Cost analysis of dual-fuel engines and phosphoric acid fuel cells for ship propulsion and electrification

Onur Yuksel[1,2], Eduardo Blanco-Davis[1], Viknash Shagar[1*], David Hitchmough[1], Andrew Spiteri[1], Maria Carmela Di Piazza[3], Marcello Pucci[3], Nikolaos Tsoulakos[4], Jin Wang[1]

[1]Liverpool Logistics Offshore and Marine Research Institute (LOOM), School of Engineering, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK.

[2]Zonguldak Bülent Ecevit University, Marine Engineering Department, Maritime Faculty, Kepez District, Hacı Eyüp Street, No:1 67300, Zonguldak, Türkiye.

[3]National Research Council of Italy (CNR), Institute of Marine Engineering (INM), via Ugo La Malfa 153, 90146 Palermo, Italy.

[4]Laskaridis Shipping Co., Ltd., 5 Xenias Str. and Ch. Trikoupi, Kifissia, 14562 Athens, Greece

(*Corresponding author e-mail address: g.v.shagar@ljmu.ac.uk)

Abstract

This study examines the economic performance of four-stroke liquefied natural gas (LNG)-powered dual-fuel (DF) engines incorporating shaft generators (SGs) designed to provide auxiliary power when the engines operate above 50% load. Two distinct configurations involving large DF engines with mechanical propulsion (DF-MP) and smaller DF engines with diesel-electric propulsion (DF-DEP) are modelled using sensor data obtained from a Kamsarmax bulk carrier. Furthermore, integrating LNG-powered phosphoric acid fuel cells (PAFCs) and batteries into ship electrification systems is analysed for operations in the port and under low-load main engine conditions. The economic assessment employs the primary metric of the Levelized Cost of Energy (LCOE). Comparative evaluations are conducted for systems, considering a range of fuel price variations and carbon emission scenarios. The results show that the DF-MP configuration delivers a 12.88% decrease in tank-to-wake CO_2 emissions, while the DF-DEP setup achieves a more substantial 27.21% reduction. The conventional system exhibits LCOE values ranging from 2.65 to 3.80 $/kWh, compared to 4.80 to 6.12 $/kWh for DF-MP and 6.05 to 8.09 $/kWh for DF-DEP. The evaluated carbon tax levels, spanning from 54.34 to 104.52 $/t-$CO_2$, fail to provide adequate incentives for transitioning to the investigated configurations.

Keywords

Dual-Fuel Engines, Phosphoric Acid Fuel Cell (PAFC), Shaft Generator (SG), Levelized Cost of Energy (LCOE), Carbon dioxide (CO_2) Reduction

1 Introduction

Dual-fuel (DF) engines are a key alternative for reducing emissions from maritime vessels. They can use cleaner fuels like liquefied natural gas (LNG) or methanol alongside traditional marine fuels, leading to lower environmental impact and compliance with stricter emissions regulations (Ammar & Seddiek, 2023). Integrating these engines with diesel-electric propulsion (DEP) can further decrease emissions.

DEP utilises electric motors driven by diesel generators to propel a ship, enhancing efficiency and flexibility while improving fuel management and reducing emissions. This system optimises power distribution by converting diesel into electrical energy, boosting performance and reliability in marine operations (Nguyen et al., 2021).

Fuel cell (FC) systems are viable options for ship electrification due to their low emissions of hazardous gases. The loads in electrification systems are generally more stable than those in propulsion systems, making this a feasible application area for FCs in combination with batteries (Korkmaz et al., 2023). Phosphoric Acid Fuel Cells (PAFCs), with their medium operating temperature and suitability for LNG decomposition, are commercially available, positioning them as a practical choice for electrification plants (Xing et al., 2021).

This study demonstrates the economic performance of four-stroke LNG DF engines with a shaft generator (SG) for auxiliary loads, using the Levelized Cost of Energy (LCOE) as the primary metric and analysing both DEP and mechanical propulsion (MP) systems. Additionally, PAFCs powered by LNG and a battery pack are coupled with DF configurations. The analysis considers various fuel and carbon scenarios.

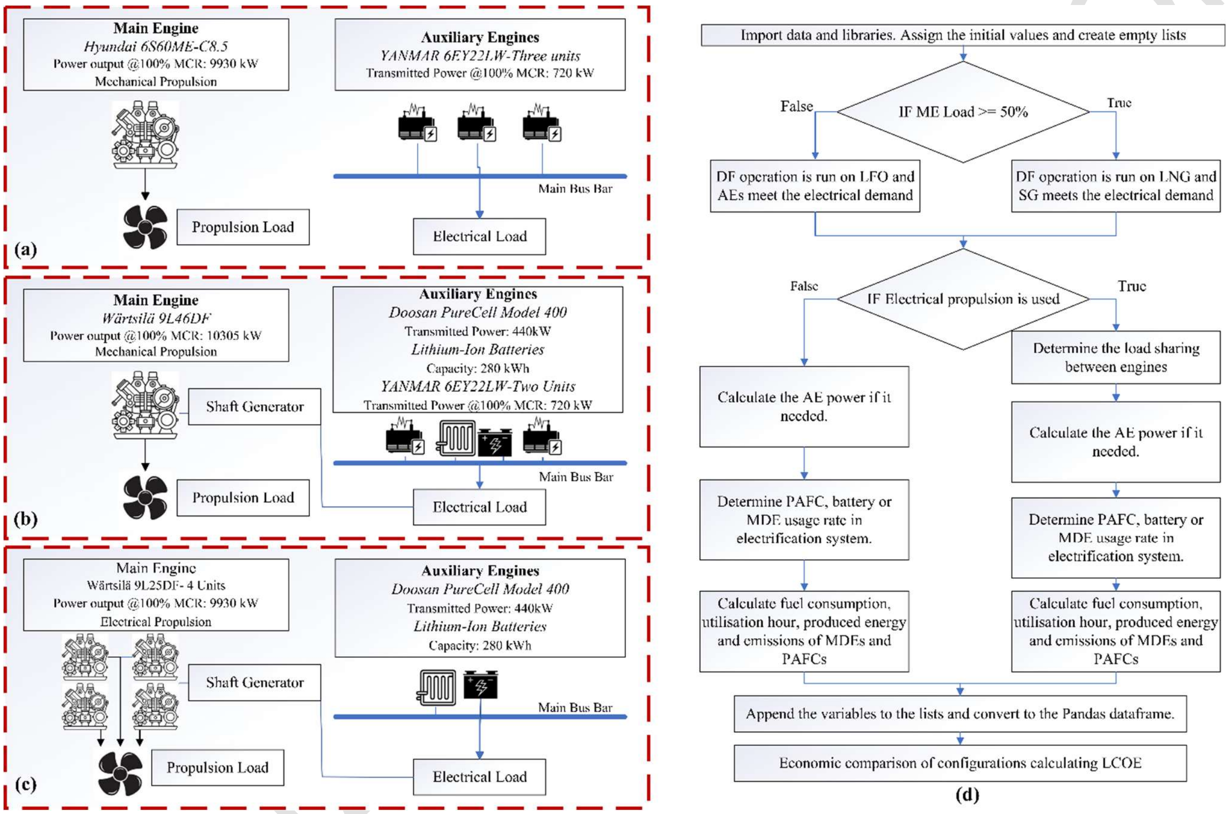
This research supports the International Maritime Organization (IMO)'s decarbonisation goals, aiming to significantly reduce greenhouse gas (GHG) emissions in the shipping sector by 2030. By investigating innovative propulsion and energy systems, this study aids in developing sustainable maritime practices essential for meeting the IMO's targets. The findings will offer economic insights into solutions for transitioning to cleaner energy sources, enhancing the maritime industry's commitment to environmental stewardship and global decarbonisation initiatives.

2 Methodology

The case study utilised sensory fuel and load data from a Kamsarmax bulk carrier over 1.96 years. Figure 1 depicts the base case, the configurations examined and the simplified model logic.

Figure 1

System and model description: (a) base, (b) DF-MP, (c) DF-DEP cases, and (d) model simplified logic.



In the base case (Figure 1a), the propulsion is provided by a large and low-speed, two-stroke diesel engine and three medium-speed, four-stroke diesel engines to meet electrical demand. In the DF-MP scenario (Figure 1b), the main engine (ME) is retrofitted with a four-stroke, medium-speed DF engine, supplemented by an SG for electrical load. During low ME loads and berthing, auxiliary engines (AEs) using PAFCs, batteries, and marine diesel engines (MDEs) supply power. In the DF-DEP configuration (Figure 1c), four smaller engines address propulsion and electrical needs, with PAFCs and batteries supplying power during berthing.

The process in Figure 1d involves importing data, initialising values, and defining operational conditions. The ME load is crucial for determining the fuel type for DF engines and whether the SG can fulfil electrical demand. LNG-mode operation in DF engines is feasible only when the ME load exceeds 50%, affecting the SG's contribution to the electrical load.

The proposed configurations' DF engines and AEs utilise light fuel oil (LFO) at low loads. In contrast, the base case employs heavy fuel oil (HFO) for the ME and AEs.

In the DF-DEP configuration, engine load-sharing is determined. The fuel consumption of DF engines and AEs is calculated based on the manufacturer's specific fuel consumption curves (Wärtsilä, 2024).

The model also evaluates power requirements for auxiliary equipment, total fuel consumption, utilisation hours, energy production, and emissions for electrification and propulsion systems. Lastly, the resulting variables are structured into a data format suitable for an economic comparison based on the LCOE.

The operational carbon dioxide (CO_2) emissions are calculated by multiplying the carbon emission factors (Cf) for internal combustion engines (ICEs) provided in Table 1 by the corresponding fuel consumption of the ICEs. Table 1 also specifies the CO_2 emission factor for the PAFC (Cf_{PAFC}) and the system's LNG consumption coefficient.

Table 1

Cf, Cf_{PAFC}, and LNG consumption values.

ICEs	HFO	**LFO**	**LNG**
Cf (g-CO_2/g-fuel)	3.11	3.15	2.75
PAFC	Cf_{PAFC}(kg/MWh)	LNG Consumption (Nm^3/h)	
Coefficient	454	98.4	

Source: (Doosan, 2018; IMO, 2024)

The economic comparison has been ensured by calculating the LCOE employing Equation (1) (Hansen, 2019).

$$\text{LCOE}\left(\frac{\$}{\text{kWh}}\right)=\frac{\sum_{n=1}^{LT}\frac{(C_{plant}+C_{fuel}+C_{C}+C_{o\&m})\ (\$)}{(1+r)^{n}}}{\sum_{n=1}^{LT}\frac{P\ (kW)\times t(h))}{(1+r)^{n}}} \tag{1}$$

The installation expenses are denoted as C_{plant}, while fuel expenditures are depicted as C_{fuel}, the carbon tax is denoted as C_C and the operational and maintenance costs are represented as $C_{o\&m}$. A discount rate (r) of 10% and the operational lifespan of the plant (LT) of 25 years are used (Shu et al., 2017). Table 2 demonstrates the LT, C_{plant} and $C_{o\&m}$ for the equipment.

Table 2

LT, C_{plant} and $C_{o\&m}$ of the equipment.

Equipment	C_{plant}	$C_{o\&m}$	Unit	LT (years)
PAFC	1,802,117	1.5%	$/unit	40,000 hours
LNG Storage	2,000	1.5%	$/m^3	25
HFO Storage/Transfer	1,497.10	1%	$/m^3	25
LNG Transfer	836.20	4%	$/t	10
Battery	11.36	1%	$/cell	10
Conventional ME	3,067,138	1.5%	$	25
MDE (AE)	589,007	1.5%	$	25
DF-MP	5,600,000	1.5%	$	25
DF-DEP	1,671,158	1.5%	$/unit	25

Source: (Ammar & Seddiek, 2023; Fikri et al., 2018; Kim et al., 2021; Seo et al., 2016; Terlouw et al., 2022; Zubi et al., 2020)

The $C_{O\&M}$ is calculated by multiplying the ratio given in Table 2 with C_{plant}. The analysis uses United States Dollars ($), with an exchange rate of $1.04 for 1 Euro (€) on 07 January 2024. Historical prices are adjusted by applying the relevant year's exchange rate, and the most recent Chemical Engineering Plant Cost Index reported at 798.8 for June 2024 (Maxwell, 2024). C_{fuel} and C_C are evaluated under cost cases based on low, medium, and high values shown in Table 3.

Table 3

C_{fuel} ($/t-fuel) and C_C ($/t-CO_2).

Fuel	High	Average	Low
LFO	587.00	534.00	499.50
HFO	530.00	467.00	395.00

LNG	893.50	783.50	652.00
C_C	54.34	86.96	104.52

Source: (ShipandBunker, 2024; Tiseo, 2024)

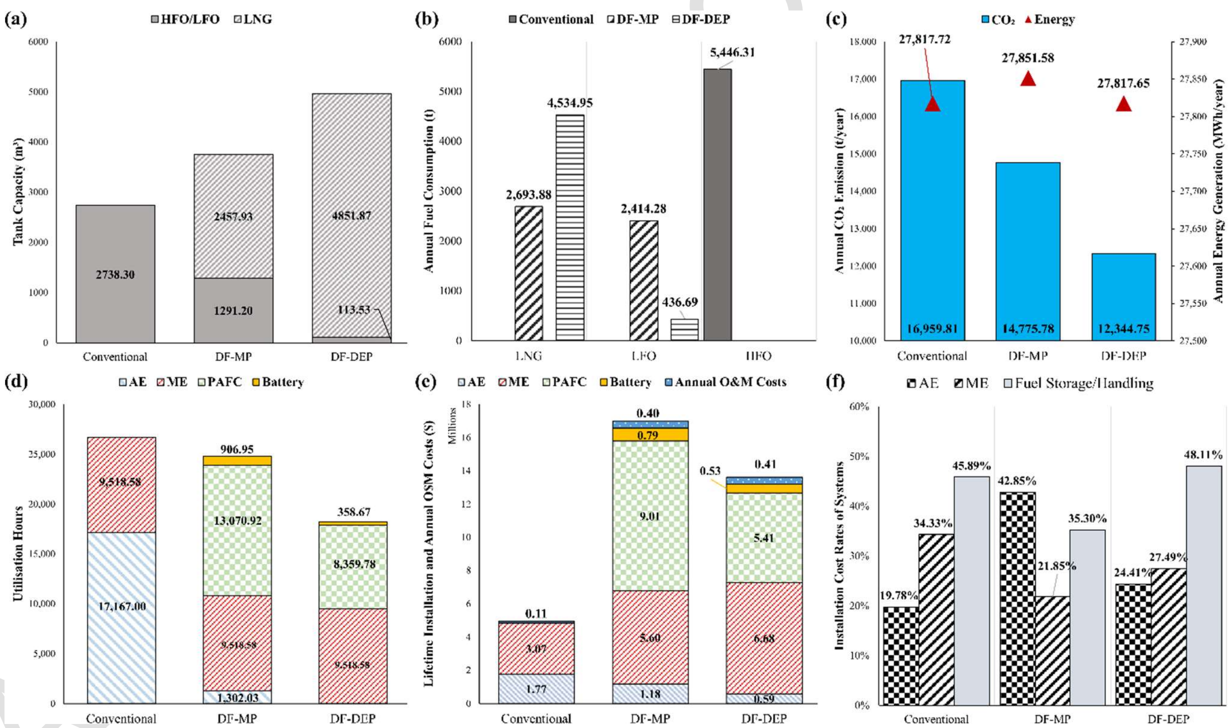
C_{fuel} was taken on 7 January 2025. The fuel and carbon scenarios were evaluated separately, resulting in the investigation of nine distinct cases.

3 Findings

Figure 2 presents the annual fuel consumption, tank capacities adjusted for a maximum six-month bunkering interval, yearly total CO_2 emissions/produced energy from the configurations, utilisation hours, lifetime C_{plant}, and annual $C_{O\&M}$.

Figure 2

(a) Tank capacities, (b) annual fuel consumption, (c) annual CO_2/energy generation, (d) utilisation hours, (e) lifetime C_{plant}, (f) annual $C_{O\&M}$ of investigated configurations.



The growth in LNG usage requires increased storage capacity. Figure 2a shows that DF-MP needs 1.57 times, and DF-DEP requires 1.91 times more fuel storage than conventional systems. DF-MP operates on 50% LNG, while DF-DEP uses 95% LNG due to better load allocation among smaller engines (Figure 2b). In conventional scenarios, AEs and MEs consume 930.18 t and 4,516.13 t of annual HFO, respectively.

In the DF-MP, the ME annually consumes 2,212.14 t of LNG, 2,181.17 t of LFO for power, and 37.4 t of LFO as pilot fuel. ICEs as AEs in DF-MP use 188.22 t of LFO, while the PAFC consumes 481.74 t of LNG. In the DF-DEP, the ME uses 4,229.01 t of LNG, 25.75 t of LFO for operation and 201.26 t of LFO as pilot fuel. The PAFC in this scenario utilises 305.94 t of LNG.

The energy produced by the three configurations is comparable, as shown in Figure 2c. DF-MP reduces tank-to-wake CO_2 by 12.88%, while DF-DEP decreases CO_2 by 27.21%.

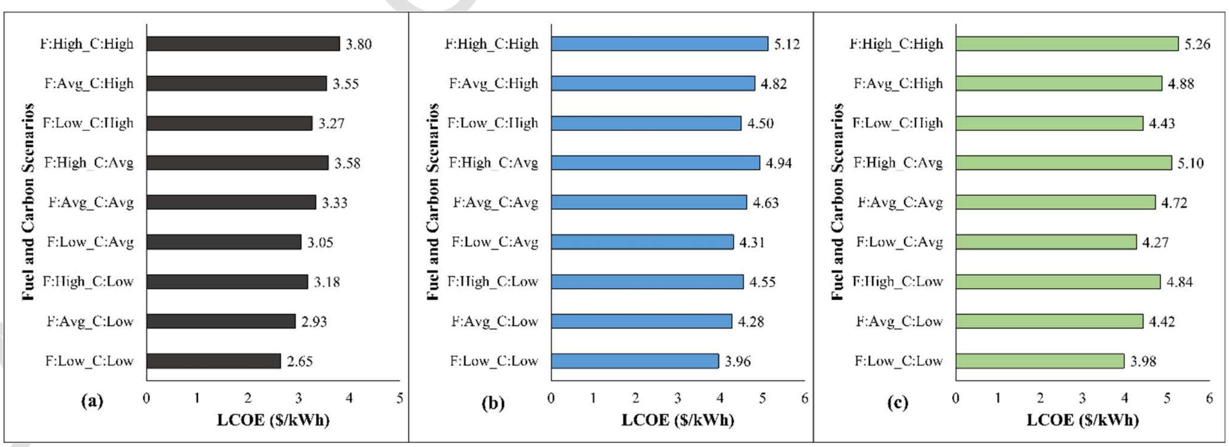
Figure 2d shows that the MP-DEP configuration is more efficient for propulsion and electrification and uses fewer batteries and PAFCs than DF-MP. In DF-DEP, batteries achieve a 98.74% state of health (SoH) after 1.96 years and require only two replacements over ten years. The PAFC has an estimated lifetime of 9.38 years and needs two replacements.

In DF-MP, the increased battery usage results in a SoH value of 96.80%, necessitating three replacements. The PAFC, in this configuration, has an estimated lifetime of six years, requiring five replacements, which increases the AE costs, as indicated in Figure 2e.

Figure 2f shows that in DF-MP, the AE installation cost is the highest relative to the total price, followed by the ME costs. In contrast, DF-DEP's most significant expense is the fuel storage-handling cost, while ME and AE costs are similar in percentage terms. Figure 3 indicates the LCOEs of the fuel and carbon scenarios configurations.

Figure 3

LCOEs for fuel (F) and carbon (C) scenarios: (a) conventional, (b) DF-MP, and (c) DF-DEP



The three fuel and carbon scenarios are represented using abbreviations. For instance, a low fuel scenario combined with an average carbon scenario is denoted as "F: Low, C: Avg". The conventional system achieves LCOE ranging from 2.65 to 3.80. DF-MP increases LCOE by 41.01% on average, while DF-DEP rises them by 41.75%, primarily due to elevated LNG prices. The assessed carbon tax levels do not offer sufficient incentives to transition to the configurations considered in this passage.

4 Conclusion

This study illustrated the economic performance of four-stroke LNG DF engines with SG and PAFC battery systems for auxiliary loads. It highlighted their potential to support the IMO decarbonisation goals by 2030.

The DF utilisation in MP reduced CO_2 emissions, but the reduction fell short of the 2030 GHG reduction targets. Integrating multiple DF engines with smaller power outputs in the DEP configuration resulted in higher emission reduction rates and longer lifetimes for PAFCs and batteries. However, the LCOE values remained significantly higher than those of conventional engines. This suggests that the examined carbon tax levels did not provide adequate incentives for transitioning to the explored configurations. The fluctuating price of LNG due to the Ukraine-Russia conflict also contributed to elevated LCOE values for the investigated configurations.

The findings provided valuable insights into economically viable solutions for transitioning to cleaner energy sources, enhancing the maritime industry's commitment to environmental stewardship and global decarbonisation initiatives.

Acknowledgements

The authors would like to acknowledge the financial support for Retrofit Solutions to Achieve 55% GHG Reduction by 2030 (grant number: 10064483) from UKRI and from EU (grant number: Horizon Europe 101096068).

Disclaimer

This paper is the opinion of the authors and does not necessarily represent the belief and policy of their employers.

References

Ammar, N. R., & Seddiek, I. S. (2023). Hybrid/dual fuel propulsion systems towards decarbonization: Case study container ship. *Ocean Engineering*, *281*, 114962. https://doi.org/https://doi.org/10.1016/j.oceaneng.2023.114962

Doosan. (2018). *PureCell Model 400*. Retrieved 01/05/2021 from https://www.doosanfuelcellpower.com/download/pdf/catalog/pafc-400kw_en.pdf

Fikri, M., Hendrarsakti, J., Sambodho, K., Felayati, F., Octaviani, N., Giranza, M., & Hutomo, G. (2018). *Estimating Capital Cost of Small Scale LNG Carrier* Proceedings of the 3rd International Conference on Marine Technology (SENTA 2018), https://www.scitepress.org/Papers/2018/85421/85421.pdf

Hansen, K. (2019). Decision-making based on energy costs: Comparing levelized cost of energy and energy system costs. *Energy Strategy Reviews*, *24*, 68-82. https://doi.org/https://doi.org/10.1016/j.esr.2019.02.003

IMO. (2024). *2024 GUIDELINES ON LIFE CYCLE GHG INTENSITY OF MARINE FUELS (2024 LCA Guidelines)*. Retrieved 13/11/2024 from https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.391(81).pdf

Kim, H.-S., Kim, D.-H., & Hur, T. (2021). Life cycle assessment of molten carbonate fuel cell system for power plants. *Journal of Cleaner Production*, *302*, 126911. https://doi.org/https://doi.org/10.1016/j.jclepro.2021.126911

Korkmaz, S. A., Erginer, K. E., Yuksel, O., Konur, O., & Colpan, C. O. (2023). Environmental and economic analyses of fuel cell and battery-based hybrid systems utilized as auxiliary power units on a chemical tanker vessel. *International Journal of Hydrogen Energy*, *48*(60), 23279-23295. https://doi.org/10.1016/j.ijhydene.2023.01.320

Maxwell, C. (2024). *Cost Indices*. Retrieved 25/06/2024 from https://toweringskills.com/financial-analysis/cost-indices/

Nguyen, H. P., Hoang, A. T., Nizetic, S., Nguyen, X. P., Le, A. T., Luong, C. N., Chu, V. D., & Pham, V. V. (2021). The electric propulsion system as a green solution for management strategy of CO emission in ocean shipping: A comprehensive review. *International Transactions on Electrical Energy Systems*, *31*(11), e12580. https://doi.org/https://doi.org/10.1002/2050-7038.12580

Seo, S., Chu, B., Noh, Y., Jang, W., Lee, S., Seo, Y., & Chang, D. (2016). An economic evaluation of operating expenditures for LNG fuel gas supply systems onboard ocean-going ships considering availability. *Ships and Offshore Structures*, *11*(2), 213-223. https://doi.org/10.1080/17445302.2014.984389

ShipandBunker. (2024). *EU-ETS Understanding the EU Emissions Trading System for Shipping*. Retrieved 25/06/2024 from https://shipandbunker.com/eu-ets

Shu, G., Liu, P., Tian, H., Wang, X., & Jing, D. (2017). Operational profile based thermal-economic analysis on an Organic Rankine cycle using for harvesting marine engine's exhaust waste heat. *Energy Conversion and Management*, *146*, 107-123. https://doi.org/https://doi.org/10.1016/j.enconman.2017.04.099

Terlouw, T., Bauer, C., McKenna, R., & Mazzotti, M. (2022). Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. *Energy & Environmental Science*, *15*(9), 3583-3602. https://doi.org/10.1039/d2ee01023b

Tiseo, I. (2024). *EU-ETS allowance prices in the European Union 2022-2024*. Retrieved 26/12/2024 from https://www.statista.com/statistics/1322214/carbon-prices-european-union-emission-trading-scheme/

Wärtsilä. (2024). *Online engine configurator - Find the right ship engine for you*. Retrieved 29/04/2024 from https://www.wartsila.com/marine/engine-configurator

Xing, H., Stuart, C., Spence, S., & Chen, H. (2021). Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives. *Sustainability*, *13*(3).

Zubi, G., Adhikari, R. S., Sánchez, N. E., & Acuña-Bravo, W. (2020). Lithium-ion battery-packs for solar home systems: Layout, cost and implementation perspectives. *Journal of Energy Storage*, *32*, 101985. https://doi.org/https://doi.org/10.1016/j.est.2020.101985