Evolution of ship design from energy efficiency towards holistic sustainability

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This article was originally published in the HIPER 2025 conference in Tullamore, Ireland.

Abstract

Sustainability is an important design criteria today, and the framework of rules is constantly developing. Within the EU, the 'fit for 55' framework introduces direct costs for carbon-emitting ships. This highlights the importance of modelling ship energy consumption in operation already during the ship's conceptual design stage and evaluating ship lifetime operational costs. We provide examples of the cost impact of these rules. The model of ship energy flows and consumption is at the heart of the required analysis. We review the development steps taken and the process of sustainable ship design from Deltamarin's perspective.

1. Introduction

Ships have to be designed today for good environmental performance and sustainability, overall. This is an important overarching theme in developing solutions for the industry. The existing and constantly developing framework of rules supports this trend. Globally, ships must comply within the limits of the carbon intensity indicator CII, and they must also pass the energy efficiency index. In Europe, the 'fit for 55' package is a legal framework that also guides maritime transport towards the green transition. A part of this framework is the EU emissions trading system (ETS), which defines a price for carbon emissions emitted from ships. Another part of the package is the FuelEU maritime initiative for reducing the carbon intensity of the energy that is utilised onboard ships. In addition to these, the alternative fuels infrastructure (AFIR) regulation focuses on the infrastructure of the recharging or refuelling of ships, and it sets, for instance, demands for arranging shore power for container vessels and passenger ships by 2030.

Nevertheless, the profitability of the ship is always a key criterion for the decisions made for a new building vessel or when upgrading the fleet. The energy efficiency of ships has long been an important factor to consider in ship design with a direct connection to ship operational costs. Today, ship owners also face direct cost consequences due to the ETS and FuelEU Maritime regulations in the form of carbon tax and penalties for not complying with the ship energy carbon intensity targets.

The new rules, cost pressures and the overall need and desire to increase ship sustainability introduce many new variables to the process of designing ships. On top of the traditional ship design process, including the optimisation of the ship and its systems technically and managing ship building costs, the process must absorb new analysis criteria. Examples of these are speculations for future rule requirements regarding ship technical performance and especially the economic variables regarding future fuels, carbon emissions and energy prices.

This publication discusses the new requirements for ship design and the development of the process of energy-efficient ship design with examples from Deltamarin's design process and recent projects. The article is structured in the following manner: first, we take a specific view of the FuelEU Maritime and ETS regulations, followed by a practical example from our recent development project of the regulatory costs, compared to the ship's pure energy costs in chapter 3. After presenting Deltamarin's framework for modelling the ship's operating costs in Chapter 4, the next chapter reviews the core elements and our history in the process of ship energy modelling. In Chapter 6, we discuss another aspect of ship decarbonisation with the case of a battery-powered ferry. Finally, we conclude with a glimpse at other new future focus areas concerning maritime sustainability.

2. A closer look at ETS and FuelEU Maritime

The EU ETS is a cap-and-trade system that has existed for power plants and industry for many years. As of 2024, it is being extended to cover maritime shipping. Under this system, shipowners must purchase and surrender emissions allowances (EUAs) for their CO_2 emissions. Similar to FuelEU Maritime, the coverage is 100% of emissions for intra-EU voyages and 50% for extra-EU voyages, including emissions at berth. The cap on total allowances will gradually tighten, which typically drives up the price of EUAs.

By incorporating shipping into the ETS, the EU is effectively putting a price on carbon emissions. Over time, as the cap decreases, allowances will become scarcer and more expensive, intensifying the financial pressure to cut emissions. Vessels that continue burning fossil fuels will pay increasingly high costs, whereas ships using cleaner fuels or more efficient operations will reduce their EUA requirements and overall expenses.

Currently, the ETS scope is on a Tank-to-Wake basis and includes only CO_2. The scope will expand in 2026 and start covering nitrous oxide and methane emissions as well. The development of the ETS cost is uncertain but expected to increase progressively as the market becomes more constrained.

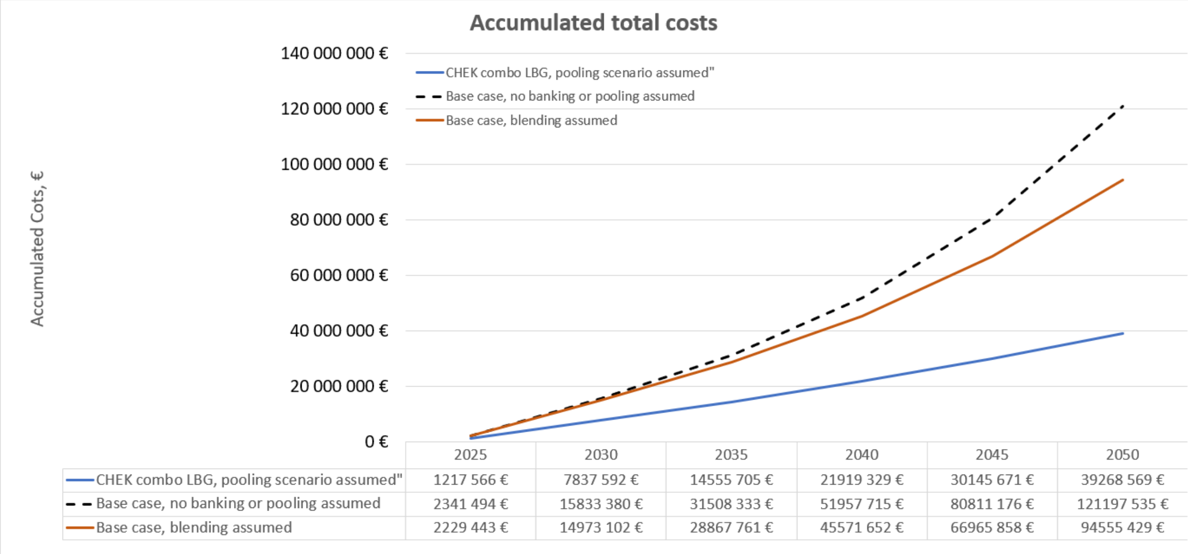
The FuelEU Maritime is an EU regulation to significantly reduce the carbon intensity of marine fuels used in shipping. The regulation is in effect from 2025 and applies to vessels with a gross tonnage (GT) of 5,000 or more that call at EU/EEA ports. This measure covers all emissions produced during intra-EU voyages, including those at berth, as well as 50% of the emissions for voyages between EU and non-EU ports.

At the core of FuelEU Maritime are its greenhouse gas (GHG) intensity targets. These targets require progressive reductions in well-to-wake CO_2-equivalent emissions, starting from a reference value of 91.16 gCO_2-eq/MJ established in 2020. Over time, the allowable GHG intensity will be tightened, pushing shipowners towards cleaner energy options and more efficient operational practices. Compliance with FuelEU Maritime is enforced through a system of penalties and incentives. Shipowners who exceed the prescribed intensity thresholds will face financial penalties, while those who achieve greater reductions may earn credits. This dual approach is designed to create a strong economic incentive for early movers and effective action in reducing emissions. The non-compliant vessels are charged €2,400 per tonne of VLSFO-equivalent for every unit of energy that exceeds the compliant threshold, resulting in significant financial penalties. Therefore, in many cases, even high-cost fuels such as e-fuels will most likely be more economical than paying the penalties.

There are multiple options to comply with the regulation. As an example, the surplus credits for over-compliance can be banked for upcoming years and used when needed. Blending more sustainable energy sources into the fuel mix might be a feasible option as well, of course depending on the availability and infrastructure of such resources. Also, pooling with ships using a more sustainable energy mix is a economically wiser option than paying the penalties, and likely an easier option than bunkering sustainable fuels. For a sustainable and over-compliant vessel, credits/revenue can be earned by pooling with less sustainable vessels, and thereby balancing the cost of a most likely more expensive bio/e-fuel.

3. Money, money, money

How relevant can these new rules be regarding ship operational costs? Figure 1 presents a recent example from EU-project CHEK regarding projected operating costs for a Kamsarmax-sized bulk carrier. The project and simulation results are presented most recently in a white paper published originally at a conference in 2024 (Elg et al., 2024). This kind of ship is designed for global operation, and the rules within the EU might not apply most of the time. Nevertheless, in this example calculation, we assume that the ship would operate for a third of its time within the EU. The "Base case" ship in Figure 1 represents a modern ship equipped with traditional fuel and machinery, and "CHEK combo" represents a conceptual design including a liquid bio gas (LBG) efficient hull, fuel-flexible machinery and a combination of energy-saving technologies. The accumulated costs include fuel price, carbon tax and FuelEU Maritime penalty where relevant. It is also assumed that the "CHEK vessel" will get certain benefits from utilising biofuel and being, thus, over-compliant regarding the fuel's carbon intensity requirements. This kind of vessel can pool its surplus compliance balance with other ships, and the possible impact of pooling on her lifetime energy and compliance costs is estimated in Figure 1.



	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 1: Operational costs for CHEK bulk carrier

The associated fuel costs are presented in Table I, and sources of assumed costs in Table II.

Table I: Development of prices for the CHEK project calculation in €/ton of fuel

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

Table II: Sources of the fuel and ETS Prices assumed in the CHEK bulker and RoPAX examples

Fuel type	**Source for price scenario**
HVO	It's time to de-risk vessel construction | LR
LFO	Fuel Cost Calculator | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
LBG	CHEK_D8.3 Report on cost comparison for the fuel options_final pdf
ETS	https://doi.org/10.1016/j.apenergy.2021.116914
MDO	23% added on top of LFO prices
LNG	Fuel Cost Calculator | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
Electricity	10068_LR_Methanol_Institute_White_Paper_200320_4.4.pdf Renewable electricity (The average of lower and upper cost scenario)

Figure 2 illustrates the fuel and regulatory costs separately for the base case vessel, assuming the two different strategies for coping with the rules. We can clearly see that, during the early years of operation, a ship such as the CHEK "combo LBG" bulker would create operating savings mainly due to consuming almost 50% less fuel than the baseline vessel. In future decades, the difference might grow three-fold due to the increasing weight of the regulatory costs. The black line in Figure 1 presents the maximum costs, including rule compliance by paying penalties. Nevertheless, another possible scenario is presented regarding operating costs for the baseline ship, including FuelEU maritime rule compliance by blending just enough bio-diesel to avoid triggering the FuelEU penalty. The difference in these two compliance strategies is visible in both figures 1 and 2, considering the selected price development scenarios in Table I.

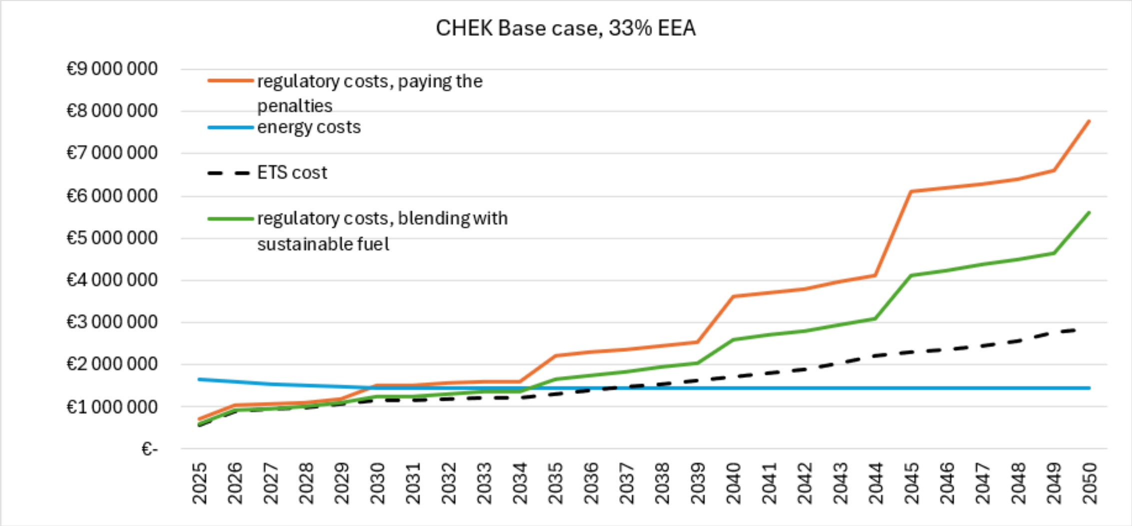


Figure 2: Operational costs for CHEK "Base line" bulk carrier separated into energy costs and regulatory costs

4. Anatomy of ship lifetime cost, energy and environmental modelling

For producing the operating cost results illustrated in figures 1 and 2 for a ship still on the design table, a model regarding FuelEU Maritime rule compliance is required, in addition to data regarding the fuels. In this fuel framework, the ship energy consumption is one of the inputs, as this factor defines the magnitude of the potential penalties or "credits" due to over-compliance to be either given, sold or kept for own later use. Figure 3 illustrates how Deltamarin typically models the various aspects of ship sustainability.

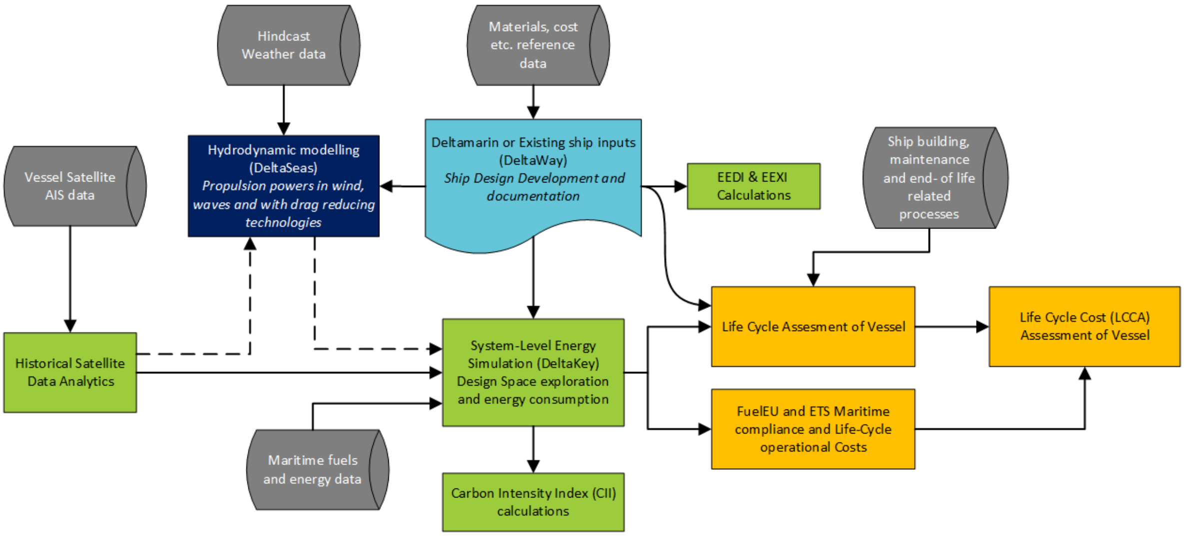


Figure 3: Principal illustration of the main processes in ship sustainability and energy modelling

The energy modelling, which is named “DeltaKey” within Deltamarin, is at the core of the sustainability analysis. The energy model requires input from the ship design and systems regarding the energy consumption. DeltaKey and the history of energy modelling in this context are further explained in Chapter 4. The ship structural and volume model of the ship and the general naval architectural analysis process is illustrated in Figure 3 with light blue colour and is called “DeltaWay”. For instance, ship hull creation is a part of the DeltaWay process. In general, all ship equipment and dimensions impact the ship's energy consumption due to the energy system interactions and, for instance, the weight included, which influences the ship's propulsion power. Therefore, certain ship design data is always a starting point for modelling energies.

For ship energy consumption, the ship operating profile is one of the single most important inputs. The operating profile includes knowledge of ship speed and loading conditions, but also the operating environment including weather influences on it. Existing ship operating data can be utilised as a direct source of ship speed, draft and location for the energy model. Deltamarin acquires satellite data for this purpose and has created a script that prepares the relevant data for the energy model. The ship propulsion power is modelled as a function of ship hull resistance, propulsion efficiency and external forces. In some cases, the simplified approach is included in the projects, where a “sea margin” is added on top of ship's calm water propulsion power prediction to cover the environmental loads. Nevertheless, the “DeltaSeas” approach of combining historical or statistical weather data with a vessel's typical operating profile is a necessary approach, especially in modelling ships with sails. The CHEK bulk carrier-related publication also included a brief overview of the DeltaSeas algorithm (Elg et al., 2024). Figure 4 illustrates how the CHEK vessel propulsion power requirements vary on global routes, even if the simulations expect operation at one selected speed and only two different loading conditions.

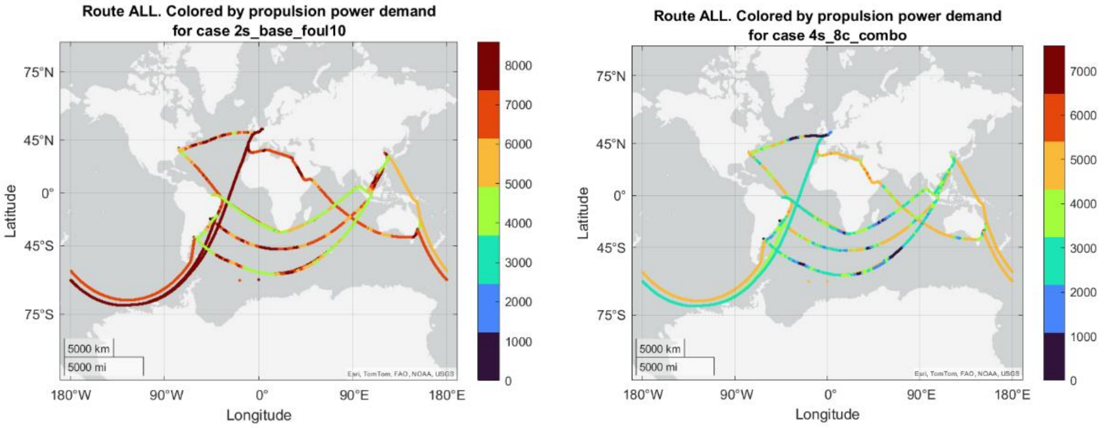


Figure 4: CHEK Bulker – All routes. Visualisation of propulsion power demand (kW) on different sections of the route. Left: Base case 2-stroke configuration. Right: CHEK Combo.

As Figure 3 illustrates, ship energy flow simulation may also be the source of “design-based” ship life cycle assessment (LCA) in addition to decarbonisation-related regulatory compliance or cost minimisation. For the ship designer, it is relevant to create a modular network of the processes, since the projects are different and not every piece of the analysis is required in every project.

5. A brief history of the energy modelling at Deltamarin

Deltamarin’s energy flow simulation tool was developed from the start for quantifying ship energy flows and analysing the efficiency in ship processes and energy conversions. The model is an engineer’s tool for mapping the greatest energy consumers and for simulating the yearly fuel consumption of the ship with various design alternatives. As visualised in Figure 3, the ship fuel consumption and emission results are further utilised for analysing the ship's regulatory compliance and costs.

Before the current simulation tool, ship energy balance calculation was performed by simplifying the ship’s operating profile into various operational modes (such as loading, unloading, port stays and various speed and draft conditions at sea) and the relative total time spent in these modes. The main item which separates the current energy simulation method from the conventional and static energy balance calculations is the possibility to utilise the time-vector. Thus, fuel consumption, power demand and other variables can be monitored at each time step without the need for approximations and averaged values over longer time periods. The holistic nature of the simulation platform enables testing different improvements and design alternatives for the ship and their multiplicative effects across the different systems.

Numerous other applications exist for ship energy modelling, such as the COSSMOS environment by DNV. (Dimopoulos et al., 2014). The software APROS has also been used to simulate ship energy systems (Lepistö et al., 2016). Tillig et al. provided a comprehensive but compact overview of ship energy modelling principles and software that existed at the time for the purpose (Tillig et al., 2015). The paper lists four dimensions according to which the models can be considered. For instance, the level of detail in the model is one of these dimensions, such as white-box, black-box or grey-box models. The other dimensions include model developing time domain, model application time domain and a dimension for model data characteristics.

For the ship designer in general, it is relevant to have insight into the processes, so white-box modelling has been the focus for Deltamarin regarding the core processes of the energy model developed. However, the white-box modelling approach is mainly relevant to those variables that the designer is in control of, so the holistic ship energy and emission model may very well be a grey-box model combining parts of black-box models, such as producing response surfaces from measured data as input for a physical process model. This was also recently demonstrated in the DeltaKey tool while absorbing an external model in the form of a functional mock-up unit to describe the main functions of a ship’s machinery (Elg et al., 2024).

The roots of Deltamarin’s current energy model date back to a joint industry development project SEEE (Ship’s Energy Efficiency and Environment) during 2009-2014 under the Finnish research programme “Energy and life cycle cost efficient machines” (EFFIMA) funded by Tekes (Finnish Funding Agency for Technology and Innovation) and FIMECC Ltd. (FinnishMetals and Engineering Competence Cluster). During this project, VTT, Deltamarin and ABB joined forces to compile a multi-domain, dynamic ship energy flow simulation tool. The tool was configured with Matlab, Simulink and Simscape. Several papers have been published regarding the tool. The most relevant examples are a publication at the CIMAC conference in 2013 (Zou and Tammi, 2013) and another publication at the 13th COMPIT conference in 2014 (Zou et al., 2014). These publications also present limited case studies of a cruise ship and container vessel. Deltamarin started to develop its own approach to energy simulations during this project and, in the beginning, the simulation tool was strongly based on the results of the cooperation. Deltamarin’s first relevant publication was also introduced at the 13th COMPIT conference (Elg et al., 2014), and the published case involved a bulk carrier. The paper focused on finding energy-saving potential with alternative steam system pressures and various cooling system settings. After that, the model was further developed for Deltamarin’s own use, and was utilised to study further efficient ship cooling water systems and multiple energy saving alternatives, including waste heat recovery with Organic Rankine Cycle (Elg et al., 2016, 2015). The latter studies were performed as a part of a joint industry project, SET (Ship Energy Efficiency Technologies) during 2014-2016 (Zou, 2017).

Already during the SET project, when performing simulations in Deltamarin's commercial projects, the utilisation of Simscape physical domains was reduced mainly due to the fact that the current setup of auxiliary processes, such as cooling systems, did not scale very well to different sizes of machinery. It also required a lot of manual setup work for the model, such as sizing pipes. In addition to this, the computing times easily became very long since the auxiliary systems were modelled relatively realistically as actual loops.

Later, the focus in the energy modelling was in efficiently integrating into the model data measured from the ships in growing magnitudes. Another important area has been introducing mathematical optimisation in ship energy modelling work. Deltamarin's first advances in this field were summarised in an extended abstract for the development project INTENS, which ran between 2018 and 2021 (various, 2021). The publication included an example of converting the energy model of a RoPAX ship into an executable. and running it with a genetic algorithm to evaluate the optimal set-up of installed battery capacity and choosing between waste heat recovery system dimensioning. Another example in the same publication was a cruise ship optimisation case, which was later upgraded to a journal article (Elg et al., 2023). The developed method allowed the assessment of thousands of configurations instead of selected pre-set scenarios. This is also the current direction in developing the modelling: developing the model interfaces for various types of input and enabling optimisation in suitable cases.

The energy model is currently compiled with Mathwork's Matlab and Simulink software. The model is especially utilised during ship conceptual design or for retrofit studies. Typically, the time span of these projects is short, so the model for this use has to be extremely flexible, fast and easily configurable. The current model and its utilisation is a result of evolution in the focus areas of the energy efficiency improvement work over a decade. It has also evolved in the context of the other digital design layers, such as propulsion modelling and the current sustainability and decarbonisation-related regulation, and to enable optimisation. The model is constantly being developed to include new devices and operating strategies and to accommodate more efficient working methods for the team. The latest version of the model is thoroughly presented in the context of project CHEK with decarbonising cruise ships. The published journal article focused on analysing the impact of several ship energy-saving technologies and hydrogen as fuel for the entire ship energy consumption (Elg et al., 2025). Figure 5 illustrates the high level of processes included in the energy model in case of a diesel-electric ship and with only Organic Rankine Cycles enabled as a waste heat recovery solution.

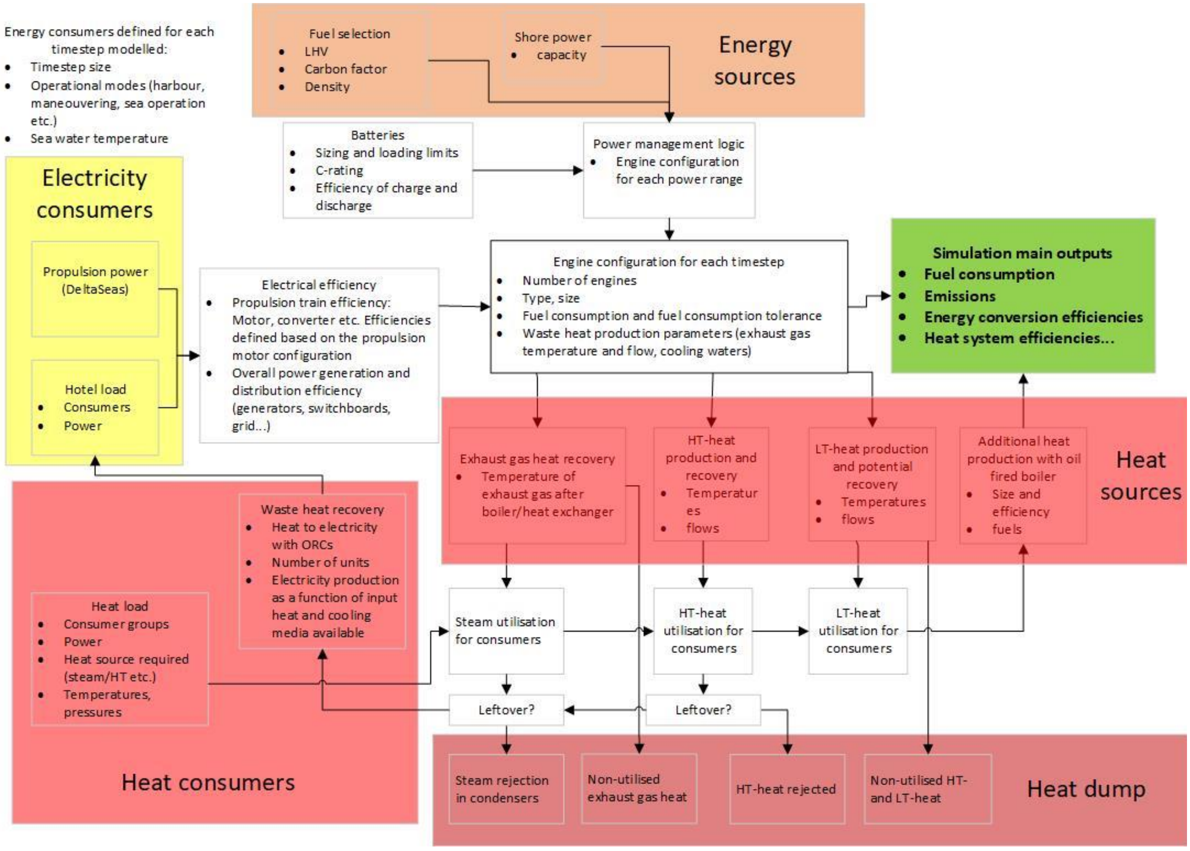


Figure 5: DeltaKey energy simulation model high-level factors and elements (Elg et al., 2025)

6. Case example: electrification impact on ship operating costs

In addition to fuels with low carbon intensity, shore power is currently being considered as a carbon-free energy source for ships within the FuelEU and ETS framework. For exploring the opportunities of electrification, we present a case of a conceptual RoPAX ship. The ship's main dimensions are presented in Table III. The RoPAX vessel was studied with both LNG as the main fuel alternative and with a fully electric version operating on batteries. This study was performed by simply assuming that all ship heat would be generated with an electrical boiler without analysing further technologies.

Table III: Main dimensions of the conceptual RoPAX ship

Length between perpendiculars	208,10 m
Length overall	221,00 m
Beam	31,80 m
Design draft	7,00 m
Scantling draft	7,20 m
Service speed	22 kn
Lane-meters	4080 m

For such a vessel, fully electrical operation with the selected battery capacity would be possible, for instance in the English Channel. The operating profile for the study was received by following a suitable relevant vessel in the English Channel and obtaining the satellite data. Figures 6 and 7 illustrate the main operating speed and operating modes included in the study.

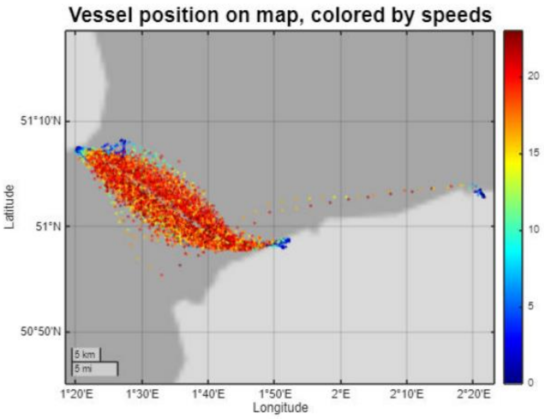


Figure 6: RoPAX ship reference operational speed distribution

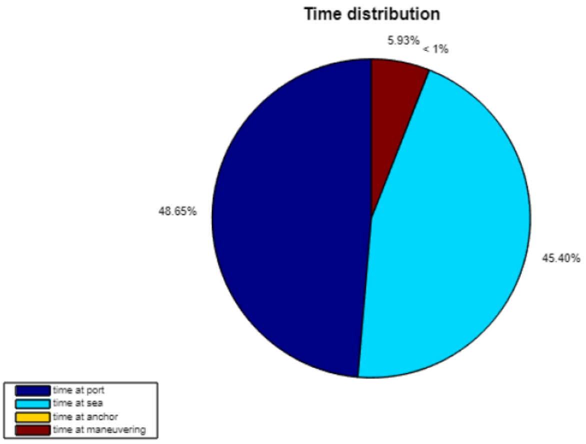


Figure 7: RoPAX ship reference time distribution for different operating modes

Figure 8 presents the simulated operating costs between an LNG-fuelled alternative and a fully electric vessel, assuming that only 50% of the operation would be considered within the EU rule framework. The calculation assumes that the LNG vessel selects blending LBG in the energy mix to avoid penalties, but the scenario of paying penalties is also illustrated. A new element is added for the battery-operated vessel to illustrate the theoretical maximum potential of how a low-carbon ship could reduce the FuelEU maritime penalties if pooling with ships within its own fleet. This figure should be understood as "avoided FuelEU penalty costs by other vessels in the fleet" calculated for over-compliant ships. The real-life benefit of pooling ships varies on the compliance avoidance strategies available for the other ships in the pool and any pool administration costs. Thus, it cannot be evaluated without knowing the details of the pool.

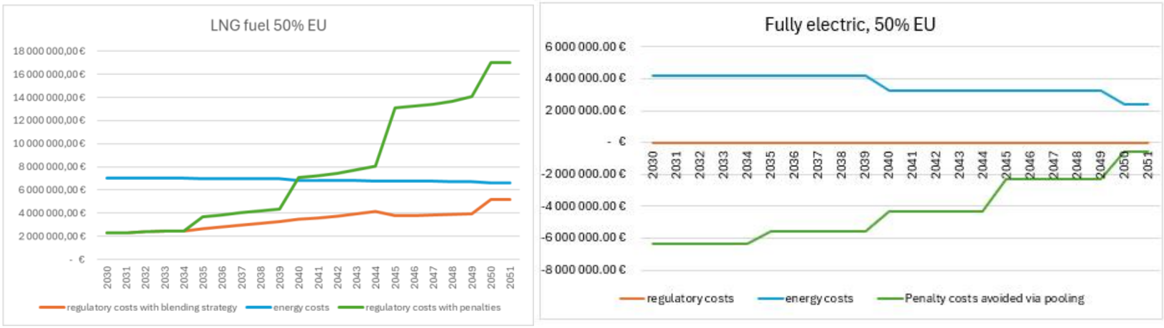


Figure 8: Operating costs for RoPAX case with LNG fuel (on the left) and fully battery-operated ship (on the right)

Table IV lists the price-related variables in the study, and sources for price assumptions are summarised in Table II. With the selected prices for energy, the electric vessel already clearly has lower operating costs than the LNG-fuelled ship due to energy savings and energy costs.

Table IV: Development of prices for the RoPAX case calculation in €/GJ of fuel

	2025	2030	2035	2040	2045	2050
LNG	19,3	14,4	14,2	14,1	14,0	13,9
LBG	24,0	27,0	27,0	29,0	29,9	33,0
MDO	18,9	16,6	16,6	16,6	16,6	16,6
Electricity	21	17	17	13	13	10
ETS	100	140	160	210	280	350

We can also speculate how the operating cost figures would change if the vessel operation on a similar energy profile, if it operated 100% within EU area. Figure 9 illustrates these results.

Figure 9: Operating costs for RoPAX if operating 100% within EU

The regulatory costs (ETS), energy costs and theoretical fleet penalty avoidance benefit are also illustrated for the best case of the CHEK bulk carrier, adding to the figures discussed in chapter 3

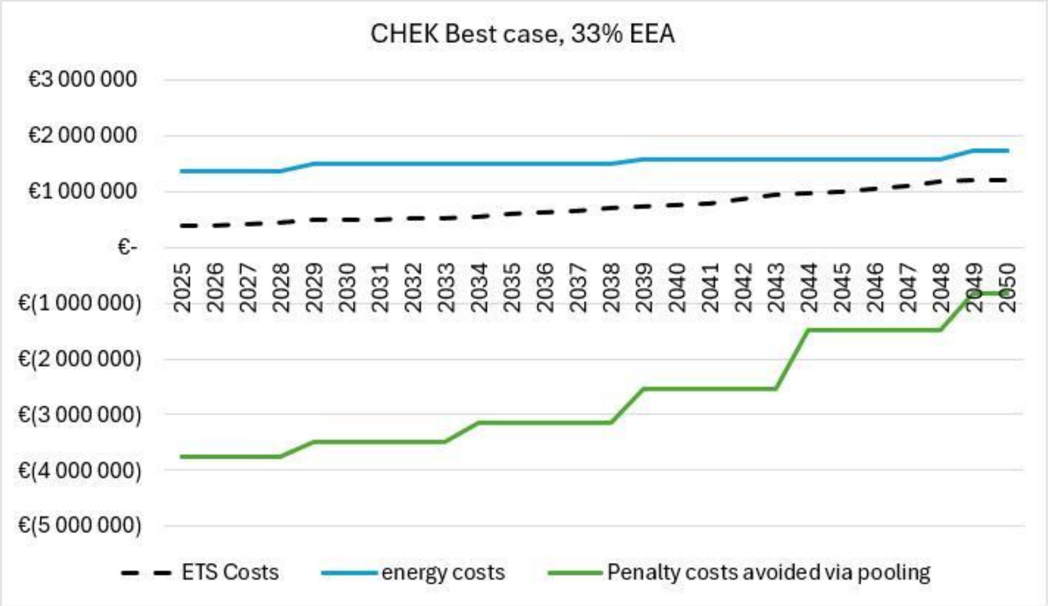


Figure 10: Operating costs for the CHEK bulker's case with the best combination of technologies and biofuel

In all cases, it is clear that, while the regulatory cost burden is considerably increased in the later decades, the opportunities for environmentally efficient vessels to generate additional revenue by pooling within their own fleet or external pools will be greatest in the near future.

7. Discussion, future work and conclusions

With the case stories reviewed, we can conclude that energy saving and ship electrification can bring to ship operators considerable fuel and energy savings from day one. With conventionally fuelled vessels, the regulatory push wil be increased over the coming decades. For instance, LNG as fuel enables ships to operate with merely the ETS cost impact influencing the regulatory side until 2035 if methane slip is low. For electric vessels that could utilise shore power, the benefits of both energy costs and regulatory framework will materialise faster, and there will be opportunities to gain further revenue by pooling compliance balance with less sustainable ships.

Introducing new equipment to the ships also inevitably introduces added weight to the ship and added investment. Ship electrification might also not be possible in all locations without considerable investment in infrastructure, so all projects are very case-dependent. Nevertheless, technically, we evaluated the impact of the most weight-increasing technologies for the CHEK bulker in our article. We concluded that the combined effect of two large sails and LNG machinery, including the fuel storage, compared to the baseline ship, would increase the ship draft by 20cm. This would increase the propulsion power by 1,6% at a typical operating speed of 12.5 kn, which is much less than the achieved fuel savings. In the case of fa ully electric RoPAX, we estimated that replacing the main propulsion machinery and LNG tanks with 45 MWh batteries would increase the ship's lightweight by a bit more than 200 tonnes, which is approximately equivalent to 1% of the lightweight. The installation costs have to be analysed separately as they are always case dependent. In some cases, it might also be sensible to prepare the ship for a variety of energy-saving technologies or electricity storage, but to install some of the capacity later when the economical calculations support the installation. This is the core idea of future-proof ship design.

Ship sustainability is a broad and complex topic. This article focuses specifically on the cost impact of two European regulations. However, more rules are expected to be implemented in the shipping industry over time. As operating carbon emissions from ships are gradually reduced, attention will inevitably shift toward a more comprehensive evaluation of environmental impact through Life Cycle Assessment (LCA). In line with this, the International Maritime Organization (IMO) has revised its decarbonisation strategy, placing more emphasis on a Well-to-Wake (WTW) approach to assess greenhouse gas (GHG) emissions.

LCA is a holistic method used to evaluate the environmental impacts of a product, process or service across its entire life cycle, from raw material extraction and production to use and disposal. In the maritime sector, it is increasingly recommended for estimating the full WTW GHG impact of fuels. It also serves as a valuable tool for assessing overall environmental sustainability.

Applying LCA across all stages of a ship's life cycle is one of the most effective ways to measure sustainability. Among the key indicators are GWP100 and GWP20, which reflect global warming potential over 100- and 20-year time horizons, respectively. These are calculated using methods defined by the Intergovernmental Panel on Climate Change (IPCC).

Figure 11 presents the LCA results for the CHEK bulk carrier project, specifically reporting GWP100 in grams of CO_2-equivalent per tonne-nautical mile. Further analysis is available in Dong et al. (2024).

While this assessment is limited in its coverage of shipbuilding and end-of-life materials and processes, it offers a valuable glimpse into the future of ship sustainability assessments.

Expanding ship LCAs to include more stages and cost factors could provide a competitive edge for future vessel investments. Although comprehensive LCAs are not yet mandatory across all sustainability categories, they offer deep insights into the most impactful factors. Such analyses enable stakeholders to stay ahead of evolving regulations and make better-informed decisions.

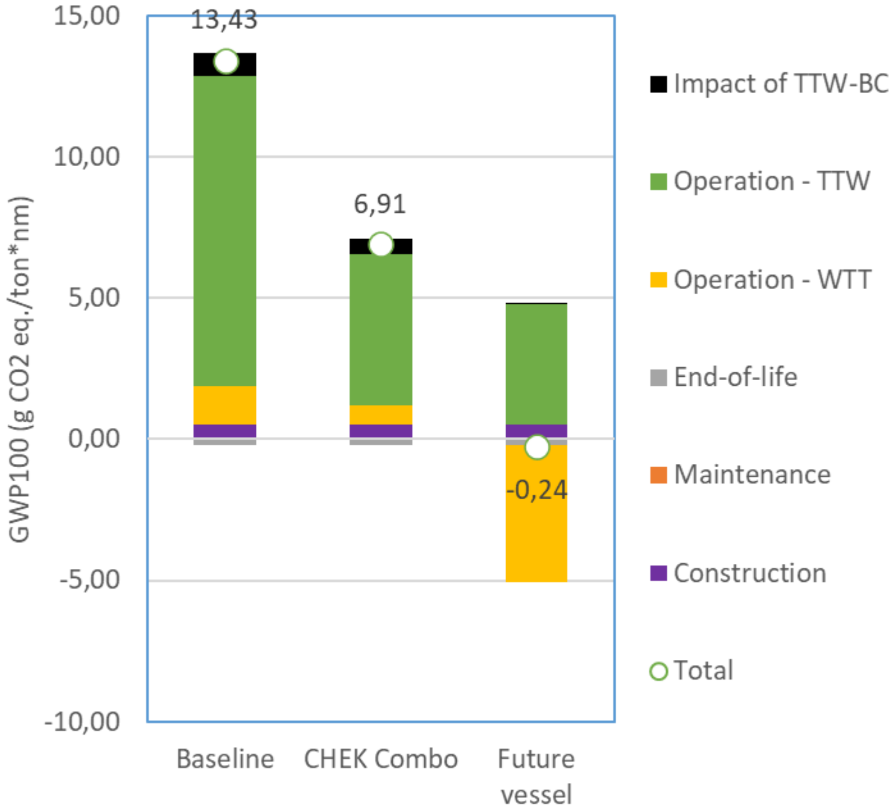


Figure 11: Ship LCA results for CHEK bulk carrier

Regarding FuelEU and ETS regulatory costs from a strategic perspective, compliance is the most cost-effective approach. Early investments will not only offer regulatory flexibility but might also improve the vessel's freight rates and resale value. For global trade, EU regulations apply only partially, and added compliance costs will only be seen when travelling into or out of the EU region.

When predicting the FuelEU compliance costs and carbon costs, there are several sensitivity factors and insecurities. Fluctuations and future development in fuel prices are critical and sensitive factors in the calculations. There is also uncertainty in infrastructure and regulatory development. The regulation is highly political and therefore vulnerable to, for example, uncertainty regarding the future development of the political landscape.

By simulating different compliance scenarios in an early phase, it is possible to get a clear idea of future costs and the most suitable compliance strategies. Careful planning of space provisions, system integrations and structural considerations will facilitate a seamless transition to lower-carbon energy sources as infrastructure matures and, in the best case, will result in a future-proof vessel. This paper provided some examples of how important a holistic view of ship systems is. It is possible to identify solutions that are beneficial in terms of ship energy efficiency, regulatory compliance and costs.

Nomenclature

AFIR	Alternative Fuels Infrastructure
CII	Carbon Intensity Index
EU	European Union
Eq.	equivalent
ETS	Emissions Trading System
EUA	Emissions Allowance
GT	Gross tonnage
GHG	Greenhouse Gas
GWP	Global Warming Potential
LBG	Liquid Bio Gas
LNG	Liquified Natural Gas
LCA	Life Cycle Assessment
MJ	Mega Joule
IMO	International Maritime Organization
TTW	Tank-to-Wake
WTT	Well-to-Tank
WTW	Well-to-Wake
VLSFO	Very Low Sulphur Fuel Oil

Acknowledgements

Several examples presented in this article were from the EU Horizon 2020 project deCarbonising sHipping by Enabling Key technology symbiosis on real vessel concept designs (CHEK – Contract No. 955286). We acknowledge and thank all CHEK project partners for enabling us to produce and present the results. The authors would also like to thank the entire energy team at Deltamarin for contributing to this article.

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