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Adaptability and efficiency analysis of hybrid-electric propulsion systems for ocean-going vessels

New Engine Concepts & Systems

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ABSTRACT

In 2023, the International Maritime Organization, through MEPC (80) resolutions, adopted a revised and increasingly ambitious strategy to reduce and eventually eliminate GHG emissions from the international maritime shipping sector.

To enact this vision, shipping is required to introduce progressively stricter rules to ensure that specific emissions of each vessel (i.e., grams of CO2 emitted per cargo-carrying capacity and nautical mile) are reduced. This will be achieved mainly by enforcing a Ship Energy Efficiency Management Plan (SEEMP) that certifies the vessel's specific Carbon Intensity Index (CII). Each year the ship's CII will be compared with the required annual operational CII, allowing ship to operate if it is below a certain threshold and requiring action if it is above.

In this scenario, owners face the perspective of investing in an asset that might become stranded or severely limited before completing its lifecycle and it is therefore essential to ensure that newly constructed vessels can adapt and upgrade to retain full operativity throughout their projected life.

This paper aims to explore how hybrid-electric propulsion systems effectively address three key concerns in the maritime industry: adaptability to new fuels, adaptability to new operating profiles, and adaptability to new technologies.

The study compares hybrid electric propulsion systems with alternative propulsion across a range of different operating profiles, encompassing various average vessel speeds and operating conditions., specifically for LNG carriers. The analysis will consider key efficiency parameters, including engine brake specific energy consumption (BSEC), propulsion power, auxiliary power, propeller efficiency, power and electrical losses, as well as design parameters such as hydrodynamic performance and cargo carrying capacity.

Using system simulation, key vessel performance parameters such as energy consumption, emissions performance, unit freight cost and trading revenues will be evaluated in alternative operational and future decarbonization scenarios to understand the pros and cons of the alternative propulsion systems.

The findings of this study will contribute to a better understanding of the key advantages hybrid electric propulsion systems can offer to meet increasingly stringent environmental requirements over the lifetime of the vessel. The results will provide valuable insights for decision-makers in the maritime industry, helping them make informed choices regarding propulsion system selection to secure future proof and sustainable assets.

ADAPTABILITY AND EFFICIENCY ANALYSIS OF HYBRID ELECTRIC PROPULSION SYSTEMS FOR OCEAN GOING VESSELS

ABSTRACT

In 2023, the International Maritime Organization (IMO), through MEPC (80) resolutions, adopted a revised and increasingly ambitious strategy to reduce and eventually eliminate greenhouse gases (GHGs) from the international maritime shipping sector. This strategy mandates progressively stricter rules to ensure that specific emissions of each vessel are reduced, primarily through the enforcement of a Ship Energy Efficiency Management Plan (SEEMP) that certifies the vessel's specific Carbon Intensity Index (CII). This paper explores how hybrid electric propulsion systems can effectively address three key concerns in the maritime industry:

- adaptability to new fuels
- adaptability to new operating profiles
- adaptability to new technologies

The study compares hybrid electric propulsion systems with alternative propulsion systems across various operating profiles, specifically for LNG carriers. Key efficiency parameters such as engine Brake Specific Energy Consumption (BSEC), propulsion power, auxiliary power, propeller efficiency, power and electrical losses, and design parameters like hydrodynamic performance and cargo carrying capacity are analysed. Using system simulation, the study evaluates energy consumption, emissions performance, unit freight cost, and trading revenues in alternative operational and future decarbonization scenarios. The findings provide valuable insights for decision-makers in the maritime industry, aiding in the selection of propulsion systems that ensure future-proof and sustainable assets.

KEYWORDS

Hybrid Electric Propulsion, Alternative Fuels, Modularity, Operative Flexibility, Integration

1. INTRODUCTION

In the current market context, ship owners are faced with the prospect of investing in assets that may become stranded or severely limited before completing their lifecycle. Therefore, it is essential to ensure that newly constructed vessels can adapt and be upgraded to maintain full operability throughout their projected lifespan.

While there are several minor measures that can contribute to improving the vessel efficiency and carbon footprint, such as hull cleaning and smart routing, the most significant results are achieved by utilizing low carbon fuels and designing ships that are holistically more efficient. These efficient designs allow for the transportation of more goods while consuming less fuel. It is crucial to recognize that this efficiency is essential to enable the sustainable use of alternative fuels from a financial perspective, as these fuels are expected to be scarce and expensive in the medium term.

Electrifying the design and implementing a modular hybrid electric propulsion system enhance a vessel's cargo capacity by reducing the size of the machinery space. Additionally, the flexibility of such a concept enables the utilization of lower carbon fuels like LNG, bioLNG, Methanol, Ammonia, and even Hydrogen.

This paper aims to analyse how a 174kcbm LNG carrier can benefit from a hybrid electric machinery. A comprehensive analysis will be provided, starting with an examination of the operating profiles and how the propulsion machinery concept influences the overall efficiency of the vessel. This analysis will demonstrate the advantages of utilizing a modular hybrid electric system compared to traditional setups. Detailed information will be provided to highlight the specific benefits and improvements that can be achieved today with this innovative solution. The paper will delve into the enhanced fuel efficiency, reduced emissions, and improved operational flexibility that can be achieved in this vessel type. We will also show how using a hybrid machinery can impact the whole ship design, unlocking benefits that go beyond energy efficiency. By showcasing a real-world example and data, this paper aims to provide a comprehensive understanding of the tangible benefits and positive impact that this technology can have on the maritime industry.

In conclusion, the paper also examines the potential for future upgrades that can be made possible by adopting a hybrid system. By comparing these possibilities with traditional designs, the paper highlights the additional advantages and opportunities that arise from embracing hybrid technology. The potential for further advancements in energy efficiency, emissions reduction, and operational flexibility is explored, showcasing the long-term benefits of investing in a modular hybrid electric system. By considering the evolving landscape of the maritime industry and the increasing focus on sustainability, the paper presents a compelling case for the adoption of hybrid systems as a pathway towards a more efficient and environmentally friendly future.

2. THE BENEFITS OF HYBRID ELECTRIC PROPULSION MACHINERY

There is a common understanding that hybrid systems are suitable for ships with flexible and short operating mission profiles. This is because batteries can typically replace engine power for a limited amount of time. However, it is important to note that this perspective is somewhat narrow, and hybrid systems can offer significant benefits even in deep-sea shipping.

While batteries may not be able to solely power the vessel for the entire journey, they can be utilized strategically to optimize the overall performance and efficiency of the propulsion system.

One of the key benefits of hybrid systems in deep-sea shipping is their ability to suppress fluctuations and stabilize the load curve. This is achieved through techniques such as peak shaving, which is typically controlled automatically by an Energy Management System (EMS) to optimize the vessel's operation.

When peak shaving is enabled, the energy storage system, such as batteries, actively counteracts rapid changes in the main engine's load (**Figure 1**). By providing additional power during periods of high demand or sudden load changes, the energy storage system helps to smooth out the load curve and maintain a more stable and efficient operation.

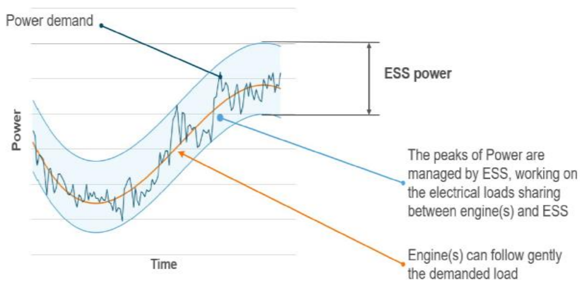

Figure 1: Peak Shaving Function

Moreover, the passive effect of having an Energy Storage System (ESS) connected to the switchboard in a hybrid system enables the operation of generating sets at higher load factors, typically up to 95% of their Maximum Continuous Rating (MCR), before bringing online an additional generating set (**Figure 2**). This approach helps to lock the load factor and maximize the efficiency of the system.

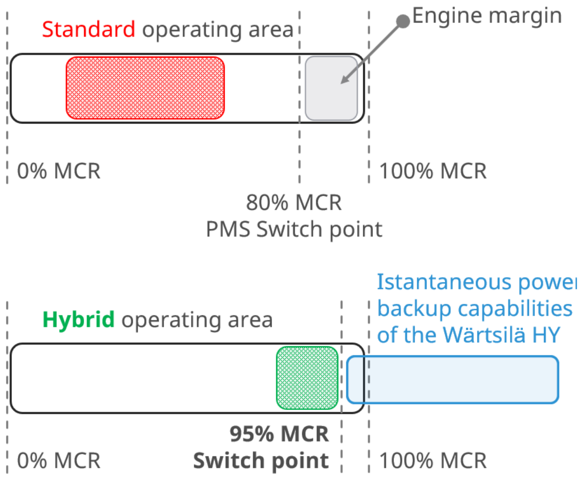

Figure 2: Load factor locked at higher MCR

Finally, ESS acts as a reserve power source, minimizing the number of generating sets needed to be online at any given time. By having the ESS connected to the switchboard, it can quickly respond to sudden changes in power demand or in the event of a generator failure, providing power to the critical loads, preventing blackouts and ensuring continuous operation.

The whole system is managed via an Energy and Power Management System (EPMS), that is based on the use of PCs and PC based screen system together with PLCs as processing units. PMS calculates the spare capacity for each engine-driven generator in a percentage of its nominal value. The total load and available power for all engine-driven generators are displayed on the human-machine interface. If the load exceeds a pre-set limit, the PMS will initiate the start of the next standby engine-driven generator.

The EPMS will also adjust charging and discharging of the battery to regulate the state of charge towards its set point. The system will limit the charging of the battery based on the available power, charging rate set in EPMS, limits in drives and limit from the battery management system. During discharging of the battery, it will limit based on the limits from the batteries and drives.

3. WÄRTSILÄ LOW LOSS CONCEPT

Wärtsilä hybrid electric is based on electrical distribution system of the “Low Loss Concept” (LLC).

Traditionally, each propulsion unit comprises a propulsion transformer, a frequency converter for speed control, a motor, and a propeller. This means all the energy supplied to each unit passes through the system, resulting in electrical losses.

The LLC transformer uses phase-shifting to filter out undesirable harmonic currents before they reach the generator. It achieves this by passing energy around the transformer rather than through it. The phase shift in the LLC transformer cancels the 5th and 7th harmonics, preventing these currents from loading the generator. In detail, main windings are phase-shifted by 30° to cancel out the 5th and 7th harmonic currents introduced into the network by rectifying bridges. The bridges are supplied from the two phase-shifted sides of the LLC transformer, with each providing 50% of the required power (**Figure 3**).

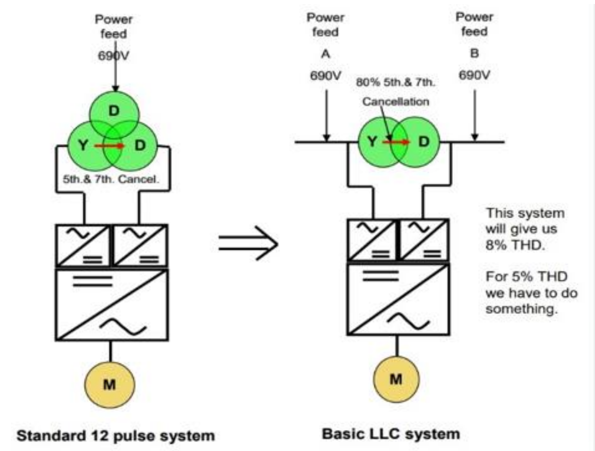

Figure 3: Standard vs LLC system

In case a total harmonic distortion (THD) of less than 5% is required, an LC filter, combined with a filter winding in the LLC transformer can be provided (**Figure 4**).

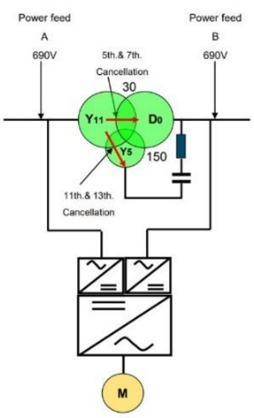

Figure 4: LC filter for low harmonic distortion

Most of the harmonic currents pass through the transformer rather than into the generators. This eliminates the need for traditional propulsion transformers by allowing genset power to be applied directly to the frequency converters used for speed control.

This process involves splitting the electrical supply into several parts, with each part's phase arranged to eliminate harmonics, by shifting harmonic currents to the opposite phase, they are effectively cancelled out (**Figure 5**). Fourier analysis is used to build a mathematical model that identifies which harmonic frequencies cause voltage distortion. The phase-shift transformer is then designed to eliminate these dominant harmonic components.

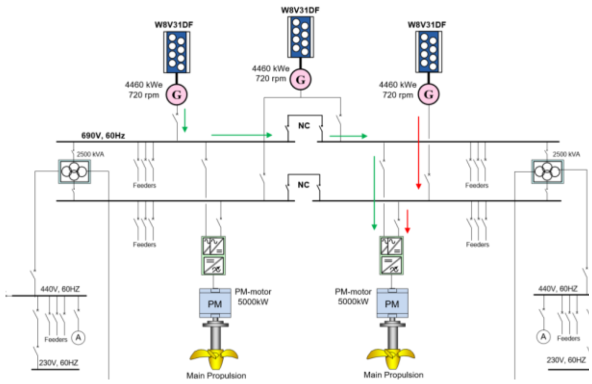

Figure 5: Current passage through LLC system

This configuration enhances system efficiency by 2-4% compared to traditional transformer-based systems.

In LLC system, the main switchboard is constructed in four separate sections, each section connected to one genset. Thrusters are connected to the four switchboard sections in such a way that each frequency drive is fed by two switchboard sections. If a failure occurs in one section, electrical energy from the other section can still be supplied to both propulsion motors, resulting in more efficient power distribution in damage scenario.

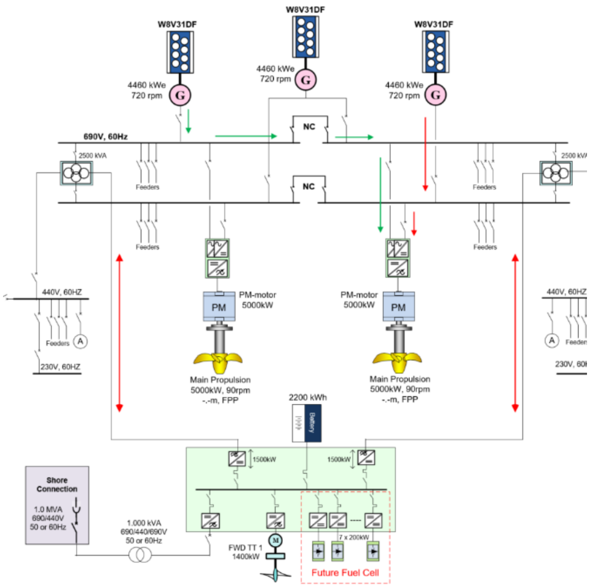

Figure 6: ESS integration

As the above SLD is showing, the vessel will be equipped with an ESS (Energy Storage System) as batteries (**Figure 6**). These batteries will be connected to a standard 1000 VDC switchboard and the battery power (in and out) will be achieved via an inverter from DC to 690VAC and connected to the fourth winding on each LLC transformer. This will give redundant battery back up to all 690V switchboard sections and the 440V distribution through the LLC transformers.

The batteries will give the possibility to reduce the use of generators both in sailing and in Port mode. In addition, there will be a possibility to charge the batteries from shore and thereby also avoid running generators in harbor.

When leaving harbor with assistance from batteries, the batteries will be charged to maximum SOC (State of Charge) during transit. In operation modes with variable load, waves/thrusters etc., the batteries will act as peak-shavers. This means that fast increases/decreases of load will be powered/absorbed by the batteries, giving a more constant load on the engines (generators). The use of battery as spinning reserve and as an additional generator will also allow for an optimal running of the gensets with a high load percentage.

In addition and eventual future development of other new energy producers like from wind, fuel-cells, sails etc., the DC switchboard provides a suitable platform to connect them into the same DC switchboard.

4. CASE STUDY: 174 000 CBM LNG CARRIER

4.1 REFERENCE SHIP

We will now see how hybrid electric propulsion can radically change the ship design of a 174 000 cbm LNG Carrier. In this case we don't have a clear preferred configuration, so the study will analyse and compare the three prevalent engine room configurations found in LNGCs, against a hybrid system. The first configuration is a low-pressure 2-stroke engine which is commonly used in LNGCs. The second configuration is like the first one but includes the addition of a shaft generator. Lastly, the third configuration involves a high-pressure 2-stroke engine with a shaft generator. All vessels of the study use air lubrication system. For the sake of the study, we will use low pressure 2 stroke as the reference and compare all other configurations to this one.

For this comparison, the study is using hull designs that guarantee full terminal compatibility. This means that the maximum length overall (LOA) of the hull is 300 meters, the maximum breadth (width) is 45 meters, and the maximum draft (depth below the waterline) is 11.5 meter. This approach allows to explore different ship designs, exploit the vessel's fullest potential, and allows for an assessment of the benefits and trade-offs associated with different engine room configurations, considering factors such as cargo capacity, fuel consumption, emissions, and overall operational costs. By exploring the potential of the hybrid system within the specified terminal compatibility requirements, the study aims to provide insights into the most effective and efficient utilization of the vessel space.

4.2 VESSEL OPERATING PROFILE

In last years, the LNG market has matured with more stable supply chains and better forecasting capabilities. This has reduced the need for rapid deliveries, allowing for more optimized and planned shipping schedules. Moreover, advances in LNG carrier design and technology have improved the efficiency of vessels, particularly on the boil off gas which has been greatly reduced with latest membranes tanks, allowing them to maintain operational effectiveness even at lower speeds.

Still, the most important factor in the years to come will be the stricter environmental regulations that will be enforced. The International Maritime Organization (IMO) has implemented regulations aimed at reducing greenhouse gas emissions from ships, and Europe has started imposing taxations on the emissions via its Fuel EU and EU ETS regulations.

As a result, we have seen a sharp decline of average speeds, which, according to Clarksons are already between 14 and 15kn (**Figure 7**), with some routes trading even slower, as highlighted by latest Poten and Partners reports (**Figure 8**)

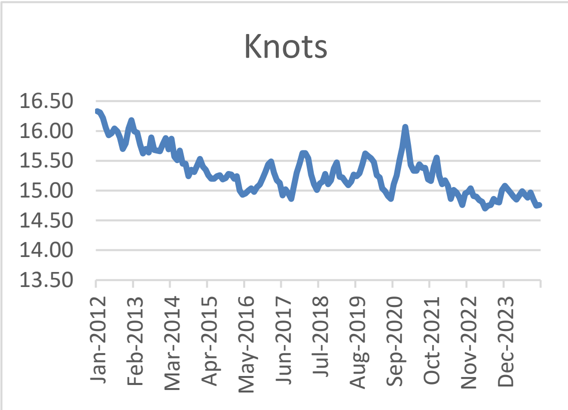

Figure 7: Average Laden Speed 2012-2025. Source: Clarksons

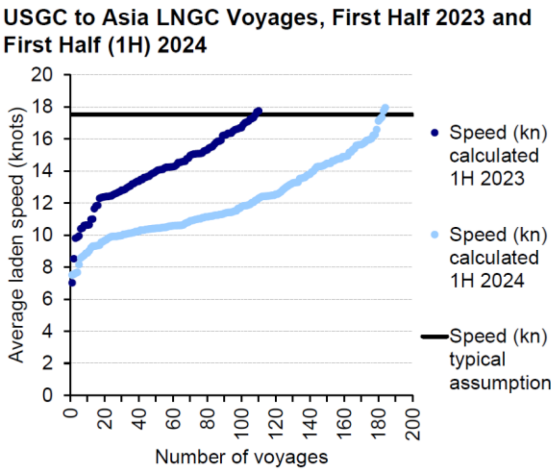

Figure 8: Average Laden Speed on selected routes. Source: Poten and Partners “Multi-dimensional Routeing Decisions for USGC LNG Supply”

4.3 MACHINERY SELECTION

The study will consider three different operating profiles for LNG carriers (LNGCs). We have considered three different operating profiles: high steaming, which corresponds to an average speed in laden of 17 knots and was used in the past due to high boil-off from the tanks; average steaming, which corresponds to an average speed in laden of 15 knots and matches the operating profiles observed in today's markets; and slow steaming, corresponding to an average of 14kn, which is the one we are directed to as observed by latest reports. The table below (**Figure 9**) indicates the speed distribution for each operating profile: high steaming, average steaming, and slow steaming

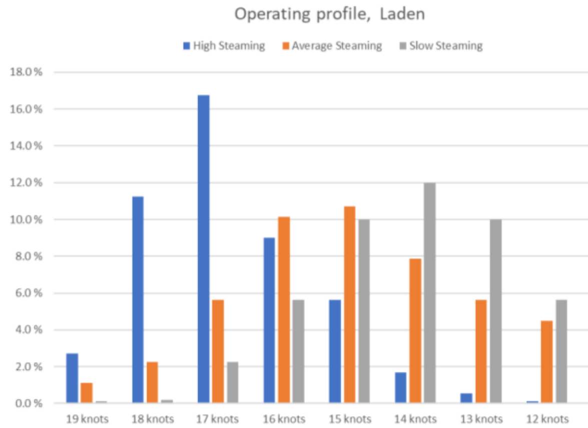

Figure 9: Operating profiles speed distribution in Laden condition

As observed earlier in this paper, LNGCs are slowing down, with current laden speeds close to the medium speed profile. By analyzing the three operating profiles, the study aims to provide a comprehensive overview of the flexibility of different engine room configurations in various operational scenarios.

The hybrid electric plant consists of three Wärtsilä 8V31SG engines (pure gas) and two Wärtsilä 10V31DF engines (dual fuel), along with a 2MWh 3C energy storage system (**Figure 10**). The generators and battery are connected to a Wärtsilä Low Loss system and the electrical motors are of permanent magnet type.

The use of pure gas engines in the hybrid electric plant offers several advantages. Firstly, it allows for the minimization of liquid fuel onboard and eliminates heavy fuel oil (HFO) equipment typically present in traditional engine configurations. This reduction in liquid fuel requirements and connected equipment helps offset the added displacement caused by additional cargo, contributing to improved efficiency and environmental sustainability.

Additionally, the reduced dimensions of the engines and the possibility of placing them on a deck above the electrical motors result in a significant reduction in engine room length.

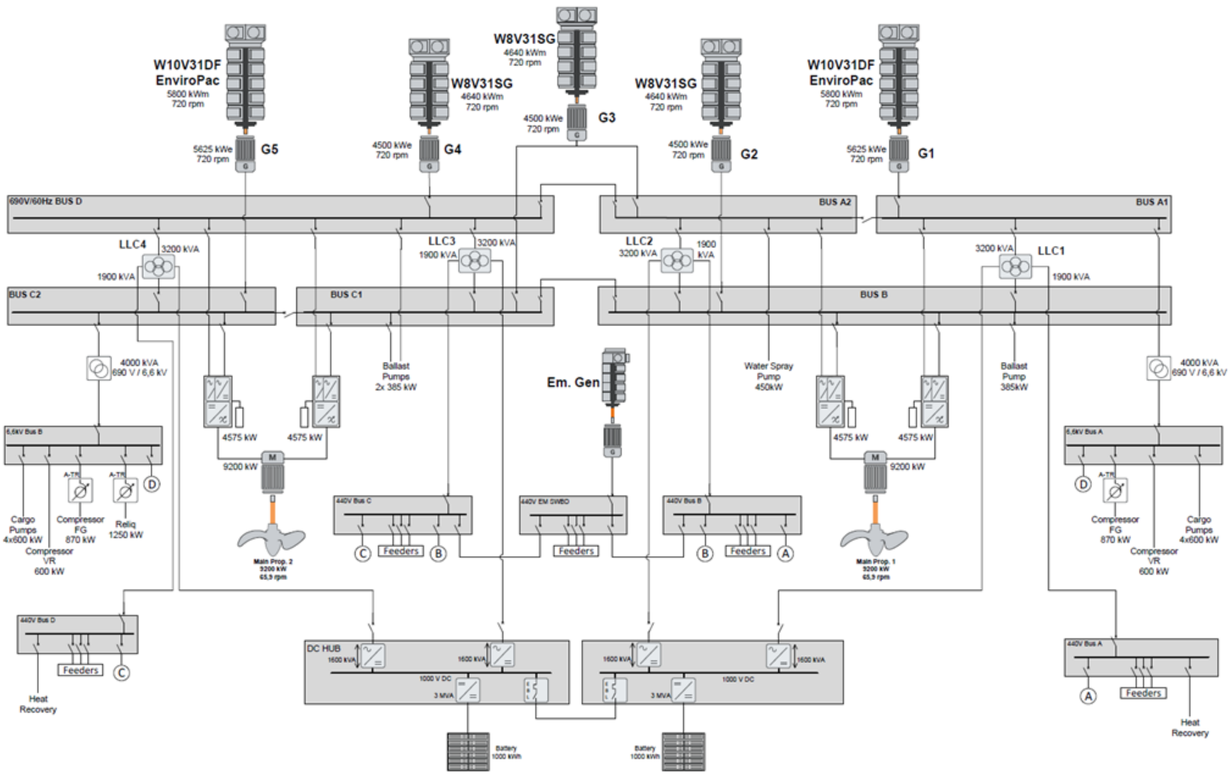

Figure 10: Wärtsilä Hybrid Electric Concept for LNG Carriers

This reduction in engine room length creates additional space that can be utilized for transporting more cargo, further optimizing the vessel's cargo capacity. In detail, it is possible to accommodate up to 186,000 cubic meters (cbm) of cargo below deck (**Figure 11**) while maintaining dimensions and draft within standard 174k terminal compatibility dimensions. This allows for increased cargo capacity without compromising the vessel's performance. Considering these different operating profiles and the ability to accommodate a larger cargo volume below deck, the study aims to assess the performance, efficiency, and flexibility of this novel configuration against the industry standard.

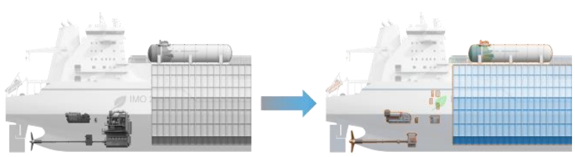

Figure 11: Increased cargo thanks to reduced hybrid electric machinery footprint

4.4 MACHINERIES COMPARISON

We evaluated how the alternatives compare to the baseline case on 2 different aspects:

1) Energy consumption comparison at different operating profiles (**Figure 12**)
2) Emissions comparisons at different average speeds (**Figure 13**)

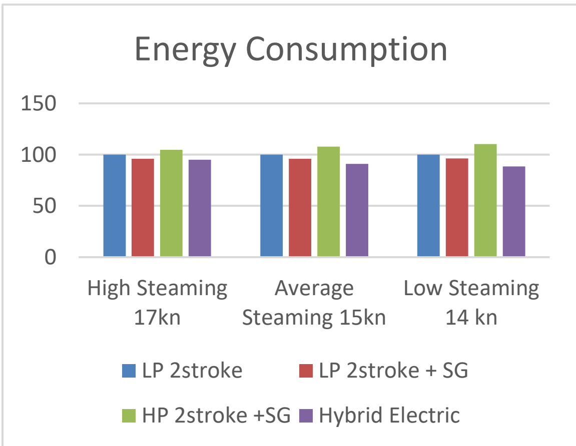

Figure 12: Energy consumption at different operating profiles

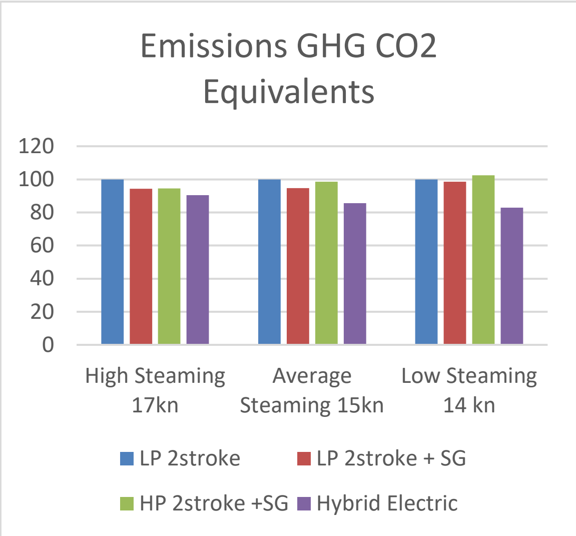

Figure 13: Emissions at different speeds

Based on the observations from the graph, it is evident that the hybrid electric concept is more competitive than all other designs, regardless of the operating profile considered. This competitiveness becomes more pronounced as the average speed decreases, with 12% better efficiency.

The modularity of the hybrid electric concept allows the generating sets to lock the engine load factor between 80% and 95% of the maximum continuous rating (MCR). This ensures that the entire power plant operates at its maximum efficiency point. As a result, the hybrid electric concept maintains high efficiency even at lower speeds, making it more competitive in terms of fuel consumption and overall performance.

In contrast, the 2-stroke engine concept experiences a decrease in efficiency as it deviates from the design speed. This is primarily due to the fact that the engine naturally loses efficiency when operating away from its optimal load point. Additionally, as the load decreases, the shaft generator is disconnected, and more auxiliary systems such as blowers are required. This further reduces the main engine load and necessitates the operation of more generating sets, leading to decreased efficiency.

The hybrid electric concept demonstrates better emissions compared to other designs across all speeds, with the benefits becoming more pronounced at lower speeds, reaching a decrease of 17%.

However, it is worth noting that the difference in emissions is greater than what the fuel consumption alone would suggest. This difference can be attributed to the fact that the hybrid electric concept utilizes engines that are highly efficient in terms of methane emissions. On the other hand, the auxiliary gensets in the 2-stroke concepts have higher methane emissions. When these auxiliary gensets are activated, the cumulative effect of methane emissions on total greenhouse gas (GHG) emissions increases more rapidly.

Methane is a potent greenhouse gas, and its emissions have a significant impact on overall GHG emissions. The higher methane emissions from the auxiliary gensets in the 2-stroke concepts contribute to a faster buildup of GHG emissions compared to the hybrid electric concept.

The results presented so far are expressed in absolute terms, comparing the performance of different ship designs without considering the additional benefit of increased cargo capacity. However, when we consider specific consumption and emissions, which are referred to the freight unit (such as per ton of cargo), the results become even more favorable for the hybrid electric concept, reaching 15% more efficiency (**Figure 14**)and 21% less emissions than the reference configuration (**Figure 15**).

By considering specific consumption and emissions, we can assess the efficiency and environmental impact of each ship design on a per unit of cargo basis. The increased cargo capacity provided by the hybrid electric concept, while maintaining the same design speed, not only helps to reduce the unit freight cost but also lowers the emissions per cargo ton mile, which are crucial factors in forthcoming legislations and environmental regulations.

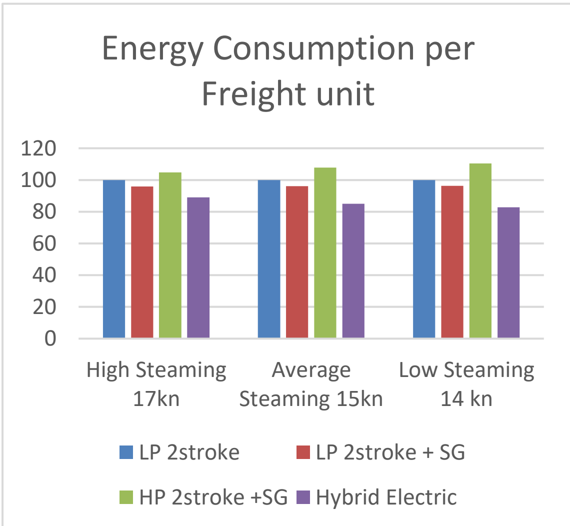

Figure 14 Energy Consumption per Freight Unit

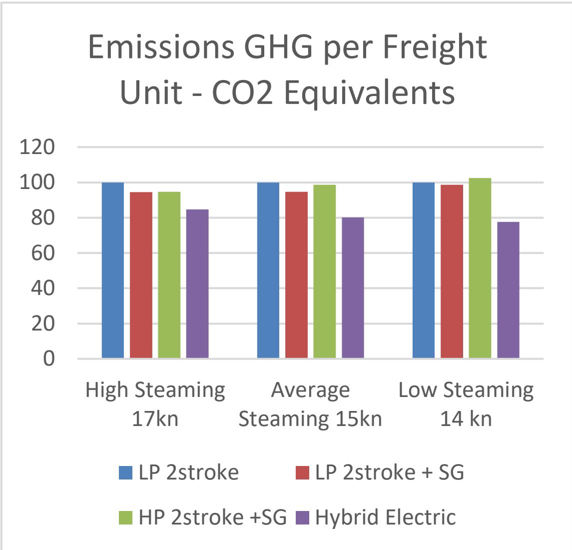

Figure 15 Emissions per Freight Unit

5. EU ETS and Fuel EU

EU ETS is a cap-and-trade system extended to the maritime sector from 2024.

It sets an overall limit (cap) on Tank-to-Wake GHG emissions in terms of EU Allowances (EUAs), reduced yearly. Companies must compensate their emissions with EUAs.

FuelEU Maritime comes into force in 2025 and aims to increase the use of renewable and low-carbon fuels by limiting the Well-to-Wake GHG intensity of energy used onboard by a ship in EU/EEA voyages.

In both cases, emissions are accounted as 100% of energy used at EU ports and for intra-EU voyages, and 50% of energy from/to EU voyages.

For our analysis we have considered vessels trading in Europe and we have compared cost as aggregated of fuel, EU ETS, and Fuel EU.

The following costs have been taken into consideration for our calculation:

- EU Allowances: 70 Eur/EUA
- MDO: 650 Eur/ton
- LNG: 400 Eur/ton

Below (**Figure 16**) we can observe a graph reporting cumulative costs over years for the different configurations.

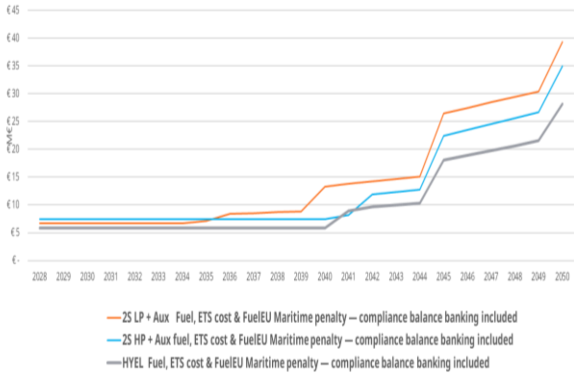

Figure 16: cumulative Fuel, ETS and Fuel EU costs for the different configurations

When vessels start to incur costs for emissions, they quickly overcome fuel expenses. As shown in the graph below, most of the expenses are attributed to emission-related costs. (**Figure 17**).

In this study, we have conducted a comprehensive analysis of the performance of hybrid electric systems compared to traditional configurations using LNG as fuel.

By examining the isolated Fuel EU data, it becomes evident that it is very difficult to continue beyond 2040 without upgrading the vessel. This is where hybrid electric concepts shine, as their modularity allows for confident future planning.

Regarding new fuels, it is worth noting that 4-stroke engines already offer compatibility with methanol, ammonia, and hydrogen blends. Furthermore, they are expected to be capable of running on pure hydrogen in the future.

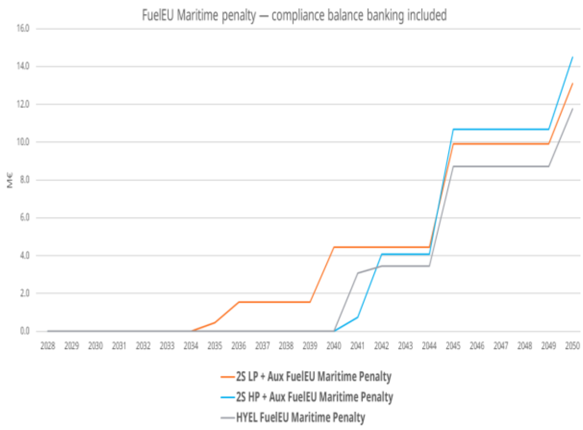

Figure 17: cumulative Fuel EU costs

The new generation of engines from Wärtsilä has been designed with the flexibility to accommodate these alternative fuels, allowing for easy retrofitting as they become more widely available and economically viable. By considering the potential for future fuel upgrades, vessel owners can future-proof their investments and adapt to evolving industry trends and regulations.

Also, when electrifying a vessel's propulsion system, it becomes easier to retrofit alternative power sources such as photovoltaic (solar) panels. These panels can be connected to an existing grid, allowing all the power produced to be efficiently distributed to where it is needed, whether it is for propulsion or for hotel (auxiliary) loads. The same principle applies to fuel cells as well, the installation of fuel cells can be done at any time, whether during the initial vessel construction or as a retrofitting option. If the technology allows, it may even be possible to replace traditional generating sets with fuel cells, depending on the specific requirements and compatibility of the vessel's power system.

Also, in the case of Wind Assist Ship Propulsion (WASP), hybrid electric system provides additional benefits, thanks to its modular design where only the necessary engines are online it is possible to take full advantage of the power reduction. In the case of a 2-stroke system, the full benefit of the energy-saving device may not be realized due to the ultra-low engine load created by the device. This results in reduced engine efficiency, offsetting some of the savings achieved through the use of the energy-saving device

The modular nature of the hybrid electric concept allows for the integration alternative sources or energy saving devices into the vessel's power system, providing additional flexibility and options for power generation. This adaptability ensures that vessels can take advantage of emerging technologies and advancements in fuel cell technology as they become more commercially viable.

6. CONCLUSIONS

The analysis of the case has demonstrated that the hybrid electric concept can be applied successfully to LNG carriers. While it may not be a one-size-fits-all solution, it proves to be a valid competitor to many established solutions, particularly in operating profiles where flexibility is required.

It is important to note that the successful implementation of this concept relies on ship design that considers the specific characteristics and footprint of this system, simply swapping the traditional concept for hybrid electric may not fully capture the benefits and potentialities. However, when the ship design is fully optimized around a hybrid electric system, the advantages become very evident.

By optimizing the ship design to integrate the concept effectively, vessels can benefit from increased efficiency, reduced emissions, and improved operational flexibility. The modular nature of the hybrid electric system allows for customization and adaptation to specific operating profiles, resulting in enhanced performance and cost-effectiveness.

One notable benefit is the potential for future conversions to alternative fuels. As the maritime industry continues to explore and adopt alternative fuels, such as hydrogen or ammonia, the hybrid electric system can be adapted to accommodate these fuels through modular upgrades and modifications.

Furthermore, the hybrid electric concept allows for the integration of alternative energy sources, such as fuel cells. Fuel cells offer the potential for even greater efficiency and reduced emissions, and their integration into the hybrid electric system can further enhance the vessel's performance and environmental sustainability. Additionally, it can easily incorporate energy-saving devices like rotor sails without compromising the system efficiency.

By embracing the modular nature of the hybrid electric concept, vessel owners and operators can future proof their investments and adapt to evolving industry trends and regulations. This flexibility allows for the incorporation of alternative fuels, alternative energy sources, and energy-saving devices, ensuring that the vessel remains competitive, efficient, and environmentally friendly in the long term.