State-of-the-art sustainable energy efficiency technologies roadmap for waterborne transport towards the fit-for-55 guidance compliance

Project 101192661 - FLEETfor55

Deliverable D4.1 - Specification and requirements of energy systems modelling

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Acronyms and Abbreviations	Meaning
AF	Alternative Fuel
ALS	Air Lubrication System
AWA	Apparent Wind Angle
AWS	Apparent Wind Speed
CAPEX	Capital Expenditure
CB	Block Coefficient
CCS	Carbon Capture and Storage
CFD	Computational Fluid Dynamics
CII	Carbon Intensity Indicator
COG	Course Over Ground
DC	Direct Current
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EET	Energy Efficiency Technology
EU ETS	European Union Emissions Trading System
Fr	Froude Number
GA	Grant Agreement
GHG	Greenhouse Gas
GPS	Global Positioning System
HVAC	Heating, Ventilation, and Air Conditioning
IDL	International Date Line
IMO	International Maritime Organization
ITTC	International Towing Tank Conference
JIT	Just-In-Time
KPI	Key Performance Indicator
LCB	Longitudinal Centre of Buoyancy
Lpp	Length Between Perpendiculars
MCR	Maximum Continuous Rating
MEA	Monoethanolamine
OPEX	Operational Expenditure
OPS	Onshore Power Supply
ORC	Organic Rankine Cycle
PEM	Proton Exchange Membrane
PTH	Power Take-Home
PTI	Power Take-In

Acronyms and Abbreviations	Meaning
PTO	Power Take-Off
QFD	Quality Function Deployment
Re	Reynolds Number
SFOC	Specific Fuel Oil Consumption
SOFC	Solid Oxide Fuel Cell
SOG	Speed Over Ground
STW	Speed Through Water
TIN	Technology Innovation Network / Industry Input
UC	Use Case
VFD	Variable Frequency Drive
WAPS	Wind-Assisted Propulsion Systems
WHR	Waste Heat Recovery
WP	Work Package

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Executive Summary

This deliverable reflects the work performed within task 4.1 “Energy systems modelling requirements and modifications”. The objective of this work is to define the data requirements and potential constraints for each use case that has been defined and assessed within WP3 and will be modelled within T4.3.

The required data for the holistic modelling are presented for each energy efficiency technology identified in WP2 and WP3, based on the operating principles and distinguished characteristics of each system (e.g. aerodynamic dimensions and geometry for WAPS, at berth auxiliary power demand for OPS, etc).

Afterwards, the data required for the correlation of each energy system model with ship operating effects are accounted for. The effects of hull roughness, wind conditions (speed, direction), sea state (wave height, wavelength) against ship heading and route have a significant impact on the performance of each technology. The dependency will be assessed within T4.3 based on potentially available actual data, empirical methods and available online databases (wind, currents per geographic location).

For every energy system assessed, a data input template is created. Each template contains the quantity, type of the required information and the potential providing source.

1 Introduction

1.1 Overview

To assess ship performance in terms of EU and IMO under the regulations of FuelEU, Carbon Intensity Indicator and all other measures intended for environmental compliance, the energy used onboard for ship operation has to be estimated. Minimizing onboard energy consumption directly enhances vessel efficiency; consequently, fuel consumption is lowered, greenhouse gas emissions are mitigated, operational reliability is enhanced, and the vessel's regulatory compliance lifespan is prolonged. To this end, within WP4 of Fleetfor55 (T4.3 specifically), energy-emissions models correlating the Energy Efficiency Technologies to the use case vessels (UC) are going to be developed, allowing the assessment of current ship performance along with the impact of implementing innovative energy systems.

Task 4.1 “Energy systems modelling requirements and specification” lists all data necessary for this energy modelling. Data inputs vary across individual energy systems, necessitating distinctive requirements and customized modelling approaches for each technology. The primary objective of this task is to classify these variations and identify their respective originating data sources.

The proper modelling procedure includes a technology model, simulating the operation of a selected technology, capturing the shipboard energy use and emissions. The energy model is connected to a ship operational module, which exploits the position of the vessel and the available information from the online Copernicus database to estimate the ship added resistance due to wind, currents and waves and evaluate its effect on the performance of the installed EET. The models developed within T4.3 would be of the following generic form, illustrated in Figure 1:

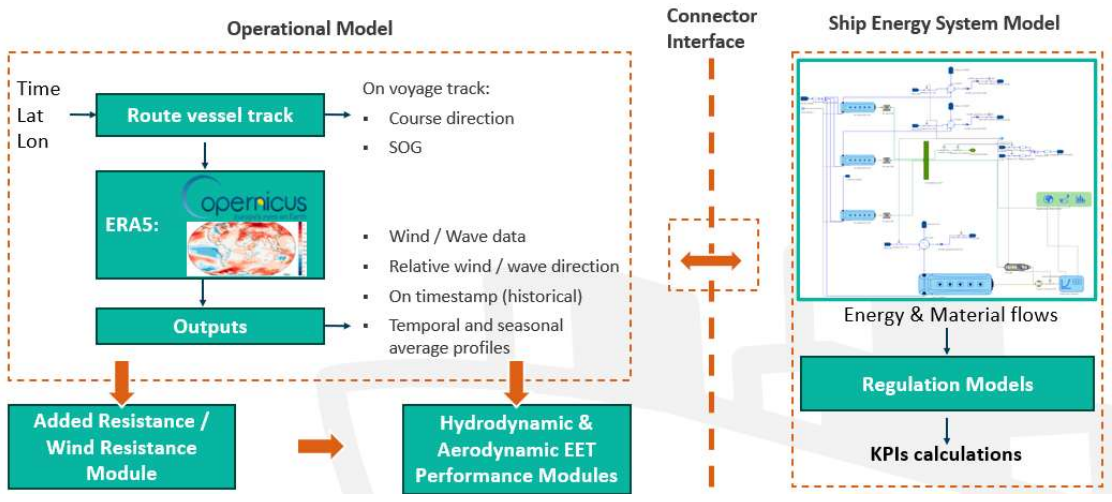

Figure 1. General structure of the simulation models

Each EET model approach on the calculation of energy efficiency and emissions depend on the selected technology. Mainly emissions reduction is achieved through fuel oil consumption reduction (elimination of use of a carbon fuel); which can be achieved through resistance reduction, hydrodynamic power recovery, less thermal/electrical energy demand onboard, post-combustion treatment methods and engine(s) load improvements. The type of EET also defines the time step of the energy system simulation; e.g. a shaft generator is operated when the sails under constant speed but OPS is used while the ship is at berth. Whether the energy model is steady-state or dynamic is also correlated to the EET type. However, the ship-energy system runs are dynamic. Calibration and verification of the ship-energy consolidated models are covered by the ship operational data already provided by the end users.

1.2 KPIs calculation

Through the energy modelling and post-modelling activities, the following set of KPIs, which are originated from the work T3.3" Development of KPIs [1], assessment metrics and QFD method for evaluating use cases" [1], are expected to be calculated, based on the restrictions and outcomes of each model:

KPI	KPI index (T3.3)	Type	Target	Unit	KPI Domain	KPI Category	Calculation approach
Impact on vessel consumption	8	Quantitative	Max	kg/t·nm	Technical	Energy Efficiency	Through resistance reduction, reduced power requirements or improved engine(s) load
Propulsion efficiency	9	Quantitative	Max	% or kW	Technical	Energy Efficiency	Through resistance reduction or wake, thrust improvements.
Auxiliary power demand	10	Quantitative	Max	% or kW	Technical	Energy Efficiency	Through reduced load, operation or demand
Steam demand	10	Quantitative	Max	% or kW	Technical	Energy Efficiency	Calculation of required steam flow/generation.
GHG reduction potential	19	Quantitative	Max	$gCO2_e$/t·nm or %	Environmental	Emissions impact	Through reduction of fuel oil consumption

KPI	KPI index (T3.3)	Type	Target	Unit	KPI Domain	KPI Category	Calculation approach
Pollutant reduction	21	Quantitative	Max	g/t·nm or %	Environmental	Emissions impact	Through reduction of fuel oil consumption

1.3 Assumptions

In this paragraph the assumptions of the work are listed. Specifically:

- EET categorization is based on the final output of tasks T2.4 “Evaluation of the preliminary technical application and feasibility of each available EET”.
- Currently, this work is based on the preliminary UC definition of T3.2 “Use case definition, requirements and planning”. However, the modelling procedure (T4.3) will focus solely on the use cases, which will be finalised within T3.5 “Investigation of EETs onboard integration and performance feasibility for the use cases” and T4.2 “Conceptual design for the new vessel designs and retrofit use cases”.
- The potential data requirements are being extended to all EETs identified in WP2 and WP3, to account for supplementary modelling that may be performed for tasks T6.2 “Detailed requirements & data collection from technologies and ships” and T6.4 “Digital integration of the developed simulation models”.
- Globally applied EETs and vessel – specific EETs are analysed separately.
- The data requirements are defined considering the modelling of a single EET. At this stage, except for Waste Heat Recovery Systems, interactions between EETs are not taken to account.
- Data requirements may be updated upon progression of T4.3.
- Batteries, DC grids, electric propulsion, steam improvements and waste heat recovery, have been described in the simplest possible form, since their simulation is meaningful combined with other EETs.
- For each EET, a data requirement template is provided, showcasing the type of data needed and highlighting the providing source with a colour coding (dark teal for vessel – specific input, orange for TIN/industry input).

2 Energy systems data requirements

In chapter 2, the data requirements for each EET are analysed. The structure is based on the technology categorization developed within WP2 and WP3.

2.1 Renewables

This section includes the data requirements for all EETs belonging to the “Renewables” category.

2.1.1 Wind assisted propulsion

Wind-Assisted Propulsion Systems (WAPS) are innovative energy efficiency technologies that harness wind power to generate auxiliary thrust to reduce a vessel's propulsive power demands and fuel consumption. The following prominent WAPS categories are explored [2]:

- Rotor Sails (Flettner Rotors): Rigid, motorized cylinders installed on the deck that spin to exploit the Magnus effect.
- Wing Sails / Suction Wings: Rigid or semi-rigid foil-like structures vertically installed on the deck that mimic airplane wings to maximize lift.
- Soft Sails: Utilizing lighter fabric similar to traditional sailing setups, these flexible setups often use telescopic masts and boom structures to catch the wind and generate thrust.
- Kites: Large, dynamic, and lightweight sails deployed from the bow using high-strength towing lines. Flying more than 200 meters above deck, they harness increased wind energy available at higher altitudes to move the vessel.

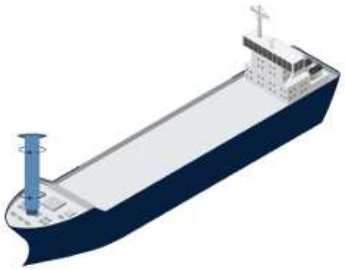

Figure 2. Rotor sails schematic, source: [2]

Figure 3. Suction wings schematic, source: [2]

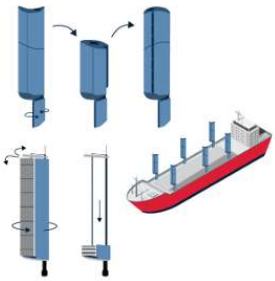

Figure 4. Rigid wings schematics, source: [2]

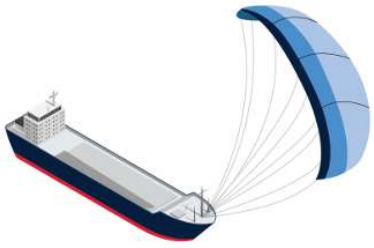

Figure 5. Kite sail schematics, source: [2]

WAPS have been proposed for the following vessels:

- Blue Star I
- Kriti King, Kriti Future
- Cape Brazil, Eco Merlin

Below, table 1 presents the required data for the modelling of all WAP technologies.

Table 1. WAPS data requirements

Configuration	Data type	Ship (End user) input	TIN input
Applicable to all WAPs *-	Apparent wind speed (AWS)		
	Apparent wind angle (AWA)		
	Ship speed and heading		
	Ship roll/heel angle		
	Density of air		
	Effective aerodynamic area		
Soft sails	Lift and drag coefficients against angle of attack		
	Allowable deployment per AWA		
	Electric/hydraulic power requirements		
	Geometry and dimensions		
Flettner rotors	Spin ratio		
	Lift and drag coefficients as a function of AWA		
	Power requirements		
	Cut in – cut out AWS range		
	Geometry and dimensions		
Rigid wing sails	Lift and drag coefficients as a function of AWA		
	Baseline drag when the wing is placed in neutral alignment		
	Geometry and dimensions		
Kite propulsion sails	Wind shear gradient		
	Azimuth and elevation angles		
	Power consumption for deployment/retraction of the system		
	Geometry and dimensions		
Suction wings	Lift and drag coefficients as a function of AWA and the suction velocity ratio (volumetric flow/max volumetric flow)		
	Fan electric consumption as a function of volumetric flow		
	Geometry and dimensions		

**these stochastic data are analysed in chapter 3 "Consolidation with Use Cases".*

2.2 Electrification

In this section, the data requirements for electrification solutions are analysed [3].

2.2.1 Onshore Power Supply (OPS)

Onshore Power Supply (OPS) represents a viable alternative for minimizing auxiliary engine deployment and maximizing vessel energy efficiency. This infrastructure strategy is strongly incentivized by FuelEU Maritime regulations and has become mandatory for containerships and passenger vessels. This technology has been assessed throughout T2.4 and T3.2 and, with time spent at berth as the main criterion, is proposed for the following UCs:

- Cape Sorel
- Superfast XI, Blue Star Paros, Blue Star I
- Marget Deymann

OPS supplies electricity to the ship while at berth. Although the system architecture is similar across different ships, configuration and scaling depend on the ship power demand, operational profile and capabilities of the port services. Thus, an OPS can either completely cover the vessel electric demand (cargo operation, secondary loads, batteries charging), or, if required, run in parallel with the ship Auxiliary Engines, through proper frequency conversion.

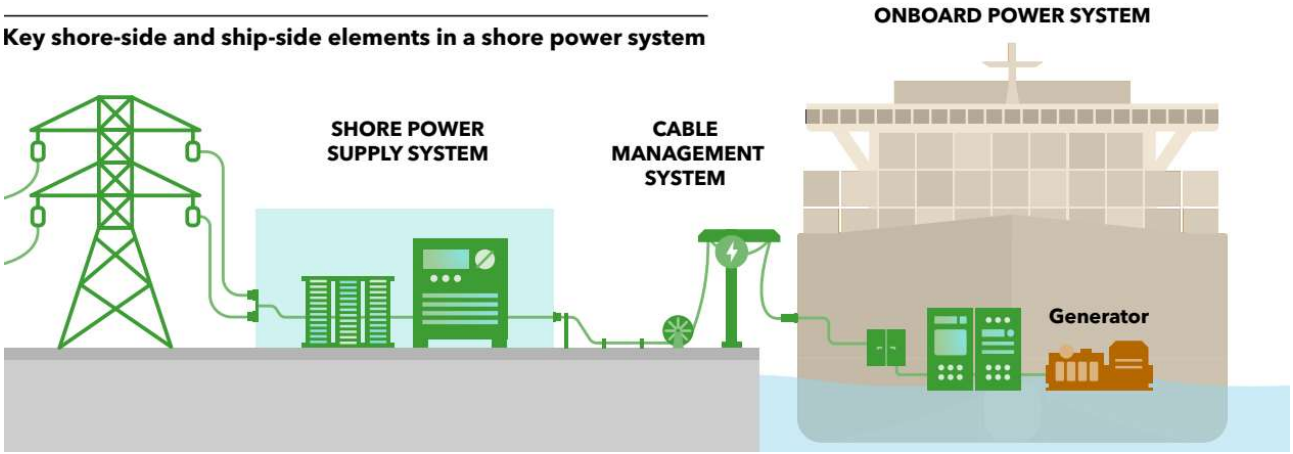

Figure 6. Illustration of an OPS application, source obtained from [3]

The modelling procedure would be of the following form:

1. Substitution of electric demand or parallel running.
2. Accounting for OPS efficiency (η_{ops})
3. Calculation of ship emissions

Thus, the required data would be:

Table 2. OPS data requirements

Data type	Ship (End user) input	TIN input
Auxiliary power demand per operation stage at port		
Auxiliary Boiler consumption		
Time at berth (annual average) and number of port calls		
OPS efficiency		
OPS maximum power capability		

OPS could be combined with batteries or with any energy system that is a part of a fully electric – hybrid ship concept.

2.2.2 Batteries

Upgrading a ship's energy efficiency can be achieved more easily by utilizing battery technology [4]. Although batteries alone are not energy systems that improve the ship's carbon footprint and fuel consumption significantly, they can offer considerable effect by being combined with other electric concepts. Electricity being supplied from shore side can be exploited to charge batteries. This is reasonable especially for the ROPAX UCs. Batteries are necessary in the case of applying fuel cell technology; they are either being charged through the DC grid or regulate peak loads. Use of batteries is mandatory for the case of a fully electric (or hybrid) ship, where consideration of DC grid application is also justified. Thus, a battery energy model alone does not provide with adequate information the extent to which the ship's energy efficiency is improved. The DC requested power from the batteries depend on the used electric consumer. On this basis, the required data for a battery energy model are gathered below in table 5.

Table 3. Battery model required data

Data type	Ship (End user) input	TIN input
Required power at each operational stage		
Installed battery capacity and nominal voltage		
Efficiency and DC-AC conversion losses		
Maximum continuous C-rating		
State of Charge		
Thermal requirements		
Degradation against discharge and cell temperature		

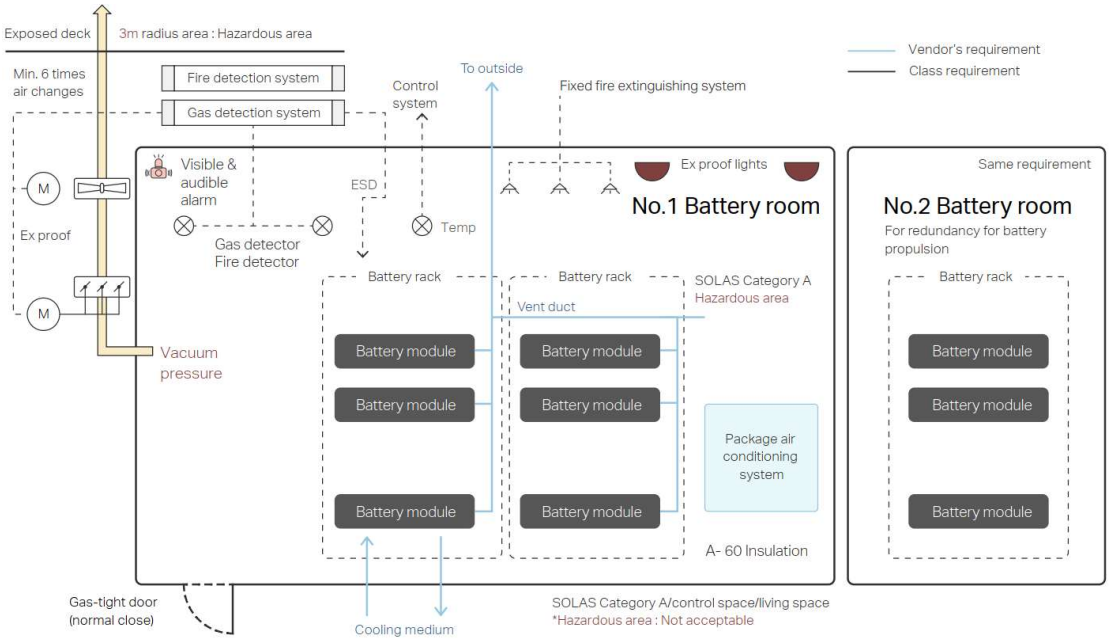

Figure 7. Typical equipment for a battery room design, source obtained from [4]

2.2.3 Electric propulsion

The concept of electric propulsion is an alternative ship design pathway existing in the marine market more than 100 years. In principle, the propeller is rotated via an electric motor, which is supplied electricity from the ship's grid. Depending on the installed power electronics, the electric motor can be either of AC or DC technology.

In the wake of decarbonization and the requirement for improved vessel efficiency, variations of the traditional electric concept are emerging. Thus, the combination of propulsion with PTI/PTO, fuel cells, DC ship grids, batteries and OPS can be investigated. The effect of electric propulsion is enhanced when the prime mover is a dual fuel engine.

The electric propulsion concept has been proposed for the following UC:

- Blue Star Paros and Superfast XI
- Marget Deymann

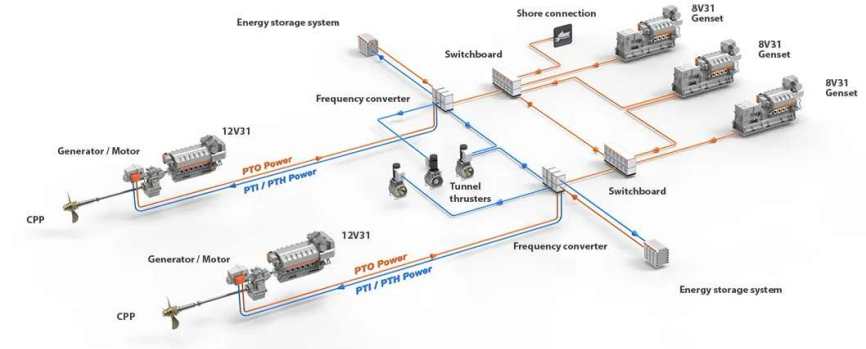

Figure 8. Diesel electric PTI/PTO concept, source obtained from [5]

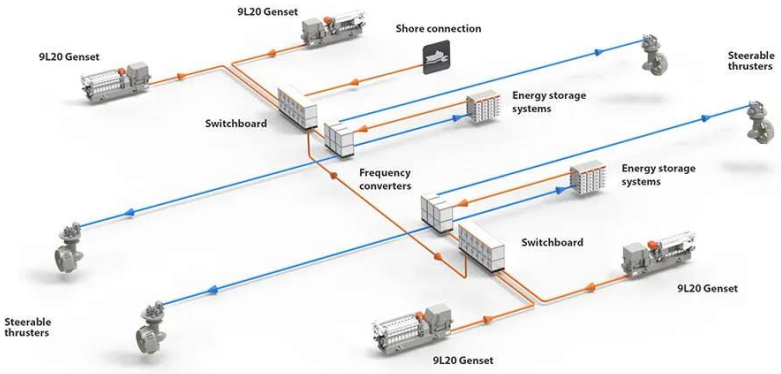

Figure 9.Diesel electric concept, source obtained from [6]

The model that will be developed is of the simplest form: the propeller is powered by the electric motor, instead of the Diesel Engine. The emission profile is compared to the reference case. The required data are illustrated below in table 4:

Table 4. Full electric propulsion required data

Data type	Ship (End user) input	TIN input
Propeller shaft power		
Propeller speed		
Electric power demand as a function of voyage state		
Engines SFOC curves		
Ship operational data (time during sailing, fouling condition, routes, speed, draft, trim, wind and wave added resistance).		
Electric motors efficiency		
Efficiency of installed power electronics (VFDs, transformers) and transmission losses (cables, switchboards).		

2.2.4 Solar Panels

Solar panel installation is an energy efficiency improvement strategy with the potential to reduce auxiliary engines load and fuel consumption with minimal OPEX. Solar panels harness sunlight by converting it to DC electrical energy. Through DC/AC converters and power transformers, the electric power is supplied to the ship's main switchboard, allowing for the reduction of the gensets load. Widespread integration of solar panels onboard is hindered by volumetric requirements; to generate significant electricity, increased space must be allocated on the deck, rendering compatibility with different ship types difficult [6]. A conceptual diagram of solar panel installation is illustrated in figure 10.

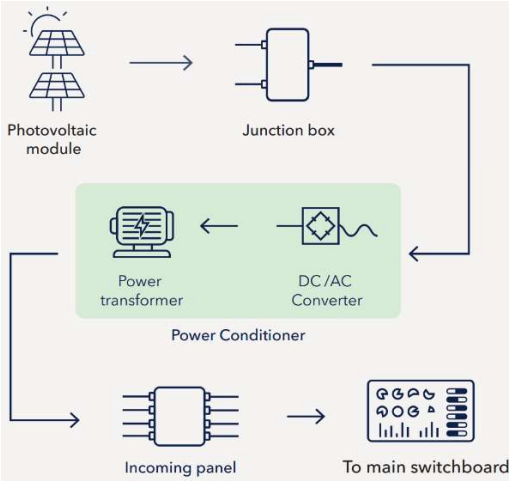

Figure 10. Solar panel installation concept, source obtained from [7]

Apart from the available space, the impact of solar panels on efficiency depends on the routes and position of the vessel. In general, ships sailing at lower latitudes are exposed to sunlight more intensely; which is the key parameter for electricity generation. As of project month 18 (M18), photovoltaic systems have not been allocated to any baseline use case. A typical simulation model would require the following data:

Table 5. Solar panels model required data

Data type	Ship (End user) input	TIN input
Ambient temperature [K]		
Wind speed [m/s]		
Geographic coordinates and heading		
Panel orientation and tilt		
Structure shading		
Time of day		
Global Horizontal Irradiance		
Direct Normal Irradiance		

Data type	Ship (End user) input	TIN input
Diffusive Normal Irradiance		
Electric load profile per voyage/operation condition		
Total panel area		
Panel efficiency, salt deposition effects		
Temperature coefficient of power		
Maximum power point tracking		

2.3 Power Conversion

In this section, the data requirements for power conversion energy models are examined.

2.3.1 Two-stroke/four-stroke Alternative fuel Internal Combustion Engines

Two stroke alternative fuel engines have been proposed for the following UC:

- Cape Sorel
- Kriti Future
- Cape Brazil, Eco Merlin

Four stroke alternative fuelled engines have been proposed for:

- Blue Star Paros, Blue Star I, Superfast XI
- Kriti Future
- Cape Brazil, Eco Merlin

In this section, the data requirements for for a model of either a two-stroke or a four-stroke Internal Combustion Engine operating on an alternative fuel (regardless of type) is presented.

Table 6. AF 2S/4S engine data requirement

Data type	Ship (End user) input	TIN input
Propeller shaft power [kW]		
Engine speed [rpm]		
AF lower heating value		
Pilot fuel lower heating value		
Pilot fuel ratio		
Engine thermal efficiency as a function of torque and speed		
Engine load as a function of voyage state		
Key temperatures of engine operation (Scavenge air upstream and downstream of the compressor, Exhaust gas temperature).		
Fuel slip factor (wherever applicable)		
Storage, handling and transfer efficiency		
Shafting losses		

2.3.2 Four stroke Alternative fuel Generator sets

The data requirements for a generator engine combusting an alternative fuel are similar to those for the propulsion engine. . The differences arise from the number of generators onboard and the number operating under the different voyage conditions and cargo operations.

Table 7. AF 4S Generator set data requirement

Data type	Ship (End user) input	TIN input
Number and load of generator units in operation as a function of voyage state		
Ship electric power demand		
Net power from other electric sources (batteries, OPS, solar panels).		
AF lower heating value		
Pilot fuel lower heating value		
Pilot fuel ratio		
Engine thermal efficiency as a function of torque and speed		
Alternator efficiency		
Key temperatures of engine operation (Scavenge air upstream and downstream of the compressor, Exhaust gas temperature).		
Fuel slip factor		
Storage, handling and transfer efficiency		

2.3.3 PEM fuel cells

Proton Exchange Membrane fuel cells operate at temperatures between 60 ^{o}C and 200 ^{o}C. The temperature range corresponds to the type of electrolyte used; polymer acid membranes for temperatures up to 80 ^{o}C and mineral acid membranes for up to 200 ^{o}C. As every fuel cell technology, they convert chemical energy to DC electrical energy by exploiting pure H_2. Different PEM configurations have been proposed for onboard integration, depending on the handling of hydrogen; it is either stored on board in liquid or gaseous form, or obtained from reforming or cracking procedures from a hydrogen carrier fuel. This leads to differencesin installed auxiliary machinery and the resulting emission profile [7]. PEM FCs have been proposed for: Blue Star Paros and Superfast XI.

2.3.3.1 Hydrogen from ammonia cracking

In this section the required data for a model of a PEM fuel cell utilizing H_2 obtained from ammonia are presented.

Table 8. PEM FC - Ammonia cracking data requirements

Number of individual units	Ship (End user) input	TIN input
Ship electric power demand		
Net power from other electric sources (Generators, batteries, OPS, solar panels).		
Stack efficiency curve		
Cracking efficiency		
Purifier H_2 recovery rate		
Cracker thermal energy requirements		
Electric power for auxiliaries		
Potential waste heat recovery (e.g. ammonia preheating)		
Key temperatures of engine operation (Scavenge air upstream and downstream of the compressor, Exhaust gas temperature).		

2.3.3.2 Hydrogen from external reforming

In this section, the data requirements for a PEM fuel cell operating on Hydrogen obtained from external reforming are reported.

Table 9. PEM FC - external reforming data requirements

Data type	Ship (End user) input	TIN input
Number of individual units and nominal power		
Ship electric power demand		
Net power from other electric sources (Generators, batteries, OPS, solar panels).		
Stack efficiency curve		
Reformer efficiency		
Water methanol ratio (for MeOH application)		
Reforming sequence emissions		
Electric power for auxiliaries		

2.3.3.3 Hydrogen storage

In this section, the data requirements for PEM fuel cell operating on pure hydrogen stored onboard.

Table 10. PEM FC - H_2 storage data requirements

Data type	Ship (End user) input	TIN input
Number of individual units and nominal power		
Ship electric power demand		
Net power from other electric sources (Generators, batteries, OPS, solar panels).		
Stack efficiency curve		
Storage conditions (LH_2 or CH_2)		
Containment system geometrical parameters		
Boil off estimate and H_2 handling efficiency		

2.3.4 Solid Oxide Fuel Cells

The key differences of Solid Oxide fuel Cells in comparison to PEM fuel cells include the following:

- High Operating Temperatures: SOFCs typically operate at high temperatures (generally between 500°C and 1,000°C), which allows for internal reforming of hydrocarbon or alternative fuels (such as green methanol, LNG, or ammonia).
- Waste Heat Recovery (WHR) Potential: Because of their high exhaust temperatures, SOFCs are exceptionally well-suited for integration with Waste Heat Recovery Systems (WHRS). The high-grade exhaust gas can be captured to generate auxiliary steam or additional electricity, driving up the vessel's total system efficiency.
- Fuel Flexibility: Unlike Proton Exchange Membrane (PEM) fuel cells that strictly require high-purity hydrogen, SOFCs can utilize a variety of alternative fuels directly or via localized cracking/reforming zones.

Table 11. SOFC data requirements

Data type	Ship (End user) input	TIN input
Number of individual units and nominal power		
Ship electric power demand		
Net power from other electric sources (Generators, batteries, OPS, solar panels).		
Stack efficiency-degradation curve		
Fuel properties and boil off estimate		
Electric power for auxiliaries, reforming and fuel handling		
Exhaust gas (due to the reforming sequence) mass flow		
Stack operating temperatures and radiation loss factor		

2.3.5 Shaft generator (PTI, PTO)

A shaft generator is a mature technology, which has the potential to lower fuel oil consumption and ship wake emissions. It allows for propulsion hybridisation, for both Power Take-Off (PTO) and Power Take-In (PTI) operations. In PTO mode, the mechanical energy produced by the main engine's propulsion shaft is converted into electrical power to supply onboard auxiliary systems, resulting in lower fuel costs and reducing exhaust emissions during sailing. Conversely, in PTI mode, the system reverses roles to act as an electric motor, providing supplemental torque back into the main propeller shaft to assist the main engine, low speeds during manoeuvring or to serve as a redundant propulsion safeguard in case of Main Engine loss of operation (PTH-Power Take Home) [8].

The shaft generator concept has been proposed for the following UC:

- AAL Pusan
- Blue Star Paros, Superfast XI, Blue Star I
- KRITI FUTURE, KRITI KING
- CAPE BRAZIL

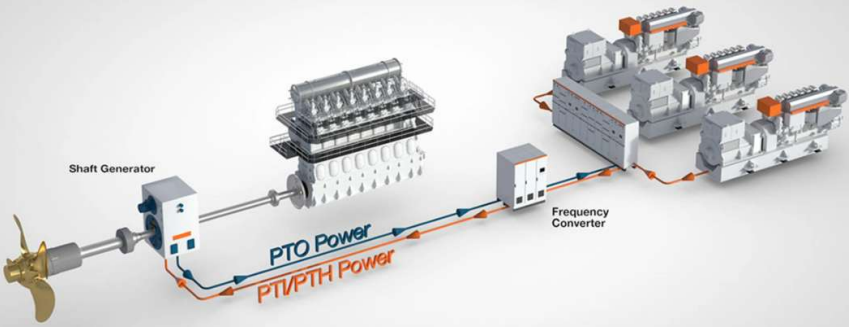

Figure 11. PTO-PTI-PTH configuration, source obtained from [6]

Table 12. Shaft generator data requirements

Data type	Ship (End user) input	TIN input
Engine maximum operational point [kW]		
Average engine load during sailing [% of MCR]		
PTO/PTI layout diagram		
Propeller speed [rpm]		
Time during sailing		
Time during maneuvering		
Time at port		
Main engine thermal efficiency curve		
Installed number and power of generators/auxiliary engines [kW]		

Data type	Ship (End user) input	TIN input
Generator efficiency as a function of load		
Power electric demand per voyage state		
Power electronics efficiency (transformers, converters, VFDs)		

2.4 Hydrodynamic efficiency improvements

In this section hydrodynamic efficiency improvement systems are analysed.

2.4.1 Air Lubrication System

According to [9], Air Lubrication Systems (ALS) represent a promising but still maturing technology for reducing hydrodynamic frictional resistance and improving vessel energy efficiency. By generating a continuous layer of air bubbles, beneath the ship bottom, the system decreases the wetted surface area in contact with water, lowering friction, fuel consumption and the resulting greenhouse gas emissions. However, the maritime industry still lacks a universally agreed-upon methodology to precisely measure steady-state performance in service, as computational fluid dynamics (CFD) models often overestimate efficiency gains. In general, ALS systems require moderately high speeds, low drafts and increased flat bottom surfaces. Thus, not all ship types are compatible with this technology.

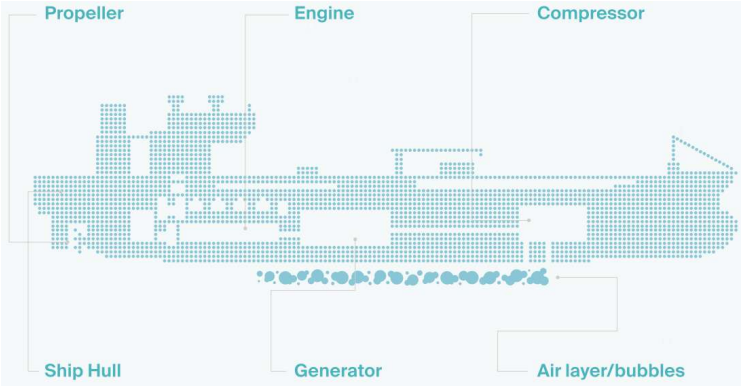

Figure 12. ALS concept, source obtained from [10]

ALS has been proposed for the following use cases:

- KRITI FUTURE
- CAPE BRAZIL, ECO MERLIN

Table 13. ALS data requirements

Data type	Ship (End user) input	TIN input
Ship speed		
Ship draft,trim and hydrostatic tables		
Time at sailing		

Data type	Ship (End user) input	TIN input
Required compressor power and electrical capacity		
Compressor efficiency curve		
Ship electric demand during sailing		
Cut-off parameters of the system		
Generator efficiency as a function of load		
Frictional resistance reduction against ship speed and air flowrate		

2.4.2 Hull efficiency improvements

This paragraph considers the model requirements of the following solutions [11]:

- Hull form optimization (proposed for Cape Sorel)
- Bulbous bow optimization (proposed for AAL Pulsan)
- Hull openings and skegs (Proposed for Blue Star Paros, Blue Star I and Superfast XI).
- Block coefficient variation/lengthening (proposed for Blue Star Paros and Superfast XI).

The data requirements of these solutions are gathered in the following table 15:

Table 14. Hydrodynamic solutions required data

Data type	Ship (End user) input	TIN input
Ship speed, draft, trim and Froude number		
Ship body lines model with and above load line areas (freeboard, accommodation and superstructures, forecastle, etc.)		
If the model does not exist, body lines plan and drawings where the above surfaces are identified.		
Hydrostatic table (baseline).		
Geometrical details of each hull opening		
Bulbous bow baseline form and transverse area		
Water density and river/canal dimensions		

2.5 Propeller ESDs

In this section, the data requirements for propeller energy saving devices are gathered. The analysis is based on the following source [12]. Propeller ESDs have only been proposed for UC Cape Sorel and will be further evaluated in T3.5 and T4.2.

2.5.1 Pre swirl ESD: Wake equalizing ducts and Fins

In this section, the data requirements for Propeller Energy Saving Devices are presented.

Table 15. Pre-swirl required data

Data type	Ship (End user) input	TIN input
Ship speed		
Ship draft,trim and hydrostatic tables		
Ship thrust force		
Wake deduction factor (baseline)		
Hull efficiency (baseline)		
Wake modification against draft and speed		
Added appendage resistance (or at least geometry of the devices)		
Open water propeller efficiency (baseline and installation)		

2.5.2 Post swirl ESDs

This paragraph includes all data requirements for Post Swirl Devices.

2.5.2.1 Contra rotating propellers

Two coaxial propellers positioned in series that rotate in opposite directions. The aft propeller recovers the rotational energy losses generated by the forward propeller, significantly improving hydrodynamic efficiency.

Table 16. Contra rotating propellers data requirements

Data type	Ship (End user) input	TIN input
Propeller torque		
Propeller rotation [rpm]		
Speed of advance		
Split load share ratio		
Energy recover coefficient		
Open water efficiency of the twin system		

2.5.2.2 Cap fins and Grim vane wheel

Energy-saving devices fitted to the propeller hub (like Propeller Boss Cap Fins) or positioned immediately behind it. They disintegrate the hub vortex, reduce drag, and convert kinetic wake energy into additional forward thrust.

Table 17. Cap fins and grim vane wheel data requirements

Data type	Ship (End user) input	TIN input
Propeller torque, propeller thrust		
Drag profile at the vortex		
Drag reduction factor		
Open propeller water efficiency curve		

2.5.2.3 Manoeuvring devices

Optimized rudders, twisted rudders, or steering modifications designed to reduce baseline resistance. They minimize the parasitic aerodynamic and hydrodynamic drag caused by constant course corrections.

Table 18. Manoeuvring devices data requirements

Data type	Ship (End user) input	TIN input
Rudder angles range		
Baseline rudder resistance		
Thrust generation coefficient		
Steering drag vs baseline		

2.5.2.4 Propeller nozzle

A hydrodynamic duct surrounding the propeller, homogenizing the water inflow to the propeller blades and optimizing thrust generation and efficiency at lower operating speeds.

Table 19. Propeller nozzle data requirements

Data type	Ship (End user) input	TIN input
Ship speed		
Thrust and propeller disc area		
Nozzle efficiency		
Duct thrust contribution		

2.5.2.5 Advanced blade sections

Propellers designed with non-traditional, highly customized foil profiles. These geometries optimize localized blade-section pressure distributions to delay cavitation, cut tip drag, and improve overall open-water efficiency.

Table 20. Advanced blade sections data requirements

Data type	Ship (End user) input	TIN input
Propeller rpm		
Speed at the blade tip		
Blade section efficiency		
Drag reduction matrix		

2.6 Optimized Engineering Approaches/Systems

In this section, optimized engineering approaches are analysed.

2.6.1 Steam – heat plant improvement/optimization

Optimizing steam and heat plant management can offer considerable energy improvements, particularly for crude and product tankers where cargo handling and discharge operations rely heavily on increased oil-fired boiler installations. Operational efficiency gains can be realized through technical and procedural updates, including the deployment of advanced sensor networks, targeted maintenance to eliminate network leakages, and minor physical retrofits such as upgraded steam piping insulation on deck. Furthermore, fine-tuning boiler combustion control parameters—specifically adjusting excess air intake, feed water temperature, and drum pressure settings—directly optimizes steam production efficiency. However, successful implementation relies heavily on overcoming key operational challenges: identifying transient sources of thermal loss and delivering specialized crew training to actively manage the network during transit [6].

Table 21. Steam/heat plants improvements/optimization data requirements

Data type	Ship (End user) input	TIN input
Time sailing		
Time at port		
Number and type of operations		
Heat transfer coefficient of the piping (baseline and updated)-insulation material-dimensions		
Number of piping equipment (valves, joints, flanges) and steam local loss.		
Steam demand per voyage condition and cargo required temperatures		
Oil fired boiler efficiency curve		
Number and type of upgrade equipment (sensors, air fuel ratio control)		
Auxiliary engines number and operation per voyage stage		

Data type	Ship (End user) input	TIN input
Exhaust gas mass flow, temperature and specific heat capacity of auxiliary engines		

2.6.2 Advanced HVAC and cooling systems

Advanced HVAC systems have been proposed for the UC vessels Blue Star Paros, Blue Star I and Superfast XI. The following data are foreseen to be required:

Table 22. Advanced HVAC data requirements

Data type	Ship (End user) input	TIN input
Ambient air temperature		
Relative humidity		
Sea water inlet temperature		
Passenger zone heating profiles		
Heat transfer through windows and scuttles (e.g. solar radiation)		
Baseline electrical consumption		
Coefficient of performance of upgraded systems (e.g. chiller with VFDs)		
Thermal energy requirements of the advanced systems (e.g. hot water inlet at 85 ^{o}C).		
Auxiliary engines load per voyage condition		

2.6.3 Waste heat recovery

Waste Heat Recovery (WHR) serves as a highly effective decarbonization and energy-efficiency mechanism by converting heat from the engine exhaust into onboard electrical power or service heat. WHR systems are categorized into two primary technologies, tailored to distinct operational profiles:

- High-Temperature Exhaust WHR: Employing a traditional Rankine cycle with steam turbine systems, this method captures high-temperature main engine exhaust gas. It yields efficiency gains of 5% to 12% but demands substantial footprint space, complex integration, and a high CAPEX (from 1500 to 9000 thousand USDper unit) [6]. Consequently, it is most economically viable for newbuilds and large vessels operating on long voyages (such as large containerships, tankers, and LNG carriers).
- Low-Temperature WHR (Organic Rankine Cycle - ORC Systems): Utilizing lower-grade heat sources like jacket cooling water, scavenging air, or low-temperature exhaust gases, ORC systems utilize refrigerant-based working fluids. They feature a lower CAPEX ($0.05-0.5 thousand USD per unit) [6], reduced physical footprint, and modular skid configurations that

make them highly adaptable for retrofits on smaller or mid-sized vessels, cruise ships, and LNG-fueled ships—delivering modest but valuable efficiency gains of 1% to 4%.

Despite offering positive regulatory compliance impacts across indices like EEDI/EEXI, CII, and EU ETS, integrating WHR technologies presents notable techno-economic challenges. High-temperature systems necessitate extensive structural modifications, complex high-pressure steam piping, and significant off-hire dry-docking periods during retrofits. Meanwhile, ORC systems remain highly sensitive to fluctuations in main engine loads and require careful sizing to maintain economic viability. To manage these complexities and mitigate system failures without interrupting core propulsion, vessel-specific techno-economic design and optimization studies that align the selected WHR technology with the ship's actual operating profile, control systems, and automated monitoring arrangements are recommended [6].

Table 23. WHRS and CCS data requirements

Data type	Ship (End user) input	TIN input
Main Engine Exhaust gas flow		
Main Engine Exhaust gas temperature		
Main Engine Exhaust gas specific heat capacity		
Heat transfer coefficient of the piping (baseline and updated)-insulation material-dimensions		
CCS mass capture rate		
CCS thermal energy requirement for the solvent		
Re-boiler operating temperatures		
Economizer effectiveness and dew point temperature		
Steam demand per voyage condition and cargo required temperatures		

Table 24. WHRS and SOFC data requirements

Data type	Ship (End user) input	TIN input
Exhaust gas mass flow (if a hydrocarbon fuel is reformed)		
Stack exhaust temperature		
Fuel flowrate		
Heat demand for reforming or, if applicable, for cracking		
Effectiveness of the employed heaters		
SOFC cooling medium inlet/outlet temperatures		
Shipboard steam demand for each voyage stage		

2.7 Carbon capture

Carbon Capture and Storage on board marine vessels involves separating CO_2 from exhaust gases before atmospheric discharge, followed by liquefaction and onboard storage for long-term geological isolation or industrial utilization. Among various post-combustion capture techniques, the aqueous chemical absorption using alkanolamines remains the commercial benchmark. Specifically, Monoethanolamine (MEA) is the primary reference solvent because of its rapid reaction kinetics and strong affinity for CO_2, even under low partial pressures [6]. Carbon capture has been proposed for:

- Blue Star Paros, Blue Star I, Superfast XI
- Kriti Future, Kriti King
- Eco Merlin

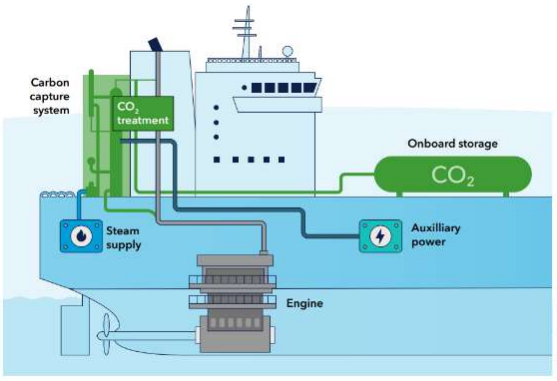

Figure 13. CCS typical schematic, source obtained from [10]

Table 25. Carbon capture data requirements

Data type	Ship (End user) input	TIN input
Exhaust gas mass flow (if a hydrocarbon fuel is reformed)		
Exhaust mass temperature		
Baseline CO_2/mass flow concentration		
Capture efficiency		
Thermal requirements for reboiler and auxiliaries		
Electrical energy requirements		
Liquefaction/compression requirements		
CO_2 storage capacity requirements and limits		
Chemicals/solvents required quantity		

2.8 Globally applied systems

The following sections analyse the required data for the Globally applied EETs, as identified in WP2 and WP3.

2.8.1 Optimized Engineering approaches

In this section, the data requirements for VFDs and Main Engine Tuning are presented.

2.8.1.1 Variable frequency drives

In table26, the data requirements for VFD application (without assuming electric/hybrid propulsion) are presented. VFDs have been proposed for:

- KRITI FUTURE, KRITI KING
- ECO MERLIN
- MARGET DEYMANN

Table 26. VFD application data requirements

Data type	Ship (End user) input	TIN input
Auxiliary engines number and load as a function of voyage state		
Engine room equipment list drawing (to list heavy consumers including motors for pumps, fans, compressors and other auxiliaries).		
Aux. Engine SFOC curve		
Heavy consumer motors' power curves		
Efficiency of VFDs and power electronics		

2.8.1.2 Main Engine Tuning and Optimization

The Main engine can be electronically tuned so that combustion parameters there are set to their optimum values for slow steaming or partial engine loads, leading to reduced fuel oil consumption and the corresponding emissions.

Main Engine tuning has been proposed for the UC vessels:

- AAL PULSAN
- BLUE STAR I and SUPERFAST XI
- CAPE BRAZIL
-

Table 27. Main Engine Tuning data requirements

Data type	Ship (End user) input	TIN input
Engine rpm		
Ship power speed curves		
Main Engine SFOC curve		
Engine thermal efficiency		

2.8.2 Hydrodynamic efficiency improvements

In this section the data requirements fro hydrodynamic efficiency improvement technologies are presented.

2.8.2.1 Hull surface coatings and low-drag paints

The purpose of the innovative low-drag paints is to reduce the frictional resistance component by reducing hull fouling or exhibiting a lower friction coefficient. The reduction in frictional resistance becomes significant for ship types operating at low speeds with U-shaped body lines (tankers, bulk carriers) where the frictional resistance dominates (80%-90%), relative to the wave-making, air, appendage and eddie resistance components [13].

Table 28.Hull surface coatings date requirements

Data type	Ship (End user) input	TIN input
Hull roughness (baseline)		
Hull roughness (updated)		
Paint degradation rate		

2.8.2.2 Lightweight materials

Lightweight materials have the potential to reduce fuel oil consumption by decreasing the ship draft compared to the case of using conventional alloys. The reduced draft would lead to a decreased wetted surface, corresponding to a reduction in the frictional resistance and the fuel oil consumption for the relevant speed.

Table 29. Lightweight materials data requirements

Data type	Ship (End user) input	TIN input
Number and geometry of the altered structures		
Ship service speed, draft, trim and hydrostatic tables		
Used material properties		
Ship power curves		

2.8.2.3 Trim and draft optimization

To model a trim and draft optimization procedure, the displacement has to be distributed such that the corresponding wetted surface at the desired speed leads to a reduction in ship resistance.

Table 30. Trim and draft optimization data requirements

Data type	Ship (End user) input	TIN input
Ship trim and hydrostatic tables		
Ship capacity plan		

2.8.3 Electrification

In this section, electrification technologies' data requirements are presented.

2.8.3.1 LED lights application

To model the effect of installing LED lights, the baseline power consumption and the installed power need to be known. The effect on ship performance is then calculated as the reduction in auxiliary power demand.

Table 31. Led lights data requirements

Data type	Ship (End user) input	TIN input
Number of light units and baseline power consumption		
Ship electric demand as a function of voyage stare		
Installed LED units number and power consumption		

2.8.4 Fuels

The modelling of Biodiesel fuels will be included with all alternative fuels in the two-stroke or four-stroke models (2.2.1-2.2.2).

2.8.5 Operations & Digital Optimization

In this section, operations and digital optimization data requirements are presented.

2.8.5.1 Weather routing

Weather routing calculations required wind and wave data, which in turn, depend on the selected route. In table 31 the data requirements are presented. Weather routing is thoroughly covered in chapter 3. The weather routing solution has been proposed for the following UC vessels:

- AAL PULSAN, CAPE SOREL
- KRITI FUTURE, KRITI KING
- CAPE BRAZIL, ECO MERLIN

Table 32. Weather routing data requirements

Data type	Ship (End user) input	TIN input
Significant wave height, period and direction		
Wind speed and direction		
Current direction and speed		

2.8.5.2 Cargo load factor optimization

Cargo load factor optimization is a measure of maximizing the ship payload against its transport work.

Table 33. Cargo load factor optimization data requirements

Data type	Ship (End user) input	TIN input
Ship power speed curves		
Hydrostatic tables		

2.8.5.3 Just-In-Time Arrival strategies

Table 33 provides the data requirements for a Just-In-Time arrival model.

Table 34. Just-in-time strategies data requirements

Data type	Ship (End user) input	TIN input
Ship power speed curves		
Main Engine and Auxiliary Engines SFOC curves		
Engines load per voyage state		
Ship service speed, ship average manoeuvring speed		
Average time at anchorage		
Location and season		

3 Consolidation with Use Cases

The models that are being developed with WP4 of the EET-ship combinations, mainly focuses on assessing the performance of the ship. This includes some key parameters: Main and Auxiliary Engine fuel oil consumption under different loads, corresponding to different voyage states, the GHG emissions and the evaluation on the ship compliance with the FuelEU maritime regulation and the Carbon Intensity Indicator (CII). However, to properly account for fuel oil consumption and accurately estimate the emitted pollutants, the effects of the ship-sea water environment interaction must be accounted for. This includes three main key points:

- Hull fouling accummulating progressively on the ship wetted area within the five-year operation cycle.
- The effect of wind force on the ship resistance.
- The effect of wave energy on the ship resistance.

Wind power and wave conditions are highly correlated with the dynamic behaviour of the environment, geographic position, season, and climate; therefore, their effects on ship resistance cannot be determined accurately using a fully deterministic approach. Thus, stochastic approaches are required for reliable estimations of the added resistance. . As a result, the benefits of energy efficiency technologies installed on board can be significantly reduced or even eliminated, based on this stochastic behaviour. The increased resistance, both due to wind and waves, leads to increased fuel consumption (or unavoidable speed loss) in maintaining the seakeeping and course of the ship. Consequently, the performance of these technologies is heavily environment-dependent: WAPS capabilities degrade in low-wind conditions, ALS efficiency diminishes under severe pitching motions, and PTO systems may fail to dynamically sustain the vessel's electrical grid demands during adverse weather conditions.

3.1 Hull roughness

Hull roughness generates additional resistance primarily through separation drag behind individual micro-imperfections on the hull surface. Within a turbulent boundary layer, there is a very thin laminar sublayer directly against the hull surface. If roughness elements are small enough to remain completely submerged within this sublayer, the fluid flows smoothly around them without separating, causing no added drag; otherwise, frictional resistance is increased [14].

As the ship's speed or the Reynolds number increases, this laminar sublayer becomes progressively thinner. Eventually, a critical point is reached where the roughness elements project through the sublayer. At this critical Re, the skin friction coefficient levels off, becoming approximately constant as separation drag counteracts the natural reduction of the friction coefficient at higher speeds.

The physical arrangement of the roughness dramatically alters its impact:

- Density: As the density of roughness elements over the surface increases, the overall resistance rises. However, if the density becomes too high, a "shielding" effect occurs where one grain shelters the next, which can actually reduce the total resistance increase.
- Location: Roughness does not have a uniform effect across the entire vessel. It has the greatest impact where the boundary layer is thinnest and where the local flow velocity is highest—typically near the bow and at the bilge rather than near the stern or the waterline.

The effect of roughness on the friction resistance coefficient, for an average surface roughness (k_s) and the Reynolds number (Re) at the relevant ship speed, can be calculated by the Townsin formula [14]:

$$\Delta C_F = \left\{44\left[\left(\frac{k_s}{L}\right)^{1/3} - 10 \cdot Re^{-1/3}\right] + 0.125\right\} \cdot 10^{-3}$$

3.2 Wind effects on air resistance

The air resistance component accounts for the resistance that the ship exhibits in contact with air at calm water without wind. When the wind force increases, the component calculating air resistance has to take into account both ship and wind speed [15]. It is calculated by the following formula:

$$R_a = \frac{1}{2}\rho_a A_T C_A(\beta) U_{rel}^2$$

In the above:

- ρ_α is the air density [kg/m^3]
- A_T is the maximum transverse area exposed to wind [m^2]
- C_A is an aerodynamic drag coefficient
- β is the relative wind direction at the reference height [deg]
- U_{rel} is the apparent wind speed [m/s]

The aerodynamic coefficient can be calculated through methods adopted by ITTC [16]and depends on ship geometry. Specifically, the ship length, breadth, superstructure height above the waterline, A_T and lateral projected area above the waterline need to be obtained for the calculation.

Wind resistance depends on the wind speed. For its calculation the apparent wind angle and wind speed must be defined. True wind is defined as the wind generated by natural causes, as perceived by a stationary observer. Apparent wind is the vector sum of the ship's velocity and the true wind. It represents the wind experienced by a moving object and is the wind whose speed is measured by the ship's anemometer. The apparent wind angle is defined as the angle between the incoming wind direction and the ship's longitudinal axis, as illustrated in figure 14.

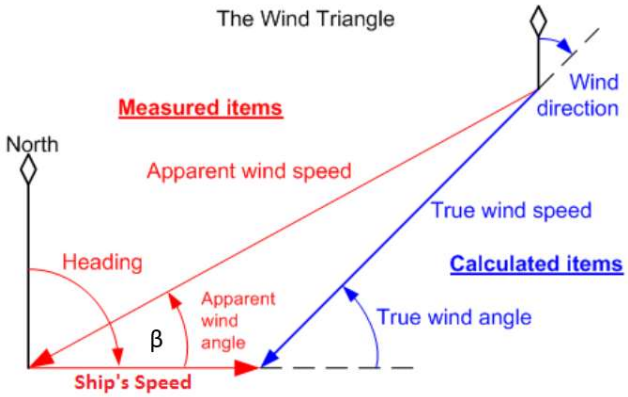

Figure 14. Apparent and true wind angle

The angle β is given as:

$$\beta = \cos^{-1}\frac{-(u_{10} * sin\psi + v_{10} * sin\psi)}{\sqrt{u_{10}^2 + v_{10}^2}}$$

- ψ: ship's heading [deg]
- u_{10}: zonal wind component [m/s]
- v_{10}: meridional wind component [m/s]

In order to calculate the relative wind angle β, the heading of the vessel ψ must be determined. The heading is defined as the direction in which the bow of the ship is pointing. If true heading data are not available it can be assumed that the direction is given by the COG (Course Over Ground), which is the actual direction of the vessel's movement between two points with respect to the Earth's surface. The COG is calculated based on the following formulas:

$$\psi = COG = \tan^{-1}(y, x)$$

$$y = \sin(lon_{i+1} - lon_i) \cdot \cos lat_{i+1}$$

$$x = \cos(lat_i) \cdot \sin(lat_{i+1}) - \sin(lat_i) \cdot \cos(lat_{i+1}) \cdot \cos(lon_{i+1} - lon_i)$$

Where:

- l_{at}: latitude in radians
- l_{on}: longitude in radians
- $\Delta\lambda = lon_{i+1} - lon_i$

The difference in longitude is adjusted in order to account for the possible crossing of the vessel over the International Date Line (IDL), which ensures the consistency of the 24-hour time system worldwide. During a potential transition of the vessel across the IDL, located at approximately ±180° longitude, an algebraic inconsistency may arise. Finally, the relative wind speed vector, is expressed by the following relation.

$$\vec{U}_{rel} = \vec{U}_{true} - \vec{V}_s$$

Essential for the determination of $\vec{U}_{rel}$ is the difference between Speed Through Water (STW) and Speed Over Ground (SOG). The Speed Through Water (STW) is the speed of the ship relative to the surrounding water, accounting for the effect of ocean currents. In contrast, the Speed Over Ground (SOG) represents the speed of the ship relative to the Earth and is obtained via GPS measurements. For air resistance calculation, STW is required.

$$\overrightarrow{U_{rel}} = \overrightarrow{U_{true}} - \overrightarrow{V_{STW}}$$

$$\vec{U}_{re} = \begin{bmatrix} u_{10} - u_{STW} * \sin\psi \\ v_{10} - v_{ST} \quad * \cos\psi \end{bmatrix}$$

If STW is not available, then relative wind speed can be calculated with the following steps.

$$u_{STW} = u_{SOG} - u_{curr}$$

$$v_{STW} = v_{SOG} - v_{curr}$$

Where:

- u_{curr}: eastward sea water velocity
- v_{curr}: northward sea water velocity

For the calculation of the Speed Over Ground (SOG), the distance traveled by the vessel between two consecutive geographical positions is first determined. This distance is calculated using the haversine formula, which is presented below.

$$\mathrm{d} = 2Rarcsin\sqrt{\sin\left(\frac{\Delta\varphi}{2}\right)^2 + \cos(\varphi_i) * \cos(\varphi_{i+1}) * sin\left(\frac{\Delta\lambda}{2}\right)^2}$$

In the above, $\Delta\varphi = \varphi_i + 1 - \varphi_i$ is the difference in latitudes between two points. Speed Over Ground (SOG) can then be calculated using the following relation:

$$V_{\mathrm{SOG}} = d/\Delta t$$

Δt is the time between two consecutive positions. SOG is converted into vector form by decomposing it into two components using the trigonometric functions sinand cosof the vessel's heading.

$$u_{SOG} = V_{SOG} sin\psi$$

$$v_{SOG} = V_{SOG}\cos\psi$$

Finally, STW is obtained as:

$$\vec{U}_{STW} = \begin{bmatrix} V_{SOG}sin\psi - u_{curr} \\ V_{SOG}\cos\psi - v_{curr} \end{bmatrix}$$

3.3 Wave effects on resistance

Wind generated waves and swells, impose substantial effects on the ship total resistance. The effects peak when the ship length to wavelength ratio approximates 100%. The waves will cause ship motion, exhibiting added resistance as the ship motion affects an increased water mass. This added resistance is further magnified with wave reflection on the hull.

Two empirical methods existing in literature are proposed for the calculation of the wave added resistance. The method developed by Liu and Papanikolaou [17] [18] and STAWAVE2 method of ITTC [16].

Liu and Papanikolaou method is a semi-empirical method designed to calculate added resistance across the entire wave spectrum considering both short and long waves for a wide variety of hull forms. It bridges the gap between pure empirical formulas and complex 3D simulation codes. The method treats short-wave diffraction and long-wave radiation separately before combining them:

- Short Waves: It refines classical diffraction theories by introducing correction factors that account for pressure decay with draft variations, forward speed effects, and the detailed geometry of the entrance waterplane area.
- Long Waves: It utilizes a simplified radiation model substituting complex hydrodynamic coefficient calculations with regression formulas derived from database analyses of various ship types.

The added resistance decomposition model used is:

$$R_{AW}(\omega,\beta) = R_{AWR}(\omega,\beta) + R_{AWM}(\omega,\beta)$$

Where:

- R_{AW}= added resistance in (regular) waves
- R_{AWR}= diffraction/reflection part
- R_{AWM}= motion/radiation part
- ω= wave radian frequency
- β= encounter direction (relative heading)

The required data required to apply this method include:

- Ship main dimensions
- Hull form coefficients
- Froude number at the ship operational speed
- Entrance length and angle of the waterline at the bow
- Radius of gyration
- Ship LCB

The STAWAVE2 method is an empirical transfer function for the mean added resistance in (long-crested) irregular head waves, built from a large regression set of seakeeping tests. In the ITTC speed/power-trial procedure it is explicitly described as covering both:

- motion-induced component (often denoted R_{AWM}) and
- reflection / short-wave correction (often denoted R_{AWR}).

The method is applicable within the following ranges:

- $75\ \mathrm{m} < L_{pp} < 350\ \mathrm{m}$
- $4 < L_{pp}/B < 9$
- $2.2 < T/B < 5.5$
- $0.10 < Fr < 0.30$
- $0.50 < C_B < 0.90$
- Wave direction within $\pm 45^{\circ}$ of the bow (treated as head waves inside this sector; outside: not corrected).

STAWAVE2 method computes the wave added resistance in regular waves as the summation of the motion-induced and the reflection induced resistance.

For a regular wave component (long-crested, heading), STAwave-2 uses:

$$R_{\text{wave}}(\omega; V) \;=\; R_{AWM}(\omega; V) \;+\; R_{AWR}(\omega; V)$$

$$R_{AWM}(\omega) = \left(\frac{\rho g \zeta_A^2 B^2}{L_{pp}}\right) \cdot \frac{raw(\bar{\omega})}{4}$$

$$R_{AWR}(\omega) = \rho g \zeta_A^2 \; B \; \alpha_1(\bar{\omega})^2$$

The required data for the STAWAVE-2 empirical method include:

- Waterline length
- Breadth and draft at bow
- Hull form coefficients
- Waterline angle of entrance at bow

- Ship speed, significant wave height and the peak or mean wave period

Regardless of the method, the resistance in regular waves has to be transformed to resistance in irregular waves. By assuming that wind generated waves and swell waves are described by independent spectra, then the following additional data are required:

- significant height H_s,
- mean direction θ,
- representative period T(mean/peak/zero-crossing).
- Ship heading
- A spectrum model (Pierson–Moskowitz or JONSWAP)

The irregular wave resistance, for long and short crested waves then is calculated as:

$$\bar{R}_{AW,\text{total}} = 2\int_{-\pi}^{\pi}\int_{0}^{\infty}\frac{R_{AW}(\omega,\alpha)}{\zeta_a^2}\cdot\left[S_{\zeta,\text{wind}}(\omega)D_{\text{wind}}(\theta)+S_{\zeta,\text{swell}}(\omega)D_{\text{swell}}(\theta)\right]d\omega\,d\theta$$

Where:

- ζ_α is the wave amplitude
- $D_{wind}(\theta)$ is the spreading function for the wave energy directed by wind.
- $D_{swell}(\theta)$ is the spreading function for the swell, focusing on the wave energy originating from storm
- α is the angle of encounter relative to the ship.

4 Conclusion

In this report the work performed in task 4.1 “Energy system modelling requirements and specification” is outlined. For each Energy Efficiency Technology that has been identified throughout the development of Fleetfor55, the data requirements for an energy-emissions simulation model have been assessed and presented. For each EET, the data sources have been identified; namely ship related data or TIN/industry available data. An analysis on the effects of ship roughness, wind and wave energy on the ship added resistance, thus the performance of the selected technologies has been performed and will be incorporated to the modelling activities of T4.3. Moreover, the foreseen KPIs that can be calculated, either through the modelling simulations or from port-modelling activities have been listed. The modelling procedure will include all promoted scenarios for the use cases, upon progression of tasks T3.5 and T4.2 and will be reflected in deliverable report D4.3 “Energy systems modelling and fast simulation assessment”.

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