CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 474

Holistic integration of battery hybrid systems in merchant vessels: evaluation of real-life data

Electrification and Fuel Cells Development

Alessandro Zanelli, WinGD Ltd.

Maciej Bendyk, WinGD Ltd.
Nikolaos Styliaras, WinGD Ltd.
Matthias Maier, WinGD Ltd.
Marco Lucarelli, WinGD Ltd.
Stefan Goranov, WinGD Ltd.

ABSTRACT

The maritime industry is continuously seeking solutions to enhance operational efficiency and reliability of operations. This abstract presents conclusions of analyses, based on data acquired during the operation of four ships equipped with battery hybrid systems delivered by WinGD. The system demonstrates enhanced performance through an integrated approach, incorporating active control of all key elements including the main engine, the hybrid powerpack consisting of a shaft generator (SG), battery pack, variable frequency drive (VFD) in a multidrive configuration, and the power management system (PMS) on board.

Central to this system is the X-EL energy manager, which not only ensures superior efficiency across the ship's operations but also enhances system reliability through active bi-directional control interactions with the PMS. The system's value proposition lies in its ability to outperform conventional systems through its holistic integration of the main engine and hybrid components, leading to improved energy distribution, reduced fuel consumption and greenhouse gas emissions, and increased operational stability.

To confirm the benefits of this approach, projections made on the basis of extensive simulations in the early project phase were validated against real-life measurements conducted on NYK ships equipped with the WinGD hybrid system. The data acquired during those measurements are thoroughly analysed in order to quantify the added value of such integrated energy management approach. The findings obtained highlight significant improvements in the overall performance, showcasing the effectiveness of the control strategies applied.

This presentation emphasizes the importance of a holistic approach in defining control strategies for ship energy systems and sets a benchmark for future maritime hybrid system implementations.

1 INTRODUCTION

The shipping industry plays a vital role in global trade, but it faces increasing scrutiny due to its environmental impact. Demanding emissions targets from international legislation aimed at reducing greenhouse gas (GHG) emissions and enhancing energy efficiency, such as the International Maritime Organization's (IMO) strategy [1] and the FuelEU regulation [2], are reshaping the operational landscape.

To thrive in this new environment, the maritime sector is pursuing strategies to improve operational efficiency and system reliability. Electrification is at the forefront of these efforts, offering a pathway to meet regulatory demands while enhancing overall performance. In this context, WinGD developed its proprietary X-EL Energy Manager [3] that manages the energy demand and power flows of the entire power generation of hybrid merchant vessels. The X-EL solution, combined with WinGD expertise in system integration, not only ensures superior efficiency across the ship's operations but also enhances system reliability through active bi-directional control interactions with the Power Management System (PMS). The system's value proposition lies in its ability to outperform conventional systems through its holistic integration of the main engine and hybrid components, leading to improved energy distribution, reduced fuel consumption and greenhouse gas emissions as well as increased operational stability.

This paper aims to demonstrate the benefits of the X-EL system in terms of both efficiency and cost-effectiveness, as well as improved reliability of the vessel. For this purpose, reference is made to the case study of four vessels featuring WinGD's X-EL HYBRID system, which have been put in service in 2023 and have accumulated thousands of running hours since then. A mixed numerical and experimental approach is used for this analysis: simulations were conducted to assess the efficiency benefits using the real operational data from the vessels, while X-EL collected data were analysed to understand specific functionalities, such as an innovative peak shaving feature and bow thruster operation. The system demonstrates enhanced performance through an integrated approach, incorporating active control of all key elements including the Main Engine (ME), the hybrid powerpack consisting of a Shaft Generator (SG), battery pack, Variable Frequency Drive (VFD) in a multidrive configuration, and the PMS onboard.

2 INTEGRATED X-EL SOLUTION

Hybridisation has evolved as a promising solution for today's ship power and energy systems, offering significant GHG emissions reduction [4] [5], while increasing reliability through key system redundancy. Spinning reserve capabilities are enhanced, enabling efficient utilisation of energy resources without the risk of black-out. The transient behaviour of main and auxiliary engines is also improved.

The benefits of hybrid power, incorporating both electric and propulsion engine power with or without Electrical Energy Storage System (EESS), have long been known to ship operators in some market segments. For many years SG systems have given efficiency advantages for deep-sea vessels.

Today, new integration approaches are enabling coastal ships with a strongly fluctuating power demand, such as feeder containerships and offshore vessels, to benefit from electrification to supplement engine power. As improvements in emissions, fuel consumption and reliability are explored for a wider range of merchant vessels, electric and hybrid arrangements are becoming increasingly significant.

The ME is evolving into the heart of the integrated vessel power system. The "integrated" hybrid energy system (see **Figure 1**) consists of a generator mounted on the main shaft line, which bridges the power generation from the ME to the electric generation typically handled by diesel gensets. In this way, part of the power produced by the ME is converted to electrical energy to supply the electric loads. To fully optimise the operational behaviour of a vessel through hybridisation, the holistic integration of all sub-systems into one system must be ensured. This includes the optimal sizing of all components and implementation of the right control strategies on a system level.

The X-EL solution can be tailored to different vessels, needs and applications. Based on the specific requirements, the main solutions can include:

- X-EL PTO/PTI: An electric machine is mechanically connected to the engine and the propeller, installed coaxially to the shaft that connects the ME to the propeller for low-speed two stroke engine configurations, or to a gearbox for medium-speed four-stroke engines. The electric machine generates electric power for the ship auxiliary load or provides power to the shaft.
- X-EL HYBRID: In addition to the X-EL PTO/PTI case, an EESS is installed. This configuration allows for more functionalities by partially offloading the instantaneous power requirement to the EESS itself.

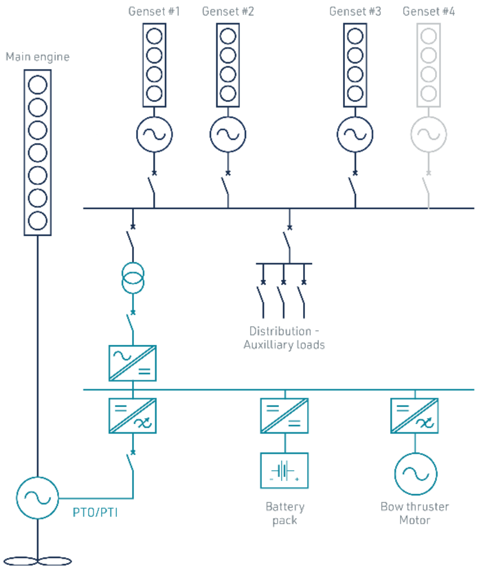

Figure 1. Block diagram of a two-stroke hybrid energy system

The ME speed varies in a rather wide range, which leads to the necessity of installing a VFD between the SG and the main switchboard. In this case, the DC-link is leveraged, and other electromechanical subsystems are integrated through it, including a battery pack, a motor-driven thruster and an interface for shore power supply that can utilise the SG converter (shore power not shown in the figure).

The thruster operational pattern can be characterised as a short and irregular one with high peaks. In the conventional case, to fulfil its power demand, multiple gensets must run in partial load during manoeuvring to provide sufficient spinning reserve. This leads to higher system fuel consumption and emissions alongside with higher maintenance cost. In the configuration shown in Figure 1, a spinning reserve is ensured by the EESS, so that the system can safely operate with a rationalised number of online gensets, running at an efficient load factor. Such an operation is particularly advantageous for coastal trading vessels.

Apart from the thruster case described above, the EESS can also be used on different occasions, including for peak shaving of the electric load, and load balancing of the engine. An appropriately sized and controlled EESS can guarantee that the electrical grid stays operational in the event of a preferential trip (when non-essential loads are disconnected during overload conditions) or blackout. These situations might occur when an auxiliary engine shuts down and goes offline, or if the engine cannot instantly handle highly transient load demand.

The different power sources of a ship with SG and EESS must be properly orchestrated. For example, the efficient operating range of ME with SG and genset must be optimised to avoid genset operations at partial load or with frequent switching on and off. The battery, on the other hand, offers an additional degree of freedom that can be beneficial or detrimental to the system, depending on how it is used.

In terms of fuel consumption, the optimum operating point of the ME does not necessarily correspond to the system's optimum operating point, as there are losses for electromechanical conversion. Therefore, an Energy Management System (EMS) strategy must consider the operational limits and efficiencies of all the components to determine the best operating conditions, or the “optimum”, for the entire system.

WinGD developed the X-EL Energy Manager to ensure optimum operational efficiency of the integrated hybrid energy system. As shown in **Figure 2**, the X-EL Energy Manager has communication interfaces with all the subsystems and its algorithms can determine the optimal operational point for the system at any time. For the decisions of how much energy should be produced, used and stored, the optimisation function considers system and real-time constraints. These include the engines' power limits and transient capabilities, the subsystems' efficiencies, the fuel and emissions reduction potential, and the battery's capabilities determined by power cycles and the cells' temperature.

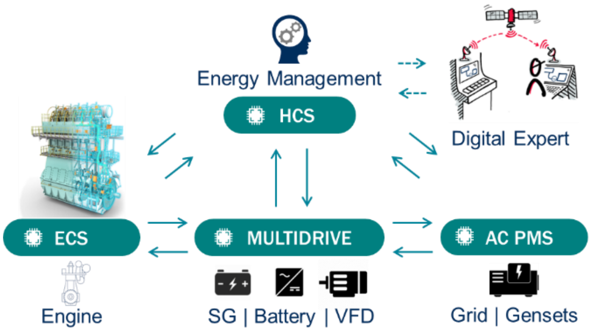

Figure 2. Control flow representative of the X-EL integrated hybrid energy system

The X-EL Energy Manager oversees and manages the integrated system in a holistic manner, aiming to maximise the overall ship's efficiency. It allows for changeover among different operational modes, such as peak shaving and load balancing, and ensures safe operation without using power produced by the gensets during sea passage, as well as optimal energy production for safe manoeuvring. As a result, ME usage is maximised, leading to increased propulsion efficiency by utilising the engine margin, without exceeding the applicable constraints, for electrical energy production through a SG. The ME's safe operation is ensured across any operational condition throughout the lifecycle of the vessel (avoiding prohibited areas, overloads, etc.).

2.1 X-EL integration with Engine Control System (ECS)

Although the potential of the X-EL integration approach is engine agnostic, the X-EL system integration solutions enable advanced and exclusive system functionalities. Those functionalities offer significant benefits in terms of GHG emission reduction, safety, reliability and manoeuvrability, especially when combined with WinGD engines. This exclusivity stems from the unique advantage of WinGD being both the engine developer and the hybrid system integrator simultaneously. Some of those functionalities are listed in **Table 1**, with benefits for the system such as minimizing the operational risks (e.g., engine over-speeding) and improved performance (e.g., higher system efficiency).

Table 1. Functionalities available with X-EL system

Hybrid Feature	Benefits
X-EL - ECS Integration	Compliance with load acceptance / rejection of the engine, reduced GHG emissions, no over speeding, minimized ageing effect on performance
Intelligent ME Peak Shaving	ME safety and stability improved, vessel speed stability improved, improved system efficiency, battery life preservation
Alternative fuel-ready	HCS adaptive to engine dynamics and operational limits when operating with alternative fuels → improved performance, safety and GHG emissions
Specific Engine tuning for hybrid application	Increased system overload limit, potential installation of a downsized engine or upsized PTO

System integration performed by X-EL features a specific design of the ME and X-EL Energy Manager to continuously communicate, effectively operating as a single control system.

X-EL is built on a modular basis, making it adaptable to different system configurations and powertrain technologies such as waste heat recovery (WHR) systems, fuel cells and energy sources like solar and wind. In this regard, innovations such as WinGD engines capable of running on methanol and ammonia, and new engine technologies such as the Variable Compression Ratio (VCR), can be also managed by the X-EL. This management ensures that the benefits of each technology are enhanced on a system level, maximizing overall efficiency and effectiveness.

2.2 X-EL Energy Manager functionality

The Hybrid Control System (HCS) is the brain of the hybrid architecture and orchestrates the operation of the whole system. The control strategies were developed considering:

- System constraints: power limits and transient capabilities.
- Efficiencies of the ME, SG, gensets, converters and batteries.
- Reduction of CO_2, CH_4, NOx emissions.
- Maintenance cost of the ME, the gensets and all the components.
- Energy storage capabilities determined by power, cycles, temperature.
- Reliability and availability of the system.
- Lifetime of the components.

2.2.1 X-EL Operating Modes and Functionalities

The X-EL system has been built to deliver various operating modes or functionalities enhancing both the vessel reliability and efficiency.

2.2.1.1 Power Take Out (PTO)

In this mode, genset usage is minimised during a voyage to take advantage not only of the high efficiency of the ME but also to make the ME operate in optimal efficiency areas. Sufficient power for vessel propulsion and for the electrical loads within the engine limits is assured.

2.2.1.2 Blackout prevention

Thanks to the battery, the system can take advantage of the stored energy reserve and power capability to prevent blackout, guaranteeing stable grid voltage on instantaneous loss of power source. This functionality guarantees full vessel reliability in case of genset trip, main engine trip in PTO mode or crash astern. If the SG suddenly stops generating electric power, the battery can supply the necessary electricity to the vessel's loads until the gensets are reactivated. The same applies if a genset is disconnected instantaneously or if there is a change in ME speed during a crash astern.

2.2.1.3 Main Engine propulsion Peak Shaving

The ME propulsion load is influenced by sea conditions and ship manoeuvres, which can lead to significant variations. These fluctuations can negatively affect fuel consumption and reduce the availability of engine margin for PTO. In the X-EL hybrid setup, the battery is utilized to mitigate ME speed fluctuations by leveraging the fast response of the SG. The SG uses the battery as a buffer to compensate for its variable power output. This operating mode not only provides additional fuel savings but also ensures that the ME operates safely within its margin, enhancing ship safety and reliability. Moreover, thanks to the higher spinning reserve of the grid, it enables extended SG operation without genset activation, the so-called ‘island mode’. This is possible even under high electric load conditions that would typically require genset activation alongside PTO operations.

2.2.1.4 Grid Load Peak Shaving

Similar to ME peak shaving, this functionality manages load fluctuations in the AC grid using the battery, up to the maximum genset power. It ensures stable grid voltage during instantaneous power demands, particularly when gensets are operating on gas fuel. Heavy consumer connections can be performed without the need to start a standby generator. This functionality significantly enhances system safety and availability while also reducing fuel consumption.

2.2.1.5 Power Reserve

In addition to blackout prevention, the energy stored in the battery ensures that the power plant system can operate at optimal load factors. Conventional power plant systems without battery storage require gensets or SG to operate with large margins or at partial loads in parallel to maintain sufficient spinning power reserve for handling instantaneous load variations. The integration of battery power reserve allows SGs or gensets to operate at their rated power without the risk of component overloading or preferential trips (when non-essential loads are disconnected during overload conditions). This functionality ensures that even prolonged power fluctuations exceeding the power producers' ratings are safely managed by the battery, resulting in significant fuel savings and reducing the operating hours of running gensets.

3 WINGD APPROACH TO SYSTEM INTEGRATION

WinGD's X-EL solutions for merchant vessels approach system integration holistically. Extensive use of our in-house digital toolset supports the entire development process, from initial feasibility and design to deployment and operation. WinGD’s virtual toolchain [6] [7], specifically designed to tailor electrified propulsion systems for hybrid marine applications, empowers customers with early-stage data, enabling informed decision-making and seamless system design and development.

The X-EL virtualization process is built on three main stages, as shown in **Figure 3**:

1. **Feasibility Study**: This initial stage involves analysing project specifics, followed by the layout and sizing of system components. Right-sizing these components is crucial for optimizing the trade-off between CAPEX and OPEX, and maximizing return on investment. For preliminary sizing of the X-EL systems, WinGD adopts a fast-running optimizer developed in the commercial software GT-SUITE. This tool reproduces the entire power generation system installed on a vessel in a virtual environment, including both power for motion and the electric power generated onboard for electric auxiliary consumers. Components are modelled using a quasi-steady map-based approach. This allows equivalent CO_2 emissions and OPEX figures to be obtained by comparing the electrified solution to a

conventional configuration. The system configuration is optimized to minimize GHG and fuel consumption using an in-house algorithm.

2. **Virtual Integration and Detailed Modeling**: After pre-sizing and assessing economic and environmental potentials, system components are integrated and operated in a virtual environment. This virtual system accurately replicates the behavior of the actual electrified system and is tested with multiple profiles, including transient power demand fluctuations. During project implementation, system components are modeled in detail to replicate dynamic scenarios and fine-tune the EMS. This helps identify potential risks and critical scenarios early, reducing calibration effort and risk of failure during commissioning. The EMS is interfaced with the ECS, ensuring reliable operation of the shaft generator across extended operational ranges. This step provides a quantitative assessment of system performance under different conditions, aiding investment decisions.

3. **Digital Twin**: This approach allows part of the virtual system to be repurposed as a Digital Twin, ensuring accurate benchmarking of real-time ship operation data from WiDE with model results. In this way, the integrated system is augmented by a digital solution, enabling operators to assess efficiency in real time, benchmark against achievable targets, and adjust real-time control as needed. Furthermore, the analysis of real data from the system ensures that the data is consistently evaluated to maintain and exceed performance expectations.

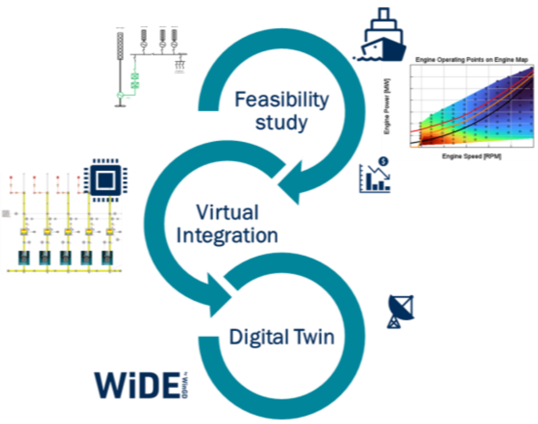

Figure 3. WinGD X-EL Virtual Toolchain: Main Steps

3.1 WinGD integrated Digital Expert (WiDE)

Access to data on the actual operation of engines and systems as well as on all kinds of influencing factors is key when aiming at the further optimisation of products, their performance, availability, and reliability. In the context of decarbonisation, a GHG reduction potential of 20% or more is attributed to the development of advanced digital solutions, when considering the complete logistics chain [8].

In order to ensure that data are not only collected but also analysed for deriving the right conclusions, either directly on board or via remote support, WinGD has introduced WiDE. This comprises three main building blocks: Data Collection & Monitoring (DCM); Engine Diagnostics System (EDS); and Remote Support. WiDE serves as the basis for identifying options for reducing operating cost and increasing availability and predicting component malfunction (see **Figure 4**), as well as the development of more advanced solutions. In view of the inevitable transfer of the data via non-proprietary channels and partly even openly accessible infrastructure, establishing proper measures for ensuring safety against theft or manipulation of sensitive data, loss of control, or even physical harm, was essential. In line with provisions by the International Association of Classification Societies (IACS) stipulating a standard that applies to all newbuilds after from January 1 2024 [9], WinGD has implemented robust cybersecurity measures for its electronic products [10].

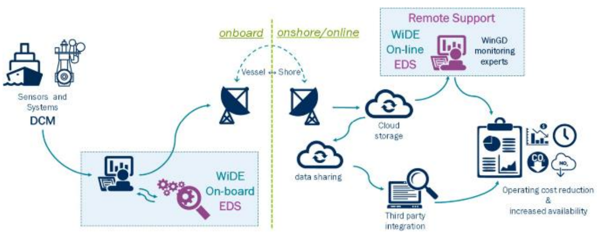

Figure 4. The main building blocks of WiDE, including DCM, EDS and Remote Support

4 X-EL PERFORMANCE ASSESSMENT

In this section, the performance of the X-EL system is assessed both in terms of efficiency and reliability improvement on a selected case study. First the case study is described in terms of main system power and components selected. Then, the analysis of the economic benefit from the adoption of different X-EL solutions, with and without the usage of battery, is discussed. Finally, a description of the main operating modes and how the system reliability is enhanced by X-EL is presented.

4.1 CASE STUDY

The potential benefits of X-EL system have been evaluated for four identical 7,000 Car Equivalent Unit (CEU) Pure Car and Truck Carrier (PCTC) vessels delivered in 2023 by a major shipping company.

WinGD managed the integration of the components as reported in **Table 2**. The ME is a dual-fuel WinGD X-DF engine able to operate with diesel or liquefied natural gas (LNG). This engine has Intelligent Control by Exhaust Recycling (iCER), a technology that recirculates part of the exhaust gas, improving fuel consumption and emissions and reducing methane slip. X-EL component sizing was carried out considering system integration performance and optimization, while bearing in mind the main engine limitations, the CAPEX of the system and the expected return on investment (ROI). Finally, available installation space in the vessels was considered. The X-EL system installed is shown in **Figure 5**.

Table 2. Specification of Integrated Hybrid Powertrain

Component	Note
Engine Type	WinGD 7X62DF-2.1
Multidrive	Active Front End + 2x AC/DC + 1x DC/DC converter
Shaft Generator	1240 kW Electrically Excited
Energy Storage System	565 kWh Li NMC
Bow Thruster	1800 kW

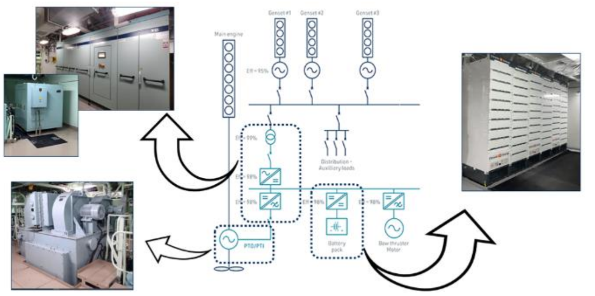

Figure 5. X-EL System installed on case study

The battery is sized for a net capacity that, if the SG cannot provide power, guarantees that blackouts are avoided before gensets can be switched on. Low and high states of charge are excluded from usage to prolong battery life. The reference state of charge is set to maximize the benefits from possible charge/discharge cycles. Additionally, the maximum battery power is sized to operate the mean load and bow thruster without the need to pre-emptively switch on gensets, ensuring maximum flexibility.

4.2 Description of data

WiDE allows for the download of extensive data concerning the engine, the ECS, the X-EL system, and the HCS of the vessels under study since their commissioning. A subset of these data, coming from the four vessels, was downloaded, sampled, and used for subsequent analysis.

The data for this analysis spans from September 2023 to January 2024, covering a period of 136 days at sea, including port operations. This timeframe encompasses three complete voyages. Even though this timespan does not encompass every possible weather and operational scenario, it is sufficiently broad to provide a good representation of the vessel's operating data.

Data collection occurred at intervals of every 10 seconds, ensuring a comprehensive and detailed dataset. To facilitate the subsequent analysis and ease the usage of this data, the data were resampled. This resampling process helped streamline the data, making it more manageable and suitable for analytical purposes, while still retaining the essential information needed for accurate analysis. The dataset includes signals such as grid power, SG power, ME power, battery State of Charge (SOC), and gensets power, providing a robust foundation for the analysis.

Figure 6 illustrates a subset of these data sampled each 20 min of the operating points of one of the vessels in terms of engine speed and engine power, along with the propeller curve, including the most notable engine limits, Line 10 and Line 6. Line 10 represents the operational limit for the engine when the PTO is active. As shown, PTO operation is not enabled at very low speeds to ensure stable engine operation. Line 6 indicates the maximum power the engine can deliver in transient operation.

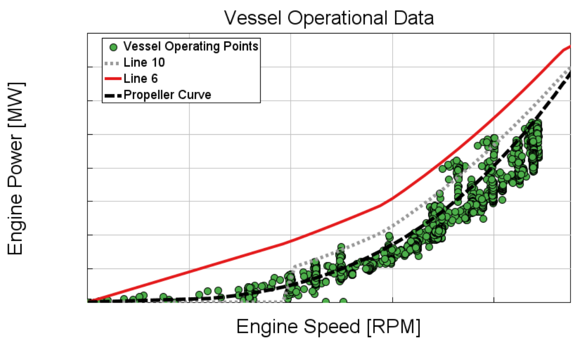

Figure 6. Vessel operating points over the course of two months. Propeller curve in black, Light Running Margin 7% in blue, max engine allowed operation in red (Line 6), maximum operation with PTO in gray (Line 10)

From the described data and with the power of the generating sets, five different scenarios were extracted, representative of notable operating profiles at different engine speed. The operating profiles extracted were:

- Sea going 1, with speed above 80% of the rated speed;
- Sea going 2, with engine speed between 65 and 80%;
- Sea going 3, with speed between 50 and 65%;
- Manoeuvring, with non-zero speed below 50% of rated speed;
- Port operation.

The share of these profiles, according to the data is reported in **Figure 7**. Sea operation, comprising including sea going profiles 1, 2 and 3, accounts for more than 70% of the operational time.

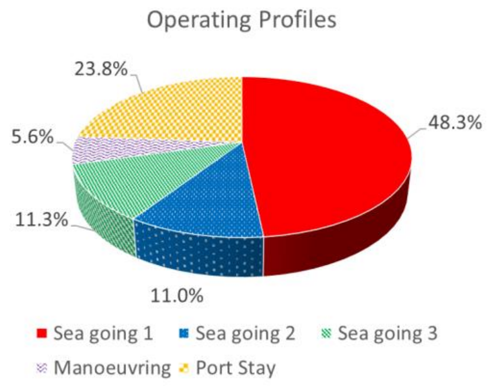

Figure 7. Time share of operating profiles

In section 4.4, results from the analysis of additional data recorded at a sample rate of 10 seconds on a single day of operation in July 2023 and January 2024 are presented. These operating days were selected for a detailed analysis of the X-EL PTO system regarding the reliability of the vessel's performance.

4.3 Feasibility study

In this section the feasibility study that uses real data to evaluate the benefit of the X-EL system is presented. Engine speed, power, and electrical load data, resampled data every 20 minutes, representing different scenarios are used as input for a model that represents the full powertrain. The model computes fuel consumption, methane slip, and genset energy. Using the share of operation, yearly OPEX is calculated based on current fuel prices. A flowchart representing the methodology followed is shown in **Figure 8**.

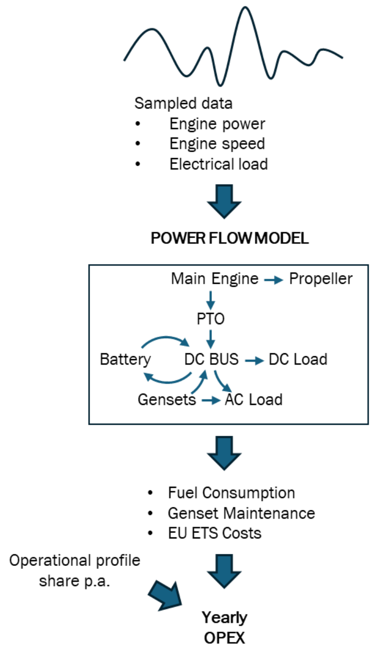

Figure 8. Schematic diagram of the assessment methodology

The sampled data described in Section 4.2 were used as boundary conditions for the virtualization platform, which was then used to assess the benefit stemming from electrification. This platform represents the whole power generation system installed on a vessel, including both power for motion and the electric power generated onboard for the electric consumers. Components are modeled using a quasi-steady map-based approach.

The engine's fuel consumption is described by maps for LNG, the main fuel used, and Marine Gas Oil (MGO) for the pilot injection. The SG is characterized by its efficiency map. Both the engine's fuel consumption maps and the SG's efficiency map are functions of the power and load of these machines.

In contrast, the gensets are described by a fuel consumption map that depends solely on the genset load. Additionally, MGO consumption due to pilot injection for gas mode operation for the ME and gensets, as well as methane slip was accounted for as a function of load. Main functional limits of the ME are also taken into account. The battery is modelled with an equivalent circuit approach.

Genset activation is controlled to guarantee a certain spinning reserve for unexpected electric load request (e.g., bow thruster operation). PTO operation is controlled in such a way to maximise its usage while at the same time avoiding running the ME at power above the limits (i.e., Line10) or at low engine speed where operation of PTO is not allowed.

In this study, the transient aspects arising from the availability of an EESS are not investigated. However, the benefit of the EESS translates into the ability to exploit the full power of the SG by delegating all the spinning reserve to the battery.

Three different cases were investigated:

- **Reference**: In this scenario, the ME is providing power only to the propeller, while up to three gensets are responsible for the generation of electric power for the grid.

- **X-EL PTO**: In this scenario, X-EL SG is active, and the ME provides power for the propeller and to generate the electric power in combination with the SG. Gensets guarantee the generation of electric energy if required because the SG cannot provide the full energy, or when it is not possible to enable it due to engine limits.

- **X-EL HYBRID**: In this scenario, X-EL system includes SG and battery. In this case, the battery can support transient load requests by the electric grid, such as bow thruster operation, which in turn allows the spinning reserve of the grid to be reduced and the X-EL system fully utilized.

4.3.1 X-EL Benefit

The virtualization platform enables the evaluation of different system parameters such LNG consumption from the ME and gensets and MGO consumption used pilot injection to ignite gas combustion. Methane slip was also tracked to correctly compute equivalent CO_2 emissions. Finally, genset generated energy was considered to account for genset maintenance costs.

Figure 9 shows the comparison of the different systems and the impact on different engine parameters, namely fuel consumption of the vessel (LNG or MGO), equivalent CO_2 emissions and electrical energy generated by the gensets. The adoption of X-EL PTO reduces LNG fuel consumption by about 2%, with a comparable consumption for X-EL HYBRID.

Where the X-EL HYBRID stands out is regarding the consumption of MGO as pilot fuel, which is reduced by about 30% compared to the reference case, and the total equivalent CO_2, reduced by more than 7% (or around 6% for the X-EL PTO case). Genset operation is also significantly reduced, with energy produced by genset 64% lower with PTO and up to 74% lower with X-EL HYBRID, where the gensets are active only in port operation.

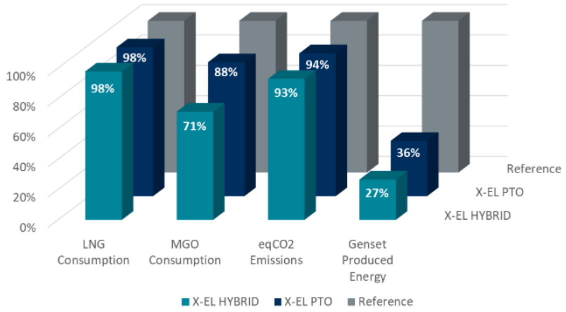

Figure 9. X-EL Solutions fuel, emissions and genset use advantages

OPEX is computed by evaluating the reduction in fuel consumption cost, EU Emissions Trading System (EU ETS) cost dependent on equivalent CO_2, and the reduction in genset maintenance. As shown in **Figure 10**, the adoption of the X-EL PTO shows a reduction of OPEX of about 3%, with an ROI payback time estimated at 3.7 years.

For the X-EL HYBRID case, the OPEX cost is reduced by up to 4%, resulting in an ROI payback time of 4.6 years due to the higher cost of the battery. The system was designed to ensure a 10-year battery lifetime with a maximum 15% reduction in battery capacity, addressing potential maintenance costs effectively. Moreover, the battery charge-discharge cycles are controlled by the X-EL manager to maximize battery life and the continuous evaluation of the battery state through WiDE will contribute to extending the useful battery life. With respect to the X-EL PTO system, X-EL HYBRID brings significant reliability features and additional fuel savings. These features will be discussed in the next sections.

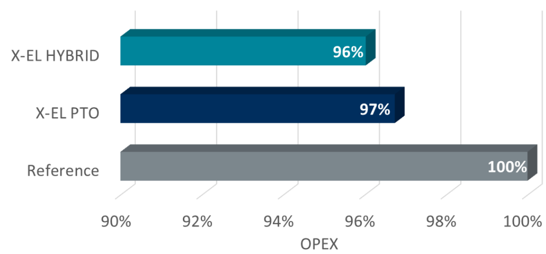

Figure 10. OPEX savings generated by X-EL Solutions

While the shown benefits in OPEX and ROI are relevant for the specific application, the savings may vary depending on trading routes and sea conditions. Additionally, these estimates might not apply as is for a different vessel. ROI can also be affected by fuel price assumptions, variations in battery degradation, and weather conditions. As an example, a 30% reduction in gas prices may increase payback time by one year, whereas a doubling of the European Union Emissions Trading System (EU ETS) allowances would reduce the payback time by one year.

As more data becomes available, a thorough evaluation of the system under different conditions and the impact of battery degradation will be performed. This will also ensure that the system maintains and exceeds performance expectations.

4.4 Reliability Functionalities

The adoption of X-EL solutions does not only improve the OPEX of the vessel but significantly benefits the safety and reliability of the vessel power system. In this section the capabilities of the system in terms of blackout prevention and SG trip, peak shaving and bow thruster operation are described, using real data from vessel operation. This data was directly collected from the vessels during sailing operations on two different days: July 2023 and January 2024.

4.4.1 Blackout prevention – SG trip

In **Figure 11**, an example response to a blackout prevention event on board a vessel is illustrated. The WiDE data shows the shaft generator (SG) power dropping to zero (visible as yellow trend) and the battery provides a power peak (visible as a red peak) to sustain the electric load. Next, the generator starts (green trend line) and gradually increases its power. At the same time the battery power reduces and finally battery is recharged. During the whole event, the minimum recorded frequency of the electricity supply never fell below 59 Hz, and the on-board supply was not affected.

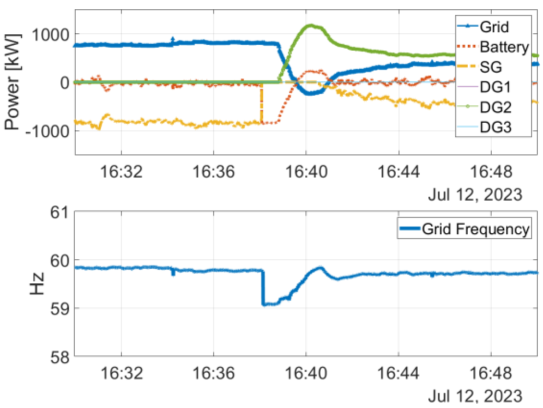

Figure 11. Reaction of the system on SG trip

4.4.2 Peak Shaving

The peak shaving function is illustrated in **Figure 12**. The top graph shows that after function is activated, at 300 seconds, the ME speed is significantly smoothened (red line vs blue line). Furthermore, the power ramps are also reduced (see middle graph). The lower graph shows in red that the fast power changes are compensated by changes in SG power.

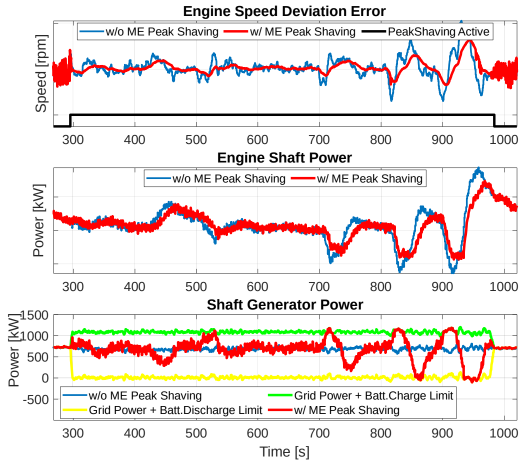

Figure 12. Power distribution with ME peak shaving mode

In September 2023, the test on board of the last ship from PCTC series was performed with ME Peak Shaving active for almost 4 continuous days. The data were extracted from the DCM with a sampling rate of 1 per second. Data have been clustered in equal intervals of 20 mins each. Every dot corresponds to one of these intervals, where peak shaving was on (green) or off (red) respectively.

Brake specific fuel consumption has been calculated, and the comparison is shown in Figure 13. ME measurements revealed fuel savings of approximately 0.7g/kWh when the peak shaving was active. This measurement was taken under moderate sea conditions; variations of ±0.2 g/kWh might be expected in rough weather or different loading.

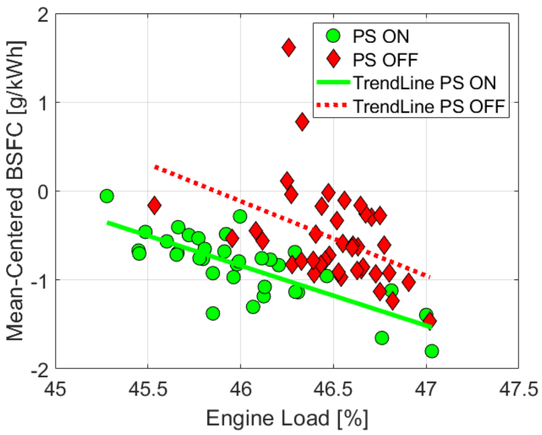

Figure 13: Peak Shaving: Fuel consumption trend lines.

The advantages of the peak shaving functionality under varying operating conditions (e.g., sea conditions) and the impact on battery life will be assessed as more data will be available.

4.4.3 Bow Thruster

In **Figure 14**, the operation of the bow thruster system in conjunction with the battery, is shown during ship manoeuvring. When the bow thruster is activated, the battery supplies the majority of required power, while the genset (DG) slowly adjusts its power output. It is visible from the trend that the genset power increases and decreases gradually, which is highly recommended, especially for gensets running on gas. Additionally, this setup makes it possible to perform manoeuvring with the thruster using only two gensets instead of the three traditionally required. Once the bow thruster is deactivated, the battery absorbs the surplus power from gensets DG2 and DG3. Once the bow thruster speed is reduced, the battery absorbs the surplus power from gensets (DG2 and DG3.

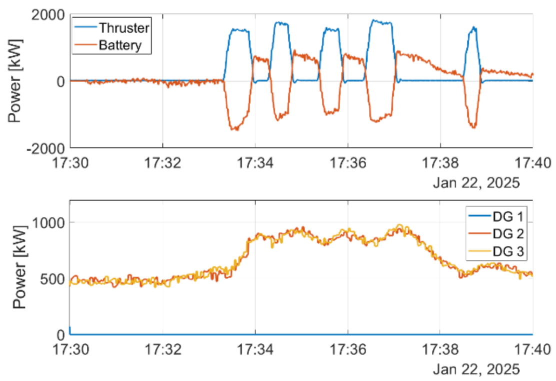

Figure 14. Bow thruster operation with battery

5 CONCLUSIONS

More efficient generation and utilization of electric power will help ship owners and operators meet continually strengthening measures to reduce carbon emissions in the shipping industry. Optimizing energy flows will benefit from a holistic approach to determine the optimal operation of the entire system, rather than focusing solely on the internal combustion engine or any other individual subsystem.

To effectively integrate alternative technologies, first the system configuration must be customised for individual vessels' characteristics and operating profiles. Then, it must consider transient capabilities of the subsystems. Finally, it must be controlled by an EMS with full insight into all elements. Following this approach, the electromechanical subsystems around the main engine can provide operators with the capability and flexibility required to meet future operational and regulatory challenges.

In comparison with a conventional energy system arrangement, the use of hybrid power brings benefits beyond emissions reduction and fuel expenditure. By harnessing the most efficient and reliable engine on the vessel – the main engine – operators will be able to minimise engine maintenance costs. Electrical propulsion support can improve power availability and response to dynamic changes in energy demand. In some instances, the extra energy supply available through electricity generation will provide operators the option of installing less engine power on board. Moreover, such integrated hybrid energy systems can be easily adapted to future requirements, including the addition of shore charging capability or other power sources such as wind or waste heat recovery.

The case study analysed in this paper, focusing on vessels integrating the X-EL HYBRID system by WinGD, demonstrates significant benefits in terms of OPEX savings and vessel reliability improvements. In particular, the analysis using operational data gathered from the commissioned vessels showed that a fuel reduction of 2% and a reduction in CO_2 emissions of up to 7% can be obtained. This translates to a reduction in OPEX of 6% and indicates that the system pays for itself in about four years, considering the usage of the shaft generator (SG) with the battery. This payback period can be further reduced by the advantages of the Peak Shaving functionality, which showed an additional benefit of about 0.7 g/kWh.

The reliability of the system is enhanced by significantly reducing the risk of blackouts, as the battery can support electrical loads if the SG or gensets trip. Additionally, the system can smooth out peaks of electric load demand, for example, coming from bow thruster load. The improved reliability of the PTO system not only enhances ship safety but also indirectly increases overall ship efficiency. This is because, thanks to the battery, the SG can be utilized for significantly longer periods, whereas, on conventional vessels, the use of the PTO is not recommended under certain ship conditions.

Overall, this paper shows the enhanced performance that can be obtained by X-EL through an integrated approach, incorporating active control of all key powertrain and power generation elements, and providing a robust solution for modern maritime challenges.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

CEU: Car Equivalent Unit

DCM: Data Collection & Monitoring

DG: Generating Set

ECS: Engine Control System

EDS: Engine Diagnostics System

EESS: Electrical Energy Storage System

EMS: Energy Management System

EU ETS: EU Emissions Trading System

GHG: Green House Gases

HCS: Hybrid Control System

iCER: Intelligent Control by Exhaust Recycling

IMO: International Maritime Organization

LNG: Liquified Natural Gas

ME: Main Engine

MGO: Marine Gasoil

OPEX: Operative Expenses

PCTC: Pure Car and Track Carrier

PMS: Power Management System

PTO: Power Take-Out

SG: Shaft Generator

VFD: Variable Frequency Drive

WHR: Waste Heat Recovery

WiDE: WinGD integrated Digital Expert

7 ACKNOWLEDGEMENTS

The authors would like to express their gratitude to NYK and MTI for providing the data and information used in the development of this paper. Their support and collaboration have been invaluable in advancing the analysis and development on the X-EL HYBRID system.

8 REFERENCES

[1] IMO, "IMO 2023 GHG Strategy," 2023. [Online]. Available: https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx. [Accessed 01 2024].

[2] EU, "Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC," 22 9 2023. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2023/1805/oj.

[3] WinGD, "X-EL Energy Management," 2024. [Online]. Available: https://wingd.com/products-solutions/energy-management/x-el-energy-management. [Accessed 27 01 2025].

[4] DNV GL, "The Future is Hybrid," DNV GL, 2015.

[5] M. H. Moradi, Route and Operating Optimization of Maritime Vessels Using Machine Learning Techniques, Logos Verlag Berlin GmbH, 2024.

[6] A. Palma, S. Goranov, M. Wenig and M. Bendyk, "Hybrid System Virtualisation for Predicting Performance and Eliminating Risks and Uncertainties," *WinGD,* 2022.

[7] S. Goranov, M. Bendyk, M. Wenig, W. Wroblewski and A. Palma, "The Low-Speed Two-Stroke Main Engine in a Hybrid Setup: The Engine Designer's Approach to System Integration," in *Large Engine Symposium*, Rostock, 2022.

[8] DNV, "https://www.dnv.com/maritime/publications/maritime-forecast/," 2024. [Online]. Available: https://www.dnv.com/maritime/publications/maritime-forecast/. [Accessed 27 01 2025].

[9] IACS, "UR E27 Rev1 CLN," 09 2023. [Online]. Available: https://iacs.org.uk/resolutions/unified-requirements/ur-e/ur-e27-rev1. [Accessed 27 01 2025].

[10] WinGD, "WinGD cybersecurity type approval from DNV prepares owners for incoming regulations," 30 11 2022. [Online]. Available: https://wingd.com/news-media/news/wingd-cybersecurity-type-approval-from-dnv-prepares-owners-for-incoming-regulations. [Accessed 27 01 2025].

9 CONTACT

Dr. Alessandro Zanelli

WinGD Ltd.

Schützenstrasse 3, 8400 Winterthur, Switzerland

alessandro.zanelli@wingd.com