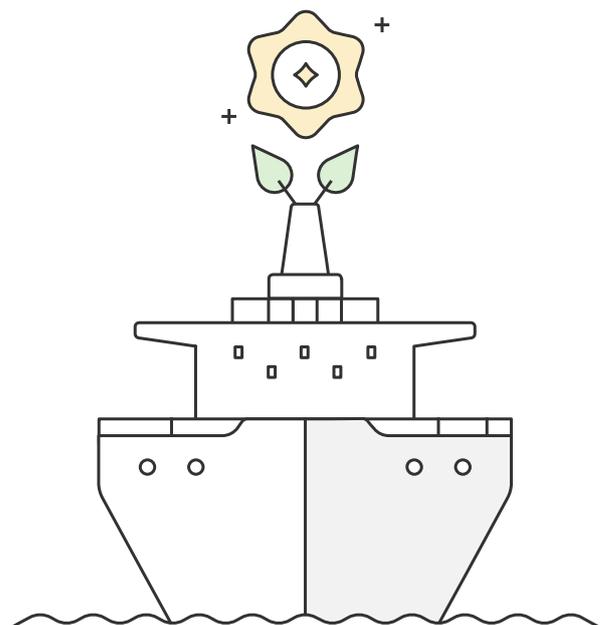
Figure 2: Procedure for calculating operational benefits by retrofitting an energy efficiency technology.
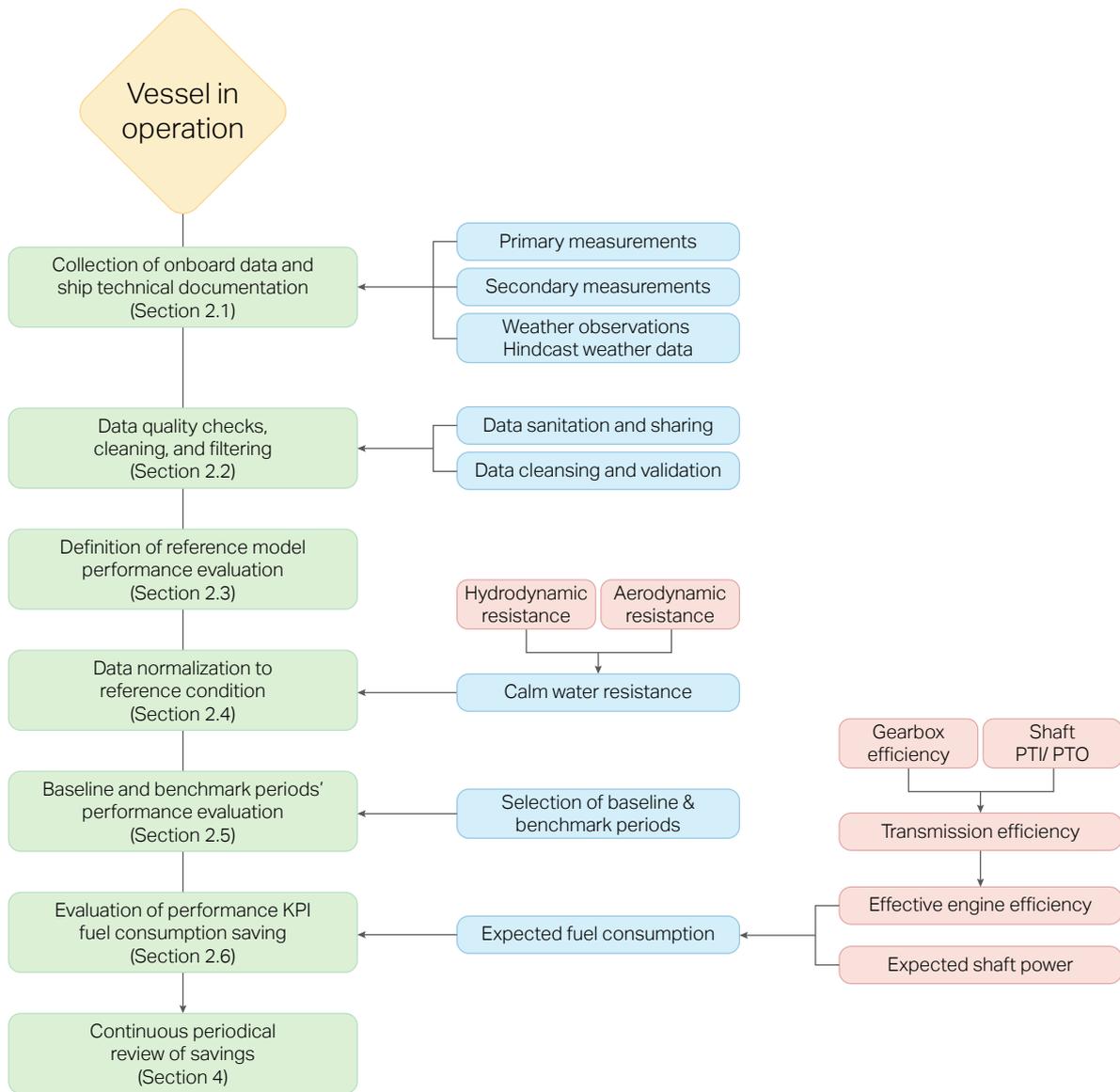
KPI = key performance indicator, PTI = power take-in, PTO = power take-off.

2.1 Performance data and vessel technical documentation

This section describes the performance parameters that should be measured to enable a performance evaluation of retrofitted EETs. Commonly used data sources are listed, together with our recommendations for obtaining data of a sufficient quality for performance evaluation purposes.

The continuous monitoring procedure can use data from noon reports or auto-logged data from high-frequency onboard measurement systems.

Sensor calibration is essential to eliminate drift or offsets in sensor signals. It is recommended to frequently and regularly check — and calibrate if needed — any sensors, particularly shaft torque meters. Original equipment manufacturers' maintenance guidance should be followed.

Data to be collected may originate from multiple sources with different sampling frequencies for each of the parameters measured. If so, the sampling rates must be aligned before using the data in a further analysis.

If possible, data should be verified by enriching with other data sources, e.g., using two independent weather providers of hindcast metocean data for verification. Another example is the use of the vessel's geographical position from an external data provider that captures the vessel's position via its automatic identification system (AIS) signal.

2.1.1 Measured parameters

This section examines the parameters to be measured and recorded to conduct a thorough performance analysis. The parameters are categorized into navigational data, fuel consumption and power production data, and weather observations.

Parameters are categorized as either **primary** or **secondary**, where:

- **Primary parameters** are used for performance (vessel speed and fuel consumption) measurements and calculations.
- **Secondary parameters** are used to apply filtering and normalization procedures necessary to make the performance before and after the retrofit comparable.

Each parameter item is also assigned a **priority level**:

- **Priority 1** defines **mandatory** parameters required to perform a basic analysis of the impact to be derived from a retrofitted EET.
- **Priority 2** defines **optional** parameters that increase the confidence of the findings in the performance analysis, e.g., parameters which do not explicitly appear in any calculations but can be used to cross-check and validate other parameters to ensure data validity.

Appendix A contains a consolidated list of measured and derived parameters, observation or measurement frequencies, and sources for measurements, along with a categorization of parameter by type and priority.

2.1.2 Navigational data

Navigational data is typically obtained on board, either directly via sensors or via noon reports. Navigational data consists of the vessel's:

- Position
- Speed over ground (SOG)
- Speed through water (STW)
- Time since last voyage/noon report
- Heading
- Course over ground
- Rudder angle
- Draft readings
- Propeller pitch (if the vessel has a controllable pitch propeller)

An external data source such as AIS can be used to calculate the SOG to validate the reported SOG and distance.

Because measurements obtained by a vessel's speed log may be associated with significant uncertainty, it is recommended that the STW is calculated from the SOG corrected for ocean currents.

Rudder angle measurements, where available, can be used to filter for steady state-periods. Alternatively, more advanced methods that correct for added resistance due to rudder drag can be applied to increase the accuracy and confidence in the results. However, this is not covered in the scope of this guideline.

Draft readings must be static and obtained from, for example, the vessel's loading computer.

2.1.3 Fuel consumption and power production data

Fuel consumption and power production data refers to the fuel consumed by primary and/or secondary movers. This data includes:

- Energy content of the fuel consumed
- Engine running hours
- Delivered power at the propeller
- Propeller revolutions
- Data points to assess the boiler, shaft generator, cargo-related electrical consumption, or other large electrical consumers, if applicable

The fuel consumption data is obtained either from a volumetric flowmeter or a mass flowmeter, capturing the consumption of individual fuel consumers.

- If the flowmeter is located before the fuel oil pump, the return flow should be measured and used to adjust the fuel consumption measurements. The return flow is excess fuel oil delivered to the fuel oil pump, which recirculates the excess fuel oil back into the fuel oil system. The recirculated fuel is not supplied to individual cylinders on the engine and injected via injectors. Therefore, the return flow should be subtracted from the measured fuel oil consumption (FOC).
- Positioning of flowmeters within the fuel system should be carefully considered to obtain the actual flow to and from each relevant consumer. This needs to be done in a way that isolates the fuel consumption related to the EET from that due to other loads.
- A means to distinguish between the consumption of individual auxiliary engines and oil-fired boilers is also needed, i.e., individual fuel or power consumption measurements for each auxiliary engine and boiler, or groups of them.
- Figure 3 illustrates an ideal case, measuring the fuel consumption of individual consumers.

Figure 3: Flowmeter positions capturing the actual fuel oil consumption of each main consumer.
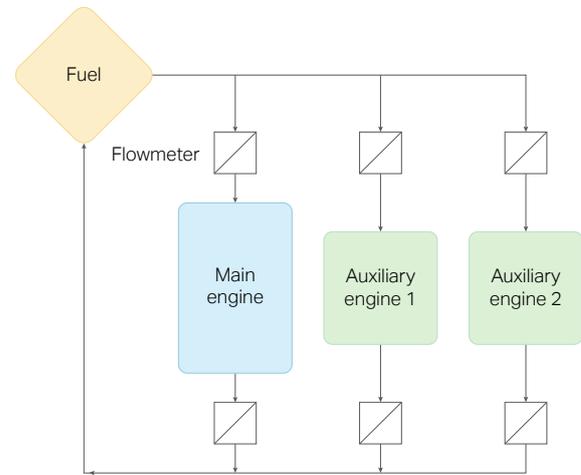
The delivered shaft power should be measured with a shaft power torsion meter with a calibrated permanent torque sensor, or strain gauges, located on the propeller shaft. To measure the propulsion power delivered to the propeller, the meter should be placed between the shaft seal and any other transmission components, such as gearboxes, clutches, or power take-off/power take-in components.

SFOC (g/kWh) is calculated as the mass of fuel consumed per unit of engine-delivered energy, i.e., engine running power multiplied by running time. SFOC is a derived value that may be used for determining correlations and filtering.

To account for variation in the lower calorific value (LCV) of the fuel oil, a correction should be made to a reference value. The correction yields a change in the quantity of fuel required to generate the same energy in the internal combustion process and is calculated in tonnes:

Equation 1

$$Q_{corr} = Q_{mea} \times \frac{LCV_{ref}}{LCV_{FO}}$$

where:

Q_{corr}	(mt) is the corrected amount of fuel consumed
Q_{mea}	(mt) is the measured mass of fuel consumed
LCV_{ref}	is the LCV (MJ/kg) of the fuel used as a reference for normalizing fuel consumption
LCV_{FO}	is the LCV (MJ/kg) of the specific fuel(s) consumed on board the vessel as per the bunker delivery note

If LCV values are not available, it is recommended to use the values in the International Maritime Organization (IMO) Resolution MEPC.376(80) in Appendix 2.[1]

For blended fuels, the LCV is calculated as an energy-weighted average of the LCV of the various fuel components. It is recommended to follow the IMO Resolution MEPC.376(80).[1]

2.1.4   Weather data

Wind, wave, and sea current data — collectively referred to as weather data hereafter — should be obtained from a third-party weather data provider as hindcast data. This is because weather observations received from human observations on board the vessel are likely to be subjective and unreliable.

Hindcast weather data is usually generated over a fixed, regularly spaced latitude and longitude grid at regular time intervals. We recommend using a spatial resolution of no more than one degree and maximum six-hour time intervals. Therefore, the obtained data must be interpolated in time and space to match the vessel's position and the date and time at which performance data is measured.

A wave radar can be used on board to measure the encountered sea state and derive the actual wave spectrum, offering a more accurate alternative to hindcast weather data. Hindcast data is modeled from

remote or atmospheric observations, while wave radar provides direct, real-time measurements of the waves around the vessel. This can have a positive impact on the accuracy of the computed results.

Where vessel-reported weather data is used, we recommend reporting weather data at least every six hours as an 'on the spot' observation.

Significant variability in weather conditions encountered by the vessel should trigger a more frequent reporting of weather observations.

2.1.5   Vessel technical data and information

Vessel technical data and associated information is data that enables the creation of adequate performance baselines for performance evaluation of retrofitted EETs.

This includes design-related items such as hydrostatic tables, the general arrangement plan, sea trial reports, towing tank tests, CFD studies, speed-power curves, engine specifications, performance curves, reports from engine test bed trials, propulsion system layout drawings, Energy Efficiency Design Index (EEDI) or Energy Efficiency Existing Ship Index (EEXI) technical file, load balance, etc.

Records of maintenance activities should be available, such as dry-docking activities and in-water hull and propeller cleaning events, as well as visual inspection reports from before and after maintenance events. These provide an important reference for the maintenance history of the vessel and are essential for establishing performance baselines.

2.2   Data validation and preparation

Once the data has been obtained, it needs to be checked carefully to ensure it is correct, realistic, and of sufficient quality to be used for the performance evaluation. This section describes methods and criteria for data quality checks, the handling of outliers, and data filtering.

2.2.1 Distance and position validation

Any position and time data reported by the vessel should be validated by comparing it with AIS data from a third-party source and by comparing the distances traveled when calculated from the two sources.

- For the data reported from the vessel, it is preferable to use a global positioning system (GPS) signal recorded at a higher frequency than once per day, i.e., more often than the noon report frequency, if available.
- Position validation can be done by comparing the reported position with the AIS position within one to two hours of the reported time.
- Distances can be checked using externally sourced positions, e.g., auto-logged GPS or AIS, between two reported positions.
- The recommended acceptable deviation between distances based on reported positions and externally sourced positions is 3%.
- If AIS positions are not available, reported positions and distance over ground can be checked against great circle distances between two reported positions. The reported distance must not be less than the great circle distance.
- The vessel must also be able to cover the calculated distance between the reported positions in the reported time interval. Unrealistic vessel speeds indicate errors in the reported or externally sourced data.

2.2.2 Logical validation

Logical validation is a process used to ensure that data and reported events are logical, e.g., aligning with an expected sequence of events. This involves cross-checking reported information against expected relationships and dependencies between different data items.

Recommended operational aspects applicable for checking logical validation:

- *Cross-measurements dependencies*: For example, if main engine running hours data exist, then main engine power, revolutions per minute (RPM), and consumption data should exist as well and vice versa.
- *Running time of machinery*: This value (in hours) should be logical in relation to the time passed since the last report. For example, a single main engine's, auxiliary engine's, or shaft generator's running hours cannot be greater than the time since the previous report.

- *Daily fuel balance*: The total amount of consumed fuel reported must correspond to the difference in the fuel remaining on board between reporting intervals.
- *Distance through water*: If this figure is larger than zero or the number of shaft revolutions is larger than zero, then main engine power and fuel consumption must also be larger than zero.
- *Mean draft in relation to reported displacement or deadweight*: The static draft measured at the beginning of a sea passage should not change from one noon report to another while on the voyage to the next port. This is validated by comparing draft with deadweight and displacement to detect unexpected changes in data.
- *Data correlation between fuel consumption, specific fuel oil consumption (SFOC), and power*: The reported data should correspond to the expected behavior. The trend of fuel consumption (when corrected for the LCV) versus engine power should follow an almost linear curve with a positive slope. For SFOC versus power, the curve should follow the trend derived from the engine shop test results within a certain tolerance, e.g., +/-5%. If not, the reported data may not be reliable, could negatively influence confidence in the results, and is not recommended to be used for performance analysis. Figure 4 shows an example of typical fuel consumption curves and data.
- *Logical sequencing of reported events*: The voyage between two consecutive ports can be split into a limited number of key events identified in the noon report or vessel data collection system when they occur, in this order:
  - **Berth departure** is the point in time when the vessel has all mooring lines on deck and is ready to leave its berth in the current port by its own propulsion or with tug assistance.
  - **Departure pilotage/maneuvering** is the time that the vessel uses for navigating safely, often under order from a local pilot, out of the port or away from offshore cargo terminals, with the purpose of sailing to the next port.
  - **Beginning of sea passage** (BOSP) is the point in time when the pilot has disembarked from the vessel and the vessel has reached its planned cruising speed for the upcoming voyage.
  - **Sea passage** is the operational mode between BOSP and end of sea passage (EOSP), where the vessel is at relatively constant operational conditions in terms of the vessel propulsion.

- **End of sea passage** (EOSP) is the point in time where the vessel starts to reduce engine power, engine revolutions, or speed, as it approaches the pilot station or pilot embarkation point on approach to its next port or terminal.
- **Arrival pilotage/maneuvering** is the time when the vessel is maneuvering in the destination port, waiting at anchorage without cargo operation, or waiting while drifting before arrival at the destination port.

- **Berth arrival** is the time when the vessel is at the arrival port berth and all mooring lines are safely fastened to the pier or shore mooring points. The main engine is stopped, and the vessel is ready to start its cargo operations.
- **In port** includes periods where the vessel is alongside at berth and/or performs cargo operations while at anchor within the port limits.
- An example of logical order of events is, e.g., a sea passage must end before dropping the anchor, the beginning of waiting/drifting, or maneuvering into the port.

Figure 4: Examples of good correlation between expected fuel oil consumption and measured data (top) and following of expected trends in SFOC (bottom).

Main engine consumption (LCV-corrected) vs. % main engine MCR

- Measured data   ······· Linear fit to data

SFOC (LCV-corrected) vs. % main engine MCR

- Based on measurements   —— SFOC from FAT
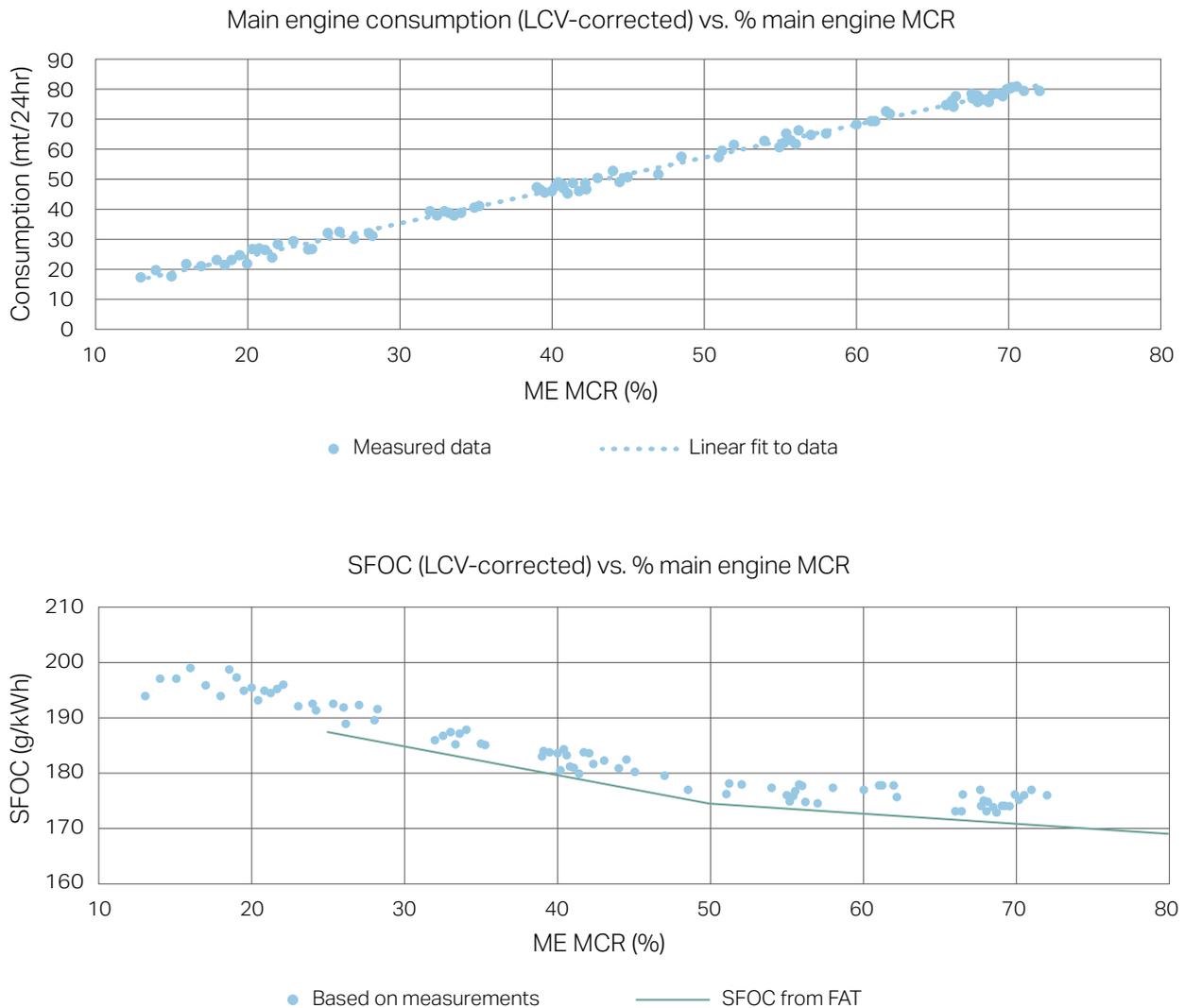
LCV = lower calorific value, MCR = maximum continuous rating, ME = main engine, FAT = factory acceptance test

2.2.3   Technical validation

Technical validation means checking that all reported values (such as engine power, RPM, and fuel consumption) adhere to the vessel's technical specifications and expected ranges. Recommended technical items to validate are as follows:

Maximum values:

Reported vessel draft, speed, deadweight, and the power and RPM of main and auxiliary engines, shaft generators, etc., must not exceed the maximum values as per the vessel technical specification. For example, the measured main engine power cannot exceed 110% of the engine maximum continuous rating (MCR) for a single data point taken at a specific instant in time or 100% of the MCR for a longer sustained period.

Range of SFOC:

The calculated SFOC of diesel engines based on the measured FOC and measured engine power delivered should be within the reference values listed in Table 1. The main engine SFOC, $SFOC_E$, (g/kWh) is calculated as:

Equation 2

$$SFOC_E = \frac{FOC_E}{P_E \times t_E} \times 10^6$$

where:

FOC_E	(mt) is the measured fuel oil consumption of the engine for the performance observation (auto-log data points or noon report)
P_E	is the engine's average delivered mechanical power (kW) for the performance observation period
t_E	is the engine's running time (hours) for the observation period

Note that the engine's delivered mechanical power is not equal to the delivered shaft power commonly measured by torque meters. The location of the torque meter relative to the engine and adjustment for efficiency losses in the gearbox, propeller shaft, and/or shaft generator needs to be considered when comparing these powers.

Table 1: Recommended SFOC threshold values for two-stroke and four-stroke diesel engines.

Diesel engine type	Minimum SFOC (g/kWh)	Maximum SFOC (g/kWh)
Two-stroke	150	240
Four-stroke	170	255

SFOC = specific fuel oil consumption

SFOC data correlation to shop test SFOC curve:

The main engine (ME) SFOC should be calculated based on reported ME fuel consumption, ME power, and ME running hours. The ME SFOC should be corrected for the fuel LCV to normalize the SFOC to the fuel used in the engine shop test, i.e., test bed trials (see Section 2.1.3 for procedures to do this). The corrected ME SFOC data should be compared with the ME SFOC curve from the engine shop test and match within a reasonable tolerance, e.g., 5%. Deviations indicate either faulty data or possibly problems with the engine.

Propeller distance cross-checking:

Compare any reported propeller distance P_{dist} in nautical miles (e.g., in noon reports) to the calculated propeller distance, $P_{distCalc}$, given by:

Equation 3

$$P_{distCalc} = \frac{n_p \times t_{ME} \times 60 \times p_r}{1852}$$

where:

n_p	is the reported propeller speed (RPM)
t_{ME}	is the running time of the main engine (hours)
p_r	is the propeller pitch (m)

The recommended maximum deviation is 2%. It should be noted that this only applies to fixed pitch propellers. This check serves the purpose of validating the reported propeller revolutions.

AIS-based validation:

Manually reported constant SOG during a noon report period considering weather conditions should be cross-checked with the SOG determined by GPS or AIS position data. The SOG from AIS positions should vary if wind, swell, and current conditions are changing.

2.2.4   Data filtering

Data for continuous performance monitoring is related to a specific operating condition of the vessel, i.e., the combination of speed, draft, and trim. The vessel should be operating in this steady condition for enough time to cover at least one data-reporting period. This is done to limit or even eliminate variations and uncertainties in the data due to conditions changing at a higher frequency than the frequency of the data collection, which are therefore not captured in the data collected.

The data should therefore be filtered for steady-state operating conditions and for more severe weather conditions, which would cause fluctuations in the propeller load and engine power. Weather conditions are filtered out when they exceed the applicability limits of the correction methods used to adjust performance data to calm water conditions.

Furthermore, the comparison of vessel performance before and after the retrofit is done assuming the water depth has no effect on the performance. Therefore, both a limit on the minimum water depth and a correction to account for shallow water effects should be applied.

Filtering for steady-state operating conditions can be done using the following criteria:

- Performance analysis and evaluation should only use data for the time the vessel is on sea passage, i.e., for periods where the vessel is underway under its own propulsion on a steady course at constant engine power, constant speed, or constant propeller RPM, depending on which method is used during navigation.
- For high-frequency sensor data, the filter criteria from DNV-RP-0675 'Vessel Technical Performance',[3] Section 4.4 'Confirmation of Steady-State Periods' can be used.

- These recommendations refer to a 'moving window' for the filtering period to consider, which can vary from 30 to 60 minutes depending on the quantity being filtered. This implies that the frequency of data collection is higher than one observation per half hour or hour.
- Note that, depending on vessel operations, application of all filtering criteria may eliminate a lot of data, but not applying certain criteria may increase the uncertainty in calculated fuel savings. The need for enough data should be balanced with the tolerable level of uncertainty in the results.
- In addition to the DNV criteria for steady state, if rudder angle data is available, periods with excessive rudder angle (above 10 degrees from center position) and/or rudder movements should be filtered out, if no correction to power or speed is applied to account for added resistance due to rudder movements.
- Performance analysis data from noon reports can be filtered as follows:
  - 'At sea' under own propulsion or events categorized as 'noon at sea' or similar should be used. This means data from operational modes such as maneuvering, canal passage, drifting, etc., are excluded.
  - The ME running time and noon report duration should be equal when crossing of timezones is accounted for correctly, e.g., by referencing all time reports to UTC time. For manual noon reporting, the following filter criteria can be applied:
    - For deep-sea voyages, use data with both a report duration/interval and ME running time between 22 and 25 hours.
    - For coastal voyages, which tend to be shorter and can often be less than one day, it is recommended to filter out events below a minimum ME running time of 12 hours. The voyage duration and reporting interval must not drop below 15 hours to account for maneuvering in port and to allow time for obtaining a steady vessel operating state.

If the vessel is running at very slow steaming, it is recommended to remove observations at engine loads below 20% of the main engine's MCR. For non-permanent engine power limitations with an approved override functionality, the same threshold applies for the engine load.

Filtering for shallow water should eliminate data according to the following criteria:[4]

- Water depths should not be less than the larger of the two values below:

Equation 4

$$h = 2.5 \times T \quad \text{or} \quad h = 2.4 \frac{v_{stw}^2}{g}$$

where:

h	is the water depth
T	is mean draft
v_{stw}	is the vessel's speed through water
g	is the gravitational acceleration 9.81 m/s²

Filtering criteria to remove unacceptable data due to high waves are given below:[4]

- Significant wave height, H_s, when it is based on the wave spectrum encountered (measured by wave radar), should satisfy:

Equation 5

$$H_s \leq 0.225 \sqrt{L_{pp}}$$

- When the significant wave height is based on visual observations or hindcast data, it should satisfy:

Equation 6

$$H_s \leq 0.15 \sqrt{L_{pp}}$$

- The significant wave height is a combination of local wind waves and swell that is derived from:

Equation 7

$$H_s = \sqrt{H_{Ws}^2 + H_{Ss}^2}$$

where:

L_{pp}	is the length between perpendiculars
H_{Ws}	is the significant wave height of local wind-driven waves in meters
H_{Ss}	is the significant wave height of local swell in meters

The direction of swell and waves is, preferably, taken from hindcast weather and alternatively from visual observations.

- Wind speed should be adjusted to a reference height, and the adjusted wind speed should not exceed:

Equation 8

$$V_{WTref} = 6.9 + 0.38 \sqrt{L_{pp}}$$

for vessels with a length of 50 m<L_{pp}<500 m.

V_{WTref} (m/s) is the true wind speed at the reference height and is calculated by:

Equation 9

$$V_{WTref} = V_{WT} \left(\frac{Z_{ref}}{Z_a} \right)^{\frac{1}{9}}$$

where:

V_{WT}	(m/s) is the true wind speed at the vertical position of the anemometer or measurement point for wind speed*
Z_{ref}	(m) is the reference height for the vessel's wind resistance coefficients (see Section 2.4)**
Z_a	(m) is the vertical position of the anemometer or wind measurement points**

*Note that onboard wind measurements are sometimes relative to the vessel, and a conversion to true wind speed and direction might be required.

**Both Z_{ref} and Z_a are relative to the mean sea surface.

2.2.5 Additional methods for improving data quality

This section elaborates on ways to enhance the data quality and reduce the uncertainty in the results of the analysis.

We recommend **a minimum number of data observations** to ensure statistical significance. The vessel is likely to require a certain amount of operational sailing time to reach an adequate number of measurements or noon reports to cover its common operational profile (i.e., combinations of speed, mean draft, and trim).

To thoroughly encompass the range of the operational profile of a vessel, it is advised to use a default period of at least three months for both the baseline period and the benchmark period (see definition of baseline and benchmark periods in Section 2.5).

If using noon report data, each period must include at least 45 manually reported performance observations in steady-state conditions after applying the data checking and filtration criteria outlined in the previous sections of this guide. This period may be extended to achieve the threshold of minimum number of reports, but it is recommended not to exceed six months due to the elevated risk of propeller and hull fouling and subsequent additional uncertainty in the performance evaluation.

If high-frequency sensor signals are available, we recommend a minimum of 100 auto-logged measurements from conditions distributed evenly over the vessel's operational profile.

If both manually reported performance observations and sensor data are available, we recommend comparing both sources to identify periods of good correlation. If significant deviations are identified between the two data sources, and if a systematic measurement error, e.g., due to faulty sensors, can be ruled out as the cause, there is reason to have low confidence in the manually reported data.

Statistical outliers for fuel consumption should be removed from the data. Outliers can be detected by means of the interquartile range (IQR) method, which categorizes a data point as an outlier if it is more than $1.5 \times IQR$ above the third quartile or below the first quartile within a sample size. The outliers are identified as follows:

Calculate the ratio expressed by:

Equation 10

$$\Delta FOC_{ME} = \frac{FOC_{ME}}{V_s^3}$$

where:

FOC_{ME} is the fuel oil consumption for the data point with vessel speed V_s

This ratio uses the assumption that the power (and thus fuel consumption through the SFOC curve) is proportional to the vessel speed raised to the third power.

- Identify the lower quartile (Q1) as the value that includes 75% of the largest observations in the dataset and the upper quartile (Q3) as the value that includes 25% of the largest observations.

The IQR is calculated by:

Equation 11

$$IQR = Q3 - Q1$$

Outlier observations in the dataset are observations with a ratio ΔFOC_{ME} that are below or above the threshold limits:

Equation 12

$$Lower\ limit = Q1 - 1.5 \times IQR$$

and

Equation 13

$$Upper\ limit = Q3 + 1.5 \times IQR$$

Using this method, the highlighted data points will be identified as outliers, as shown in Figure 5.

Figure 5: Outlier detection for reported speed and fuel consumption in a dataset. Measured data (top) and IQR method quantities used in defining the outliers (bottom). Outlier points are circled in red.

Main engine consumption LCV-corrected vs. vessel speed

ΔFOC vs. vessel speed
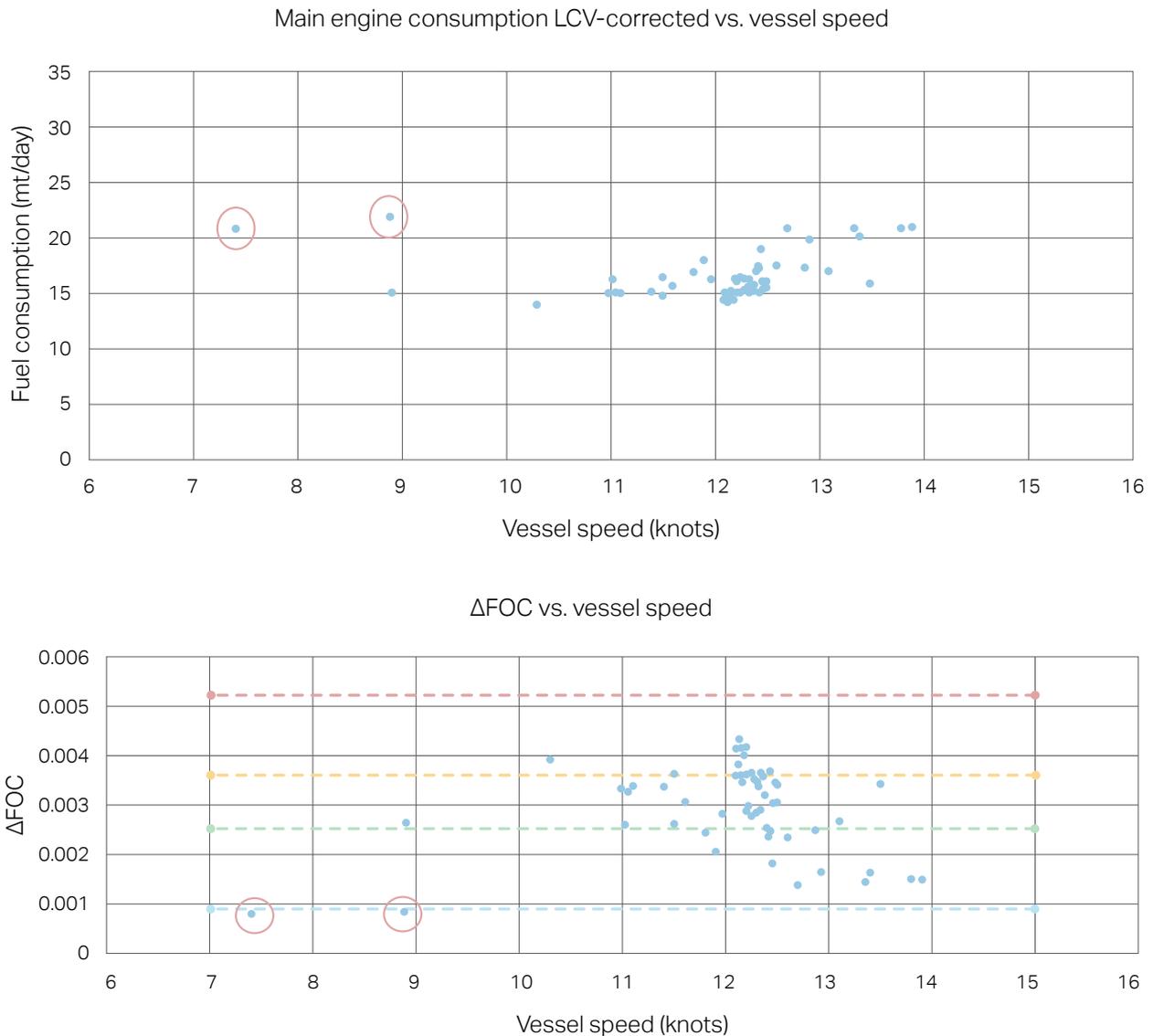
FOC = fuel oil consumption, LCV = lower calorific value

Flatline reporting/tendency refers to the observation of constant fuel consumption as a function of power or speed, which is often due to manual noon reporting intended to match commercial instructions.

Flatline tendency can also be seen as constant SFOC as a function of %MCR, or constant fuel consumption as a function of power or speed after correcting for environmental conditions (see Section 2.4).

We recommend evaluating the correlation between measurements of power and corrected speed with the calm water speed-power curve for the draft of the vessel. The power is assumed to be a function of the calm water speed to the third power. Therefore, fitting a third-order polynomial to the measured data and checking the coefficient of determination (R^2) gives an indication of the reliability of the data.

If the coefficient of determination R^2 is above 0.8, the measurements can be considered 'good', as this indicates that the data points have a reasonable fit to the regression predictions and follow the expected relationship.

As an example, Figure 6 shows the daily main engine fuel consumption as constant over part of the speed profile, due to commercial instructions for reporting a specific consumption regardless of vessel speed. We recommend a cubic polynomial function of the following form for the regression function for the fuel consumption rate (metric tonnes per 24 hours) as a function of corrected speed v_s:

Equation 14

$$FOC\ (v_s) = A_2 v_s^3 + A_1 v_s^2 + A_0$$

where:

A_0, A_1, and A_2	are coefficients determined from the regression process

Logically, A_0 should be zero and the FOC curve should increase monotonically. Depending on the data, the regression analysis may give a function that is not monotonically increasing. Therefore, the value of A_0 should be tuned manually to give a realistic FOC curve while still being relatively close to zero.

The example data in Figure 6, with an R^2 value of 0.44, does not fit the regression model well and should be disregarded in the performance evaluation.

Figure 6: Example of flatline reporting of fuel consumption.

Average ME consumption
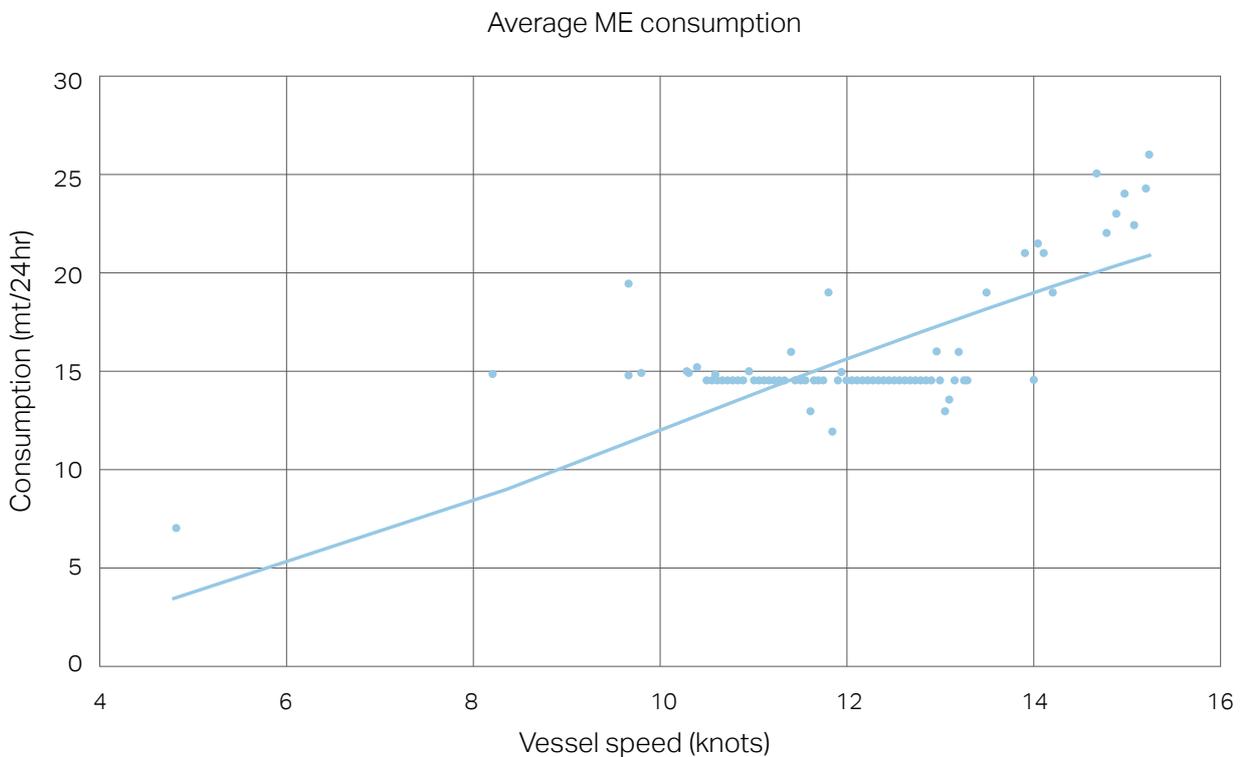
2.3 Establishing a performance reference model

Three performance curves are needed to evaluate the performance improvements achieved by retrofitting an EET:

1. A reference speed-power curve which is used to define the relative added resistance or power of the vessel in operations. This is normally not based on operational data but obtained by other means described below.

2. A baseline speed-power curve, which is a normalized speed-power curve based on operational data and measurements on board the vessel before an EET is retrofitted.

3. A benchmark speed-power curve, which is a normalized speed-power curve based on operational data and measurements on board the vessel after an EET is retrofitted.

The added vessel resistance is defined as the relative difference between the baseline or benchmark curve and the reference model speed-power curve. The performance improvement thanks to an EET is quantified by comparing the added resistance in the baseline curve and the benchmark curve. Therefore, reference models should be selected to enable clear attribution of performance improvements to the retrofitted EET(s).

The reference model estimates the vessel's resistance or power versus speed in "deep calm water" conditions, e.g., no wind, no waves, no currents, or other environmental impact at various drafts/displacements and trims. This is the reference operating condition(s) used to normalize performance measurements. The reference model should be an accurate representation of the vessel's hydrodynamic resistance and propulsion efficiency before retrofitting the EET(s), as this is the condition against which the performance gains are measured.

The reference model can be obtained from multiple sources, as listed in the following prioritized order:

1. Self-propulsion tests in a towing tank facility, which are considered the most accurate reference data

2. Self-propulsion tests by CFD simulations

3. Sea-trial report

4. Empirical methods, e.g., Harvald & Guldhammer 1974, Mennen 1982, Hollenbach 1998.[5, 6, 7] These methods are usually based on historical data of past designs from self-propulsion tests in a model basin. Selection of empirical methods should ensure that the vessel's parameters are within the range of parameters used to develop the method.

Note that the reference model is not used directly to predict the fuel savings but is instead used for defining a relative saving based on a comparison with operational data. The reason for using the reference curve as the basis for comparing the baseline and benchmark performance curves is explained in detail in Section 2.4.

Figure 7 shows an example of reference performance curves showing the variation in delivered power with floating position for a container ship. In this example, the same empirical method has been used to derive all three reference model performance curves.

Figure 7: Reference performance curves for a container vessel at three different operating conditions in calm water, two at different drafts (T) at even keel, one with 1 m trim by aft.
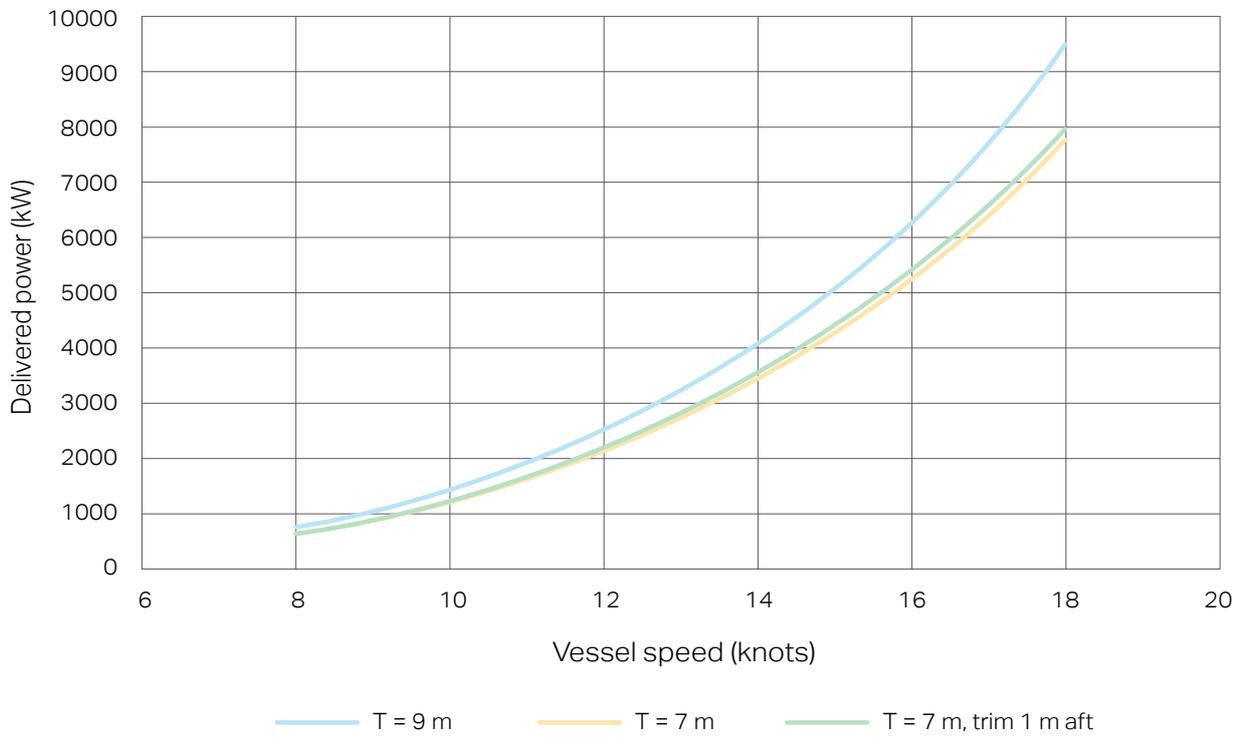
2.4   Normalization of operational data

This section provides guidance on normalizing operational performance data to ensure comparability with reference curve(s). It explains how to correct for encountered weather and other factors that affect the propulsion power demand of the vessel advancing in a natural seaway.

Vessels seldom operate in ideal conditions with no currents, waves, wind, or other environmental factors that influence propulsion power requirements. Additional propulsion power is required for the vessel to navigate through various weather conditions. Figure 8 qualitatively illustrates the added power components for a vessel to overcome the encountered environmental forces.

To quantify the impact of EET upgrades, the operational power or speed through water must be corrected for various weather conditions (e.g., added resistance due to current, wind, wind wave, swell wave added resistance, and other added resistance components) to represent the vessel's reference model performance in deep calm water conditions.

The measured delivered power of a vessel advancing in a natural seaway, P_{Dms}, is split into components according to:

Equation 15

$$P_{Dms} = P_{Did} + P_{env} + P_{SH} + P_{AF} + P_{AOF}$$

where:

P_{Did}	is the calm-water power required at the measured speed from the reference model performance curve
P_{env}	is the additional power required to overcome the added resistance due to the wind, waves, and currents
P_{SH}	is the additional power to overcome the effects of shallow water, if the vessel is operating in shallow water
P_{AF}	is the additional power required due to biofouling of the submerged hull and propeller, mechanical degradation of the hull (e.g., hull buckling), eroded welding seams, and failure of paint and anti-fouling coatings (e.g., due to flaking)
P_{AOF}	is the additional power due to other factors, e.g., added drag from excessive rudder movement and deflection, added hydrodynamic drag due to yaw, etc.

Figure 8: Schematic overview of the normalization process of measured shaft power to calm-water conditions by correcting for resistance due to encountered weather and other factors.
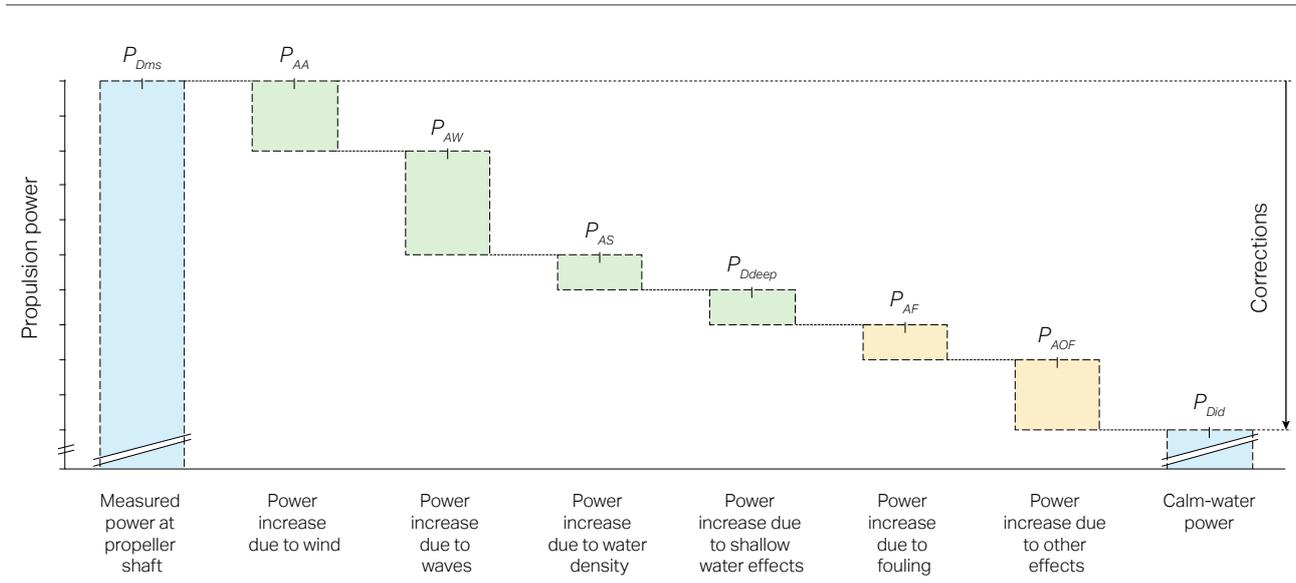
The propulsion power required to overcome the encountered weather conditions, P_{env}, is expressed as:

Equation 16

$$P_{env} = \frac{(R_{AW} + R_{AA} + R_{AS})V_{STW}}{\eta_t}$$

where:

R_{AW}	is the added resistance due to irregular wind and swell waves
R_{AA}	is the added resistance due to wind
R_{AS}	is the added resistance due to changes in air and sea temperature from that used in the reference model
V_{STW}	is the vessel speed through water
η_t	is the total propulsion efficiency in deep, calm water at speed V_{STW}, normally taken from the reference performance model and the vessel technical data

Shallow water increases the resistance of the vessel compared to the resistance in deep water. What qualifies as shallow water is determined by the method to calculate the additional power, P_{SH}, needed to maintain deep-water speed. Appendix B provides the recommended procedures for calculating P_{SH} and each of the resistance components in P_{env}. Unfortunately, an adequately accurate analytic or semi-analytic model predicting the component of fouling P_{AF} has not yet been developed.

The added power due to fouling and mechanical hull deterioration, P_{AF}, is accounted for when comparing the baseline and the benchmark period. We assume that P_{AF} remains constant across both periods when evaluating the effectiveness of the EET(s). This requires careful selection of the time periods used for data collection for the comparison to ensure a consistent hull condition across periods.

The added resistance due to other factors, P_{AOF}, is rarely recorded during operation, and this is why data points with large yaw angles are excluded as part of data filtering (see Section 2.2.4). Including a correction for power increase due to rudder action requires high-frequency rudder angle recordings via an auto-logging system, which is uncommon in the industry. This also means that P_{AF} may include unidentified power variations that have not been distinguished and/or filtered out of the data. However, it is commonly accepted that most of the power increase over time gathered in P_{AF} is due to biofouling.

Taking the equation for P_{Dms} (shaft-measured propulsion power) and inverting it to get the equivalent deep, calm water propulsion power, P_{Ddeep}, measured at the shaft with corrections for environmental forces and shallow water effects, the corrected propulsion power including fouling effects can be expressed as:

Equation 17

$$P_{Ddeep} = P_{Did} + P_{AF} = P_{Dms} - P_{env} - P_{SH}$$

Recognizing:

$$P = \frac{R \cdot V_{STW}}{\eta_t}$$

where:

P	is power
R	is resistance

and assuming η_t is not affected by any of the factors needing correction, the relative power/resistance increase due to fouling, as well as other factors not accounted for in the normalization process above, is denoted ΔAR and can be estimated as:

Equation 18

$$\Delta AR = \frac{(R_{Dms} + R_{env} - R_{SH}) - R_{id}}{R_{id}}$$

where:

R_{Dms}	is the estimated actual total resistance, corresponding to the measured delivered shaft power at a given operational condition under the influence of environmental forces
R_{env}	is the estimated resistance increase due to the encountered environmental forces
R_{SH}	is the estimated resistance increase due to shallow water effects
R_{id}	is the reference model for deep, calm water resistance for the given mean draft, trim, and speed

Note that ΔAR therefore includes:

- Differences between the assumed reference model and the real calm water speed-power performance curve inherent in the vessel design, e.g., due to EETs retrofitted on the vessel compared to the vessel condition when the reference performance curve was created
- Increased resistance due to biofouling
- Changes in η_t due to weather, fouling, or implementation of EETs designed to change η_t
- Differences in the added resistance from correction methods applied for the encountered environmental conditions and the actual resistance increase due to environmental forces
- Differences summarized in the term P_{AOF} above

The last two bullet points are the reason for filtering of more severe weather conditions, rudder motions, and yawing to reduce the influence of these on ΔAR as much as practically possible.

2.5   Selection of performance baseline and benchmark periods

This section gives advice on the selection of baseline and benchmark periods. These are required in the evaluation of the effectiveness of EET(s) on the vessel's performance when data is available from just after the last dry docking before the installation of the EET. If there is no operational data available for the period between the previous dry dock and the retrofitting dry dock, we recommend the procedures outlined in Section 2.7.

The **baseline period** is defined as the time immediately after the ordinary dry dock prior to the dry dock for the EET retrofit or installation (the retrofit dry dock).

The **benchmark period** is defined as the time period immediately after the retrofit dry dock, which should be of the same duration as the baseline period.

ΔAR values from observations during the baseline and benchmark periods are compared to quantify the change in relative added resistance resulting from the EET retrofit.

Careful selection of baseline and benchmark periods is essential for deriving reliable and accurate insights and conclusions when evaluating the effectiveness of retrofitted EET(s). Incorrect comparisons may lead to inaccurate estimates of savings attained in a benefit-tracking analysis. This could result in misallocation of monetary benefits and misjudgment of EET effectiveness. This means that relevant periods for comparing performance should reflect identical hull and propeller conditions, so that any change in vessel performance can be attributed to the EET retrofit.

This requires the vessel's operational profile to be similar during these periods and without long idle times with a possibility of significant biofouling building up. For an analysis, it is recommended to use at least 45 noon reports which pass the data cleaning and filtration process, or a minimum of 100 filtered observations from high-frequency auto-log sensors.

If a speed or draft dependency is expected for the installed EET type, e.g., new bulbous bow, the average added resistance percentage ΔAR from these two periods should be calculated for a suitable distribution of drafts, trims, and speeds. This entails an adequate distribution of data across relevant operational profiles (i.e., combinations of draft, trim, and speed).

Figure 9: Example of calculating added resistance from historical performance observations and an indication of the two periods used for performance benchmarking to determine the impact of retrofitted energy efficiency technologies.
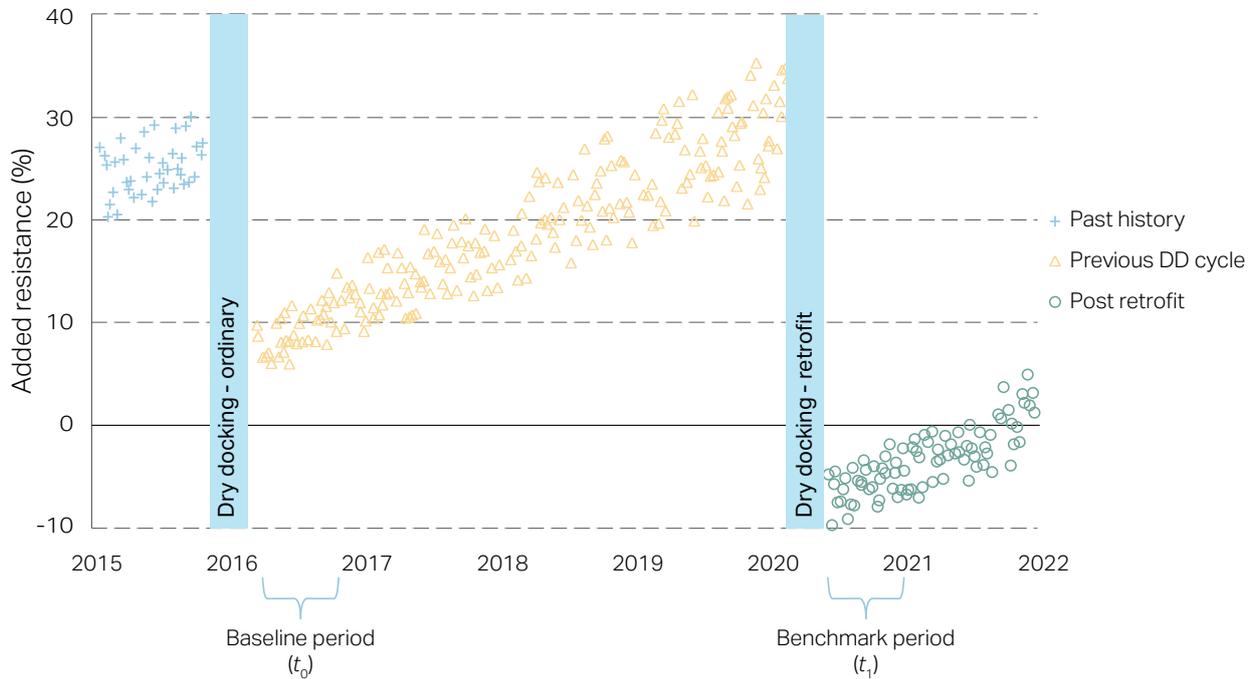
DD = dry docking

Figure 9 illustrates an example of baseline and benchmark periods in relation to ordinary and retrofit dry docks. The first set of data (2016-2020) follows an ordinary dry docking and the latter set follows a dry docking with an EET upgrade in 2020. It should be noted that the mean added resistance at the beginning of the benchmark period is notably lower than the mean added resistance at the beginning of the baseline period, which is an indication of the performance improvement caused by the retrofitted EET. The figure also shows the development of added resistance over time after the dry dock. The trend of increasing added resistance is assumed to be mostly caused by an increase in biofouling over time.

In theory, if the reference model, weather normalization, and data quality are accurate, a new vessel's mean added resistance should be close to zero immediately after delivery of the vessel from the shipyard. Any offset from the reference model in the baseline or benchmark period will be compensated in the calculation of performance improvement as explained in Section 2.6.

In practical applications, the added resistance can be replaced by speed loss or added power, as the trend will be qualitatively the same whichever quantity is used.

If activities during the retrofit dry dock are significantly different compared to the ordinary dry dock, e.g., spot blasting versus full hull blasting, then these activities must be considered as part of the EET retrofit package.

Once the baseline and benchmark periods have been evaluated, it is recommended to check the resulting added resistance for unexpected speed and draft dependencies in the reference model. If the reference model is a poor representation of the actual vessel performance, then it may introduce biases in the performance evaluation when comparing added resistance before and after the retrofit event. Speed and draft dependencies are checked by examining the trend-corrected added resistance (TCAR) using data from before the retrofit. TCAR is the error between a calculated added resistance data point and the regression line through a series of added resistance data points.

The reference model is considered reliable if the TCAR is constant over the range of speeds and drafts represented in the data, i.e., if a regression line through the TCAR values is horizontal.[8]

2.6   Quantification of savings and uncertainties

This section describes the conversion of added resistance into power or fuel savings based on the collected operational data after the EET installation. This section also considers the accuracy of both the operational data and the modelling methods described in previous sections. The method of confidence intervals (CI) from probability theory is employed to deal with uncertainties in the performance evaluation.

The impact of the EET package is quantified by comparing the difference in the mean added resistance of the periods t_0 (baseline period) and t_1 (benchmark period) illustrated in Figure 9.

The added resistance for t_0 is averaged over the operational profile in the baseline period:

Equation 19

$$\Delta\overline{AR}\,(t_0) \;=\; \frac{1}{N}\sum_{i=1}^{N}\Delta AR\,(t_0)_i$$

where:

N	is the number of performance observations in t_0

The same averaging is done for t_1.

Note that all observations receive equal weighting regardless of the time period they represent, e.g., an observation from a 10-minute period is given the same weight as an observation from a noon report. This is because the data may include quantities that are not averaged or integrated over time but are instantaneous values, e.g., weather conditions.

Depending on the installed EET, its savings may depend on the operational draft and speed profile (e.g., a new bulbous bow). If this is the case, the ΔAR values are grouped into bins defined according to the range of draft and speed. The added resistance is averaged for several combinations of mean drafts, T_m, and vessel speeds, V_s, of n number of performance observations in each bin for the respective period, e.g., for the benchmark period t_1:

Equation 20

$$\Delta\overline{AR}\,(t_1,T_m,V_s) \;=\; \frac{1}{n}\sum_{i=1}^{n}\Delta AR\,(t_1,T_m,V_s)$$

The impact of the EET is the difference between the two means of the two data samples.

A simple Student's z-test with a CI is applied to the added resistance between the two time periods, t_0 and t_1, to quantify the actual reduction in ΔAR, which is denoted ΔAR^{EET}, due to the retrofit. The z-test investigates the hypothesis that the mean of the two data samples is either equal or different. Normally, an equal mean is the null hypothesis and if it fails, the alternative hypothesis is accepted.

To verify that the retrofit had an effect and changed the mean from one data sample (t_0) to the other data sample (t_1), it is tested whether the alternative hypothesis is true:

Equation 21

$$\Delta AR^{EET} = \left[\frac{1}{n_0}\sum_{i=1}^{n_0}\Delta AR\,(t_0)_i \;-\; \frac{1}{n_1}\sum_{j=1}^{n_1}\Delta AR\,(t_1)_j\right] \pm Z^* \sqrt{\frac{\sigma_0^2}{n_0} + \frac{\sigma_1^2}{n_1}}$$

with the sample sizes n_0 for period t_0 and n_1 for period t_1.

σ is the standard deviation of each data sample and is given by Equation 22. It is recommended that at least 30 data points are available in each draft-speed bin to obtain reliable estimates. The CI is described with a confidence level of C (95%), resulting in a z-score $Z^* = 1.96$ when the data sample size $n > 30$ and approximately follows a standard normal distribution.

The mean added resistance, $\Delta(\overline{AR})$ ($t_{0\ or\ 1}$, T_m, V_s), is converted into mean relative power using Equation 23.

To convert the power to fuel consumption and fuel savings ΔFC_{bin}, the SFOC curve from the shop test may be used, where for each bin's $\overline{P}_{bin}$ we can derive the fuel consumption FC_{bin}. The absolute fuel saving for each bin is given by Equation 24.

Equation 22

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(\Delta AR_i + \Delta\overline{AR})^2}{n-1}}$$

Equation 23

$$\overline{P}_{bin}\,(t_{0\ or\ 1}, T_m, V_s) = \Delta\overline{AR}_{bin}\,\frac{V_s}{\eta_t}\,R_{id}$$

where:

$\Delta\overline{AR}_{bin} = \Delta(\overline{AR})$ ($t_{0\ or\ 1}$, T_m, V_s)	at each draft and speed combination (T_m, V_s)
η_t and R_{id}	are taken from the reference model at the mean draft and speed of the bin

Equation 24

$$\Delta FC_{bin}\,(t_1, T_m, V_s, \Delta P) = FC_{bin}\big(t_1, T_m, V_s, \overline{P}_{bin}(t_1, T_m, V_s)\big) \;-\; FC_{bin}\big(t_0, T_m, V_s, \overline{P}_{Did}(t_0, T_m, V_s)\big)$$

As stated above, the performance of some EETs depends on the operational conditions, such as draft and speed. The quantification of the savings, either power or fuel, for each operational condition has been defined for a benchmark period t_1, which normally ranges from three to six months.

The fuel savings can also be estimated for a specific period t_s, e.g., one year, by summation of the savings from each operating condition weighted by the time at the operating condition, assuming the operational profile of the vessel does not change from the benchmark period t_1 to the time t_s:

Equation 25

$$\Delta FC\,(t_s) = \frac{t_s}{t_1} \cdot \sum_{i=1}^{n} \Delta FC_i\,(t_1, T_m, V_S, \Delta P) \cdot t_i$$

where:

t_i	is the percentage of time operating at conditions, i.e., draft-speed combinations, in bin i
n	is the number of bins

2.7   Evaluating fuel savings in the case of limited operational data

This section outlines a general procedure to evaluate fuel savings for vessels with limited historical data representing the period before installing an EET, i.e., data is not available for establishing a baseline immediately after the last hull and propeller cleaning, or dry docking, before the EET retrofit dry dock.

In this case, the operational profile of the vessel and data from sister vessels are used to identify comparable periods for comparing the vessel performance before and after installing the EET.

Referring to Figure 10:

t_0	is the baseline period before retrofitting the EET
t_1	is the benchmark period after retrofitting the EET
T_m	is the operating condition being analyzed, i.e., draft and trim of the vessel
v_S	is the deep, calm water speed through water (knots) given by: $v_S = SOG + V_{wx} + V_{cu}$
FC	is the speed vs. fuel consumption curve (mt/24 hrs) fitted to noon report fuel consumption data
ΔFC	is the fuel saving (mt/24 hrs)

The technical performance speed, v_s, is the calm water speed. v_s is calculated with the SOG from GPS data, and the impact of metocean conditions are accounted for by making two absolute speed loss corrections due to weather (V_{wx}) and due to ocean currents (V_{cu}).

- A positive speed loss means that the vessel speed in calm water would be higher at the same power.
- V_{cu} can be taken either from measured or hindcast data of sea currents as the current velocity component against the direction of the ship's course over ground.
- Effects of V_{wx} can be filtered out by removing data from more severe weather conditions (see Section 2.2.4) and then estimated from the reference speed-power curve for milder conditions using the measured propulsion power, SOG, and environmental resistance components as determined according to Appendix B. This is done to derive an equivalent speed correction based on the measured STW and the power minus the power due to environmental effects P_{env}.

The process is as follows:

- Plot the vessel's fuel consumption data versus v_s, considering maintenance events such as dry docking, propeller polishing or hull cleaning, and operational status (e.g., at-sea periods).
  - Correct the fuel consumption according to the LCV of the fuels used so that both refer to the same reference LCV.
  - Check parameters such as excess consumption of the main engine, shaft power, performance speed, and mean draft relative to operational changes and the retrofit dry-docking event.

- Filter data for a certain operational profile (e.g., mean draft, main engine running hours, etc.) so that the baseline and benchmark periods match as much as possible.
- Detect and remove outliers, e.g., using the IQR method in Section 2.2.5.

- Fit third-order polynomials to the consumption data before and after the retrofit.

- If the R^2 coefficient of determination is between 0.8 and 1.0, and the first and second derivatives of the curve are positive in the speed range modeled, i.e., monotonically increasing with no inflection points, the data points fit the regression curve well and exhibit the expected speed versus fuel consumption behavior. This indicates that the measurements and calculations are reliable.

- Check for sister vessels with the same retrofit event and plot operational data for a defined loading condition at sea in steady conditions.
  - This comparison can provide data correlation insights regarding fuel performance and speed profiles at which the vessels operated.
  - It is important to check at which speeds and drafts the sister vessels have been operated to ensure that the vessels have similar operational profiles.
  - We recommend creating individual baselines for each vessel and checking the relative performance gain from an individual EET or a bundle of EETs.
  - Where vessel comparisons involve different ownership or management entities, data-sharing arrangements should generally be subject to legal review to ensure compliance with competition laws and confidentiality obligations.

Figure 10: Comparison of main engine fuel consumption at the same draft for two different time periods.

Main engine fuel consumption (LCV-corrected) as a function of vessel speed
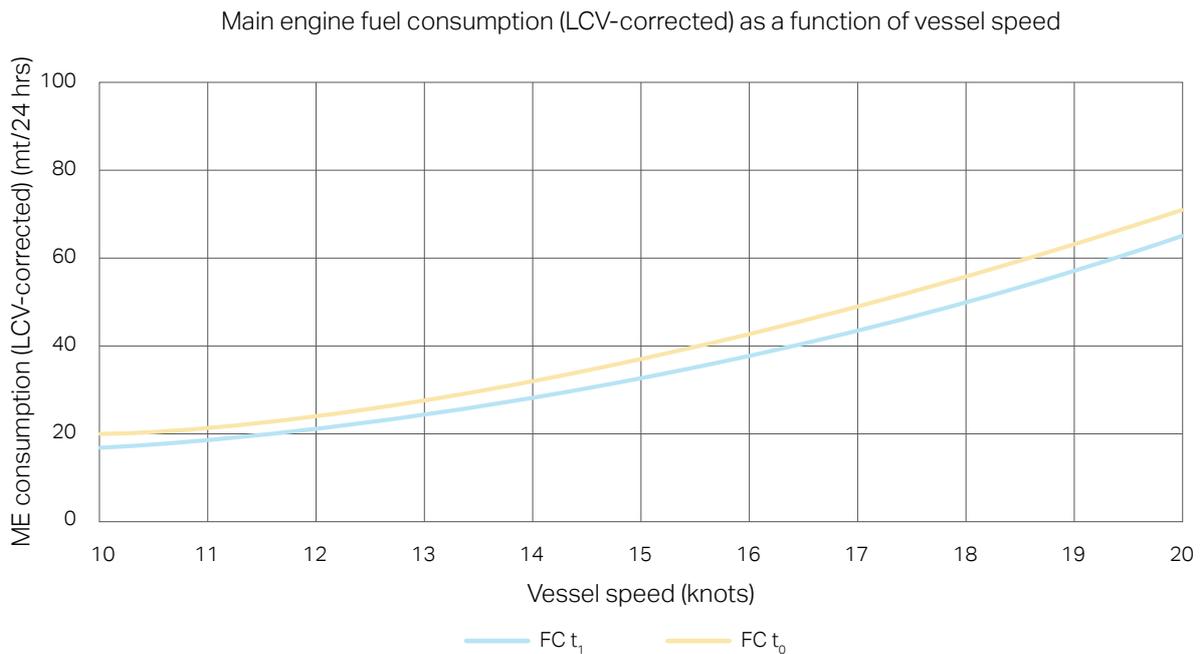
ME = main engine, LCV = lower calorific value, FC = fuel consumption

Referring to Figure 10, the fuel saving over the speed range can then be evaluated as:

Equation 26

$$\Delta FC = \sum_{i=1}^{n} [\, FC(t_0, T_m, V_{Si}) - FC(t_1, T_m, V_{Si}) \,]$$

where:

$v_S = v_{Smin}, v_{Smin} + 0.5, \ldots, v_{Smax}$ are a series of evenly spaced speeds

FC values come from the fitted third-order polynomials, i.e., the area between the curves in Figure 10 relative to the area under the curve for t_0.

03 In-service performance trials

This section describes a general approach to determining fuel savings achieved from EETs that can be switched on and off while the vessel is underway at sea. The approach consists of procedures for carrying out in-service performance trials, as well as for data collection, analysis, and evaluation of fuel savings based on these trials for this type of EET. Some EETs that can be switched on in-service include ALS, WAPS, combinator curve optimization software for controllable pitch propellers, and engine optimization software.

The method requires switching the EET between active and inactive modes under steady operational and environmental conditions. The difference in fuel consumption between active and inactive modes during a single trial is the fuel saving provided by the EET for the retrofitted vessel.

The procedure for in-service trials is similar to that for continuous performance monitoring and comprises the following steps:

1. Collection of vessel technical data
2. Specification of data to be measured and how it should be measured
3. In-service trial planning and execution
4. Data quality checks and cleaning
5. Assessment of fuel consumption savings

The main differences compared to the continuous monitoring approach described in Section 2 are:

- There is no need to establish reference, baseline, or benchmark models. The collected data is not normalized to a specific vessel condition because a single trial is carried out over a short period while the vessel is in service, normally a few hours at most. Therefore, the fuel savings are specific to the operating condition of the vessel at the time of the trial.
- A single in-service trial does not need to account for the influence of biofouling on the EET benefit because the effect of the EET is assessed by alternately turning the EET 'on' and 'off' for such a short time period that the level of biofouling does not change.

- Other requirements, such as fixed propeller RPM or constant engine load, may depend on the type of EET being tested.

It can be argued that idle or inactive modes of some technologies can affect the performance of the vessel and must also be accounted for in the fuel saving assessment, e.g., retrofitted sails folded down in unfavorable weather usually cause extra wind resistance compared to the pre-retrofit vessel without the sail installation.

If the EET technology is off and causes the performance of the retrofitted vessel to be worse than before the retrofit, this requires reference and baseline performance data for the vessel before the retrofit and benchmark performance data after the retrofit with the EET off.

The data from measurements with the EET off and the data from the baseline period is normally filtered for more severe weather conditions and normalized to calm water conditions. However, some EETs are designed to provide a fuel saving benefit when the weather is far from calm, and to be in off mode in calm water.

EET performance is dependent on weather conditions, while severe weather conditions introduce uncertainties and limitations into methods for normalizing data based on environmental resistance. As a result, reliable pre-retrofit baseline data and benchmark data with the EET off may be difficult to establish. The data is needed for comparing with the retrofitted vessel performance, with the technology on, in all varying weather conditions expected during the time-charter period.

Due to these conflicting conditions affecting the performance comparison for an EET that is deactivated in weather conditions where it offers no benefit, it is generally advisable that fuel saving assessments for these types of EETs under a cost-benefit sharing agreement rely on in-service trials. This method provides the most reliable data basis under typical operational conditions.

3.1 Vessel technical data and information

Ideally, fuel consumption should be measured on board the vessel during in-service trials. Then the fuel saving is easily calculated as the difference in fuel consumption between operation with the EET active and inactive during a single in-service trial.

If fuel consumption is not measured but must be derived from measured power and SFOC data, then an understanding of the power generation and consumption on board the vessel is necessary.

Vessel technical data required to calculate the net fuel saving due to the EET depends on how power is generated on board the vessel and how it is split into propulsion power and power to other consumers. The power demand of the EET should be considered in determining the net power savings, particularly for EETs with relatively high power demands. This requires an understanding of the vessel's machinery configuration and how the EET fits into the vessel's power generation and distribution systems. The locations of power

measuring equipment should be mapped out on the power plant layout drawing.

The following sections outline typical data extracted from the vessel's technical documentation to identify relevant consumers and system efficiencies, and to establish a method for determining the EET net power savings. The data items presented are only typical examples of the data that is generally required and available. As stated previously, the actual data required depends on the specific vessel's machinery configuration and the EET in question.

3.1.1 Engine factory acceptance test report

The FAT reports of main and auxiliary engines contain information on SFOC as a function of engine load (%MCR). The discrete SFOC values should be used to derive an empirical expression for the SFOC as a function of engine load. We recommend using polynomial regression of up to fourth order depending on the attained R^2 value, physical soundness of the regression curve, and being mindful of data over-fitting (see Figure 11).

Figure 11: Specific fuel oil consumption (SFOC) as a function of engine load (% of MCR) according to factory acceptance test (FAT) report values for a main engine and an auxiliary engine. Discrete measurement points from the FAT report (dots) and fourth-order polynomial regression curve (dashed line) fit to the FAT data.
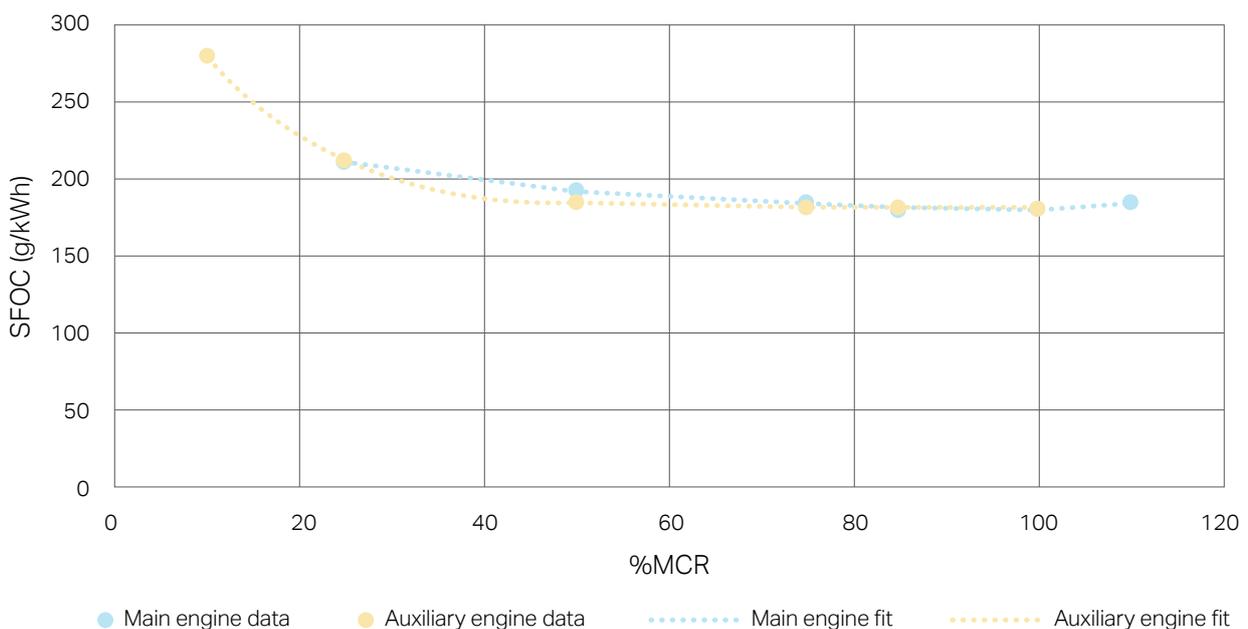
3.1.2   Shaft generators

Shaft generators use power from the main engine to generate electricity, reducing the need for auxiliary engines and leading to fuel savings and lower emissions, as auxiliary power from shaft generators is produced more efficiently.

If an EET affects the operation of shaft generators (e.g., prevents their use due to the EET causing variations in engine RPM), this impact must be factored into the overall performance evaluation.

The combined effect of disabling the shaft generator and running multiple auxiliary engines at lower loads could result in higher fuel consumption for electricity production, possibly negating some or all of the fuel-saving benefits of the EET. This setup can

also lead to increased wear and maintenance costs for auxiliary engines due to increased running hours and less efficient load levels.

The efficiency of shaft generators decreases at partial loads, as they are generally optimized for operation at stable, higher loads and at a given RPM. Permanent magnet and synchronous generators often exhibit higher efficiencies compared to asynchronous types. Further, mechanical losses in the power transmission system from the main engine to the generator slightly reduce the overall efficiency.

Generators, both shaft generators and those in diesel electric systems, can also experience large load variations. For this reason, it is important to make the efficiency load-dependent if possible — i.e., if there is access to the specific generator rating (as demonstrated by the examples in Figure 12).

Figure 12: Example of generator efficiency as a function of generator size and load.
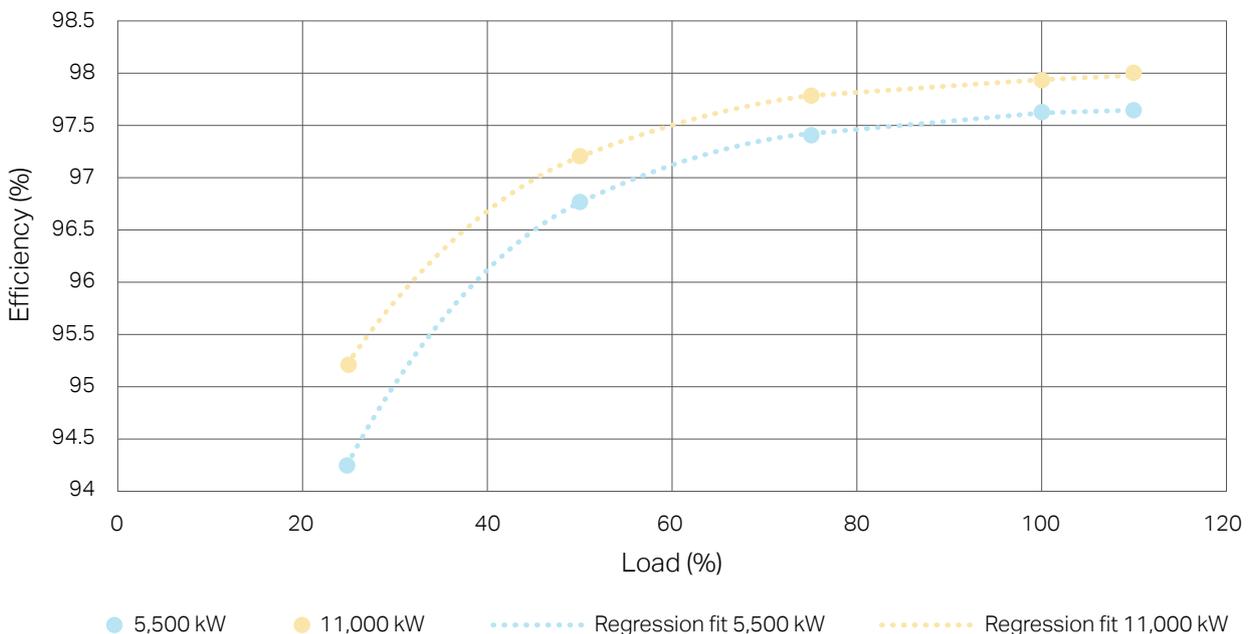
3.1.3   Cargo systems

Cargo heating and cooling represents a considerable, sometimes fluctuating, energy load depending on factors like cargo type, ambient temperature, and voyage route. Establishing a baseline for this energy demand is essential to accurately isolate the EET's impact on overall fuel efficiency.

For example, high reefer (refrigerated container) loads may impact the EET assessment negatively, if the associated high auxiliary load needs to be covered by an auxiliary engine less efficient than a shaft generator. If the increased reefer load and the additional auxiliary power demand cannot be met by a single auxiliary engine, a second auxiliary engine may need to be started. Running multiple auxiliary engines not only increases the fuel consumption but also lowers the efficiency because auxiliary engines typically operate most efficiently at higher loads. Running two engines at partial loads to cover the power demand can result in inefficient fuel use and even higher emissions per unit of power generated.

3.1.4   Gearboxes

Vessels with geared propulsion can either be single- or multi-screw. In both cases, the shaft line(s) are fitted with a gear. This is typically a reduction gear when a medium or high-speed four-stroke engine is used for the main propulsion. Losses incurred in these gears must be accounted for.

The transmission efficiency, η_S, depends on the propeller shaft length and the number of bearings and gearboxes, if fitted. For a shaft line coupled directly to a propeller, η_S can be taken as 0.97-0.98 while the shaft efficiency is 0.96–0.97 for a shaft system with a gearbox.[9] When fully loaded, a gearbox will show a higher efficiency than when it is partially loaded.[10] Although gearbox efficiency decreases quickly in low-load conditions, the difference in absolute numbers is quite small. For this reason, we suggest ignoring the gearbox losses and assuming the load fixed with η_{gear} = 0.99.

3.1.5   Electrical transmission efficiency

The discussion so far has been from the perspective of diesel-mechanical power plants, where electrical consumers are powered by auxiliary engine generator sets and/or shaft generators. However, the same principles and procedures can be applied to diesel-electric systems once the overall electrical transmission efficiency between the main engines and the consumers is known, e.g., between the engines and the propulsion motors, the engine and the EET device, or other devices affected by the EET device.

Typical efficiencies for the standard components between an engine and a consumer driven by an electric motor are:[11]

- Generator: η = 0.95-0.97
- Switchboard: η = 0.999
- Transformer: η = 0.99-0.995
- Frequency converter: η = 0.98-0.99
- Electric motor: η = 0.95-0.97

i.e., the total electrical transmission efficiency of the system can be 0.87-0.93.

It should be noted that these efficiencies are typically given at full or rated load, and a decrease in efficiency can be expected at lower loads.

The range in total electrical efficiency highlights the need for measurements of the electrical power generated and delivered to the consumers, as ~6% difference in efficiency could make the difference in a business case for installing an EET.

3.2   Data collection

Because of the time limits associated with in-service trials, data should normally be collected with high-frequency, automated measurement systems. General guidelines for sampling frequency are that the sampling frequency should be preferably 1 Hz, but at least 1/60 Hz, i.e., a minimum of one observation per minute.

Processed data must be accessible post-voyage for contract assessments and in near-real time for operational decisions, with latency depending on the specific use case. Measurement accuracy, data quality, and well-defined quantification methods are essential for obtaining reliable performance results.

If it is not possible to install high-frequency data logging instrumentation on board the ship, it may be feasible

to record key data items manually during the trials at a longer sampling interval, for example, every 10 minutes. This approach will be more prone to data recording errors and should be limited as much as possible. For this purpose, a template for logging trial data should be developed — see Section 3.2.2.

3.2.1   Measurement parameters

Recommended standard parameters to be recorded during in-service tests are shown in "Appendix C - Parameters for performance monitoring using in-service trials".

Individual EETs will influence the set of parameters that should be recorded. The technology provider should be consulted when assessing what parameters should be considered when evaluating the power demand, operational limitations, and net savings of a particular technology.

A detailed list of parameters to be measured during tests should be provided to those responsible for carrying out the trials, including units and notes on their significance. This includes both mandatory parameters and additional parameters that may be useful for analysis.

3.2.2   Data verification and logging

A high data quality is crucial for a reliable fuel-saving verification. Proper filters must be applied to exclude outliers and faulty data points. Procedures outlined in Section 2.2 should be followed for in-service trial data as well.

It is also recommended to maintain a log of in-service trials, recording the date and time of executing trial actions and any data which cannot be collected automatically. An in-service trial log provides a structured template to document data collected during in-service trials and ensures data corresponds to the timing of trial actions.

3.3   In-service trial execution

Before conducting the trials, we recommend conducting the following as part of the pre-trial setup:

1. Confirm the vessel's operational readiness and ensure that all measurement equipment is correctly calibrated, including flowmeters, speed logs, and torque meters.

2. Verify that the vessel's heading, draft, and trim are stable before starting the trials.

The procedure for in-service performance trials involves several steps to ensure comparable measurements during the active and inactive parts of the trial, as illustrated in Ruth et al 2024.[12]

The steps (also illustrated in Figure 13) are as follows:

1. Start the automatic data recording system, if not already in use.

2. Switch on the EET. Allow for a buffer period for the actions needed to switch on the EET.

3. Wait for the vessel's state to stabilize. The data and criteria used to define a stable vessel state are discussed in Section 3.3.1. This stabilizing period with the EET active will allow the system to reach stationary conditions and stabilize the EET's effect on the vessel. The duration of this step usually depends on the EET and the vessel displacement and speed, but 30 minutes is recommended as a minimum value.

4. When the vessel state has stabilized, the first performance measurement period begins. Measurements should be continuously recorded at a regular frequency during this period. A minimum period of 10 minutes is recommended for this first measurement period, for data recorded at intervals of one minute or shorter.

5. Switch off the EET. Reserve a time buffer for this activity, as it depends on the actions required to switch off the EET.

6. Wait for the vessel's state to stabilize again.

7. The data collected after the vessel's state has stabilized again should be collected for the same amount of time as when the EET was active.

8. Repeat this process as many times as desired.

The data collected from Steps 2 to 7 form one measurement set and allow the calculation of one fuel-saving data point.

Depending on the nature of the EET, either power, propeller RPM, or vessel speed should be the same during Steps 4 and 7. This defines the stable state of the vessel.

To plan the trial, expected durations of stabilizing and buffer periods should be estimated beforehand. If possible, the data used to define stable states should be monitored during the trials by onboard data displays to verify the estimated stabilizing periods.

Note that data is collected continuously during the entire process. The personnel on board conducting the test are responsible, at a minimum, for activating

and deactivating the EET and recording the exact times these actions occur. The recorded data will then be used to identify when the vessel's state has stabilized. The time used to switch the EET on and off, i.e., the beginning and end of the buffer periods, must be recorded in the trial log to enable identification of the measurement periods and, thus, the data used in the fuel-saving calculation.

Figure 13: Overview of in-service trial procedure.
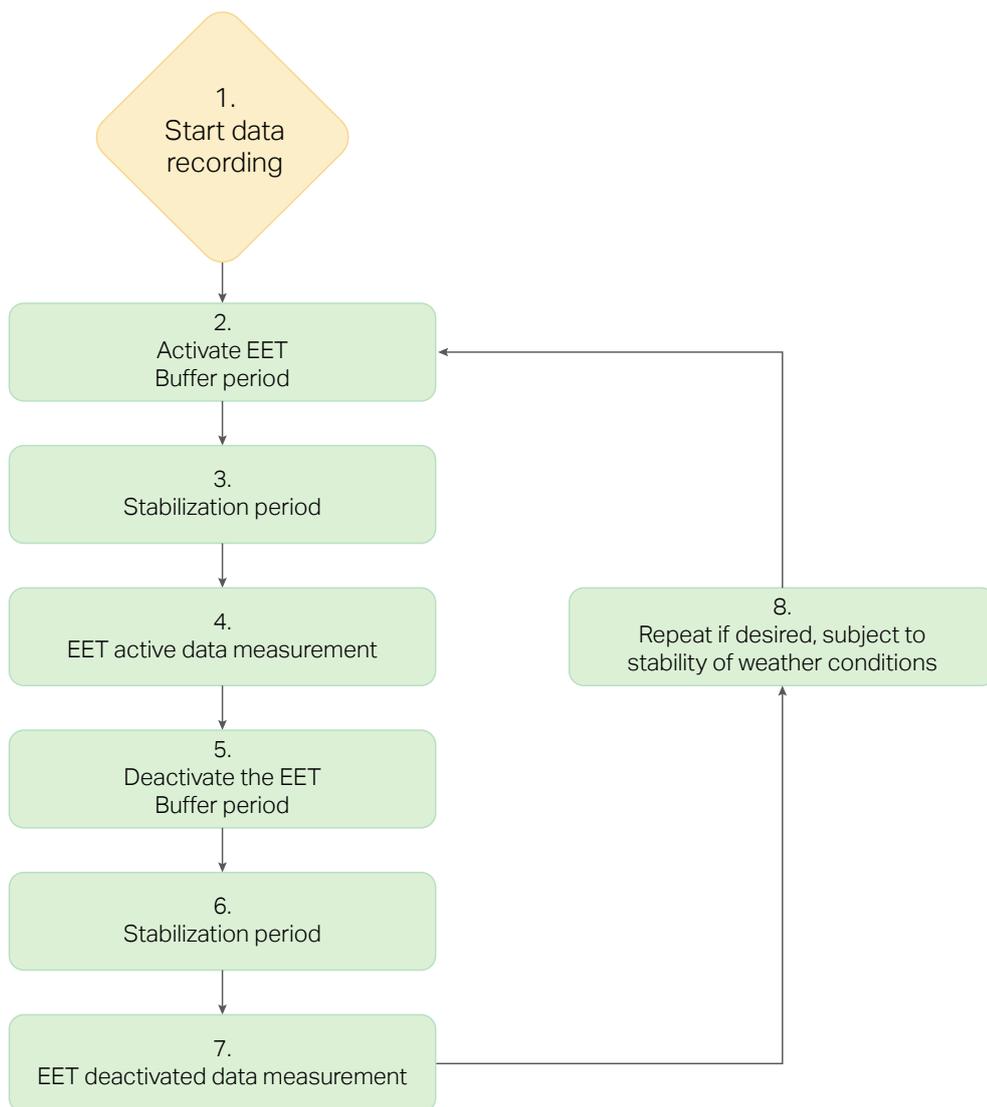
EET = energy efficiency technology.

3.3.1 Criteria for steady-state conditions of the vessel

To ensure data consistency and reliability, trials should meet specific criteria for steady-state conditions. Those criteria include:

- **Constant course and power or speed:** Depending on the EET and the nature of the test, either a constant power or speed setting should be maintained. For example, if the technology is designed to reduce resistance, then the speed should increase at constant power, whereas if the technology is designed to control the propeller RPM, the power should change with the loading on the propeller, e.g., due to waves during bad weather.
- **Minimal rudder movements:** Avoid excessive rudder adjustments as they introduce extra resistance and distort the performance data.
- **Constant draft and trim**

Limitations on weather conditions for conducting trials depend on the EET tested, as it defines the conditions for safe testing. The technology itself may impose limitations on the weather conditions in which the technology can be safely used.

Some technologies are designed to provide a benefit under more severe weather conditions and should therefore be used when there are substantial winds or waves. In these cases, environmental conditions become additional parameters defining the operational profile of the vessel along with the speed, draft, and trim distributions. Examples include WAPS and engine load optimization software.

Other EETs are expected to provide benefits in calmer conditions, e.g., ALS. In these cases, limitations on weather conditions for in-service trials and benefit tracking should follow the technology provider's recommendations. This approach eliminates the need for mathematical correction of the measured data for encountered weather (e.g., waves, wind, and rudder movements), propulsion power, or STW, as long as environmental and operating conditions between the two measurement periods in a set remain very similar.

3.4 Sources of uncertainties and mitigation techniques

Various sources can introduce uncertainties in performance trials, including:

- Variability in wind, waves, and currents can significantly affect vessel performance, altering fuel consumption and speed. Conducting trials in calm conditions helps minimize these uncertainties. Multiple trials may be required to define the statistical uncertainty for EETs measured in non-calm conditions.
- Inaccurate sensors, such as miscalibrated flowmeters or speed logs, can cause data errors. Regular calibration of all measurement equipment is essential to mitigate this issue.
- Differences in trial executor behavior, engine settings, or operational practices during trials may influence results. Standardized procedures and detailed instructions are critical for reducing variability.

3.5 Calculation of net savings

Net savings are expressed as the reduction in fuel consumption when the EET is active compared to when it is inactive.

As the operating and weather conditions during the in-service trials are kept constant during a single trial set, the measured fuel consumption can be used directly to calculate net savings. If fuel consumption cannot be measured, savings may be derived from the power measurements and engine FAT reports. In this case, an understanding of the power generation, the EET's effect on power demand, and related efficiencies is needed to derive a net fuel saving, as explained in Section 3.1.

Measurements should be repeated across a range of drafts, trims, and speeds to give a more complete picture of the EET fuel savings. A statistical analysis of the collected data should be conducted to determine the EET's effectiveness in reducing fuel consumption and emissions.

The fuel savings are specific to the operating and weather conditions at the time of the trial. We therefore recommend collecting a larger sample of test sets across various weather and operational conditions. In-service trials for this purpose should be integrated into the vessel's daily operating routine at sea, for example, by conducting one test per day at the same time, if permitted by the operating conditions.

The simplest measure of fuel saving is the average fuel saving across all in-service trials. In the authors' experience, over 100 trial sets may be necessary for certain technologies to achieve the statistical robustness necessary for calculating a weighted mean. These sets should reasonably represent variations in speed, drafts, sea state, wind and wave conditions, and geographical locations.

To evaluate the overall savings provided by the EET for any given time period t_1, the average fuel savings measured, FOC_{trials}, should be weighted by the desired time period for the evaluation divided by the duration t_{trials} covered by the trial dataset:

Equation 27

$$FOC_{t1} = \frac{t_1}{t_{trials}} \cdot FOC_{trials}$$

This assumes that the mean fuel saving, as determined from a series of trials, has approached a stable constant value and that the measurement period is representative of the operational profile of the vessel over the entire time t_1 for which fuel savings are desired.

More complicated assessments can be developed as part of the cost-benefit sharing agreement if desired. For example, the measured fuel savings could be weighted for a range of weather conditions according to distributions of hindcast weather data, speed, draft, and trim, based on fuel savings for the range of each of these parameters encountered.

However, we recommend keeping the agreement on assessment of fuel consumption as simple as possible to avoid uncertainties and disputes, and the specific methodology should be defined independently by the parties to any such agreement.

04 Monitoring fuel savings within a cost-benefit sharing framework

This section discusses issues and aspects involved in monitoring fuel savings within the framework of a cost-benefit sharing agreement during a time charter period.

In this context, there are two main points that should be followed:

1. Savings should be reviewed periodically as mutually agreed by both parties in a cost-benefit sharing agreement. These regular reviews help ensure the accuracy of the fuel saving analysis and allow for timely adjustments based on actual performance. This enables both parties to detect and address any deviations in expected fuel savings promptly.

2. Savings should be verified by an independent third party to ensure that all procedural steps have been followed according to the agreed methodology. This external, unbiased perspective ensures that all savings metrics are consistently monitored, transparently reported, and aligned with agreed performance standards.

Regular review of fuel savings involves both the fuel saving estimate as well as the monetary saving estimate. The basis for these calculations must be agreed as part of the cost-benefit sharing agreement before the retrofit.

Fuel savings performance of EETs should be monitored in operation and reviewed regularly for other reasons as well, such as:

- To detect deterioration in vessel performance, EET performance, or monetary savings, so that corrective actions can be planned and executed.
- To monitor the use of the technology to make sure that it is being switched on whenever relevant, for technologies which can be switched on and off on board the vessel.

The way to assess the total monetary savings based on the amount of fuel savings must be part of the cost-benefit sharing agreement.

Examples of ways to assess the monetary savings based on a fuel price could be:

- A fixed price agreed during the negotiations for the EET retrofit
- Actual fuel purchase (invoiced) price
- Index-linked fuel oil price which will vary over time, e.g., Singapore or Rotterdam Platts

Vessel trading patterns, applicable market conditions, and the resulting operational profile have a significant impact on the financial outcome of the EET implementation. The scale of the savings generated by the EET on a given trade should therefore also be considered when planning the vessel deployment. Some idea of this should already exist from feasibility studies conducted before the decision to carry out an EET retrofit.

The anticipated operational profile of the vessel affects the fuel savings due to the following varying market-dependent factors:

- **Steaming and idle time** – knowing how much time there will be available for the EET to generate savings.
- **Loading condition** – the actual draft and trim of the vessel may have a strong influence on the effectiveness of EETs. Therefore, it is important to know the time distribution at different drafts.
- **Operating speed** – for cargo vessels, this is arguably the least predictable factor, as it largely depends on the market conditions, where market volatility will dictate periods of speeding up or slowing down.

Similarly, GHG taxation schemes based on market-traded commodities, like European Union Allowances (EUAs) or pooling of emissions under FuelEU regulations, may require more frequent re-assessment of fuel savings due to their volatility.

When financial risks are perceived to be high due to, for example, volatility of fuel and emissions costs or a lack of data on the EET performance, tracking of costs and benefits should happen more frequently to facilitate operational decisions to optimize the vessel operation and/ or EET and maximize return on investment.

The frequency of assessment, or review, specified in the cost-benefit sharing agreement should therefore consider the needs of the parties involved in the EET implementation cost-benefit sharing and their risk assessment of the volatility of factors affecting the fuel savings and the fuel costs.

Each agreement and monitoring approach should be defined independently by the contracting parties to ensure compliance with competition law.

05 Case studies

The case studies in this section are examples of EET retrofit projects carried out by some of the MMMCZCS's partner organizations. The aim of the case studies is to show the level of fuel savings attained with various EETs using the approaches described in this guide and aspects of the fuel savings related to the operational profile of the vessel.

Four case studies are included and arranged according to the type of EET applied:

- 7,000 TEU container ship retrofitted with a new bulbous bow and propeller
- 13,000 TEU container ship retrofitted with a new propeller
- Four 2,100 TEU container ships, all sister vessels, retrofitted with a new silicone hull coating
- Two feeder class container ships of different sizes, both retrofitted with a propeller pitch-RPM optimizer system, which can be switched on and off on board

All case study data is anonymized and presented with partner consent solely to illustrate the application of the methodologies described in this guide.

5.1   7,000 TEU container ship – redesigned bulbous bow and propeller

This case study presents a container ship that was retrofitted with a redesigned bulbous bow and propeller. The case study uses the continuous monitoring procedure from Section 2 to track the fuel savings on a month-by-month basis to illustrate the variation in savings with changes in operating conditions.

The vessel's most common operating speed in service was significantly lower than the design speed of the vessel. The lower operational speeds meant that the original bulbous bow was substantially less effective than a bulb which is designed for the lower operational speed. A new bulb form was designed based on the expected future operational profile. The redesigned bulb was more slender and less protruding than the original bulb, as shown in Figure 14.

The efficiency of a propeller is closely tied to its design and how well it matches the operational profile of the vessel. Table 2 compares the relevant parameters that differ from the original and the new propeller, indicating a noticeable reduction in mass, skew, and expanded blade area ratio. Propellers with a smaller expanded blade area are often more suited to lower speeds due to their lower loading and reduced drag. Therefore, the new propeller has increased compatibility with the vessel's operating conditions. Additionally, the propeller was retrofitted with boss cap fins. The total estimated reduction in power demand due to the new propeller was about 8%.

Figure 14: Original bulbous bow design (left) and new bulbous bow optimized for expected operational profile (right).
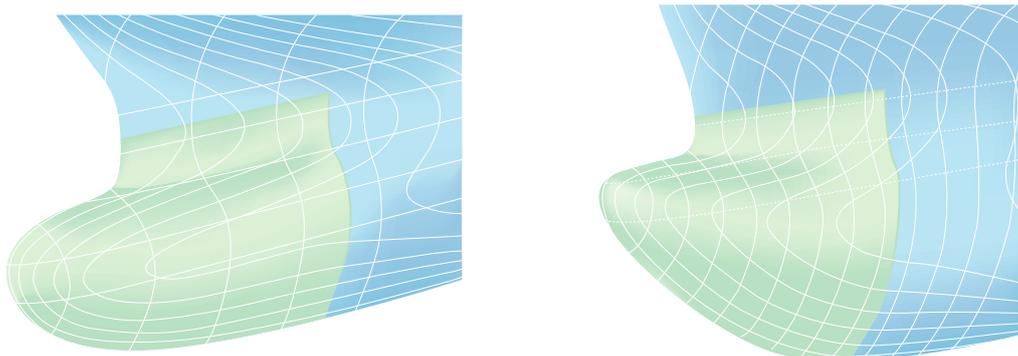
Table 2: Parameters of the original and new propellers for 7,000 TEU container ship class.

	Original design	New design
Expanded blade area	0.830	0.555
Skew	40.0˚	28.1˚
Weight	~80,000 kg	~50,000 kg

Table 3 shows the expected power reductions for the combination of new bulb and propeller at various drafts (T) and speeds (V) in accordance with CFD simulations. The table indicates that the power reductions depend significantly on the combination of speed and draft.

Table 3: Power reduction potential of redesigned bulbous bow and propeller according to CFD simulations for 7,000 TEU container ship class. A negative value means that a reduction is expected for the power required.

	V=14 kn	V=17 kn	V=20 kn
T=10 m	-25%	-19%	-12%
T=12 m	-16%	-12%	-6%
T=14 m	-5%	-3%	-3%

CFD = computational fluid dynamics, m = meters, kn = knots

The dry dock for the retrofit was the third five-year special survey. The baseline period was following the previous dry docking.

The hull treatment and paint system in both dry docks consisted of a full blast and application of a new paint system. The similarity of the hull treatments increases the confidence in the comparability between the baseline period and the benchmark period in terms of isolating the effect of the redesigned bulbous bow and propeller.

Following the procedures for continuous performance monitoring in Section 2 demonstrated a reduction

in propulsion power that is well aligned with the expectations from the CFD simulations in Table 3. Table 4 shows the evaluated fuel savings resulting from the retrofit as a function of draft and speed. Noon reports were used to develop the power saving numbers.

Table 4: Percentage reduction in shaft power across draft and speed bins. A negative value means a reduction in shaft power.

	V=14 kn	V=17 kn	V=20 kn
T=10 m	-25%	-17%	-14%
T=12 m	-23%	-14%	-13%
T=14 m	-8%	-11%	-1%

m = meters, kn = knots

Table 5 shows the change in added resistance between the baseline and benchmark periods (AR%). The low values of the confidence intervals (AR% +/- CI) indicate that there is high confidence in the results.

Table 5: Reduction in added resistance percentage with confidence interval at 95% confidence level (AR%±CI). A negative value means a reduction in added resistance.

	V=14 kn	V=17 kn	V=20 kn
T=10 m	-45±5	-26±3	-20±3
T=12 m	-39±4	-20±1	-18±2
T=14 m	-10±8	-14±2	-2±4

m = meters, kn = knots

The verified effect of the bulbous bow and propeller retrofit demonstrates dependencies on the operational speed and draft of the vessel after the retrofit. Power reductions are smallest at high draft and high speed and largest at lower speeds and lighter draft.

The attained savings in the form of reduction in fuel consumption or emissions depend on idle time versus sailing time, and the time at a particular combination

of speed and draft, with a power reduction potential spanning between a few percent to up to 25%.

Figure 15 shows the variation in fuel saving relative to the total fuel saving during the 16-month tracking period as a function of the month after the retrofit dry dock.

5.2   13,000 TEU container ship – redesigned propeller with boss cap fins

This case study also presents the application of the continuous monitoring procedure from Section 2. A 13,000 TEU container ship has been retrofitted with a redesigned propeller equipped with propeller boss cap fins (PBCF). The reason for the retrofit was that the most common operational speed was lower than the design speed when the vessel was built.

CFD simulations were conducted to assess the feasibility of retrofitting the propeller with PBCF.

Table 6 shows expected shaft power reductions as estimated by the CFD simulations. It can be seen from the table that a significant variation in the savings with draft (T) and speed (V) is not expected.

Table 6: Power reduction potential of redesigned propeller and PBCF, according to CFD simulation for 13,000 TEU container ship class. Negative values mean a reduction in power.

	V=14 kn	V=16 kn	V=18 kn	V=20 kn
T=13 m	-6.4	-6.5	-6.5	-6.7
T=14.25 m	-6.8	-6.7	-6.7	-6.7
T=15.5 m	-7.4	-7.4	-7.4	-7.6

PBCF = propeller boss cap fins, CFD = computational fluid dynamics, m = minutes, kn = knots

The retrofit dry dock was the third five-year special survey. The previous dry dock was used to define the baseline period. Noon reports were used to develop the power saving numbers from operational data.

Figure 15: Variation in fuel savings by month after the retrofit dry dock.
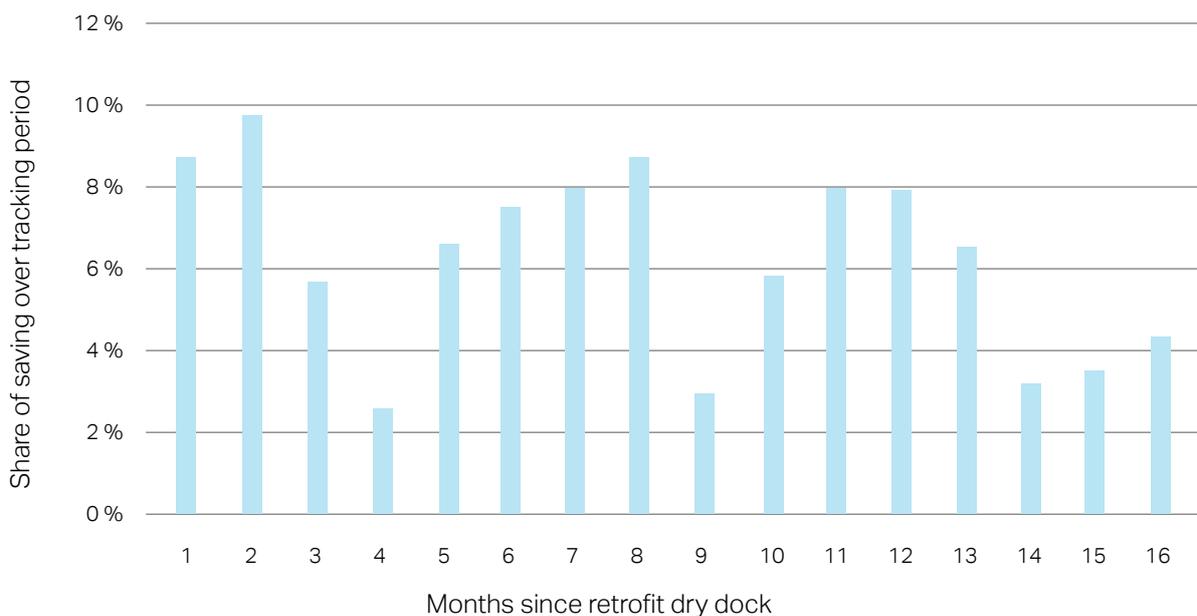
During the ordinary (baseline) dry dock, the hull was spot blasted followed by a new painting system application. During the retrofit dry dock, a similar paint system was applied, but a full blasting of the hull was also conducted. The percentage of spot blasting during the normal dry dock is unknown, so this difference may add some bias and decrease confidence in the comparison.

Applying the recommendation from Section 2 of this technical guide demonstrated a reduction in propulsion power that was well aligned with the expectations from the CFD simulations. The evaluated reduction in shaft power due to the retrofit was consistently about 7% across all operating drafts and speeds analyzed. The reduction in AR% was slightly more than 8% with a CI of ±2%, indicating high confidence in the results.

5.3   2,100 TEU container ship class – silicone coating on hull

This case study presents a 2,100 TEU container class of four sister vessels that received a silicone hull coating during two separate dry docks. An advanced silicone hull coating was applied to each vessel during the first dry dock after the vessels went into service.

The same silicone hull coating was applied during the second dry dock, five years after the first dry dock. In both cases, full blasting of the hulls was carried out in each dry dock. Thus, the effect of the first application of silicone hull coating on the vessels' hulls after a conventional hull coating and the effect of the second application of silicone hull coating could be compared.

The alternative recommendation in Section 2.7 of this guide was applied for the evaluation of the performance gain derived from the silicone hull coating application. This was done to be able to detect and compare any changes in the performance of the anti-fouling systems over time.

Data reported manually in the form of noon reports with basic onboard validation through the reporting system was used. The data included fuel consumption parameters derived from mass flowmeters, which have a higher accuracy than volume flowmeters.

Reported data was validated throughout the reporting system, data filtration was applied, and outliers were excluded if criteria such as correlation checks between parameters were not fulfilled. The following filter criteria were applied to the reported data to identify valid data:

- Leg duration and reporting interval longer than 22 hours
- Main engine running hours of 23, 24, 25 hours
- Operational mode: at sea under own propulsion
- Main engine performance code "steady" if it was reported by the vessels
- Draft in ballast and laden condition and on even keel were considered separately
- Analyzed wind condition maximum Beaufort Force 3
- Main engine SFOC was in the range of 170 to 240 g/kWh

Analyzed hindcast data was used for weather and environmental conditions to derive the technical performance speed. Only good weather days and good technical performance speed were considered to prevent higher uncertainties arising through speed log, current, sea state, etc.

Regression curves were generated using noon report data of main engine fuel consumption versus technical performance speed. These showed the first and second derivatives to be positive in the speed range modeled.

Table 7 shows the coefficients of determination, R^2, for the evaluation period after the first and second dry docking for each vessel. In all cases, the coefficient is above 0.8, which indicates that the regression curves fit the data points well and supports the conclusion that the noon reports from the vessels were reliable. Overall, the data quality was good. There was no flatline tendency observed in the data, and only a few data points had to be excluded from the evaluation.

Sufficient good-quality data covering the full speed range at laden draft was obtained for all sister vessels. Fuel savings could be derived based on a broad speed profile rather than extrapolating performance gains, which could risk high inaccuracy. Periods of 90 and 180 days before and after the application of silicone hull coating were used to compare the antifouling performance of the coatings.

Figure 16 compares fuel consumption before and after the first dry dock, when the silicone coating was

first applied, with fuel performance before and after the second dry dock, when the silicone hull coating was applied a second time. The technical performance speed indicated in these speed and consumption plots accounts for the speed loss due to weather, as well as the speed loss or gain due to currents. This is applied to normalize SOG, ensuring that the impact of metocean conditions is properly considered.

Figure 16: Speed and consumption curves of the four sister vessels within the 2,100 TEU class before and after the first and second dry docking.
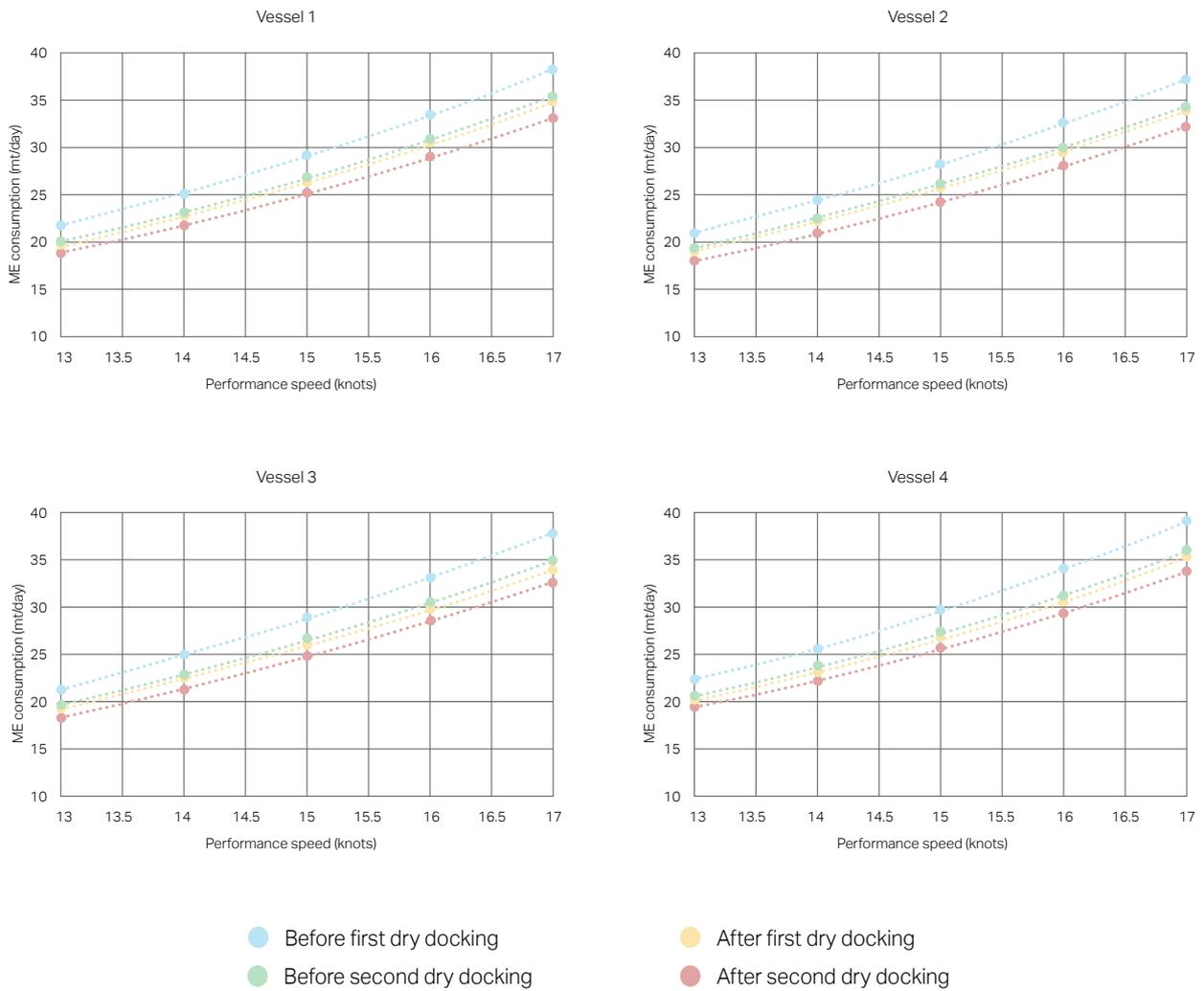
ME = main engine

The results in Table 7 demonstrate fuel savings of 9-10% over the operational profile when replacing the original conventional antifouling hull coating on the vessels with the silicone hull coating during the first dry dock. The second application of the silicone hull coating led to a 6-7% performance gain over the operational profile of the vessels, compared to the performance of the vessel before the second dry dock.

Table 7: Overview of total fuel savings from silicone hull coating after dry docking.

Vessel	Savings from first silicone coating	Savings from second silicone coating	R^2 fit of FOC vs. V_s
1	9%	6%	0.91 – 0.94
2	9%	6%	0.87 – 0.93
3	10%	7%	0.83 – 0.92
4	10%	6%	0.87 – 0.92

FOC = fuel oil consumption, V_s = vessel speed

The above points support the robustness and accuracy of the manually reported data from the vessels. Furthermore, the derived fuel savings are representative of the actual fuel reduction resulting from the hull treatments.

5.4 Feeder class container ships – in-service trials engine speed and propeller pitch control system

The study focuses on two container feeder vessels, representative of smaller container ships operating on regional and short-sea routes. This type of vessel has regular port calls and frequently requires adjustments in speed and maneuvering.

Specific characteristics relevant to the study include:

- Frequent changes in speed and loading conditions, creating a challenging environment for consistent fuel savings

- Frequent operation at low speeds to save fuel
- Slots for reefers requiring continuous electrical power supply

The two container ships have been retrofitted with an engine speed and propeller pitch control system, which can be switched on and off on board. When active, the system automatically and continuously updates the combinator curves (i.e., the optimum propeller pitch and RPM) to attain the highest propulsion efficiency.

In-service trials alternating the pitch/RPM system between active and inactive modes were used in the study to assess the system's impact on fuel consumption and vessel performance. This case study presents the results from the in-service trials, demonstrating the system's impact on fuel consumption and vessel performance across various speeds and operational modes. Key evaluation areas during the in-service trials included:

- **Fuel savings**: Assessing the system's ability to reduce fuel consumption by fine-tuning propulsion settings based on real-time operational data.
- **Performance consistency**: Evaluating how effectively the system maintains target speeds and operational stability under varying conditions.
- **Adaptability to operational changes**: Examining how the system responds to changing load and speed requirements, ensuring optimal performance across different scenarios.

Both vessels have controllable pitch propellers and shaft generators, which had to be disengaged before activating the pitch/RPM optimization system. This means that auxiliary engines must be running when the system is in use.

5.4.1 Method for assessing performance improvement

Because of the nature of the EET and its limitations on the operation of the vessel, specific procedures for evaluating the performance changes had to be developed.

The effectiveness of the combinator curve optimization software was calculated as the improvement obtained when compared with a specific baseline scenario of operating the vessel. Quantifying these savings can be challenging due to the existing awareness of the optimal pitch and RPM settings by experienced navigators.

A baseline scenario could, for example, be one of the following:

- Historical operations by the crew
- Fixed main engine speed (RPM) scenarios, defined by the speed of the shaft generator on board
- Fixed propeller pitch conditions

The second method (fixed main engine speed) was chosen as the simplest baseline scenario to apply. Due to the presence of a shaft generator operating at a fixed RPM, the shaft generator had to be disengaged to allow variations in main engine RPM when the system is active. Therefore, the additional consumption of auxiliary engines had to be considered due to the disengaged shaft generator.

The process to determine the overall fuel savings resulting from the optimization system was as follows:

- **Step 1**: Determine the theoretical fuel oil consumption (FOC) of the main engine (ME) when the shaft generator is not in use. This was calculated using the measured propulsion power during periods where the pitch/RPM optimization system was disengaged. The formula applied considered only the mechanical power required for propulsion, excluding any auxiliary loads.
- **Step 2**: ME FOC was recalculated to include the additional power required by the shaft generator. This adjustment accounted for the increased load on the ME to supply the electrical demand previously covered by auxiliary engines. Efficiency losses in the shaft generator were also factored into the calculation to maintain accuracy.
- **Step 3**: The fuel consumption was modeled for scenarios where the shaft generator was operational, but the pitch/RPM optimization system was disengaged. This step allowed for a direct comparison of ME efficiencies with and without the pitch/RPM optimization system under otherwise identical conditions.
- **Step 4**: Auxiliary engine (AE) FOC was calculated during periods when the shaft generator was not supplying electrical power. This step was particularly important for determining the trade-off between ME and AE efficiencies, as the pitch/RPM optimization system influenced the load distribution amongst engines.
- **Step 5**: The net savings achieved by the pitch/RPM optimization system were calculated as the difference in total fuel consumption between periods with the system engaged and disengaged. This included adjustments for changes in ME and AE FOC, as well as any additional power losses or gains.

- **Step 6**: The calculated net savings were applied across the vessel's operational profile. This involved integrating the savings over varying speeds, drafts, and operational conditions to estimate the total benefit of the pitch/RPM optimization system during typical operations.

Data was collected using a high-frequency auto-logged data collection system, AIS data, and hindcast weather data. A trial log filled in by the vessel crew supplemented the auto-logged data.

To ensure data consistency and reliability, the following requirements for steady-state conditions were imposed:

- **Constant course and speed**: The vessel maintained a steady heading and consistent SOG, without major deviations.
- **Stable environmental conditions**: Trials were conducted in calm weather, with conditions below Beaufort Force 3.
- **Consistent load parameters**: Engine load, draft, and trim remained constant during each measurement period. Fluctuations in these parameters could skew results and should be excluded.
- **Minimal rudder movements**: Excessive rudder adjustments were avoided, as they would introduce more resistance and distort performance data.

5.4.2   Attained savings from the retrofit

This section presents a breakdown of the fuel reduction attained for different operating conditions for each vessel. Figure 17 and Figure 18 illustrate the relative fuel saving results for Vessel A, including the penalty due to the disengagement of the shaft generator and switching on of the auxiliary engines. Likewise, results for Vessel B are displayed in Figure 19 and Figure 20.

Both vessels show a general decrease in savings with increasing speed and number of reefers. The higher electrical power demand due to a higher reefer load affects the savings of the combinator curve's optimization, as the vessels' shaft generator (without a frequency converter) cannot run when this technology is operating. Consequently, the AEs need to run to cover the electrical demand normally covered by the shaft generator, which results in a penalty in fuel savings when running this EET.

The study concluded that verification of savings would have been very difficult without high-frequency auto-log data. Results were generated for different speeds and different reefer loads.

Figure 17: Fuel savings for Vessel A as a function of speed over ground.
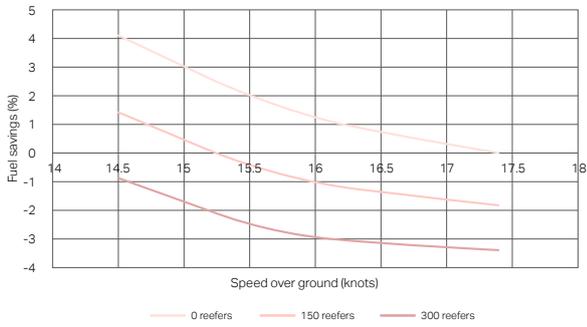
Figure 18: Fuel savings for Vessel A as a function of reefer load.
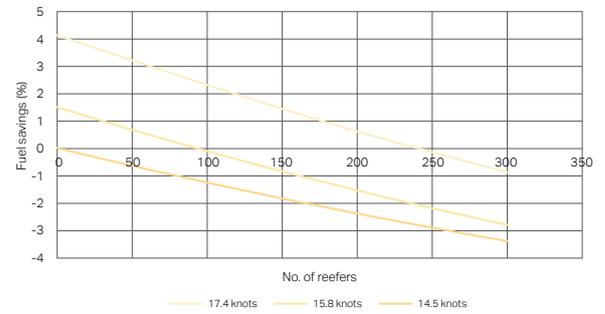
Figure 19: Fuel savings for Vessel B as a function of speed over ground.
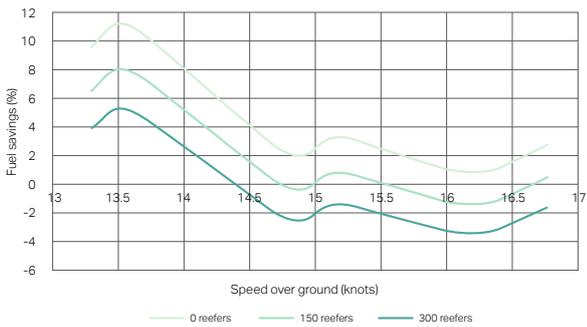
Figure 20: Fuel savings for Vessel B as a function of reefer load.
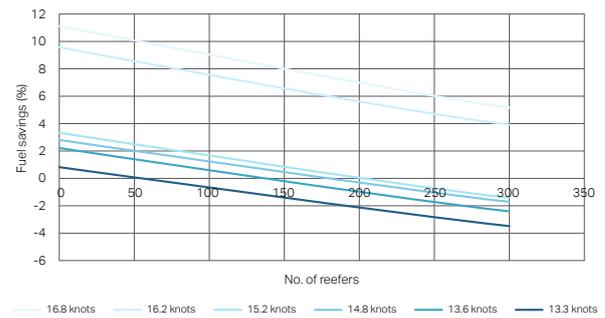
06 The project team

This technical guideline was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) in collaboration with our partners. Contributors marked with an asterisk (*) were seconded to the MMMCZCS from their home organization. All secondees and external contributors participated in a research capacity as part of the collaborative project and contributed technical input to the guideline.

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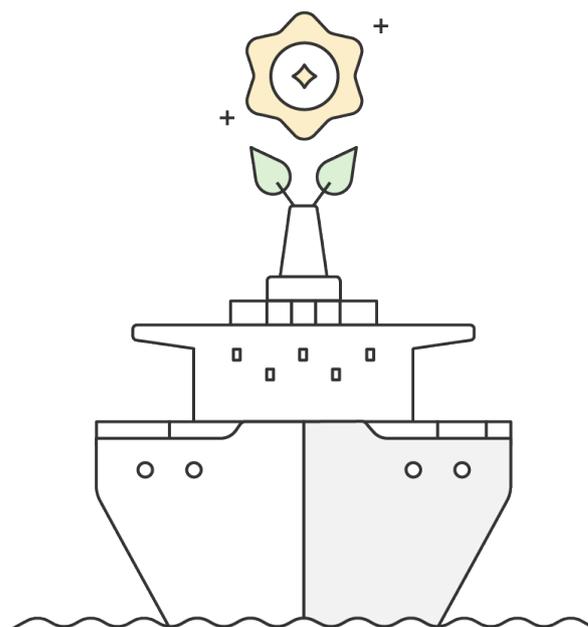
Abbreviations

AE	Auxiliary engine		IMO	Internation Maritime Organization
AIS	Automatic identification system		IQR	Interquartile range
ALS	Air lubrication system(s)		ITTC	International Towing Tank Conference
AR%	Added resistance percentage		LCV	Lower calorific value
BOSP	Beginning of sea passage		ME	Main engine
EOSP	End of sea passage		MCR	Maximum continuous rating
CFD	Computational fluid dynamics		MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
CI	Confidence interval		mt	Metric tonne
EEDI	Energy Efficiency Design Index		PBCF	Propeller boss cap fins
EET	Energy efficiency technology		RPM	Revolutions per minute
EEXI	Energy Efficiency Existing Ship Index		SFOC	Specific fuel oil consumption
EUA	European Union Allowance		SOG	Speed over ground
FAT	Factory acceptance test		STW	Speed through water
FOC	Fuel oil consumption		TEU	Twenty-foot equivalent unit
GHG	Greenhouse gas		TCAR	Trend-corrected average resistance
GPS	Global positioning system		WAPS	Wind-assisted propulsion system(s)

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Appendix A – Parameters for continuous performance monitoring

	Measured / Derived parameters	Units	Type	Priority
NAVIGATIONAL DATA	Speed over ground	m/s	Primary	1
	Speed through water	m/s	Primary	1
	Draft, aft pp	m	Primary	1
	Draft, fore pp	m	Primary	1
	Time since last report (SLR)	hr	Primary	1
	Ship's heading	degree	Primary	1
	Course over ground	degree	Primary	1
	Pitch of CPP	degree	Primary	1
	Ship position, latitude, and longitude	degree	Primary	1
	Rudder angle	degree	Secondary	2
	Measured / Derived parameters	**Units**	**Type**	**Priority**
FUEL OIL CONSUMPTION	Main engine fuel oil consumption	tonne/hr	Primary	1
	Lower calorific value, ME FOC	kJ/kg	Secondary	1
	Auxiliary engines FOC	tonne/hr	Primary	1
	Lower calorific value, AEs FOC	kJ/kg	Secondary	1
	Oil-fired boiler FOC	kg/hr	Primary	1
	Lower calorific value, OFB FOC	kJ/kg	Secondary	1
	OFB running time	hr	Primary	1

POWER PRODUCTION AND ELECTRICAL CONSUMPTION

Measured / Derived parameters	Units	Type	Priority
Delivered power at propeller	kW	Primary	2
Propeller revolutions	RPM	Secondary	2
Report period	hrs	Secondary	1
Main engine running hours	hr	Primary	1
Generators power production	kWh	Primary	1
Auxiliary engine running hours	hr	Primary	1
Shaft generator power take-out	kW	Primary	1
Shaft generator running hours	hr	Primary	1
Shaft motor power take-in	kW	Primary	1
Shaft motor running hours	hr	Primary	1
Cargo-related electrical consumption	kWh	Secondary	2
Other large electrical consumers	kWh	Secondary	2

WEATHER OBSERVATIONS

Measured / Derived parameters	Units	Type	Priority
Seawater temperature	deg. Celsius	Secondary	2
Ambient air temperature	deg. Celsius	Secondary	2
Water depth	m	Secondary	2
Surface current velocity	m/s	Secondary	1
Surface current true direction	degree	Secondary	1
True wind direction	degree	Secondary	1
True wind speed	kn	Secondary	1
Significant wave height	m	Secondary	1
Wave true direction	degree	Secondary	1
Wave period, zero crossing	seconds	Secondary	2
Significant swell height	m	Secondary	1
Swell true direction	degree	Secondary	1
Swell period, zero crossing	seconds	Secondary	2

	Measured / Derived parameters	Units	Type	Priority
TECHNICAL SHIP INFORMATION	Ship displacement and principal particulars		Secondary	2
	Speed-power curve		Secondary	2
	SFOC curve as function of engine loading (%)	g/kWh	Secondary	1
	Rating and count of main and auxiliary engines		Secondary	1
	Hotel load	kW	Secondary	2
	Oil-fired boiler specifications		Secondary	2
	Maintenance history		Secondary	2
	Other electrical consumers		Secondary	2

Appendix B – Calculation procedures for normalization of performance data

The power component P_{SH} and each of the resistance components in P_{env} can be predicted from various analytic or semi-analytic models developed in the last decades and used in the International Towing Tank Conference (ITTC) recommendation on conducting speed-power trials (hereafter 'ITTC recommendation').[4] The reader is advised to consult this reference for all details of the methods, including limits on applicability.

B.1 Wind resistance correction

Wind generates forces on the vessel's hull, superstructure, deck cargo, and equipment on deck.

The added wind resistance R_{AA} is calculated using the ITTC recommendation:[4]

Equation 28

$$R_{AA} = \frac{1}{2}\rho_A C_{DA}(\psi_{WRrel})A_{XV}V_{WRel}^2 - \frac{1}{2}\rho_A C_{DA}(0)A_{XV}V_G^2$$

where:

ρ_A	is the mass density of air = 1.225 kg/m^3 at 15°C at 101.3kPa pressure***
C_{DA}	is the wind resistance coefficient
ψ_{WRrel}	is the relative wind direction at reference height, with ψ_{Wref}=0 corresponding to head winds
A_{XV}	is the area (m²) of the maximum transverse section exposed to the wind, i.e., the vessel's hull and superstructure above the waterline; this area can be reasonably estimated from the general arrangement plan of the vessel with approximations for the cargo area for vessels with cargo storage on deck
V_{WRrel}	is the relative wind speed (m/s) at reference height
V_G	is the forward SOG of the vessel (m/s)

***Increased accuracy can be attained with correction for mass density of air by temperature and atmospheric pressure, ρ_A (kg/m^3), which can be done by:

Equation 29

$$\rho_A = \frac{p_A}{2.8705\,(T_A + 273.15)}$$

where:

p_A	(hPa) is the barometric air pressure at the reference height
T_A	(°C) is the ambient air temperature

The wind resistance coefficients are best taken from reported results of wind tunnel tests on the vessel. Using these wind resistance coefficients for wind directions at regular intervals is the most reliable method to compute the wind resistance of the vessel.

The next-best method is to derive wind resistance coefficients using CFD viscous flow simulations. This method is valid if the organization conducting the CFD can demonstrate that the software has been validated against wind tunnel tests for similar vessel types.

If it is not feasible to derive the vessel-specific wind resistance coefficients from wind tunnel tests or CFD simulations, a less accurate alternative is to reference publicly available data for wind resistance coefficients. The vessel type and overall shape should be similar to those in the database used to develop the coefficients. Appendix F of the ITTC recommendation[4] provides wind resistance coefficients for typical vessel types.

If a vessel has varying projected frontal and longitudinal areas, typically due to different configurations of containers or other cargo on deck, we apply generalized wind resistance coefficients as the best representation.

Correction for the vertical position of the anemometer above the mean sea surface or reference height for the hindcast wind speed and direction should correspond to the height used to determine the wind resistance coefficients from the wind tunnel test or CFD simulations. If the wind resistance coefficient in the ITTC recommendation[4] is used, then the reference height is 10 m.

The correct relative wind speed at the reference height (m/s) is calculated by:

Equation 30

$$V_{WRref} = \sqrt{V_{WTref}^2 + V_G^2 + 2V_{WTref}\,V_G\cos(\psi_{WT} - \psi)}$$

where:

ψ_{WT}	(deg.) is the true wind direction at the vertical position of the anemometer or wind measurement point
ψ	(deg.) is the heading of the vessel
V_{WTref}	is the true wind speed at the reference height, given by Equation 9: $$V_{WTref} = V_{WT}\left(\frac{Z_{ref}}{Z_a}\right)^{\frac{1}{9}}$$

as explained in Section 2.2.4.

B.2 Resistance increase due to irregular wind waves and swell

Wave-induced resistance increases due to diffraction from the vessel hull and motions generated by the sea condition. This resistance also leads to the radiation of additional wave energy from the vessel.

The added resistance due to waves is normally calculated using the vessel's response amplitude operator of added resistance in regular waves, denoted as R_{wave} (ω,α,V_{STW}). This calculation incorporates functions that describe the wave energy distribution as a function of wave frequency and direction. The total added resistance due to waves is the summation of the individual contributions from each wave frequency and direction at a particular vessel speed through water, given by:

Equation 31

$$R_{AW} = 2\int_0^{2\pi}\int_0^{\infty} \frac{R_{wave}(\omega,\alpha,V_{STW})}{\zeta_A^2} E(\omega,\alpha)d\omega d\alpha$$

where:

R_{wave} (ω,α,V_{STW})	is the transfer function of mean resistance increase in regular waves
$\omega_{(rad/s)}$	is the circular frequency of regular waves
$\alpha_{(rad)}$	is the wave heading with respect to the vessel
$\zeta_A (m)$	is the wave amplitude
$E(\omega,\alpha)$	is the directional wave spectrum, determined by: $E(\omega,\alpha) = S_\eta(\omega)\,G(\alpha)$

where:

$S_\eta(\omega)$	is a unidirectional wave spectrum function
$G(\alpha)$	is a directional wave spreading function

Selection of appropriate wave spectral functions and wave functions should follow the recommendations in Section 10.3 of the ITTC recommendation.[4] The following advice is given about wave spectral functions:

- It is recommended to consider the Torsethaugen wave spectrum[3] when the vessel is operating in areas where the swell is significant, resulting in two peaked spectra from wind waves and swell coming from different directions.
- For general open-ocean conditions, a Pierson-Moskowitz spectrum is recommended.
- Other forms of spectral functions can be used if supported by public references, e.g., JONSWAP for North Sea or other enclosed sea areas with limited wind fetch. This limited wind fetch results in a reduced wave energy distribution around a primary peak frequency.

Appendix G of the ITTC recommendation[4] details four different empirical methods for calculating the response amplitude operator for added resistance, R_{wave}. It is recommended to follow one of the following methods:

- The semi-empirical SNNM method is used to describe the vessel's response amplitude operator for the mean resistance increase in waves from arbitrary heading. This method has demonstrated good performance in validation against experimental results of many vessels representing the current world fleet.[13]
- Use STAWAVE-1 when small vessel heave and pitch motions are expected under the encountered wave conditions, and STAWAVE-2 otherwise.[4] STAWAVE-1 is recommended for tankers, while STAWAVE-2 is for container ships.[14]
- All three methods are subject to limitations on speed and vessel dimensions as given in Appendix G of the ITTC recommendation.[4] Additionally, STAWAVE-1 is only appropriate for head seas and bow quartering waves within 45 degrees of head seas.

B.3 Correction for resistance due to seawater temperature and salinity

Differences in seawater temperature from that used in the reference model result in changes in seawater density and viscosity. These changes will result in a change in resistance and should be accounted for in the normalization process.

The effects of seawater temperature and density difference from the reference model are calculated by:

Equation 32

$$R_{AS} = R_{T0}\left(\frac{\rho_S}{\rho_0} - 1\right) - R_F\left(\frac{C_{F0} + \Delta C_{F0}}{C_F + \Delta C_F} - 1\right)$$

where:

ρ_S	is the actual mass density of the seawater (kg/m^3)
R_{T0}	is the total resistance (N) for reference water temperature and salinity, calculated by:

Equation 33

$$R_{T0} = \frac{1}{2} \rho_0 S V_{STW}^2 C_{T0}$$

where:

ρ_0	is the mass density of seawater (kg/m^3) at the reference temperature and salinity
S	is the submerged wetted surface area (m^2) of the hull at the vessel's mean draft and trim
C_{T0}	is the total resistance coefficient for the reference water temperature and salinity, and is calculated by:

Equation 34

$$C_{T0} = C_{F0}(1-k) + C_W$$

where:

k	is the form-factor, taken from towing tank resistance tests, CFD simulations, or empirical methods (e.g., Mennen 1982)[6]

R_F is the frictional resistance for the measured seawater temperature:

Equation 35

$$R_F = \frac{1}{2} \rho_S S V_{STW}^2 (C_F + \Delta C_F) \quad (N)$$

The kinematic viscosity and density of the seawater can be found in ITTC 2011[15] or as suggested in DNV 2023.[3]

The wave-making resistance coefficient, C_W (-), can be determined by isolating the C_W in the formulation for total resistance of a vessel making forward speed in a natural seaway:

Equation 36

$$C_W = \frac{R_T}{\frac{1}{2} \rho_{S0} V_{STW}^2 S} - (1+k)C_F$$

The frictional resistance coefficients for the reference seawater temperature of 15°C, C_{F0} (-), and frictional resistance coefficients at the measured seawater temperature, C_F (-), can be estimated with the ITTC 1957 ship-model correlation line for skin friction and turbulence stimulation:

Equation 37

$$C_F = \frac{0.0075}{(\log_{10}(R_n) - 2)^2}$$

where:

R_n	is the Reynolds number defined by:

Equation 38

$$R_n = \frac{V_{STW} L_{pp}}{v}$$

where:

V_{STW}	is the vessel's STW
L_{pp}	(m) is the vessel's length between perpendiculars
v	is the kinematic viscosity of the seawater at the respective temperatures (in m²/s)

The roughness allowance associated with the Reynolds number at the seawater reference temperature, ΔC_{F0} (-), and at the measured seawater temperature, ΔC_F (-), can be calculated using:

Equation 39

$$\Delta C_F = 0.044\left(\left(\frac{k_s}{L_{WL}}\right)^{\frac{1}{3}} - 10 R_e^{\frac{1}{3}}\right) + 0.000125$$

where:

k_s	is the average roughness of the submerged hull surface
L_{WL}	is the length of the hull waterline at the draft considered

A default value for hull roughness can be assumed as $k_s = 150 \times 10^{-6}$ m.

B.4 Correction for shallow water effects

We recommend correcting the vessel performance for shallow-water effects using the Raven method, as described in the ITTC recommendation.[4]

This correction is applicable for operation in areas where a water depth lower than the outcome of the water depth filters described in Section 2.2.4 removes most available data. In this case, a compromise can be made on the data filter by applying corrections to the data measurements.

The Raven correction is applied to the measured shallow calm water resistance to determine the deep calm water resistance at the same speed through water.

The Raven correction contains two factors:

1. The first accounts for the additional sinkage in shallow water and is applied to the measured shallow calm water propulsion power.
2. The second accounts for the additional shallow water viscous resistance in the measured shallow water power.

Starting with the power component breakdown given by Equation 15 in Section 2.4:

$$P_{Dms} = P_{Did} + P_{env} + P_{SH} + P_{AF} + P_{AOF}$$

the measured shallow calm water power to be corrected is $P_{Dshallow} = P_{Dms} - P_{env}$.

The Raven method gives measured deep calm water resistance, P_{Ddeep}, as:

Equation 40

$$P_{Ddeep} = \frac{P_{Dshallow}}{r_{sink}} - \frac{R_{SHV} V_{STW}}{\eta_{Did}} = \frac{(P_{Dms} - P_{env})}{r_{sink}} - \frac{R_{SHV} V_{STW}}{\eta_{Did}}$$

where:

r_{sink}	is sinkage displacement caused by additional sinkage in shallow water
R_{SHV}	is the increase of viscous resistance in shallow water
η_{Did}	is the propulsive efficiency coefficient in ideal conditions predicted by a towing tank test or CFD simulations at the speed through water, V_{STW}

Detailed procedures and formulas for calculating r_{sink} and R_{SHV} are given in Appendix K of the ITTC recommendation.[4]

The resulting power equation when considering shallow water effects becomes:

Equation 41

$$\frac{P_{Dms}}{r_{sink}} = P_{Did} + \frac{P_{env}}{r_{sink}} + \frac{R_{SHV} V_{STW}}{\eta_{Did}} + P_{AF} + P_{AOF}$$

Appendix C – Parameters for performance monitoring using in-service trials

Parameter	Units	Comment	Priority
Technology state		Indication if the energy efficiency technology is in operation (ON) or turned off (OFF)	1
Timestamp	DD:MM:YY HH:MM	Coordinated Universal Time (UTC)	1
Geographical location	degree	Latitude and longitude position of the vessel	2
Speed over ground	knot (kn)	Vessel speed as measured by a GPS	1
Speed through water	knot (kn)	Directly measured on board; or derived from speed over ground and hindcast current data; or empirically derived speed through water, whatever is considered most accurate	1
Vessel heading	degree	Relative to true North	1
Main engine fuel oil consumption counter	t	Measurement of the main engine fuel oil consumption counter between the start and end time of the measurement period	1
Auxiliary engine fuel oil consumption counter	t	Measurement of auxiliary engine fuel oil consumption counter between the start and end time of the measurement period	1
Generators electrical power (gauge)	kW	Directly measured as electrical power on generators according to power gauge at the start and end time of each measurement period	1
Main engine speed	RPM	The average main engine speed during the measurement period	1
Propeller revolution	RPM		1
Propeller pitch angle	deg	Pitch angle measured at 0.7*R where R is propeller radius	2
Measured shaft power	kW		1
Mean draft	m	The mean of the draft at the APP and FPP according to the loading computer	1

Parameter	Units	Comment	Priority
Rudder angle	degree		2
Relative wind speed	m/s		1
Relative wind angle	degree		1
Water depth	m		1
Weather condition	BF	Beaufort scale wind force	1
Wave period	s	Characteristic wave period used in spectral representation of the wave environment	2
Significant wave height	m		2
Wave direction	degree	For the primary wind wave system	2
Shaft generator power output	kW	To be recorded if installed	1
Auxiliary engine(s) mechanical power	kW	Measurements should be done on each auxiliary engine running during a test set	1
Vertical position of anemometer	m	Height above mean sea surface or from baseline of the vessel	2
Water temperature	deg. Celsius	Temperature at sea surface	2
Air temperature	deg. Celsius	Ambient air temperature	2
Fuel lower calorific value (LCV)	MJ/kg		2

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