Decarbonising long distance shipping with alternative fuels, technology synergy and digital design – case bulk carrier

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Abstract

We review a case of wind assisted bulk carrier design from an EU-funded project CHEK, where the machinery concept and various other energy saving technologies' synergies are the key to future ship designs. The results of project CHEK do not only showcase a possible path to decarbonised shipping but also provide a pragmatic view to ship owners how various solutions could be screened for their future vessels or when planning fleet retrofits.

Acronyms

ALS	Air Lubrication System
CEAS	Computerised Engine Application System (MAN B&W engines calculation tool)
CHEK	(EU-funded project) deCarbonising sHipping by Enabling Key technology symbiosis on real vessel concept designs
CII	Carbon Intensity Index
EEDI	Energy Efficiency Design Indec
ETS	Emissions Trading System
FMU	Functional Mock-up Unit
FOS	Fleet Optimisation Solution (Wärtsilä software)
FPV	Future-Proof Vessel
GHG	Green House Gas
HT	High Temperature (engine cooling water)
LBG	Liquid BioGas
LCA	Life Cycle Analysis
LNGpac™	Wärtsilä fuel gas supply system for Liquefied Natural Gas ships
LT	Low Temperature (engine cooling water)
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
ORC	Organic Rankine Cycle
PTI	Power Take In
PTO	Power Take Out
VLSFO	Very Low Sulphur Fuel Oil

Introduction to project CHEK

Project CHEK was an EU-funded joint industry-development project running during 2021-2024. The project focused on decarbonisation of long-distance shipping. The project revolved around conceptual design of two main case ships: a Kamsarmax sized tanker and a Meraviglia class sized cruise ship. The decarbonisation of the ships was done as a combination of technology and design synergy and, finally, by considering alternative fuels. The technologies were integrated digitally for the conceptual vessels, but the data for the modelling was collected, as far as possible, either from in-lab measurements from the CHEK technology partners or from real life demonstrations. The largest real-life demonstration of technologies was installing two WindWings by BAR technologies and Manta Marine onboard an existing bulk carrier. CHEK project was recognised in 2023 by the European Commission as a research and innovation project success story.

Figure 1. Bulk carrier Pyxis Ocean fitted with two WindWings

Project CHEK partners included BAR technologies, Cargill, Climeon, Deltamarin, Hasytec group, Lloyd's register, MSC, Silverstream technologies, University of Vaasa, World Maritime University, Wärtsilä and Manta Marine. The technical improvements that were studied for the bulk carrier, in addition to improved ship hull were sails, fuel-flexible hybrid machinery, waste heat recovery, air lubrication, shore power availability during the port calls, gate rudder and solar panels.

Ship digital design features for decarbonised shipping

A ship design process itself includes many analyses that support the ship layout and documentation generation. Traditionally, the focus and aim of the design has been in verifying the ship feasibility and performance in a few, selected dimensioning conditions, such as maximum capacity and design speed etc. Also, ships will have to pass the energy efficiency design index (EEDI). However, new requirements for the ship performance are introduced continuously. Decarbonisation of the industry is one key driver behind the need to keep improving ship performance.

Ship decarbonisation is a combination of efficient operation, good design and technical improvements and, eventually, low carbon fuels. The operational profile is, thus, a leading driver and an integral part of the decarbonisation. To incorporate all this efficiently in ship design, new process to support the traditional ship design process is necessary.

The future-proof vessel (FPV) design platform was one of the development areas in CHEK. This is a developing entity that aims to produce ship designs with low emissions. We lift forward several dimensions which are considered in the FPV platform. One dimension is the physical ship hull and volume dimension, which is the typical work that is done for dimensioning the vessel correctly and it's required for compiling the ship specification and other documents for ship building. Another dimension is the ship external forces, which are not documented in ship design materials, but they impact the ship operation. A third dimension is the ship functional dimension focusing on energy system interactions and energy conversions. For decarbonised shipping, the operational stage represents a large share of the emissions, but also several other processes contribute to the ship entire environmental impact. Therefore, the fourth digital design and FPV design platform layer is the life cycle analysis (LCA), where the other layers provide input. Figure 2 illustrates the LCA framework combined with the operational analysis tools. The project CHEK bulk carrier life cycle analysis work was presented in a separate article (Dong et al., 2024).

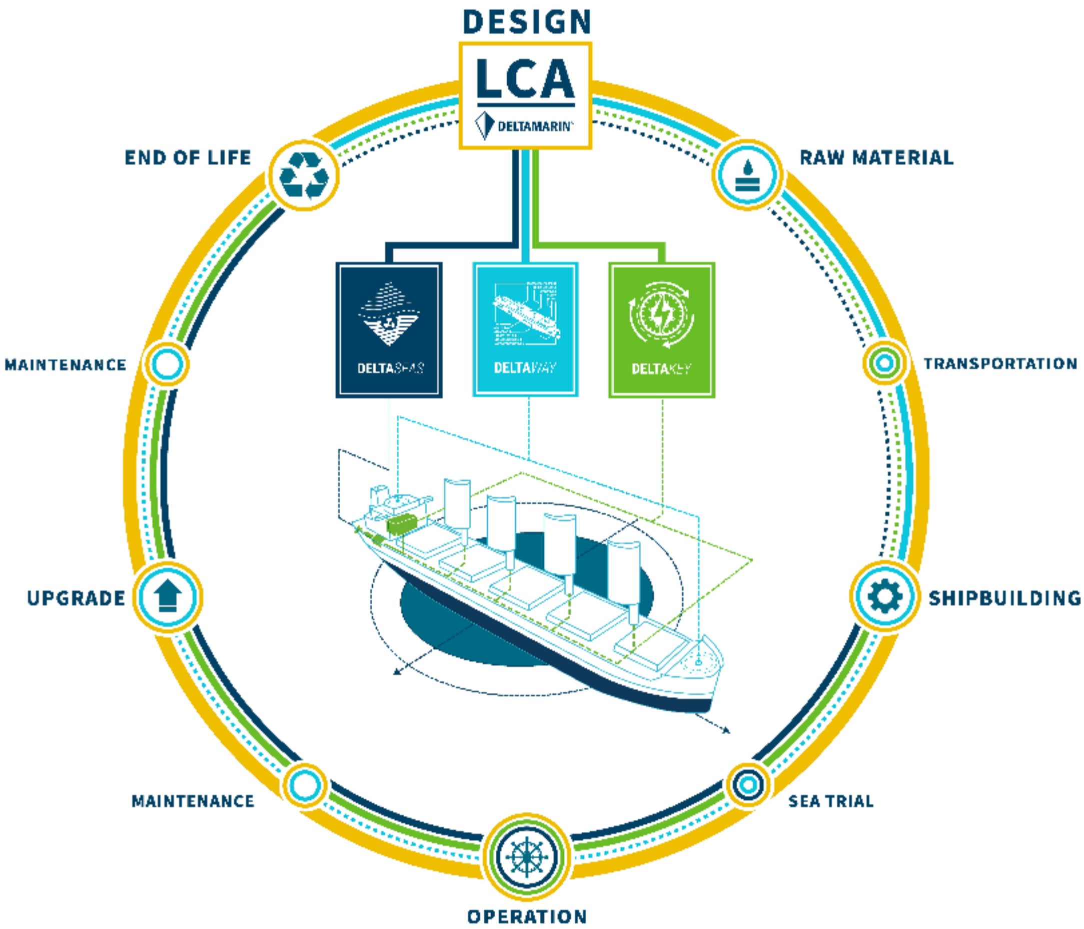


Figure 2. Digital design layers contributing to "design-based" LCA

The digital modelling for CHEK ships was developed in three separate "generations" with each round adding more details around the studied ship cases, backed up by measurements from the field. The bulk carrier ship and the studied main technologies were presented after finishing the second round of modelling in the HIPER 2023 conference (Sandberg et al., 2023). Therefore, this paper focuses on summarising the new aspects of the modelling and the final results from project CHEK bulk carrier vessel.

Integrating wind power for propulsion prediction

The operational and propulsion layer of the FPV design platform is called DeltaSeas. Typically, and in it's simplest form DeltaSeas would include a speed profile for the ship. In traditional ship design, the weather and other resistance adding factors on top of ship calm water propulsion prediction is added on top of the propulsion power in form of a fixed "sea margin."

Nevertheless, for the CHEK vessels this was not a satisfactory approach. Instead, for the ship routing, a set of geographical coordinates was generated with navigational routing software Wartsila FOS coupled with an interpolation algorithm. The operational routes are illustrated in Figure 3. The seasonal weather variation was covered by assuming that the ship sails along each of the routes 12 times, starting on the first day of each month. The main operational speed was constant 12,5kn and typical expected loading conditions for the vessel were considered in the analysis (ballast or laden). Based on the vessel's position and assumed time the wind and wave parameters were gathered from the weather database. The main databases used in the project are provided by the European Commission initiative called Copernicus (*Global Ocean Waves Analysis and Forecast*, n.d.; *Global Ocean Wind L4 Near Real Time 6 Hourly Observations*, n.d.). This initiative aggregates data provided by European meteorological institutes.

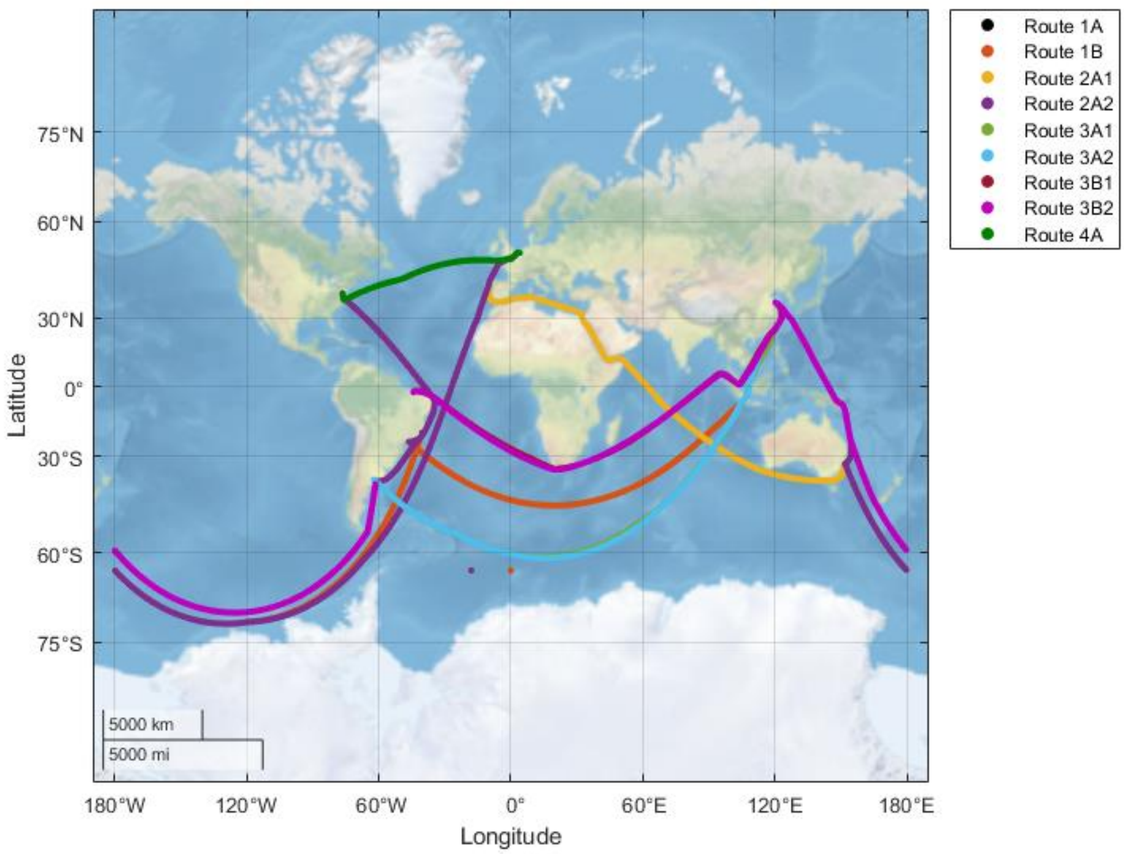


Figure 3 Waypoints of the bulk carrier routes studied

For studying more accurately the impact of sails to the ship and impact of technologies such as gate rudder, the effect of wind propulsion on the propeller thrust is considered in the study. The wind propulsion system generated additional side forces and yaw moments that must be balanced by the hydrodynamic forces and the rudder action. When in equilibrium, the total moment acting must be zero. This results in the aero- and hydrodynamic forces acting along one line (Elger et al., 2020). The procedure for finding the best possible angle of attack of sails to achieve equilibrium of forces and moments is shown in the flow diagram in Figure 4.

The effect of heel angle on the drift forces, yaw moments, driving force and the hull resistance is neglected. The first step is to calculate the lift and drag forces of the sails for an angle of attack that generates the highest lift coefficient. The initial drift angle is zero. Having calculated the driving and side force provided by the sails, the drift angle is calculated using an iterative procedure. When drift angle in steady state condition is found, the resistance due to the drift and rudder is calculated. Now, if the aero- and hydrodynamic moments are not in balance then the angle of attack of sails is decreased, and all calculations are performed in the loop again until the force and moment balance is achieved. Once this condition is satisfied, the final resistance and the effective thrust of the propeller is calculated. The full description with their respective formulas can be referred to from (Elger et al., 2020).

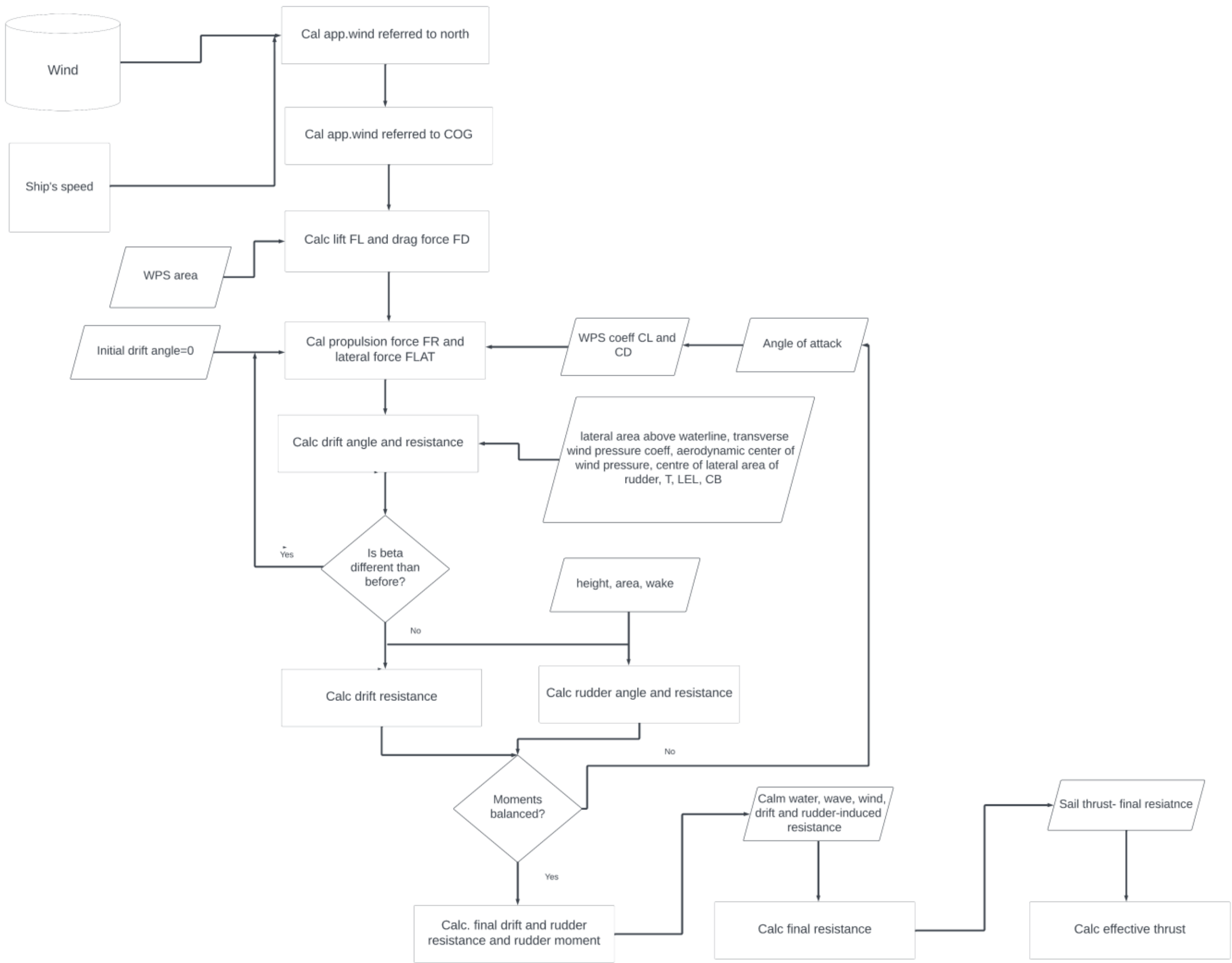


Figure 4. DeltaSeas algorithm for extraction and processing of data for ship added resistance for the bulk carrier during the final modelling round

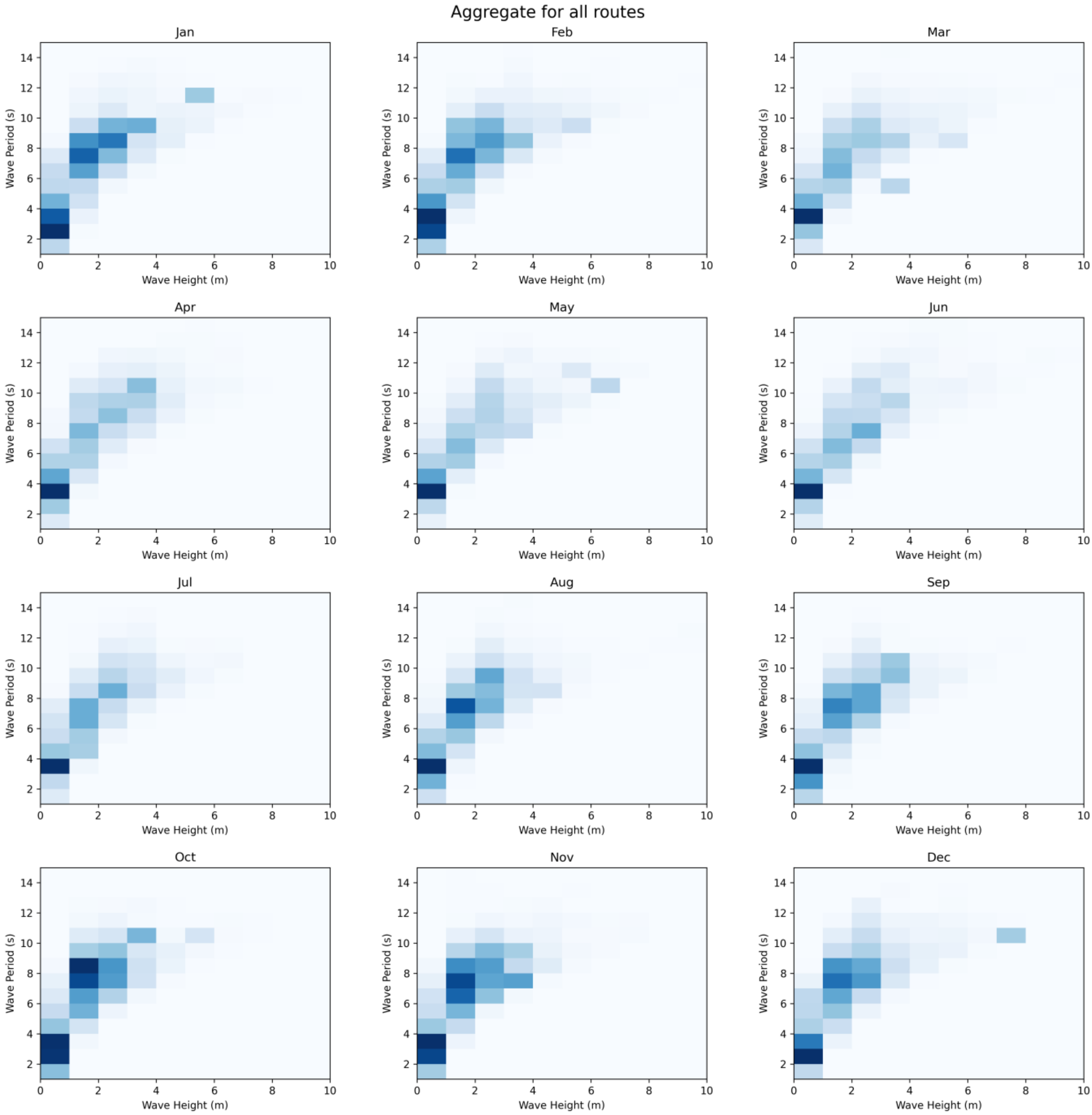


Figure 5 Scatter diagram of waves for 12 voyages

Figure 5 shows the scatter diagram of the waves for 12 different cruises. A visualisation of the relationship between wind speed and direction can be found in Figure 6.

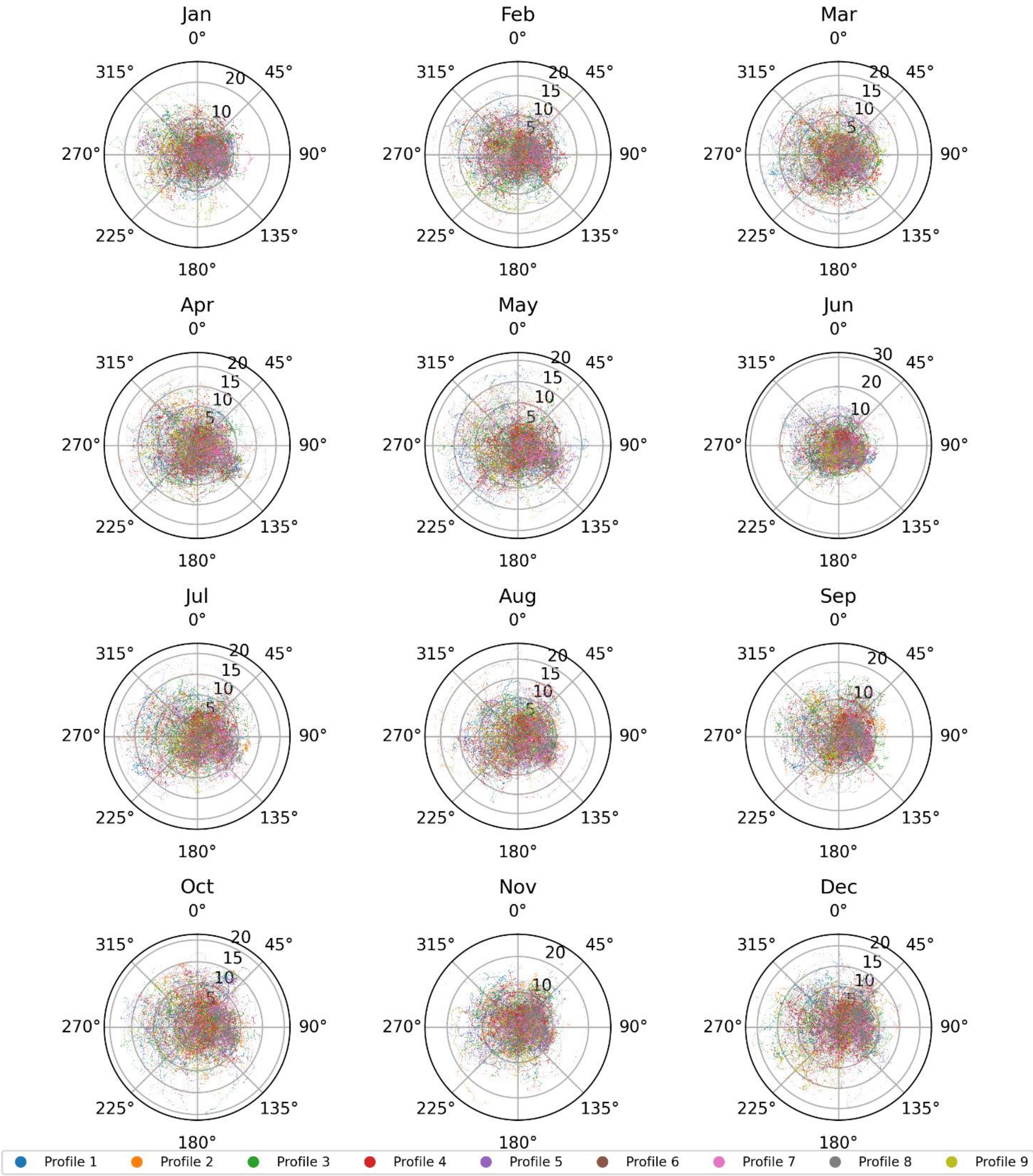


Figure 6 Polar plot true wind speed – 12 voyages

Energy system modelling and flexible machinery development for wind assisted ships

A system level energy model is another necessary layer of the FPV design platform, called DeltaKey. The inputs for the model include ship fuel types, machinery components and the energy requirements. The propulsion power is an input from DeltaSeas. The model is coded by Deltamarin and it was further developed in project CHEK on top of Matlab and Simulink tools, as described in (Sandberg et al., 2023).

In project CHEK the focus was in implementing various technologies in the ship energy system. Part of the technologies, such as sails was considered in the DeltaSeas code, but for instance air lubrication system (ALS) was considered both in DeltaSeas (reduced ship hull resistance) and in DeltaKey (the electricity need). For the Organic Rankine Cycles (ORC) an entire logic how several units would be implemented in a ship was developed during CHEK.The final round of simulations included absorbing in the master simulation loop an external powerplant model in form of a Functional Mock-up Unit (FMU), produced by Wärtsilä.

The baseline ship machinery model is comprised of a 2-stroke engine model directly connected to fixed pitch propeller (7,4m diameter with 1100kN upper thrust limit)). The fuel type utilised was VLSFO (LHV 40,6 MJ/kg) and the engine type reference was MAN 5S50ME with 9500kW installed power and variable speed (89,8 RPM at 100% load) The engine performance data was obtained from the engine maker CEAS software. The hotel load is produced by 3 x 500 kWe Yanmar auxiliary engines with an engine switch point at 65% load. Furthermore, the FMU automatically calculates added electrical consumption for Lube oil, HT and LT pumps as well as for auxiliary blower for Main engine loads below 35%. Figure 7 illustrates the baseline machinery configuration.

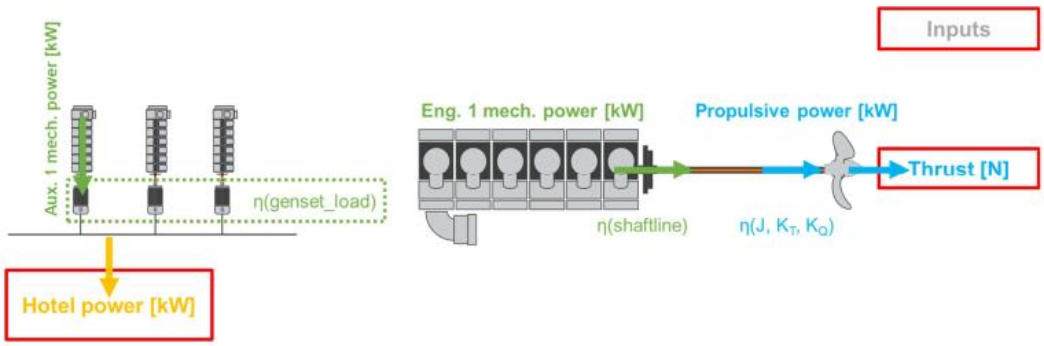


Figure 7. Bulker: Components of the 2-stroke engine model

A fuel-flexible 4-stroke engine power plant configuration was studied in project CHEK that could answer to the large variations in ship powering requirements due to the energy saving technologies. Figure 8 illustrates the principle of this configuration.

The propulsion in the 4-stroke machinery is comprised of two four-stroke Wärtsilä 31 (600 kW/cylinder) engines connected to controllable pitch propeller (diameter 7,4m, min./max pitch 0,4m/1,55m and 1100kn propeller thrust upper limit) via a two-speed gearbox as well as two Wärtsilä 20 (1170 kW) auxiliary engines that can boost propulsion via power take in (PTI) function. The electricity can be produced by auxiliary engines or shaft generators with a maximum capacity of 2000kW. Additional hotel load for the LNGPac^{TM} system is calculated automatically within the model. A battery in the power train enables allowing higher engine loads up to 100%. The main fuel is MDO or liquid biogas (LBG).

The 4-stroke FMU is an optimiser, which finds the optimum combination of propeller pitch and engine operating point that will minimise either fuel energy consumption, propeller power or total GHG emissions from the engines. The scalable powerplant has more control parameters associated with it, which are listed for the studied configurations.

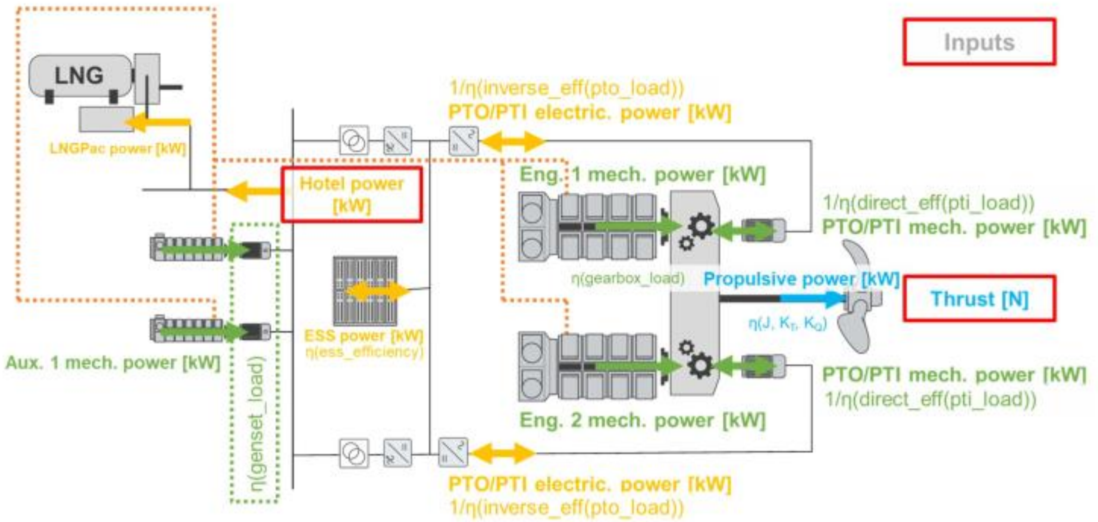


Figure 8. Bulker: Components of the 4-stroke engine model

Naval architectural considerations

The backbone of each digital ship design is the ship layout, hull, space and volume model, including all naval architectural analysis which is necessary to ensure that the ship design is feasible and efficient. All this in the FPV design platform we call “DeltaWay”. In practice, any new technology that is installed onboard or added in design during conceptual design stage, will require the necessary space. Inevitably, this influences on ship weight and, therefore, also consumption. However, the holistic impact of added systems for ship is not straight forward, since sometimes the added weight of the ship does not necessarily reduce the amount of cargo transported, if the cargo is more volume-critical than weight-critical. Therefore, the full impact of technologies on the ship layout was not the focus in CHEK and the simulations were performed with fixed draught of the vessel. Nevertheless, a stability review was performed for the ship regarding the technologies to ensure that the gained results are still relevant.

Table 1 summarises some impact that introducing the machinery with LBG as fuel and some of the largest energy saving technologies, the sails, brings. For instance, compared to the reference, more weight is added to ship, which has a theoretical impact to ship cargo carrying capacity. Slightly more volume is available for cargo, but the weight carrying capacity is reduced. We approximated based on the ship design data that a 20cm addition to draught at the 12,5kn operational speed could increase the propulsion power by 1,6%. The impact at higher speeds is larger, but still rather moderate. Obviously, if proceeding with the design to further design stages, all selected technologies are included in the ship weight calculation and, eventually, the impact is visible in ship powering.

Table 1 Examples of impact of selected CHEK combinations to vessel draught (T) and cargo carrying capacity.

		VLSFO / 2-stroke	LBG + 4-stroke	LBG + 4-stroke + sails
Cargo hold volume diff	%	ref	0,64%	0,64%
Lightweight change	%	ref	4,65%	9,41%
T @ 79800 DWT	m	14,45	14,55	14,65

Figures 9a and 9b illustrate the difference in the general arrangement between the standard vessel with a two-stroke engine having HFO as fuel and the dual fuel 4-stroke engine configuration utilising LBG as fuel.

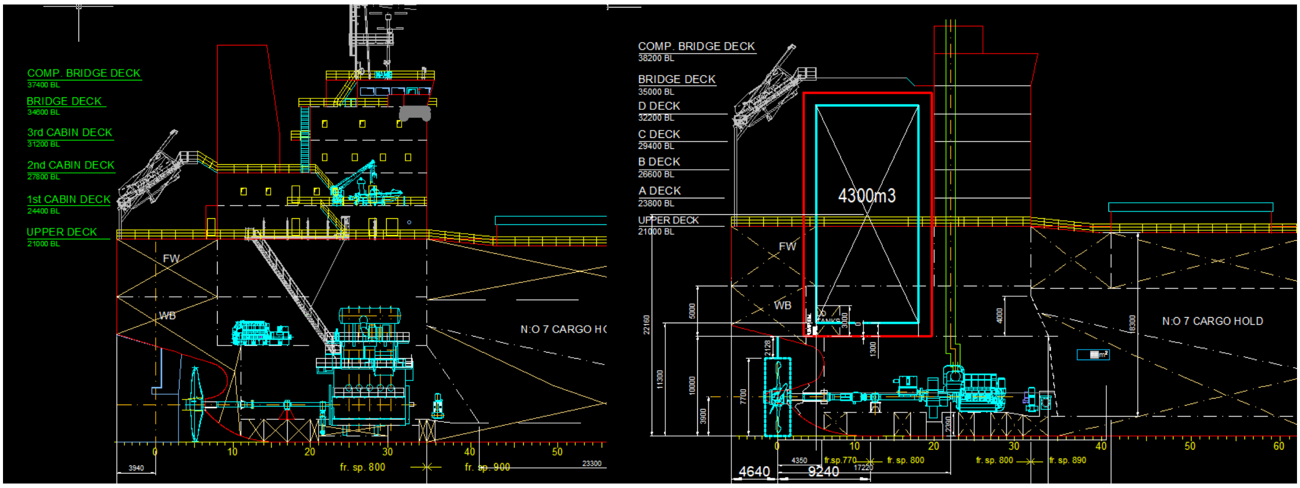


Figure 9a and 9b: Bulk carrier profile in the engine room area with HFO as main fuel (left) and gas fueled 4-stroke machinery (right)

CHEK technologies and simulation main results

The bulker simulation cases are presented in Table 2. Each of the cases has been performed on the 9 voyages presented previously and with a starting time in each of the 12 months in one year. The simulations outlined in grey are based on the 2-stroke machinery concept acting as industry baseline. The main engine uses VLSFO and Auxiliary engines with boilers use MGO. Within the 2-stroke concept, improvement in hull and fouling levels has been studied, which then serves as the baseline for the 4-stroke machinery concept. Project CHEK reference ship performance was defined as EEDI phase 2 requirements fulfilling ship.

The cases outlined in light blue are done for a 4-stroke scalable power plant concept with various combinations of technologies. All simulations are done with MDO as the primary fuel. Finally, the light green shade represents simulations with LBG as primary fuel. Additional alternative in the form of electric heaters in ports was added to calculate the final impact on the vessel's energy consumption.

Table 2. Simulation matrix in terms of technologies. Fuel types are mentioned in the second column and they show primary fuel for the Main and Auxiliary engines.

CHEK EEDI Phase 2 baseline	VLSFO/ MGO	The baseline energy consumption and emissions are calculated based on the scaling of the clean hull condition simulation.
2s_base_foul10	VLSFO/ MGO	2-Stroke engine with reference hull (BR1) and 10% resistance increase relative to clean hull due to 10% hull fouling margin
2s base hasy5	VLSFO/ MGO	2-Stroke engine with reference hull (BR1) and 5% resistance increase relative to clean hull due to Hasytec's ultrasound antifouling benefit
2s DM hasy5	VLSFO/ MGO	2-Stroke engine with Improved hull developed by Deltamarin and 5% resistance increase relative to clean hull due to Hasytec's ultrasound antifouling benefit
Below runs include the new hull form and Hasytec's ultrasound antifouling by default. Furthermore, all 4-stroke cases have 2 MW PTO/PTI capacity included by default		
4s DM hasy5	MDO	Wärtsilä's Scalable power plant, 8-cylinder engines, including PTO/PTI and Battery as spinning reserve as the base case.
4s 8c CI	MDO	Scalable power plant, 8-cylinder engines with PTO/PTI and Battery as spinning reserve. **Shore power enabled in all ports**
4s 8c ORC	MDO	Scalable power plant, 8-cylinder engines, PTO/PTI, Battery as spinning reserve. **2 x Climeon HP150 Units enabled in the system**
4s 8c ALS	MDO	Scalable power plant, 8-cylinder engines, PTO/PTI, Battery as spinning reserve. **Silverstream's Air lubrication is enabled at sea**
4s 8c Sails	MDO	Scalable power plant, 8-cylinder engines, PTO/PTI, Battery as spinning reserve. **2 x BAR Technologies WindWing sails are used**
4s 8c power	MDO	Scalable power plant, 8-cylinder engines, PTO/PTI, Battery as spinning reserve. **Combination of Shore power, ORC unit**
4s 8c power ALS	MDO	Scalable power plant, 8-cylinder engines, PTO/PTI, Battery as spinning reserve. **Combination of Shore power, ORC units, and ALS**
4s 8c power Sails	MDO	Scalable power plant, 8-cylinder engines, PTO/PTI, Battery as spinning reserve. **Combination of Shore power, ORC units and 2 x Sails**
4s 8c combo	MDO	Scalable power plant, 8-cylinder engines, PTO/PTI, Battery as spinning reserve. **Combination of all power technologies, Sails, ALS and Gate rudder**
4s 8c combo LBG	LBG/ Pilot	Same as the 4s 8c combo, with LBG as the primary fuel
4s 8c combo LBG ELB	LBG/ Pilot	Same as above, with electrical heating in the port enabled

Figure 10 illustrates the simulated energy saving related results with the bulk carrier concept developed during the project. The savings are compared against an “EEDI phase 2” compliant vessel. Therefore, the first 7,9% of energy saving are purely gained from scaling the baseline ship according to the difference between the vessel attained EEDI and the phase 2 EEDI requirements. In total, energy savings of up to 51% compared to the EEDI 2 baseline are observed with the simulated cases. Nevertheless, if not considering the EEDI scaling, the pure energy savings for the vessel simulated were at maximum close to 45%.

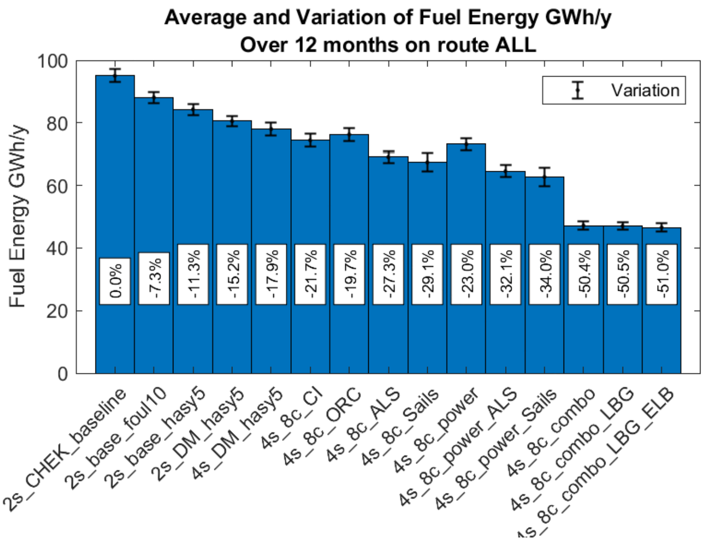


Figure 10. CHEK Bulk carrier main results with all routes. Results of Energy Consumption. absolute values shown on the y-axis, relative changes to EEDI Phase II adjusted baseline are shown on bar labels.

The bulk carrier emission reductions for the same result selection are illustrated in Figure 11. According to grant agreement, the bulk carrier carbon equivalent emissions were modelled on a well-to-wake basis. RED II standard for the biofuel was utilised for calculation. Therefore, the results with LBG fuel show even negative carbon footprint for the ship fuel operations. With another standard or analysis, the result would be slightly different.

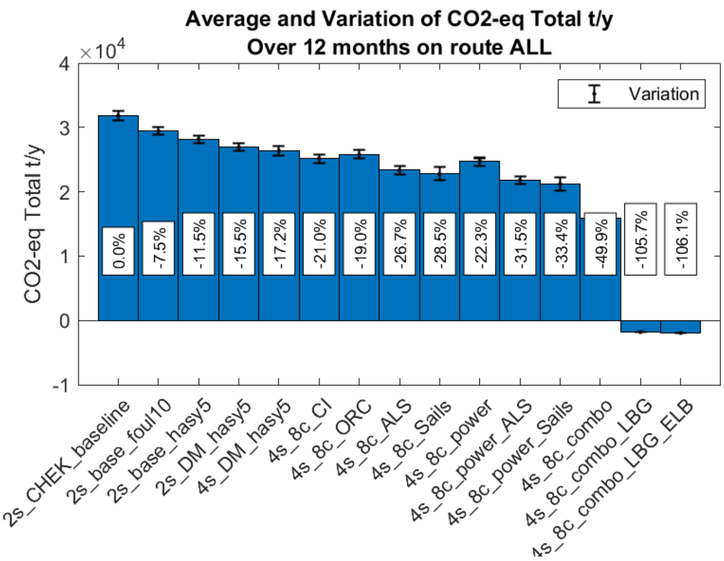


Figure 11. CHEK Bulk carrier main results regarding CO2-equivalent emission reductions

Figure 12 visualises the variation in main engine delivered power and propulsion powers in the two of the most different cases: baseline setup and the best energy saving combination. For instance, the symbiosis of ship energy saving technologies enables reducing the ship average propulsion requirements from 6 to 3MW.

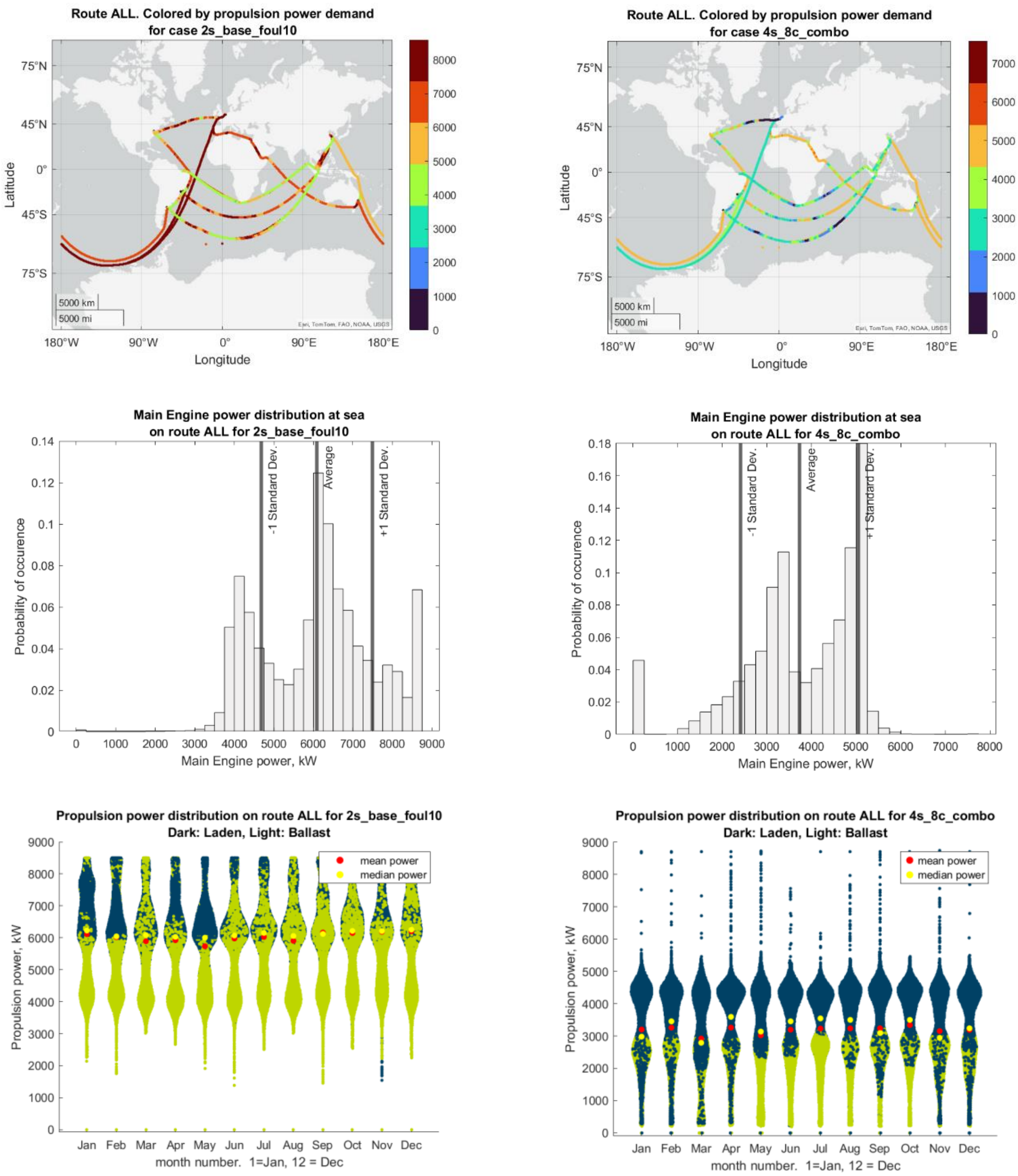


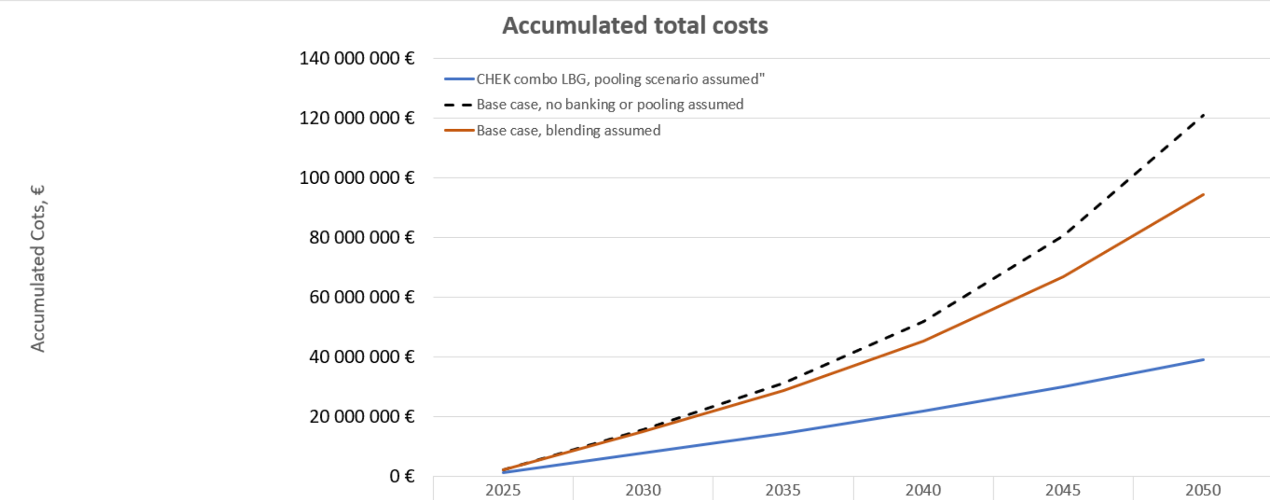
Figure 12. Bulker – All routes. Visualisation of propulsion power demand (kW) at different sections of the route. Left: Base case 2-stroke configuration. Right: CHEK Combo. Top: propulsion powers at different sections of the route. Middle: Propulsion power distribution over the year. Bottom: Propulsion power distributions in different months of the year

How about CII compliance and operational costs involving FuelEU Maritime and carbon tax?

The ship carbon intensity index (CII) can be calculated based on the simulated fuel consumption. Assuming that the development of CII requirements follow the yearly 2% reduction in the acceptable limits, the baseline vessel with VLSFO as fuel would be on the sufficient level C until year 2025 and get the first E rating in year 2030. The energy saving CHEK combo with LBG as fuel would have no compliance issues as it would receive rating A until year 2050. Thus, from the international rule framework point of view the traditional ship designs with fossil fuels will not be compliant for much longer. It should be noted that all results of CII would be completely different with another operational profile.

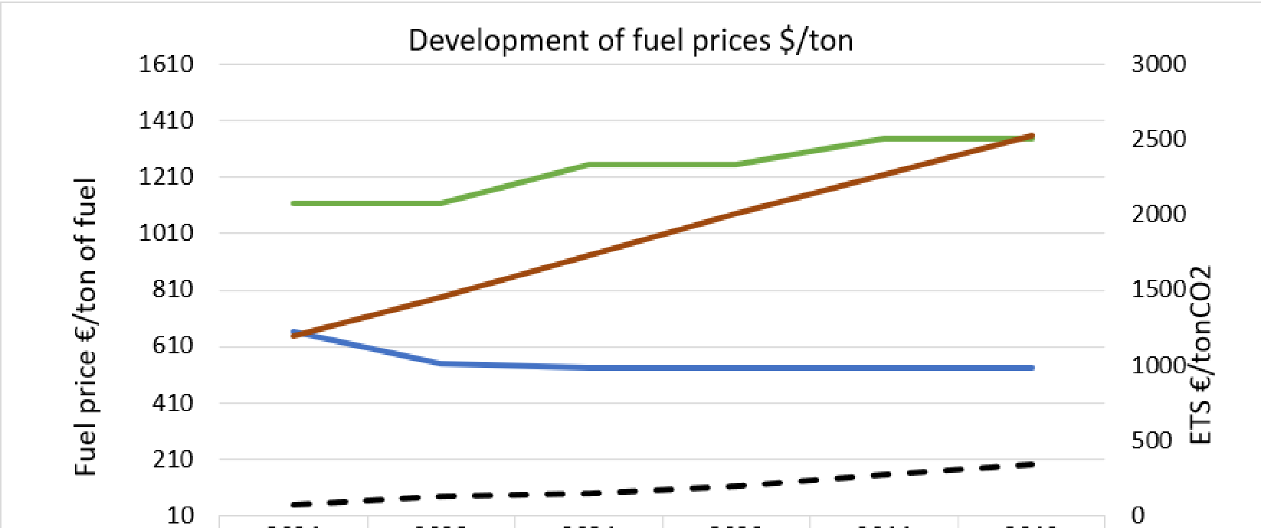
Nevertheless, for ships operating within EU, new costs are introduced through the legal framework of "Fit for 55 package", where EU emissions trading system (ETS) sets a price for carbon emissions and FuelEU Maritime reduces the carbon intensity of the energy which is used onboard ships. Figure 13 illustrates the combined costs for the bulk carrier with the baseline VLSFO machinery and with the LBG machinery including fuel costs, ETS costs and FuelEU penalties.

In this case the penalties are only valid for the baseline vessel. The CHEK combo vessel receives also a 3% reduction in the achieved carbon intensity due to installed wind power. For demonstration purposes, the calculation is performed for a scenario when the ship would be operating 33% of the time within the EU. For case with LBG (4s 8c LBG Combo ELB) a Well-to-Wake factor of -05709 gCO2/gfuel is assumed. The Well-to-Wake factors for the base case (2s_base_foul10) are according to EU guidelines (EU 2023/1805). It is assumed that the ship will pool with other ships when using LBG and therefore generate revenue. The revenue generation is assumed to be fully equivalent of reducing the penalties for "non-compliant" vessels within the pool. Another speculative scenario was generated for the baseline vessel by introducing biofuel to the vessel. The amount of fuel blending depends on the assumed price difference between fossil and biofuel and the penalty fee. When using conventional fuels, we simply assume that the ship will pay the penalties. Figure 13 illustrates how the ship with LBG machinery has less operational costs from the start and the gap between conventionally fueled vessel is expected to grow substantially in the future years. The assumptions for ETS and fuel price scenarios that were utilised in the calculation are visualized in Figure 14.



	2025	2030	2035	2040	2045	2050
CHEK combo LBG, pooling scenario assumed"	1217 566 €	7837 592 €	14555 705 €	21919 329 €	30145 671 €	39268 569 €
Base case, no banking or pooling assumed	2341 494 €	15833 380 €	31508 333 €	51957 715 €	80811 176 €	121197 535 €
Base case, blending assumed	2229 443 €	14973 102 €	28867 761 €	45571 652 €	66965 858 €	94555 429 €

Figure 13 CHEK bulk carrier operational cost speculations



	2024	2029	2034	2039	2044	2049
LBG	1117	1117	1257	1257	1350	1350
VLSFO	660	549	537	537	537	537
ETS	70	130	150	200	270	340
Bio VLSFO	1193	1452	1730	2008	2267	2525

Figure 14 ETS and fuel costs assumed for the FuelEU Maritime cost analysis

Conclusions

The results of the simulation demonstrated that we could gain considerable energy savings in ships with a combination of various technologies and design features. The operational profile is a key factor to be considered in the modern ship design, where we do not aim to optimise the ship performance only for selected operational points but for a realistic operational range. Some of the energy saving technologies, such as applying Organic Rankine Cycles and shore power resulted together in similar energy savings as when summarising the savings from individual runs. Nevertheless, typically the sum of several improvements is a more complex equation. For instance, the air lubrication reduces the required ship propulsion power and the compressors delivered air to the air release units increase the ship electricity consumption. Also, with the simulated 4-stroke machinery, the air lubrication interacted with PTO/PTI utilisation, influencing further on the engine loadings and engine configuration. The sails were the single largest energy saving means. They are strongly affected by the weather conditions and a monthly spread between 10 and 20% in energy savings was observed for the vessel.

Even if the combined fuel or energy savings over 40% are dramatically large, the CHEK approach has been rather pragmatic. In general, the CHEK technologies have a proven track record, and this kind of savings are reachable for ship owners. In fact, even further savings are within reach, when combining ship voyage optimisation and weather routing opportunities in the "CHEK mix" of improvements. Also, a larger number of sails could be fitted onboard, in addition to other technology combinations. Our calculations show that making a wise selection of technologies and fuels makes a large difference to ship operational cost, with increasing regulation regarding ship carbon emissions. In practice, not all technologies have to be installed in new ships from day one, and the future fuels can be also adopted later during ship life cycle. Nevertheless, from the design perspective certain key structural and space related selections should be made already in the beginning of the ship design project, leading to "future-proof" ship designs. The future-proof vessel design platform is the designers' answer to navigating through shipping decarbonisation. The digital design approach presented in project CHEK allows screening of various design features and fuels with the aid of the operational and energy simulations. The most promising selections are chosen for the more detailed design and naval architectural analysis with possibility to re-run the earlier performed simulations with more accurate responses from the ship systems.

Extremely energy efficient ships require also a revolution in ship machineries. Even without the energy saving technologies, the 4-stroke engine powerplant including CPP and PTO/PTI and batteries as spinning reserve resulted in a notable energy saving, compared to the base case. Nevertheless, project CHEK did not focus on making a full machinery study. For instance, the shaft generator options were not analysed for the two-stroke machinery. Despite this, a common nominator for future machineries for ships like "CHEK bulker" is that flexibility throughout a wide operational range is required. For instance, if the vessel machinery does no support low load operation, the benefits of sails might be utilised only to gain operational speed rather than reducing emissions and energy. Still, the power reserve must exist for safety reasons and for any future changes in the ship operation, for keeping the vessel also commercially attractive. This can be achieved with the holistic analysis process demonstrated in project CHEK, where unnecessary margins from systems are reduced but total powering and safety is not compromised.

Acknowledgements

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