Fuel Cell Technologies and Applications for Deep-Sea Shipping

Technology mapping and techno-economic assessment of fuel cell applications for onboard auxiliary power

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Table of Contents

Executive Summary

While strategies and forecasts for maritime decarbonization tend to focus on the promise of alternative fuels, decreasing emissions in the near term will rather be driven by technologies that can decrease net fuel consumption. Therefore, it is important to consider technologies which might more efficiently replace today's main power element, the internal combustion engine. To this end, in this report the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) seeks to share an impartial status update on the potential role for fuel cell technologies in deep-sea shipping.

Deep-sea vessels are currently responsible for the largest share (~65%)[1] of shipping's greenhouse gas emissions. As a result, if fuel cells are to play a major role in decarbonization beyond the short-sea applications (such as ferries) that already exist today, their technology must be compatible with the operations of deep-sea vessels.

Given the inherent differences between fuel cells and internal combustion engines, it appears unrealistic to assume that fuel cells will compete with or entirely replace onboard internal combustion engines in the near future, even as fuel cells reach a high technological maturity level. This is due to the high initial costs currently associated with these technologies, along with the adjustments that would be required in ships' engine-room design and standard operating procedures for the crew.

Rather, it seems more likely that different technologies will co-exist for the foreseeable future. Ship owners could combine fuel cells and internal combustion engines in order to leverage the advantages of each system. In this way, the industry could make the most of fuel cells' environmental performance while also becoming more familiar with fuel cells and progressively scaling up investments as the technology becomes more affordable.

For this reason, our investigation focused on assessing the role that fuel cells could play in auxiliary load on board ships, rather than on propulsion. We believe that auxiliary power generation represents a good starting point for phase-in of fuel cell technologies, given the lower maximum loads and resulting costs of gensets compared to main engines. Auxiliary power is traditionally generated via four-stroke engines, which are slightly less efficient than the two-stroke engines typically employed for propulsion. As a result, vessels might operate on a combination of two-stroke engines (propulsion) and fuel cells (auxiliary load). This approach could help ship owners to make the most of existing technologies while phasing in fuel cells and, in turn, potentially lower vessels' emissions.

To assess the feasibility of such configurations on deep-sea ships, we started by mapping the fuel cell technologies that are currently being developed for maritime applications. This was possible thanks to close cooperation with some of the technology suppliers who are focusing on this space. Information shared by suppliers consisted of performance data, initial cost estimates, and rough installation guidelines, including equipment size and interfaces with other ship systems. Once we gathered a sufficient level of detail from suppliers across various fuel cell technologies, we shortlisted the fuel cell technologies to focus on for this report, based on their technological readiness and the detail of the data made available.

Our main investigation centered on a desktop study examining the potential for fuel cells' integration on board deep-sea vessels. We chose to focus on the ship segments responsible for the largest bulk of shipping emissions, i.e., bulk carrier, tanker, and container ship. Within these segments, we used real-world operational data shared by the MMMCZCS's partner organizations to establish realistic operational profiles for one specific ship type in each segment. Building on this insight, we estimated the impact of fuel cells from several angles, aiming to capture information about their potential environmental performance along with the financial and business implications. Specifically, we analyzed the likely impact of fuel cell integration on energy efficiency, greenhouse gas emissions, fuel and equipment costs, and ship design for selected combinations of ship types, fuels, and fuel cell technologies from 2025 to 2040.

The results of this analysis show that, under the assumptions of our study, fuel cells could reduce both onboard fuel demand and the resulting greenhouse gas emissions. Further, these new technologies do not appear to require design modifications that would affect ship operations or costs beyond what can be expected for the combination of alternative fuels and internal combustion engines. However, our results also indicate that, on top of the high costs currently forecast for alternative fuels – which appear hard to compare to conventional fuels in the absence of a carbon tax – the additional cost premium of fuel cells affects their competitiveness in the short and medium term. If we focus on the long-term forecasts, the financial outlook for fuel cells improves but remains conditional on a carbon tax or similar mechanism.

To summarize, our assessment shows that fuel cells could play a relevant part in shipping's decarbonization, should certain boundary conditions be fulfilled. Stakeholders across the shipping industry can use the information in this report for guidance as they each play their important roles in the adoption of this technology. For example, our results suggest that shipowners or operators may be able to affordably improve their assets' environmental profile by phasing in fuel cells as described in our study. For technology providers, our report sheds light on the optimal commercial operational combinations of fuel cell technologies and alternative fuel pathways. From a policy perspective, the report provides guidance on what is possible and needed to enable fuel cells to contribute to shipping's zero-carbon transition in the coming decades. Finally, this report uses insights from expert interviews and analysis to clarify industry perspectives and increase awareness of fuel cell technology and its potential to support decarbonization of shipping.

01. Introduction

1.1 Purpose of this project

Decarbonization of the shipping industry is a complex task. Given this complexity, it is important to ensure that all options that can contribute are adequately considered and assessed. While alternative fuels for shipping are a major area of research and development, this report puts the spotlight on fuel cells as an alternative fuel conversion technology of potential interest to the shipping industry.

Making fuel cells' contribution to shipping's decarbonization a reality will require both acceleration of technological development and increased awareness of this technology across the different stakeholders in the maritime value chain. To this end, this report seeks to provide an impartial status update on fuel cell technologies from a maritime industry perspective. This information will help ship owners and charterers make informed decisions as they consider whether to include fuel cells as a viable option in their short-, medium-, and long-term strategies.

We begin this report by introducing fuel cells and describing the main technologies of relevance for shipping applications (Sections 1-2). Next, we analyze the potential for integration of these technologies with different ship types and alternative marine fuels (Sections 3-5). Our analyses cover energy demand, greenhouse gas (GHG) emissions, fuel costs, capital expenditure (CapEx), total cost of ownership (TCO), and physical integration of fuel cell technology. We also consider how a theoretical carbon tax could impact the business case for fuel cells in shipping. Finally, we outline some conclusions and possible avenues for future research (Section 6). Safety implications of fuel cells were outside the scope of this specific project.

1.2 What is a fuel cell?

Whereas internal combustion engines (ICE) convert chemical energy through combustion into mechanical motion, fuel cells convert chemical energy through electrochemical reactions into electricity. While the designs of fuel cells are comparable to those of batteries, the former use a flow of fuel and oxygen to supply a continuous production of electricity as long as fuel is supplied to the system.

A fuel cell generally consists of two electrodes (anode and cathode) and an electrolyte. As fuel and oxygen are supplied to the system, a voltage is triggered by the chemical reaction at the contact between fuel and the anode. This generates direct current (DC) electricity that can be used for different applications, along with an outflow of heat and water.

Several fuel cell technologies exist or are being developed, each focusing on a different combination of materials and fuels. While some of these technologies are common in other industrial applications, shipping applications are still limited. For example, fuel cells' applications in the space industry date back to the 1960s, when a range of different technologies were deployed across different programs.[2] More recently, fuel cells have been successfully used on land for material-handling applications and backup power generation.[3] By contrast, the first type approval for a marine fuel cell was only issued in 2022.[4]

1.3 Benefits of fuel cells

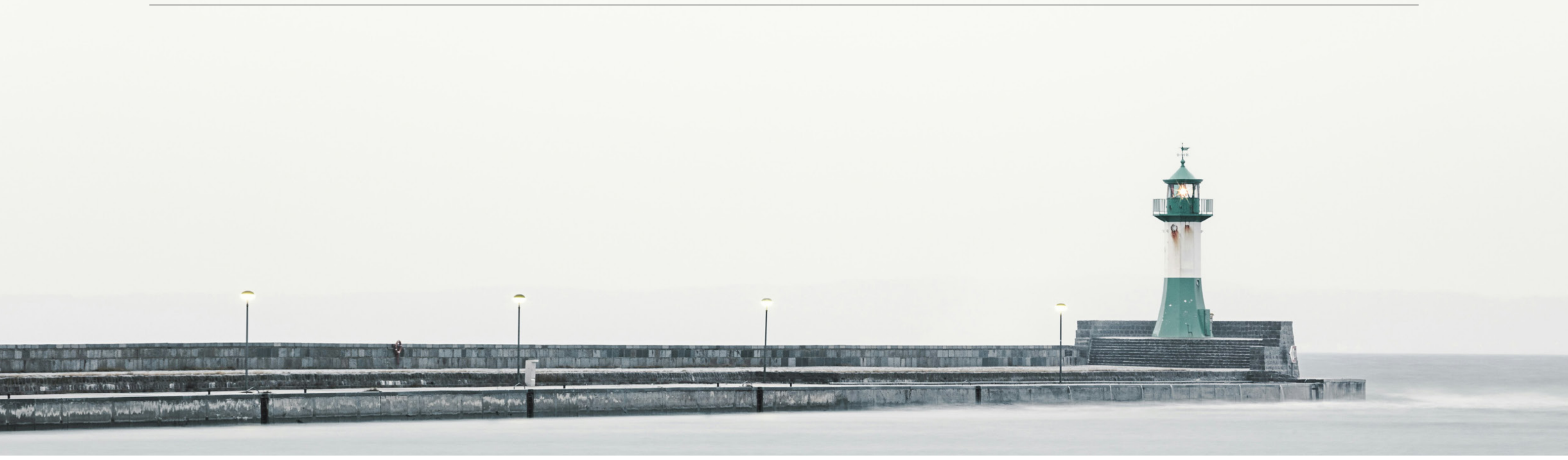
Notwithstanding the wide variety of fuel cell technologies, their common benefit is efficient conversion of chemical energy to electricity, compared to combustion-based processes. Fuel cells can additionally provide a reduction of certain emissions, such as nitrogen oxides (NO_x), sulfur oxides (SO_x), nitrous oxide (N_2O), and particulate matter (PM). Furthermore, certain types of fuel cells could enable their users to work with a wide range of alternative fuels. Lastly, fuel cell systems have fewer moving parts than ICE, which will likely simplify design and maintenance.

1.4 About this project

The project was a collaboration between the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) and our strategic partners and mission ambassadors: Stolt Tankers, Mitsubishi Heavy Industries, Tsuneishi Shipbuilding, Siemens Energy, Seaspan Corporation, ABB, American Bureau of Shipping, Royal Caribbean Group, Maersk, NYK Line, TotalEnergies, and Alfa Laval.

Further, we thank the following technology suppliers, who supported this project and provided input on the report: AFC Energy, Ballard Power Systems, Bloom Energy, Corvus Energy, Elcogen, Freudenberg, PowerCell Group, and RIX Industries.

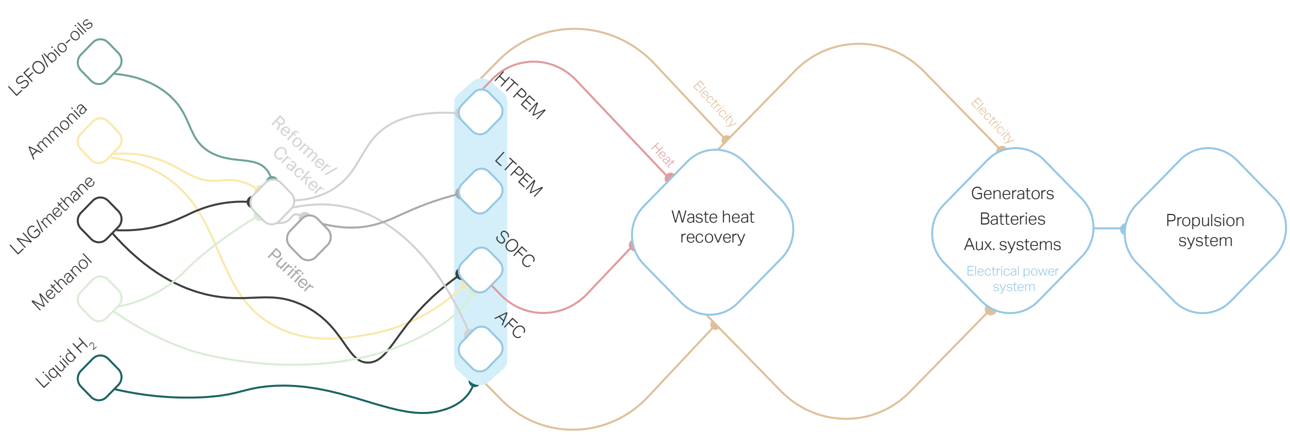
Strategic partners and mission ambassadors



02. Overview of fuel cell technologies

Based on market evaluations and direct dialog with key market players, we identified the energy conversion pathways shown in Figure 1 as those closest to commercial availability in marine applications. The following subsections provide an introduction and basic description for each individual technology, while Table 1 at the end of this section summarizes the key features of each technology.

Figure 1: Mapping of main cells technologies for marine applications.



LSFO = low-sulfur fuel oil, LNG = liquefied natural gas, HT PEM = high-temperature proton-exchange membrane, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cells, AFC = alkaline fuel cells

2.1 Fuel cell technologies

2.1.1 Alkaline fuel cells (AFC)

Alkaline fuel cells (AFCs) use a liquid alkaline electrolyte such as potassium hydroxide (KOH) in water and cathodes usually made with nickel. Operating at 60-70ºC, AFCs are among the most efficient fuel cells, reaching up to 60% efficiency operating on hydrogen.[5]

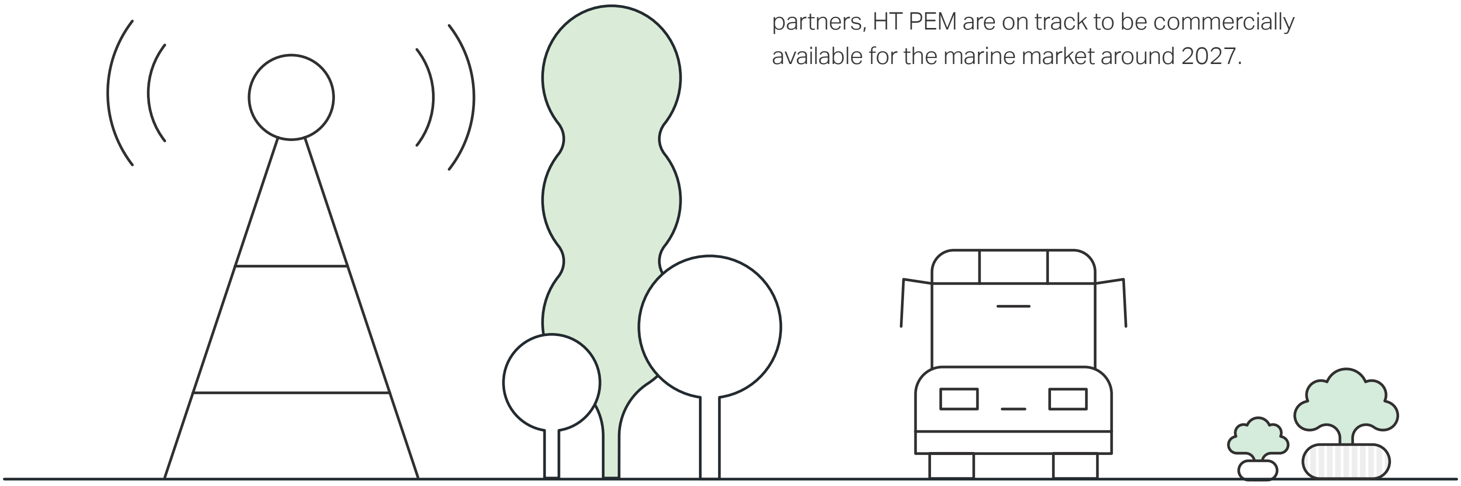
AFCs are used as backup generators or long-duration uninterrupted power supplies for powering telecom towers and urban buses.[6] Even though this technology has already been used for certain applications since the 1960s, AFCs are still early in their development for maritime projects.

2.1.2 Proton-exchange membrane fuel cells (PEMFC)

Proton-exchange membrane fuel cells (PEMFC or PEM fuel cells) use a water-based or mineral-acid-based polymer membrane as an electrolyte and platinum group-based electrodes. The water-based PEM fuel cells operate at 80-100ºC and are normally referred to as low-temperature (LT) PEM. The mineral-acid-based PEMs, known as high-temperature PEMs (HT PEM), operate at up to 200ºC.

These fuel cells require precise humidity conditions (stricter for LT PEM than HT PEM) for operation, and their acidic nature requires the use of a platinum catalyst, which comes at high cost. PEM cells are not fuel-flexible (see Section 2.2.1). Compared to LT PEM, HT PEM are less sensitive to hydrogen purity and can be used in combination with waste heat recovery (WHR) systems, but they are still in the early stages of development for marine applications.

PEM fuel cells are smaller and lighter than other types of fuel cells and are therefore the leading fuel cell technology used in material-handling applications, such as forklifts, and for transportation applications, including cars, buses, and trucks. As such, PEMFC are the fastest-growing type of fuel cells, with the first LT PEM systems with marine type approval already commercially available,[7] albeit at a small scale. According to market intelligence from MMMCZCS partners, HT PEM are on track to be commercially available for the marine market around 2027.



2.1.3 Solid oxide fuel cells (SOFC)

Solid oxide fuel cells (SOFC) are made using a very thin layer of ceramic as the solid electrolyte. The ceramics used in SOFC (yttria-stabilized zirconia or cerium gadolinium oxide) do not become electrochemically active until they reach 500-1,000ºC. This high temperature enables them to oxidize nearly any fuel, including gasoline, diesel, methane, biofuels, hydrogen, and even coal gas. This makes these systems fuel-flexible and well-suited to combination with WHR systems.

SOFC are among the most efficient fuel-flexible type of fuel cells, reaching peak electrical efficiencies beyond 70% at stack level when using natural gas.[8] Unlike PEM, SOFC do not require steam reforming, but rather adiabatic pre-reforming, which requires a lower temperature and has no significant impact on system efficiency.[9] At a balance-of-plant level (i.e., including all the supporting equipment), SOFC systems are expected to have a larger physical footprint than PEM.

While SOFC systems have already been deployed in large-capacity (multi-megawatt) systems for land applications,[10] maritime demonstration projects are still in the early stages, with expected commercial availability between 2025 and 2026.[11]

Table 1: Fuel cell technologies summary.

	Alkaline (AFC)	Proton exchange (LT PEM & HT PEM)	Solid oxide (SOFC)
Anode	Platinum or carbon	Platinum	Ceramic
Electrolyte material	Potassium hydroxide	Polymer membrane	Yttria-stabilized zirconia
Electrolyte state	Liquid	Solid	Solid
Fuel	Hydrogen	Hydrogen	Methane Methanol Ethanol Biogas Ammonia
Temperature	60 - 70ºC	80 - 100ºC (LT PEM) 200ºC (HT PEM)	500 - 1,000ºC
System efficiency	60 - 70%	45 - 60%	50 - 65%
Power	0.5 - 200 kW	0.12 - 5 kW	0.01 - 2,000 kW
Start-up time	< 1 minute	< 1 minute	Hot: < 1 minute Cold: ~12 - 24 hours
Pros	Quick startup Temperature-resistant	Quick startup Small Lightweight	Fuel-flexible
Cons	Liquid catalyst adds weight Large	Sensitivity to humidity or dryness Sensitivity to salinity Sensitivity to low temperatures	Long start-up time from cold Intense heat
Maturity within marine applications	In development	LT PEM: Marine type-approved applications commercially available HT PEM: In development	Marine applications still in development

2.2 Supporting systems

This section aims to provide more context around the supporting systems described in Figure 1, aiding understanding of the additional complexities of onboard fuel cell system setups.

2.2.1 Reformers

Reformers can enable onboard production of hydrogen from other fuels. This ability is particularly interesting considering the complexities linked to storing hydrogen, such as extremely low temperatures and large volume requirements. In particular, the combination of a fuel reformer and an LT PEM fuel cell allows operation with fuels such as methanol (CH_3OH) or methane (CH_4).

Fuel reformers use heat and water to 'crack down' fuels to a hydrogen-rich gas, which is then purified and used in the fuel cells. The purity level varies depending on the specific technology. It is worthwhile highlighting that, at an overall system level, CO_2 emissions generated by methane or methanol during this reforming process would not be different from the expected emissions profile of combusting these fuels in an ICE. In fact, reformers themselves could achieve lower CO_2 emissions than ICE. However, as the reforming process itself requires significant heat (around 400-800°C) and such heat cannot be generated by PEM fuel cells, the overall emissions are very similar. To put things in perspective, combining a reformer with an efficiency of approximately 75%[12] and a fuel cell system with an efficiency around 60% (see Table 1) will result in an overall efficiency of 75% x 60%, or 45%, which is not uncommon for ICE systems.

As a result, while reformers open up new opportunities for onboard use of hydrogen and fuel cells, they will lower the overall system efficiency compared to using hydrogen fuel directly (see Section A.2 in the Appendix for more details). Regarding technological development, reformer prototypes of a few hundred kilowatts (kW) are currently being developed, and megawatt-scale prototypes are forecast to arrive around 2026.[13]

2.2.2 Crackers

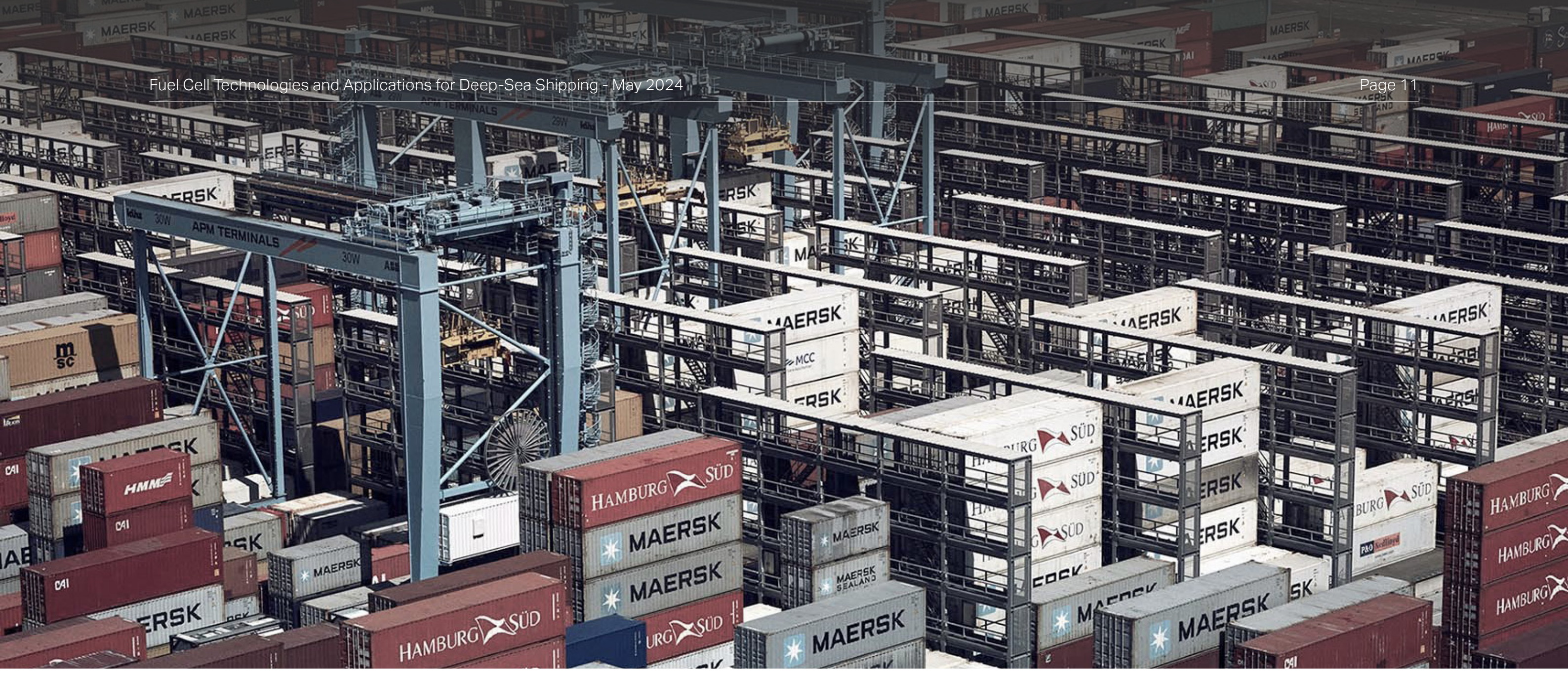
Like reformers, (ammonia) crackers can facilitate the onboard use of PEM fuel cells by mitigating the issues related to onboard storage of hydrogen. These systems are designed to crack ammonia into hydrogen using heat and will generate nitrogen oxide. Similarly to the reformer case, this process reduces the overall efficiency of the combined fuel cell system.

2.2.3 Batteries

A battery system is needed to balance out power demand peaks where a fuel cell is not able to cover the high transients needed. Further, 'excess' energy generated by the fuel cell can be stored using battery packs for later use. This allows the fuel cell to run with an optimized operational profile that increases the system efficiency and reduces noise. The main challenge with batteries is their limited volumetric energy density. Selection of fuel cell technology also has an impact on the battery size, as the dynamic performance varies between different fuel cell types and fuels. High-temperature fuel cells and reformers cannot follow load steps very quickly and require substantial battery capacity as dynamic support, whereas low-temperature hydrogen fuel cells can follow electrical loads with very low added battery capacity.

2.2.4 Waste heat recovery (WHR)

WHR systems are designed to recover thermal energy and convert it to power for onboard systems. Such systems are particularly interesting for fuel cell technologies operating above 100ºC, such as HT PEM or SOFC, and can improve the overall efficiency of these fuel cell systems.



03. Case studies methodology

3.1 Description of integration case studies

To provide a practical view of how fuel cell technologies could be phased into the shipping industry, we developed a set of integration case studies. The case studies are based on information shared by fuel cell technology suppliers and additional expert knowledge from the MMMCZCS and our partner organizations.

For this project, we chose to focus on onboard electrical load rather than vessel propulsion. We judged it more realistic that ship owners will consider using fuel cells to reduce the load on auxiliary power generators (diesel generators, D/G) before they contemplate replacing main engines with fuel cells. Furthermore, using fuel cells for auxiliary power is likely to offer greater efficiency improvements compared to propulsion. We estimate that maritime fuel cell systems would have an efficiency of around 40-60% (see Appendix A.2), while the typical efficiency for a four-stroke auxiliary engine is around 40% (excluding losses to alternating current (AC)) and a two-stroke main engine around 50% (excluding losses to shaft).

We used the following reference values for ICE efficiency based on the MMMCZCS's transition simulation model, NavigaTE – which is built on aggregated knowledge and insights from experts and partners at the MMMCZCS:

Diesel generator efficiency:
210 g/kWh at 42.6 MJ/kg → 40.2%

Main engine efficiency:
175 g/kWh at 42.6 MJ/kg → 48.3%

Implementing fuel cells for auxiliary power generation first would allow more time for the technology to further improve and for ship owners and operators to gain experience with the technology.

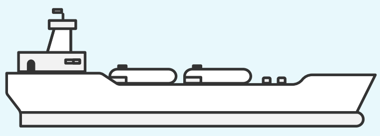
We selected a combination of specific ship types, fuel cell technologies, and fuels (described in the upcoming subsections) to explore the potential for fuel cell integration. We compared the case studies to one another and to a baseline using only D/G for auxiliary power in terms of onboard energy demand, GHG emissions, fuel costs, CapEx, and TCO. We also investigated how fuel cell technologies could plausibly be physically integrated into representative vessel arrangements.

In order to provide a reasonable time horizon for development of fuel cell technology in maritime applications, we selected a timeline for the case studies stretching from the present day to 2040, with data points in 2025, 2030, and 2040.

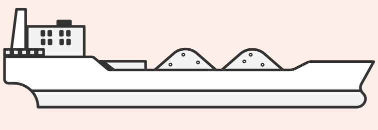
Our intention in this project is to provide a realistic snapshot and informed projections based on current knowledge. As maritime fuel cell technology is still developing, and due to the difficulty in predicting how supply and demand will affect future costs, our results cannot be taken as definitive; however, they can help put maritime fuel cells in perspective compared to other decarbonization options, such as D/G operating on alternative fuels.

3.1.1 Ship types

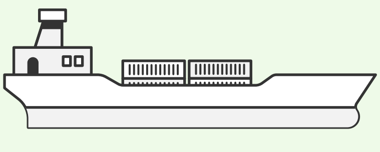
We selected the following three representative vessels to use as case studies for this report:



LR2 tanker



82,000 DWT bulk carrier



15,000 TEU container ship

These vessels were chosen to represent the shipping segments of tankers, bulk carriers, and container ships, respectively. This choice does not imply that other ship types are not considered candidates for fuel cell applications. Rather, we reasoned that if it is possible to confirm technical feasibility for these deep-sea segments, similar rollouts in other shipping sectors will likely be possible.

Ship owners participating in the project kindly shared representative operational profiles for each ship type (see Section A.1 in the Appendix). We used these data to understand the typical electricity demand for each ship type in our case studies, assuming that existing business structures and operational profiles continue through the time horizon considered in our scenarios (i.e., that ships keep doing what they are doing today).

3.1.2 Technologies

We considered the following fuel cell technologies in our integration studies:

- LT PEM
- LT PEM + reformers
- SOFC

In making this selection, we were guided by the availability of information supplied by technology providers. This does not mean that other technologies are not viable, but rather that we gave priority to those assessments where it was possible to use first-hand information gathered directly from suppliers, instead of basing our conclusions on assumptions or default values.

We next defined representative assumptions regarding the efficiency of fuel cells and supporting technologies for use in our calculations. This process is summarized here, but interested readers are encouraged to refer to the Appendix of this report (Section A.2) for more detailed information on our efficiency assumptions. Briefly, to estimate the efficiency of fuel cell technologies, we generated average curves for the efficiency of the fuel cell system based on anonymized and aggregated performance information from fuel cell suppliers. We subsequently adjusted these values based on expert knowledge from project participants to estimate the fuel cell systems' overall efficiency when installed on a working vessel.

We estimated an efficiency value for reformers based on the thermodynamics of the steam reforming reaction. Finally, we used a dynamic simulation approach to estimate the efficiency of an entire onboard fuel cell system, including batteries, in order to guide our assumptions about battery capacity for our calculations. These simulations are also described in more detail in the Appendix (Section A.3).

3.1.3 Fuels

We considered the following fuels in our integration studies:

- Liquid hydrogen
- Methanol
- Methane

We considered each fuel option paired with a specific fuel cell technology option as follows:

Fuel	Fuel cell technology
Liquid hydrogen	LT PEM
Methanol	LT PEM with reformers
Methane	SOFC

As with the choice of fuel cell technologies, our selection of fuels was guided by the availability of reliable and detailed performance data from fuel cell technology suppliers. This does not imply that other technology/fuel combinations are not possible or viable.

For example, we were unable to include ammonia as a fuel option in our study as we did not have access to sufficient data on ammonia-fueled fuel cell systems. We have included a qualitative discussion on ammonia's potential for use with SOFC in Section 5 of this report.

We compared our selected fuel cell technology/fuel combinations to a baseline of D/G running on either low-sulfur fuel oil (LSFO), bio-methanol, or bio-methane. While it would have been ideal to directly compare fuel cell technologies to ICE (here D/G) using the same fuel type, we were constrained by the low technological maturity level of hydrogen-fueled ICE.

Our selected fuels can be produced via multiple pathways, each with different implications for affordability and environmental impact. Therefore, for the purposes of our analyses of cost and GHG emissions (see also Sections 3.2 and 3.3), we specifically assumed that the fuels were blue hydrogen, bio-methanol, and bio-methane. The availability of specific fuels is beyond the scope of this paper, but we refer interested readers to the Fuel Pathway Maturity Map[14] and Maritime Decarbonization Strategy 2022 previously published by the MMMCZCS.[15]

3.1.4 Technological configuration

Table 2 summarizes the technological configuration of the onboard fuel cell/engine systems considered for each case study in our analysis.

As the table shows, we assumed that a certain number of D/G would be retained in each case because ships are likely to initially combine fuel cells and ICE as the performance and technological feasibility of fuel cells is further evaluated. Further, D/G are necessary to provide support during startup and shutdown of the system during normal operating conditions, as well as backup in case of emergency. The respective capacity of each technology setup was defined according to the relevant operational profile (see Appendix A.1).

For the container ship case, the maximum capacity of generators was decided according to maximum reefer capacity, even though vessels rarely reach this capacity in practice. As a result, we also defined an additional case based on minimum number of reefers ('SOFC min'), wherein additional reefers are assumed to be powered by D/G. This helped us to assess whether SOFC could lead to a reduction of emissions (or an improvement in efficiency) even when its capacity is minimized, to optimize costs.

To provide additional context, we have also created simplified one-line diagrams to describe how fuel cells and D/G could be integrated in the ship grid. These diagrams can be found in the Appendix (Section A.4).

Table 2: Ship configurations defined for ship integration case studies.

			Ship types		
			14K TEU container	LR2 tanker	82 DWT bulk carrier
	Original	D/G	3,700 kW x 2 sets 2,800 kW x 2 sets	1,000 kW x 3 sets	400 kW x 3 sets
Case studies	LT PEM + LH_2	Fuel cell	6,300 kW	2,000 kW	800 kW
		Battery	400 kW with 3c[16]	200 kW with 3c	75 kWh with 3c
		D/G	3,700 kW x 1 set (FO) 2,600 kW x 1 set (FO)	1,000 kW x 1 set (FO)	400 kW x 1 set (FO)
	LT PEM + reformer + bio-methanol	Fuel cell	6,300 kW	2,000 kW	800 kW
		Battery	3,000 kWh with 3c	1,000 kWh with 3c	400 kWh with 3c
		D/G	3,700 kW x 1 set (DF)	1,000 kW x 1 set (FO)	400 kW x 1 set (FO)
	SOFC	Fuel cell	6,300 kW	1,500 kW	700 kW
		Battery	3,000 kWh with 3c	1,000 kWh with 3c	400 kWh with 3c
		D/G	1,700 kW x 1 set (DF)	1,000 kW x 1 set (FO)	400 kW x 1 set (FO)
	SOFC min	Fuel cell	1,700 kW		
		D/G	1,350 kW x 2 sets (DF) 4,300 kW x 2 sets (DF)		

LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell, D/G = diesel generator, LH_2 = liquid hydrogen, FO = fuel oil, DF = dual-fuel

3.2 GHG emissions

To estimate the GHG emissions associated with the selected fuel/technology combinations, we used emissions factors from NavigaTE. To be more specific, well-to-wake (WTW) factors shown in Table 3 are the combination of well-to-tank figures extracted from NavigaTE and tank-to-wake figures based on input from technology suppliers.

Table 3: GHG emissions factors used in this study.

Energy converter	Fuel	WTW GHG emissions factor (gCO_2eq/MJ)
Engine	LSFO	93.23
Engine	Bio-methanol	3.82
Engine	Bio-methane	4.52
Fuel cell	Bio-methanol	1.74
Fuel cell	Blue hydrogen (liquid)	1.64
Fuel cell	Bio-methane	0.80

LSFO = low-sulfur fuel oil

3.3 Fuel costs

Fuel prices are difficult to forecast, as they are heavily affected by the dynamics of supply and demand.
For our purposes, we relied on the fuel costs assumed in NavigaTE, as shown in Table 4.

Table 4: Overview of fuel costs assumed in this study.

	LSFO	Bio-methane	Bio-methanol	Blue hydrogen (liquid)
Fuel cost (USD/tonne) - cost per tonne of LSFO equivalent				
2025	635	980	1,480	1,555
2030	554	917	1,252	1,054
2040	554	807	1,067	992
Fuel cost (USD/GJ)				
2025	15.4	23.8	35.9	37.7
2030	13.4	22.3	30.4	25.6
2040	13.4	19.6	25.9	24.1

LSFO = low-sulfur fuel oil

3.4 Carbon tax

To assess whether a carbon tax would theoretically facilitate the acceptance of fuel cell technology in the shipping industry, we referred to the carbon price estimated in the MMMCZCS's 2021 Industry Transition Strategy.[1] This report indicated that a carbon price of USD 230/tCO_2eq would be required to close the gap between shipping's current emissions and net-zero in 2050. The impact of such a carbon tax is presented separately in figures throughout the results section of this report, allowing readers to clearly visualize and compare this impact.

Our goal for this report is not to predict future fuel prices nor to present a business case for a carbon tax, but simply to provide high-level insight into the impact such a tax might have on the adoption of fuel cell technology in the maritime industry. This issue of appropriate market-based measures can and should be explored further in future work, if a more detailed proposal for a large-scale or global carbon pricing scheme becomes available.

3.5 CapEx

To provide an outlook on the price development of different fuel cell technologies, we gathered forecasts through the technology suppliers who participated in this project. These forecast trends are based on current knowledge and expectation of future supply and demand.

As such, the information shared in this section should not be read as a commercially binding quotation linked to a particular technology or vendor, but rather as the aggregated average built upon information collected from a group of technology suppliers. Through this data aggregation, it is possible to anonymize the estimates while averaging out differences that might relate to a particular angle used by a supplier when estimating such trends. Furthermore, these price forecasts are only indicative and should be taken as the best estimate available today.

3.5.1 Fuel cell initial costs

As shown in Figures 2 and 3, suppliers tend to agree that the initial cost per kW_{el} should asymptotically converge to similar figures, meaning that substantial price parity across different fuel cell technologies can be expected in the long term.

Figure 2: Forecast unit (initial) costs for different marine fuel cell technologies.

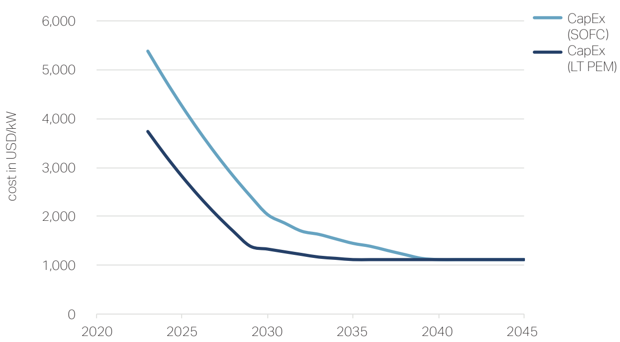
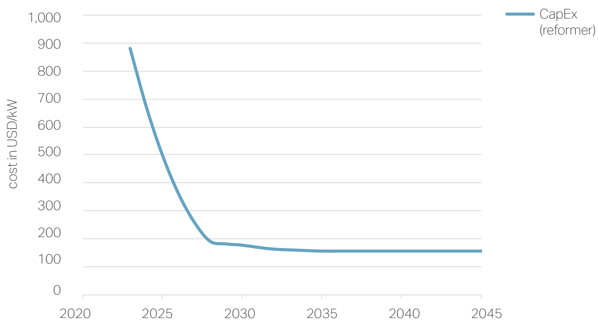


Figure 3: Forecast unit costs for marine reforming technology.

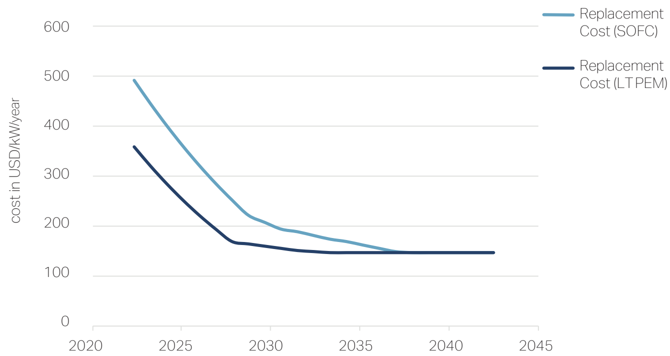


3.5.2 Fuel cell stack replacement costs

Replacement costs for fuel cells are expected to be significant, with approximately 30-40% of the initial system being replaced every 3-4 years. The costs shown in Figure 4 were calculated accordingly and validated by technology suppliers.

To provide some guidance, Figure 4 shows replacement costs in terms of cost per kW per year. This means that if we took, for example, a 2,000-kW LT PEM in 2035, after four years we would expect a cost of 100 USD/kW/year x 2,000 kW x 4 years, or 800,000 USD. Within the calculation, we assumed that such a replacement would be required every four years, based on the general input received from fuel cell suppliers involved in the project.

Figure 4: Forecast unit (stack replacement) costs for different marine fuel cell technologies.



04. Results

This section presents the key results of our case study analysis, organized as follows:

– **Onboard energy demand outlook:** This subsection shows how converting to the shortlisted fuel cell technologies would affect fuel demand across the three ship types in terms of energy required on board, compared to traditional D/G.

– **Emissions outlook:** The main objective of this subsection is to summarize the results relating to GHG emissions, considering the energy efficiency described in the previous subsection. In other words, what level of emissions can we expect from fuel cells using alternative fuels, based on their expected technical performance?

– **Fuel cost outlook:** In this subsection, we forecast realistic yearly fuel costs for the considered onboard configurations by combining estimated efficiency performance for the various fuel cells with the fuel cost forecasts extracted from NavigaTE.

– **CapEx:** This subsection considers the estimated initial costs of fuel cell supply, supporting systems (batteries, reformers), and miscellaneous costs (i.e., fuel tank costs, fuel management system costs, ship conversion costs). In this way, we can provide a useful data point to shipowners who are curious about how initial costs for a fuel cell system compare to those for a conventional setup.

– **Total cost of ownership (TCO):** This subsection summarizes the total costs expected for equipment, fuel, and maintenance, expressed as yearly cost in net present value.

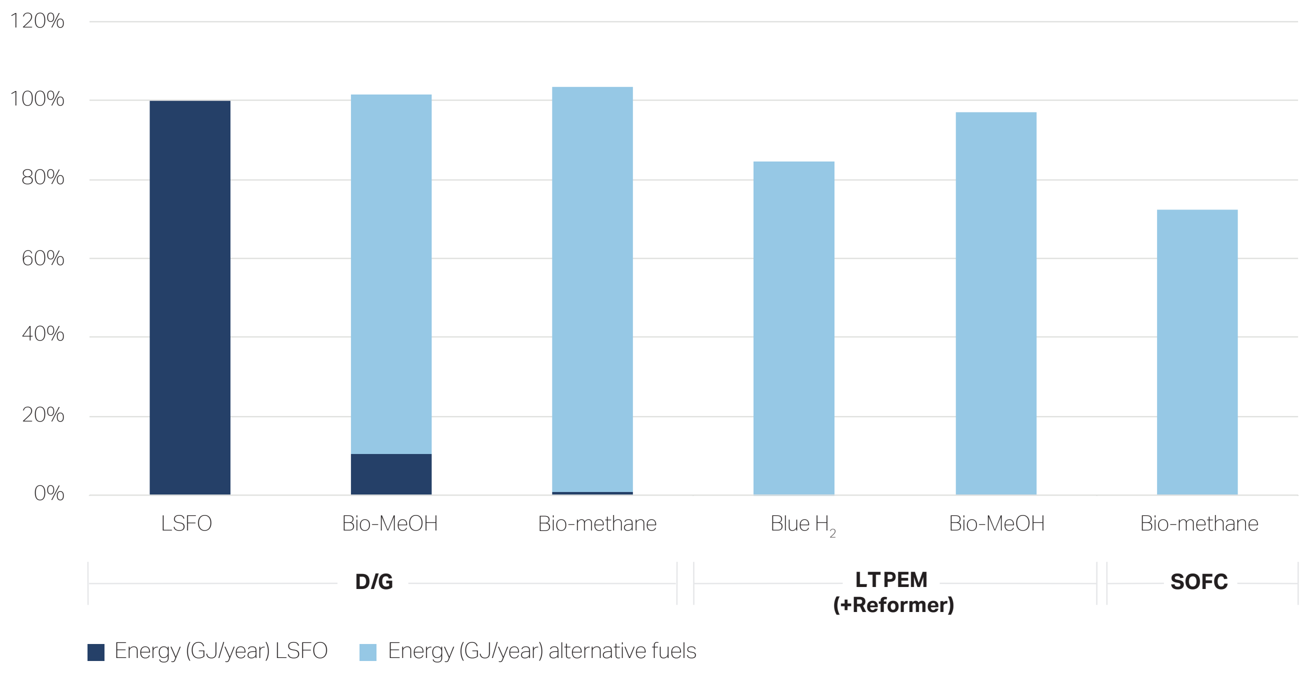
Please note that not all ship types are shown in each results subsection. Instead, each subsection shows specific results for one ship type, unless the results vary noticeably across the different ship types. Results for all the cases not shown in the main text can be found in the Appendix (Section A.5).

4.1 Estimated onboard energy demand outlook

In this section, we decided to zoom in on the bulk carrier, since the performance does not vary remarkably across the different ship types. Comparing D/G burning conventional fuels to fuel cells fed by alternative fuels would make it hard to isolate the effect of technology from the impact of fuel type; therefore, we have compared fuel cells to an ICE (D/G) burning the same alternative fuels (except for liquid hydrogen, where the corresponding ICE technology is not yet available).

Figure 5 shows that the combination of our selected alternative fuels and fuel cell technologies is likely to lead to lower onboard energy demand and hence an overall improvement in onboard fuel efficiency, compared to the D/G options. The improvement varies across the different technologies and fuels, and it is largest for the combination of SOFC and bio-methane, thanks to the absence of intermediate systems (e.g., steam reformers).

Figure 5: Relative onboard energy demand comparison for the shortlisted case studies (bulk carrier).

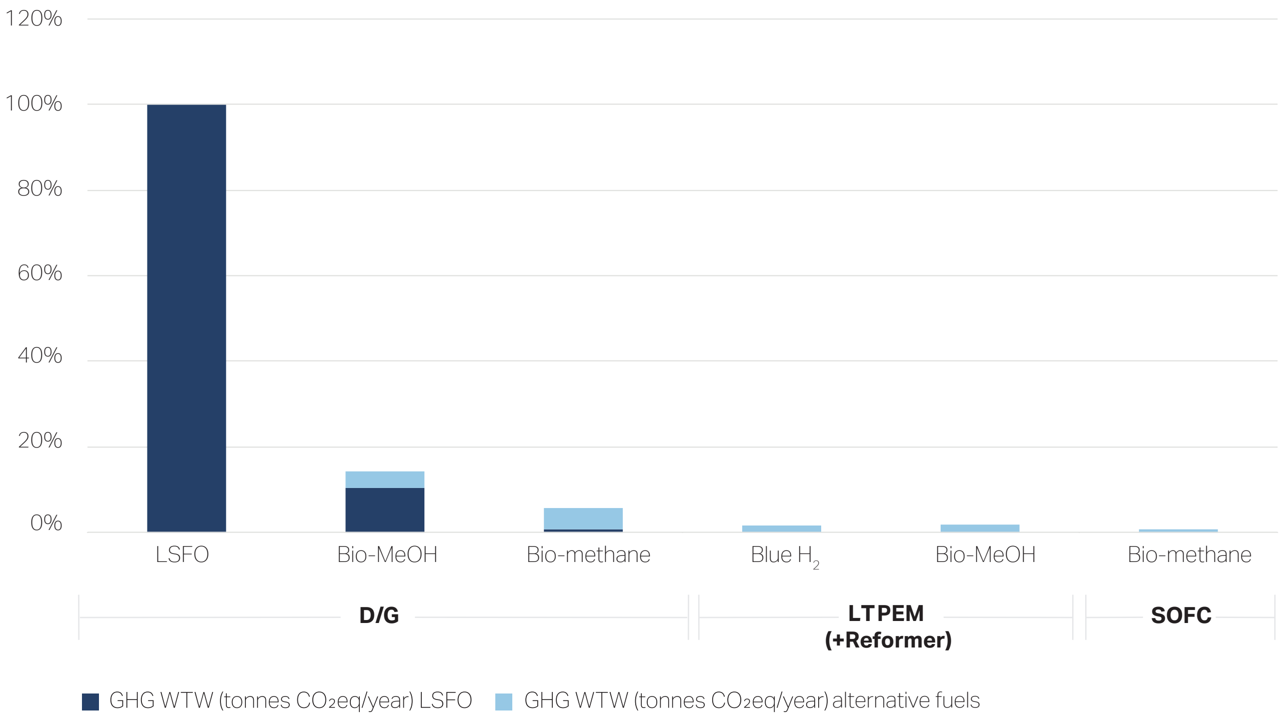


LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell

4.2 Estimated greenhouse gas emissions outlook

Figure 6 shows that the shortlisted combination of alternative fuels and fuel cells could significantly cut the forecast WTW GHG emissions compared to conventional fossil fuel (here LSFO). This is not surprising, as the CO_2-equivalent emissions associated with the alternative fuels we considered are generally much lower than those associated with fossil fuels. Nevertheless, the results (shown here for the bulk carrier case) also indicate that fuel cells can meaningfully reduce GHG emissions even compared to the same alternative fuels feeding ICE.

Figure 6: Relative onboard GHG emissions for the shortlisted case studies (bulk carrier).



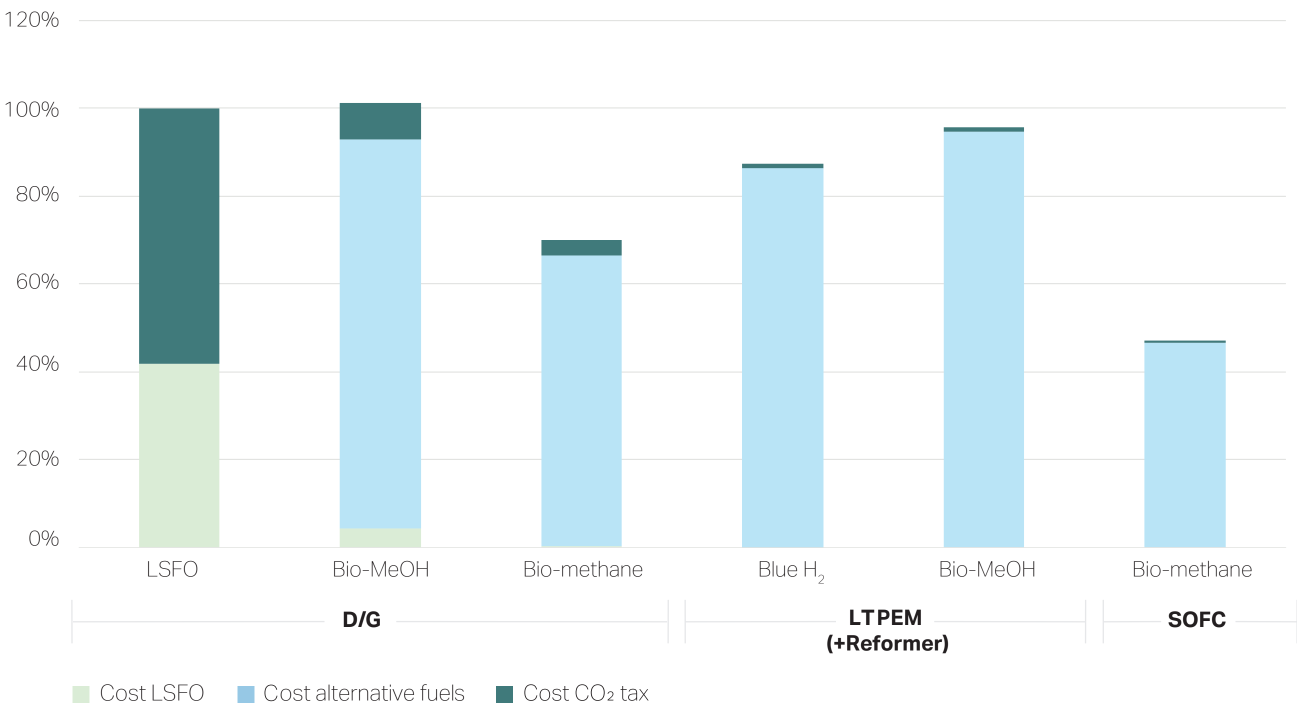
GHG = greenhouse gas, WTW = well-to-wake, LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell

4.3 Estimated fuel cost outlook

To estimate fuel cost outlook, we combined supplied performance data with forecast fuel costs as shown in Figure 7, along with a theoretical carbon price of USD 230/tCO_2eq as described in Section 3.4. Figure 7 shows that fuel cells could, under certain circumstances, lead to a reduction in fuel costs, especially in the long term and if a carbon tax is implemented.

The addition of a carbon tax is particularly attractive for the combination of blue hydrogen and LT PEM in the medium/long term, but also for SOFC when fed by methane. Without a carbon tax, only the combination of SOFC and bio-methane in the (very) long term appears to be able to compete with the base case of LSFO-fueled D/G, in terms of fuel cost.

Figure 7A: Relative onboard estimated fuel costs comparison for the shortlisted case studies (bulk carrier) for the year 2025.



LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell

Figure 7B: Relative onboard estimated fuel costs comparison for the shortlisted case studies (bulk carrier) for the year 2030.

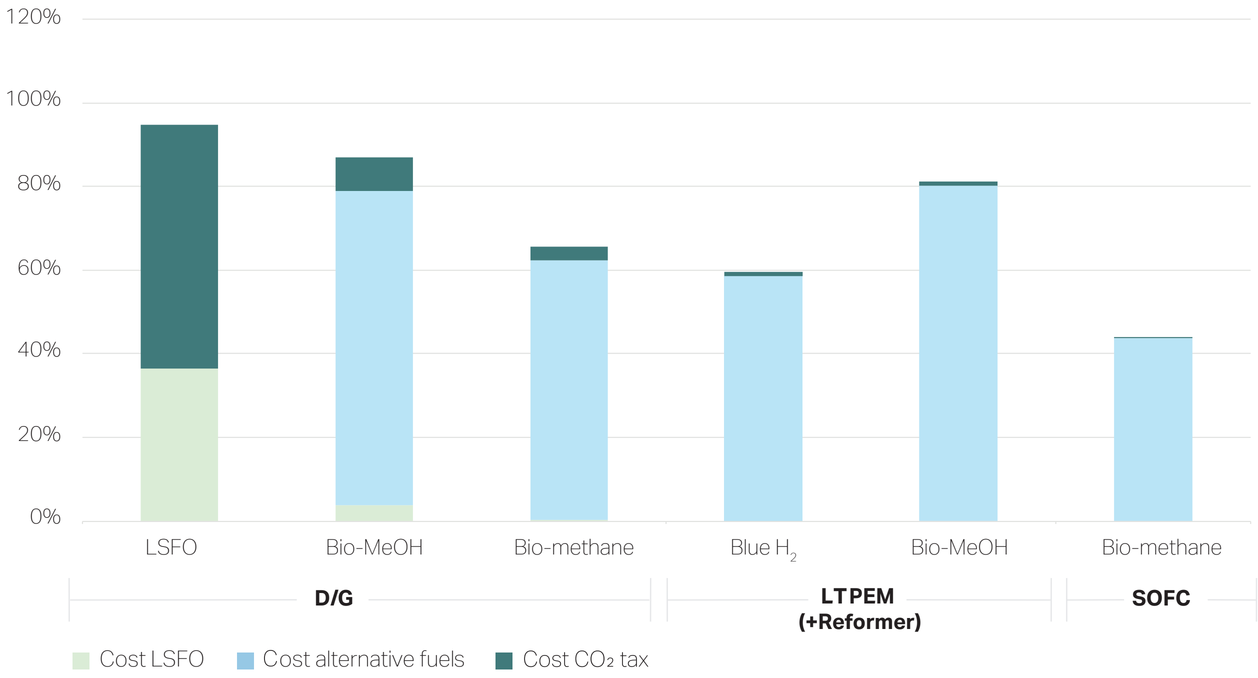
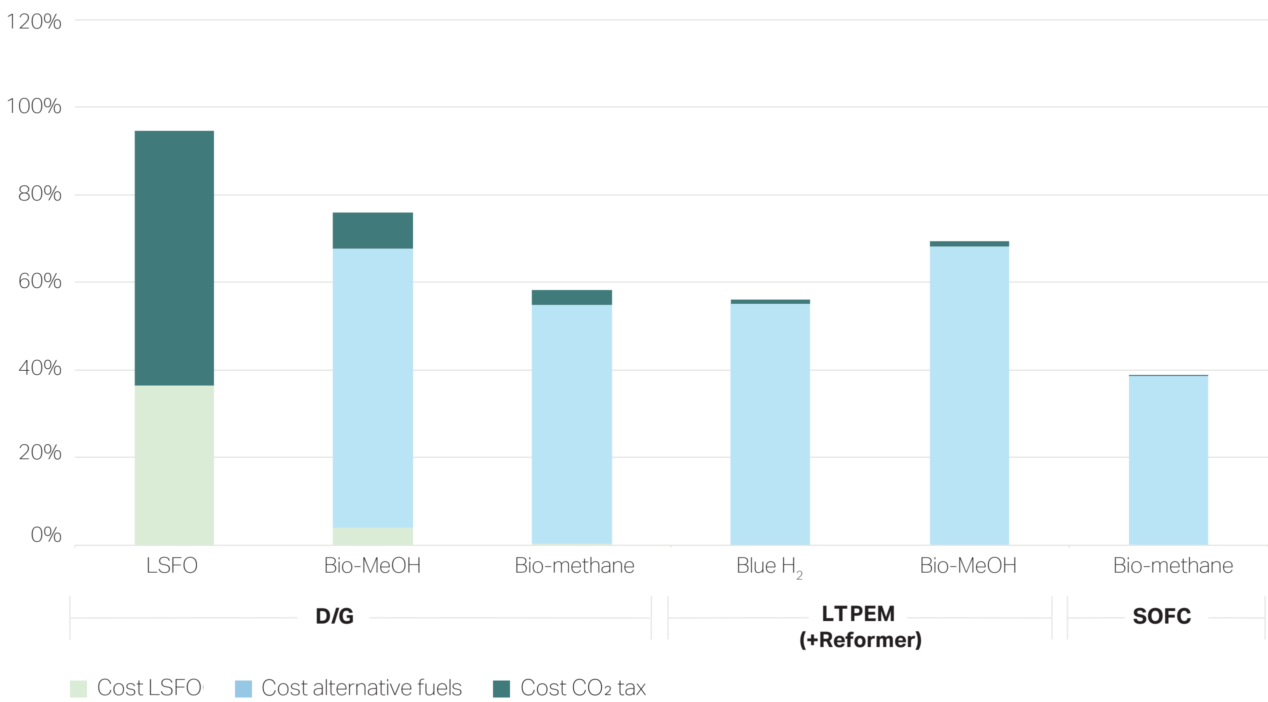


Figure 7C: Relative onboard estimated fuel costs comparison for the shortlisted case studies (bulk carrier) for the year 2040.



LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell

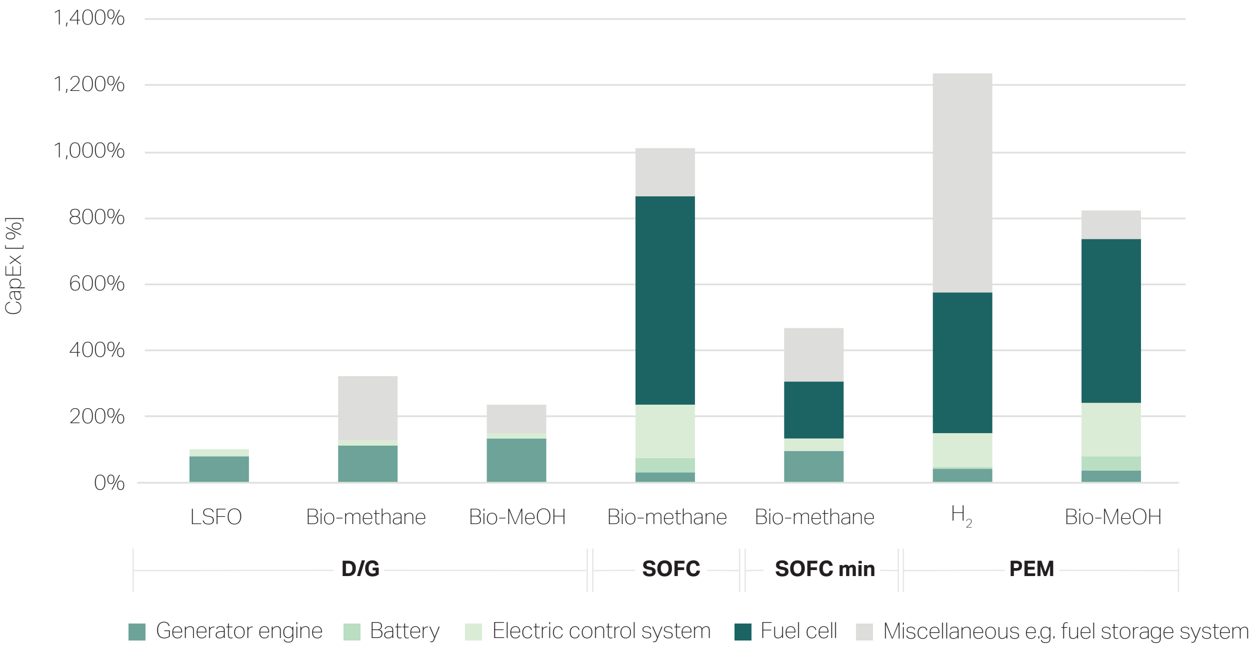
4.4 CapEx

CapEx might represent one of the main barriers for wider onboard application of fuel cell technologies, especially in the early stages. On the one hand, initial costs do not reflect the full economics of the business case. Accordingly, the upcoming section on TCO (Section 4.5) further explores overall costs, including fuel and maintenance. On the other hand, CapEx can give a useful picture of expected costs when comparing fuel cell systems with other costs, such as fuel system or ship modifications to existing (conventional) setups.

To estimate CapEx for our case studies, we included the initial cost of equipment, fuel cell replacement costs, and an estimate for ship conversion (fuel systems, fuel tanks, structural modifications, and installation costs). The results are shown in Figures 8-10.

These figures show that, even using current forecasts for initial costs, some combinations of alternative fuels and fuel cell technologies (e.g., LT PEM with bio-methanol or SOFC with bio-methane) could become competitive with D/G in the long run. Zooming in on the PEM + hydrogen cases, we can see a large impact of 'miscellaneous' items on CapEx. This is mainly due to the (currently) very high costs of onboard liquid hydrogen storage systems, which represent the vast majority of such costs.

Figure 8A: Relative capital expenditure (CapEx) comparison for the shortlisted case studies (container ship) for the year 2025.



LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, PEM = proton-exchange membrane, SOFC = solid oxide fuel cell

Figure 8B: Relative capital expenditure (CapEx) comparison for the shortlisted case studies (container ship) for the year 2030.

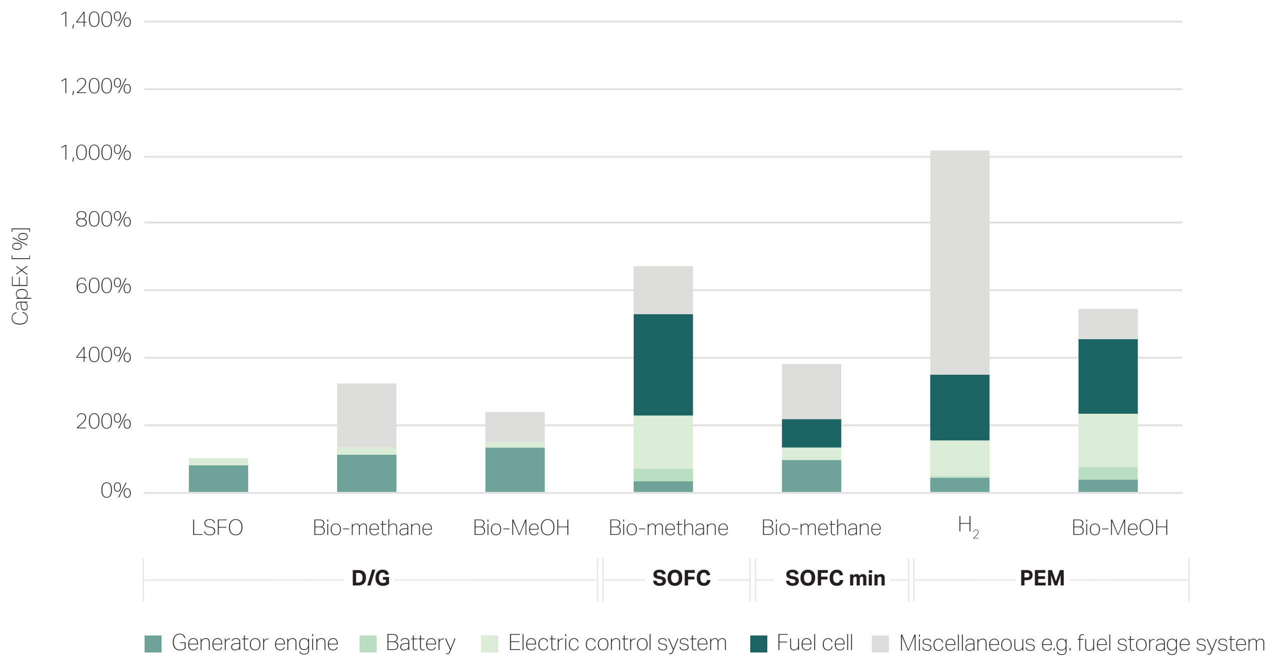
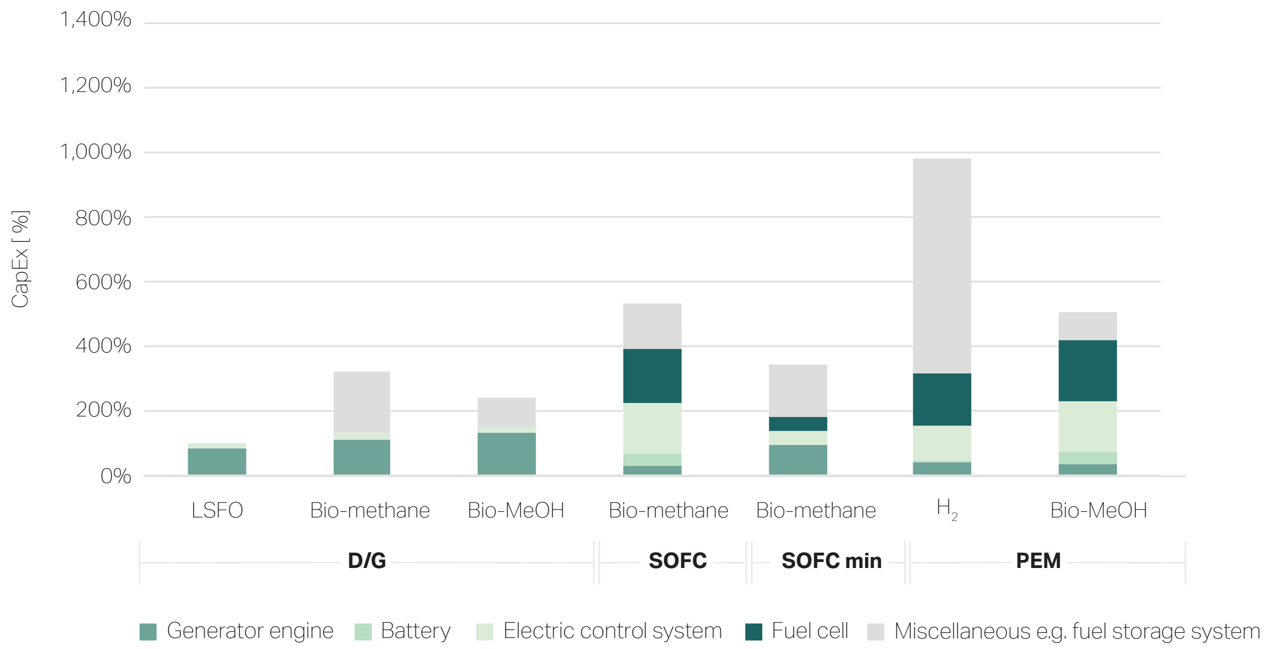


Figure 8C: Relative capital expenditure (CapEx) comparison for the shortlisted case studies (container ship) for the year 2040.



LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, PEM = proton-exchange membrane, SOFC = solid oxide fuel cell.

Figure 9A: Relative capital expenditure (CapEx) comparison for the shortlisted case studies (tanker) for the year 2025.

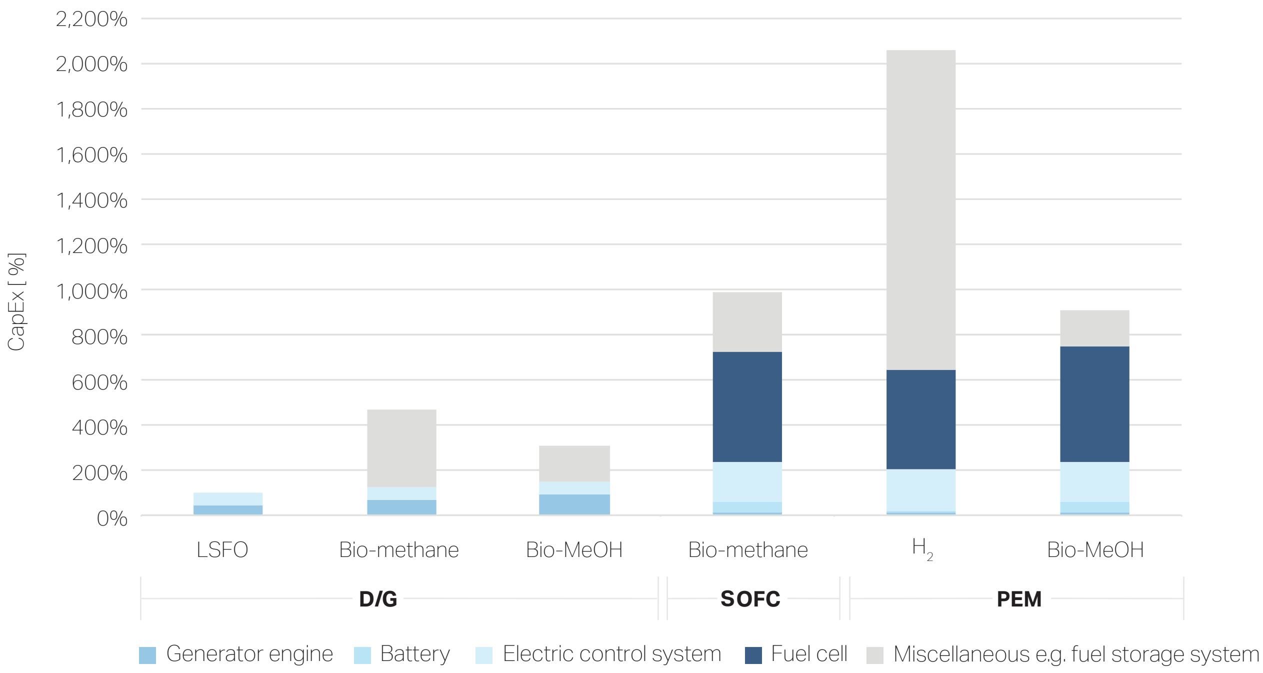
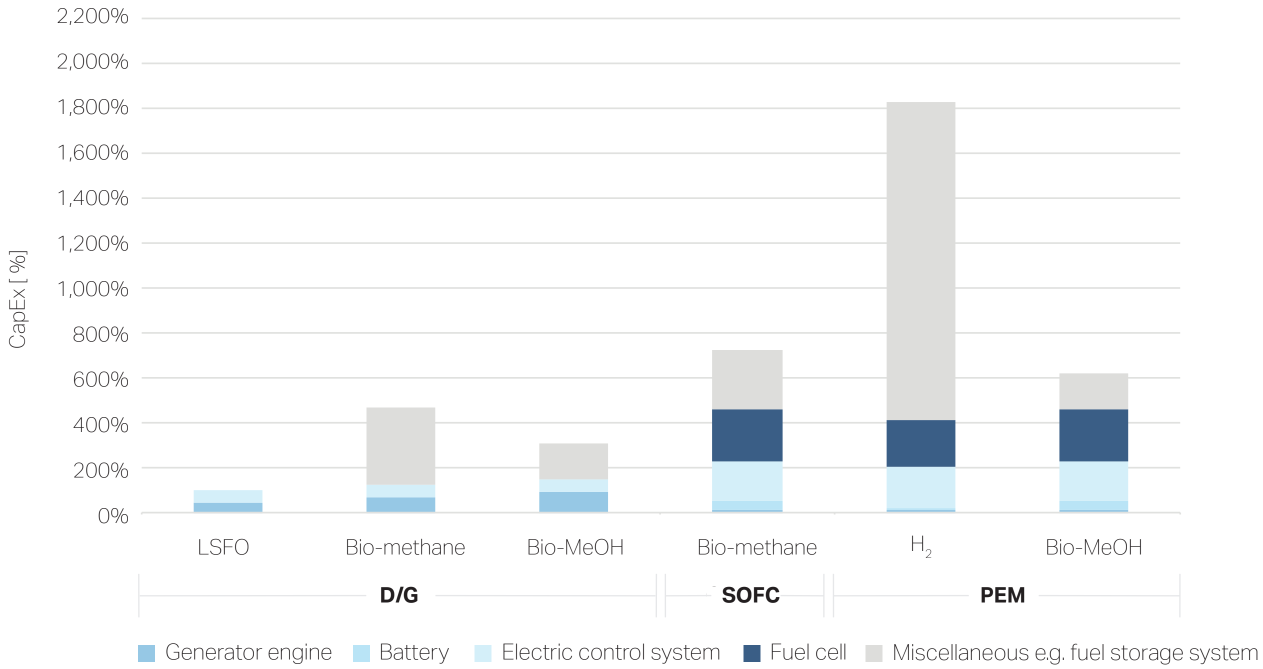


Figure 9B: Relative capital expenditure (CapEx) comparison for the shortlisted case studies (tanker) for the year 2030.



LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, PEM = proton-exchange membrane, SOFC = solid oxide fuel cell.

Figure 9C: Relative capital expenditure (CapEx) comparison for the shortlisted case studies (tanker) for the year 2040.

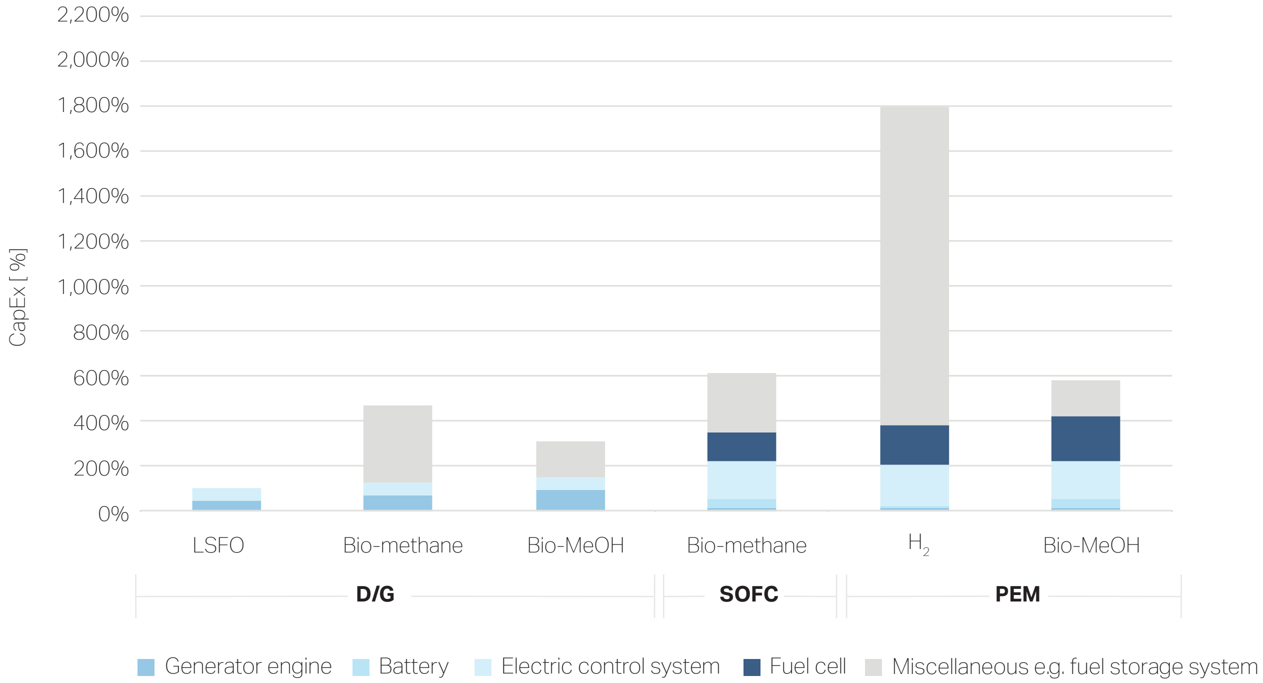
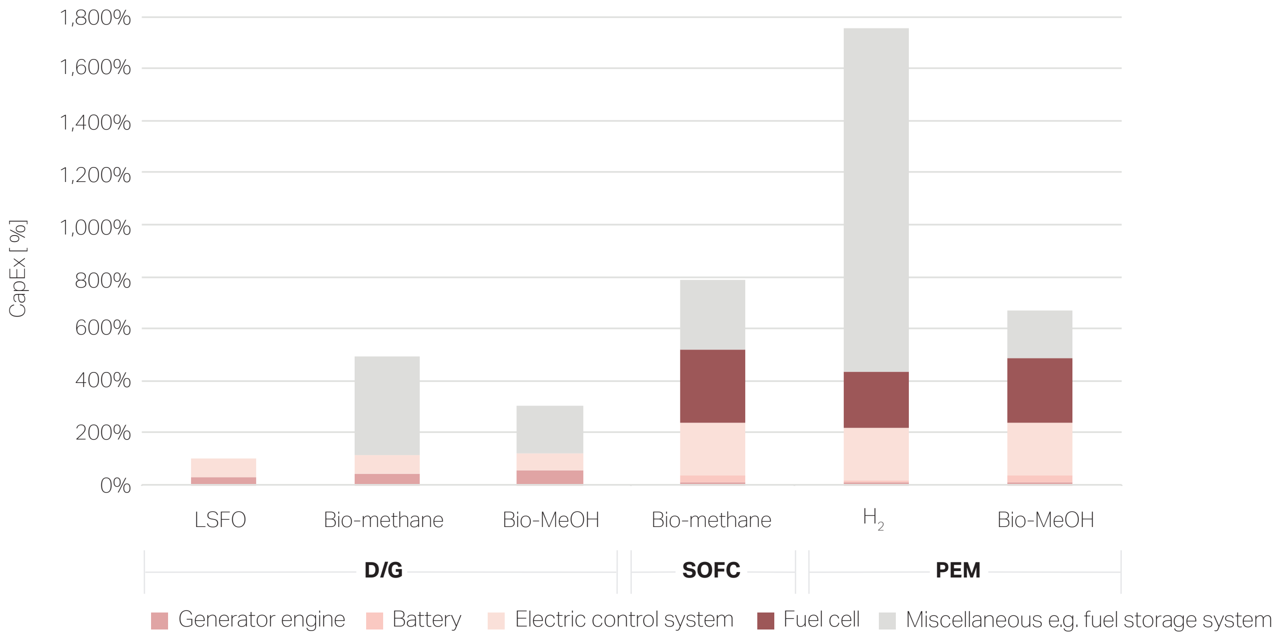


Figure 10A: Relative capital expenditure (CapEx) comparison for the shortlisted case studies (bulk carrier) for the year 2025.



LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, PEM = proton-exchange membrane, SOFC = solid oxide fuel cell.

Figure 10B: Relative capital expenditure (CapEx) comparison for the shortlisted case studies (bulk carrier) for the year 2030.

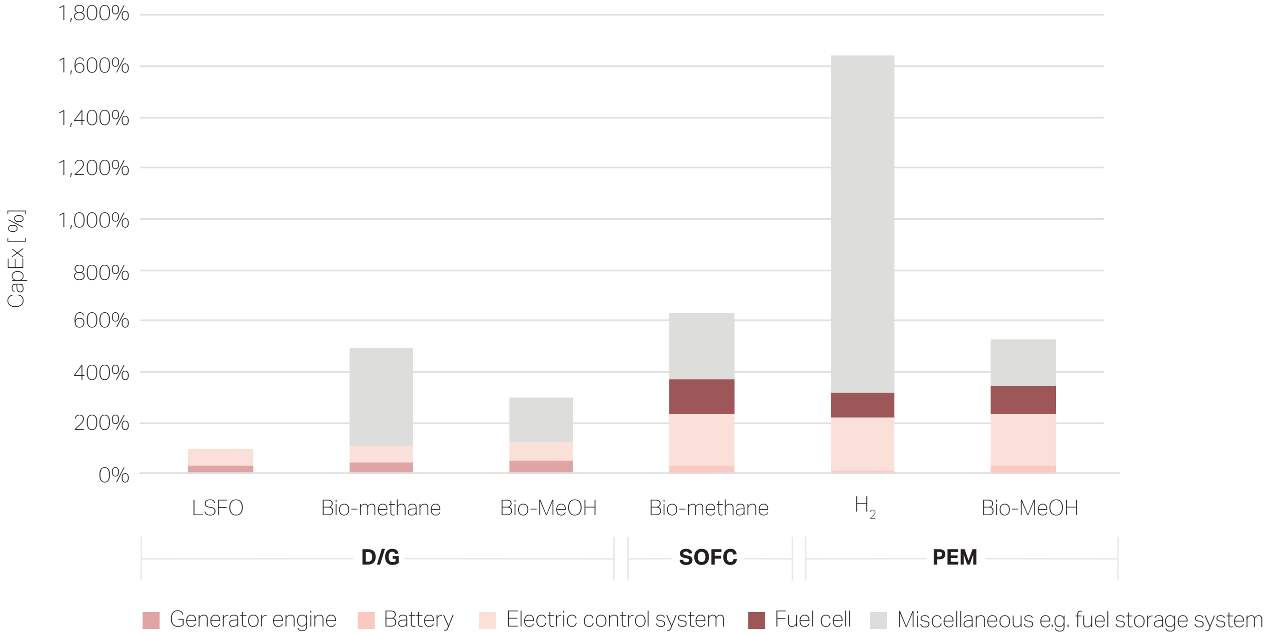
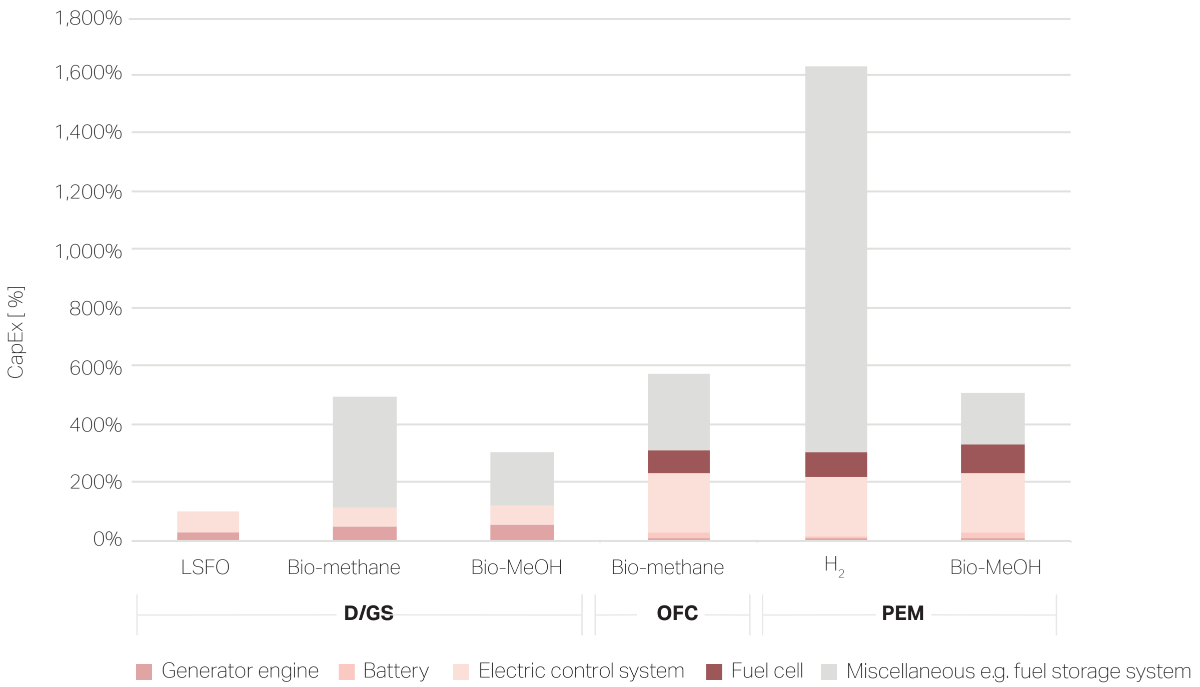


Figure 10C: Relative capital expenditure (CapEx) comparison for the shortlisted case studies (bulk carrier) for the year 2040.



LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, PEM = proton-exchange membrane, SOFC = solid oxide fuel cell.

4.5 Estimated total cost of ownership (TCO)

We used the following approach to describe total cost of ownership (TCO). The costs considered are expressed as relative costs compared to a base case of D/G running on LSFO.

These costs are annualized costs discounted to present value, calculated as:

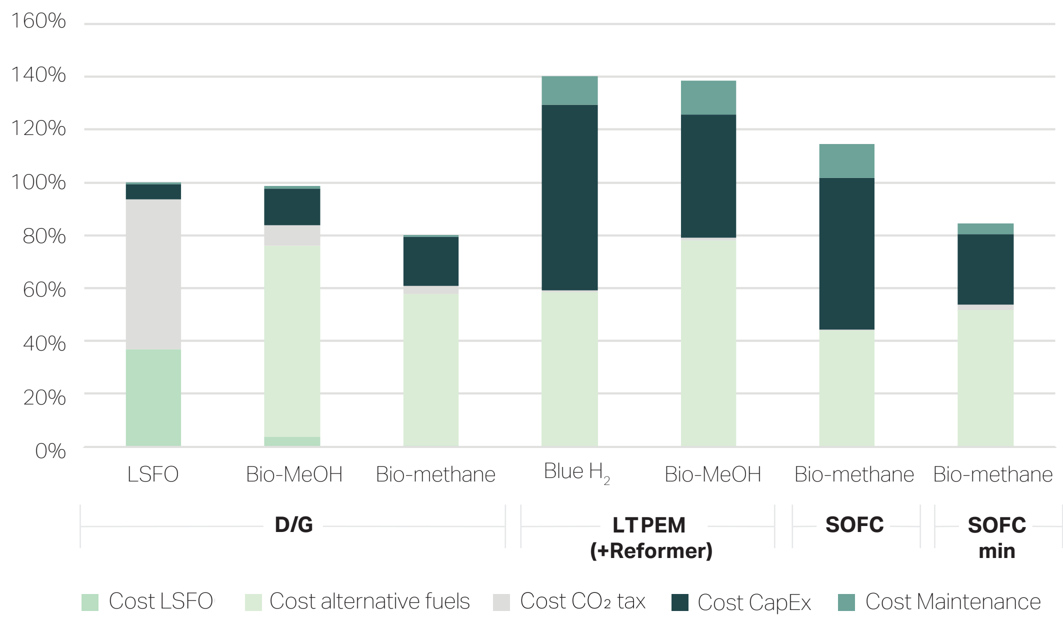
$$TCO_{PV} = \sum_{i=1}^{n} \frac{TCO_i}{(1+r)^i}$$

Where:

- TCO_i is total cost of ownership (in future value, for each year): initial costs + fuel costs + maintenance + carbon tax
- i: individual years
- r: interest rate (7%)
- n: number of years (25 years for this assessment)

The results are summarized in Figures 11-14. According to these figures, the cost gap between fuel cells and D/G is sometimes not as large as one might expect. For certain combinations of technologies and alternative fuels (i.e., SOFC + methane beyond 2030), fuel cells might even be cheaper than existing setups in the long run. This effect is, however, largely a result of the carbon tax included in these calculations, as can be seen from the large contribution of the gray bar segments for the D/G + LSFO cases. If we assume a lower carbon price, or no carbon tax at all, the results do not show fuel cells becoming economically competitive against conventional D/G.

Figure 11A: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (container ship) for the year 2025.



PV = present value, LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell, FO = fuel oil, CapEx = capital expenditure.

Figure 11B: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (container ship) for the year 2030.

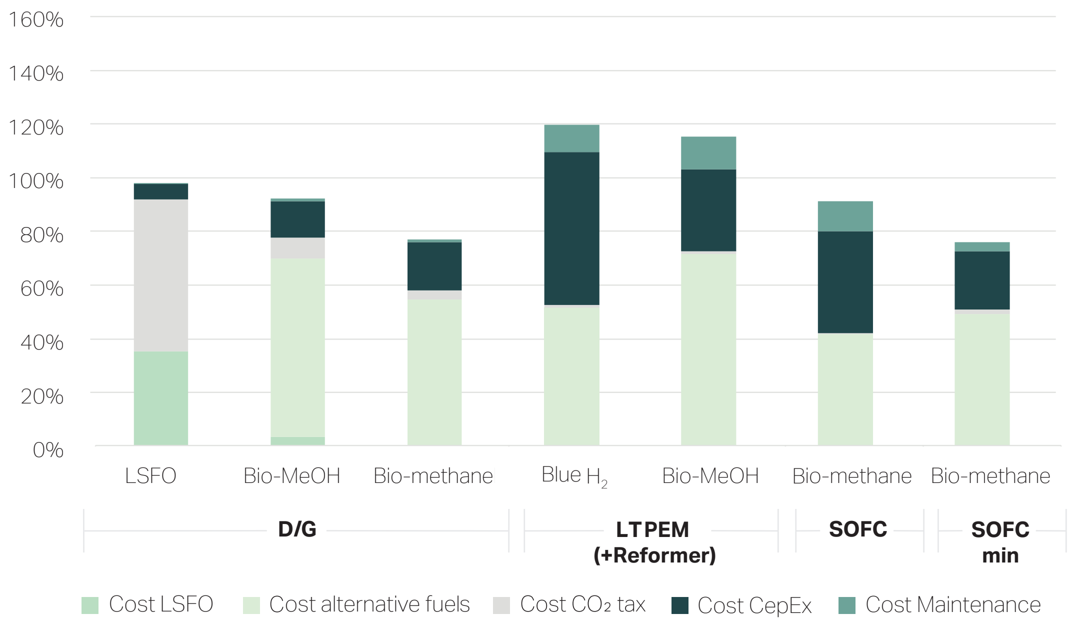
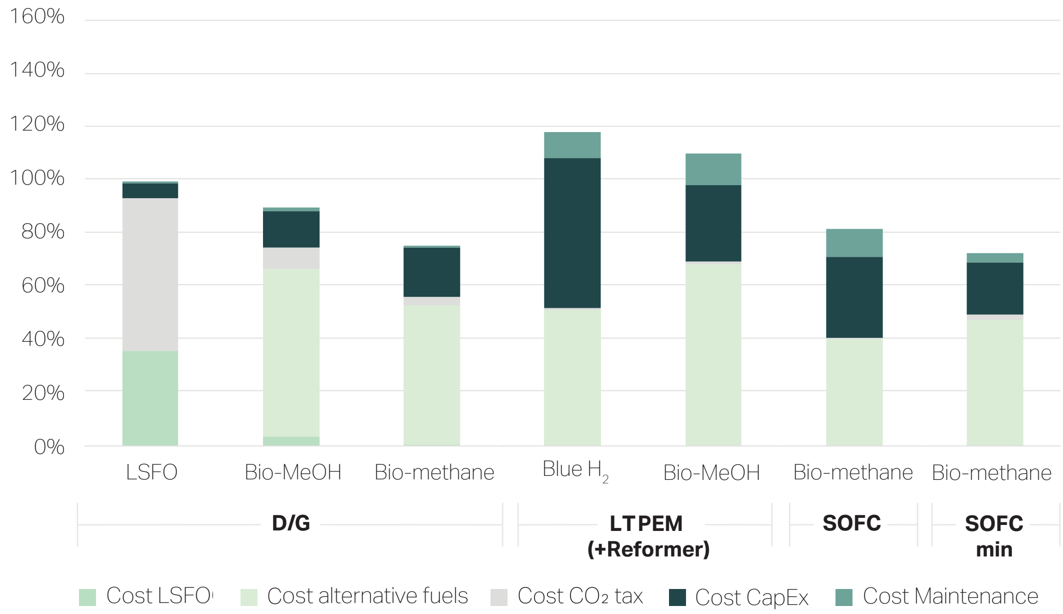


Figure 11C: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (container ship) for the year 2040.



PV = present value, LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell, FO = fuel oil, CapEx = capital expenditure.

Figure 12A: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (container ship with reefers) for the year 2025.

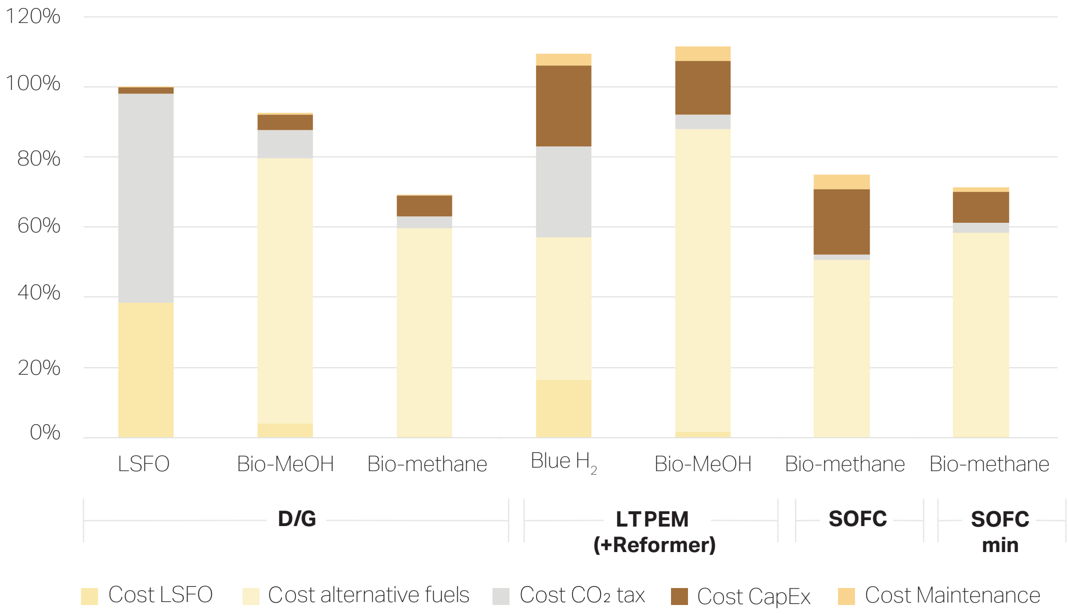
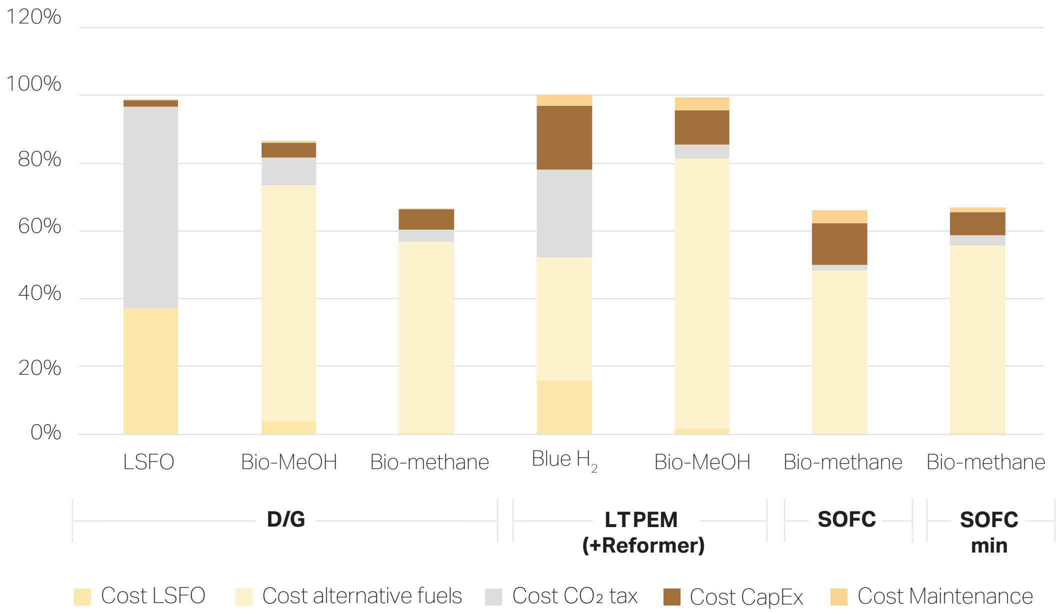


Figure 12B: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (container ship with reefers) for the year 2030.



PV = present value, LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell, FO = fuel oil, CapEx = capital expenditure.

Figure 12C: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (container ship with reefers) for the year 2040.

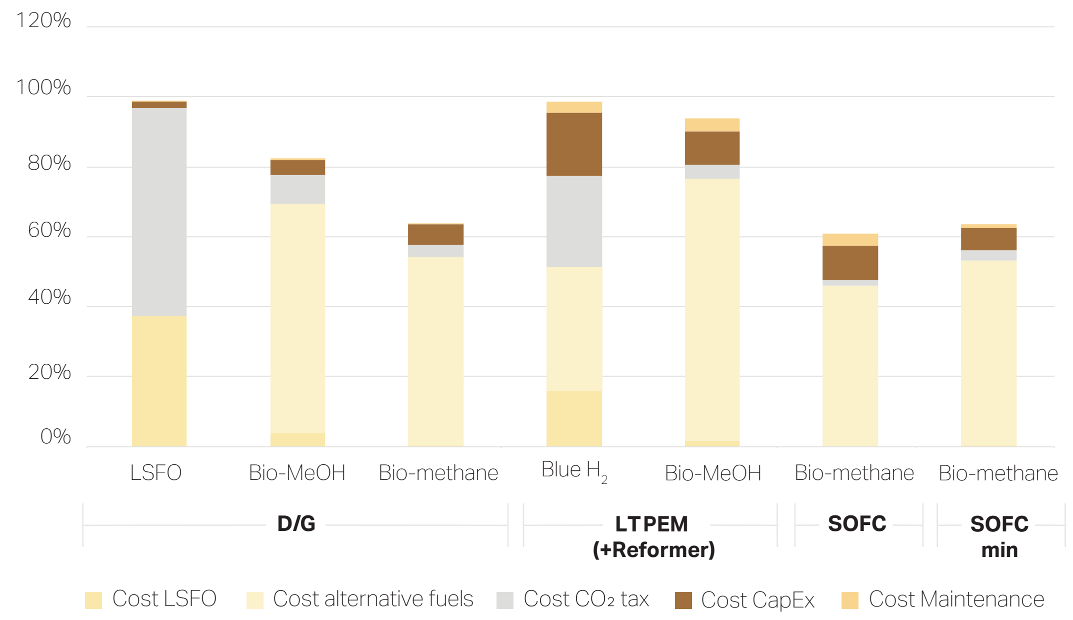
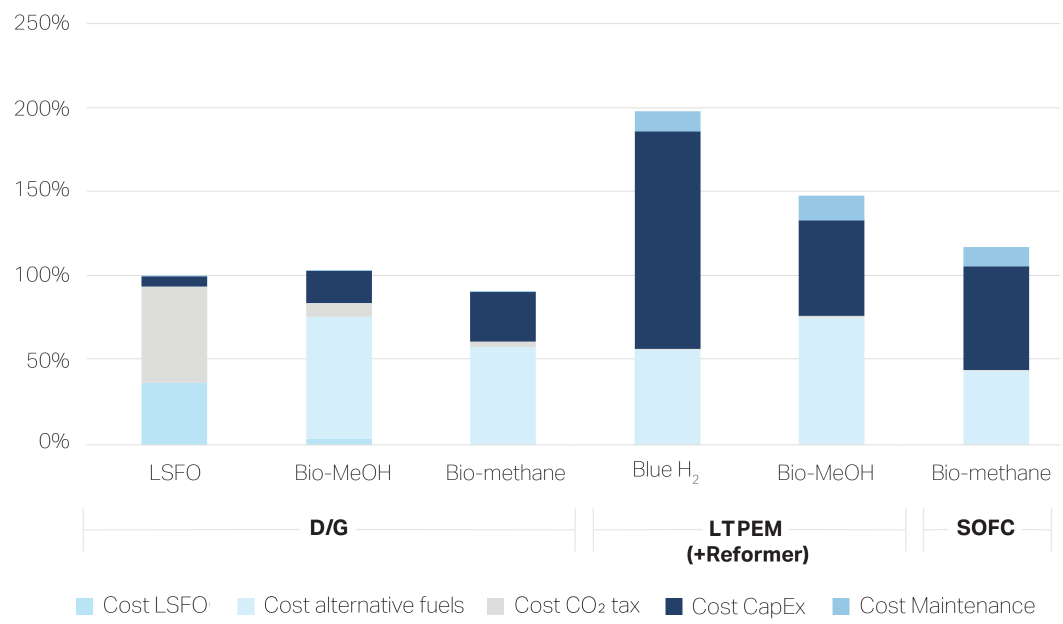


Figure 13A: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (tanker) for the year 2025.



PV = present value, LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell, FO = fuel oil, CapEx = capital expenditure.

Figure 13B: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (tanker) for the year 2030.

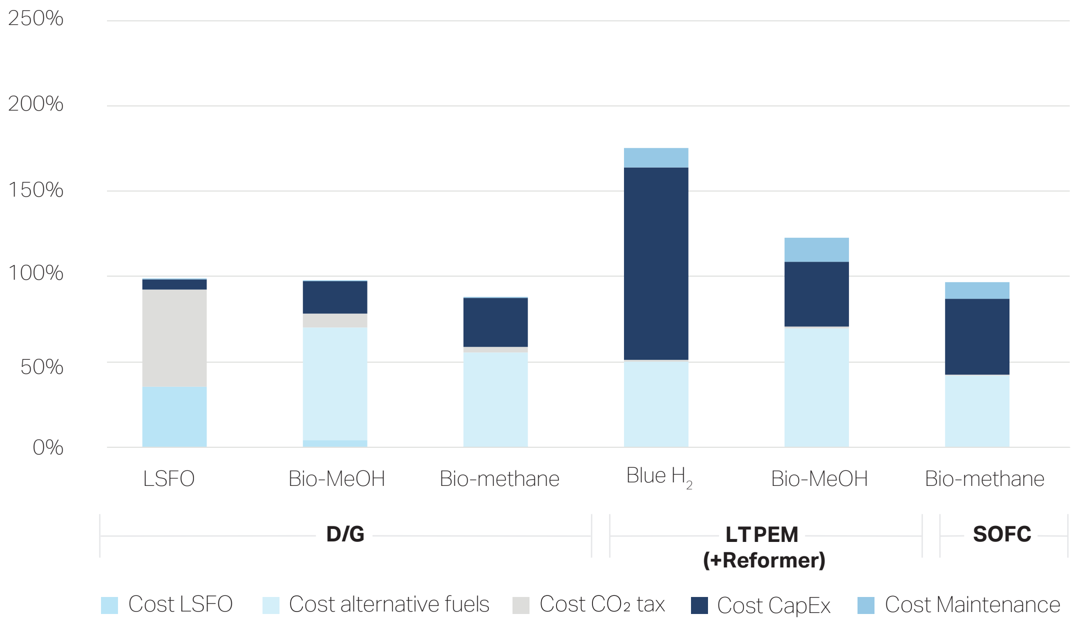
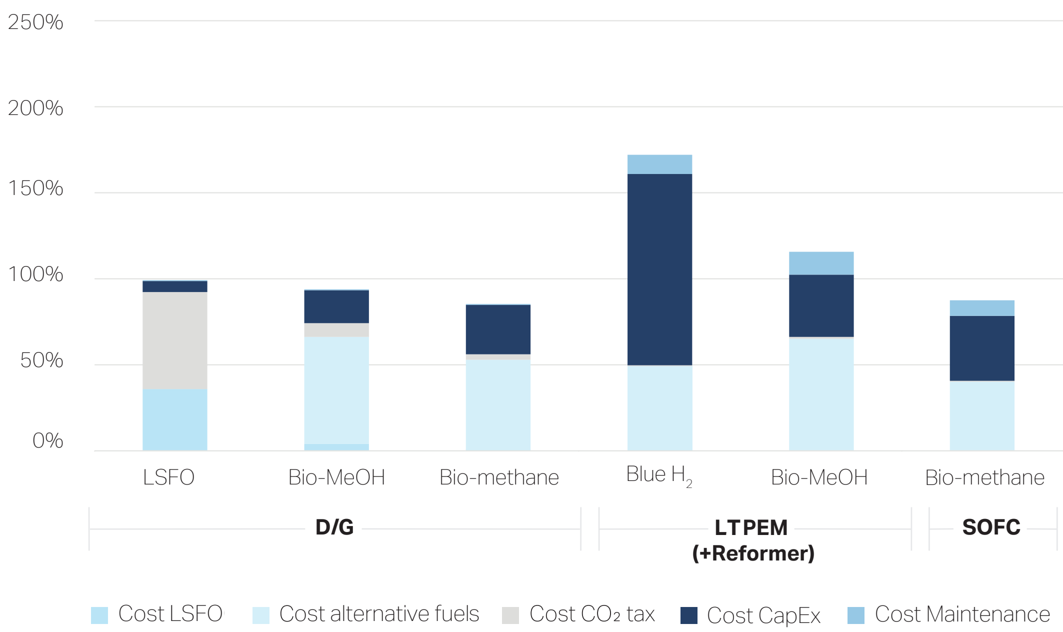


Figure 13C: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (tanker) for the year 2040.



PV = present value, LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell, FO = fuel oil, CapEx = capital expenditure.

Figure 14A: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (bulk carrier) for the year 2025.

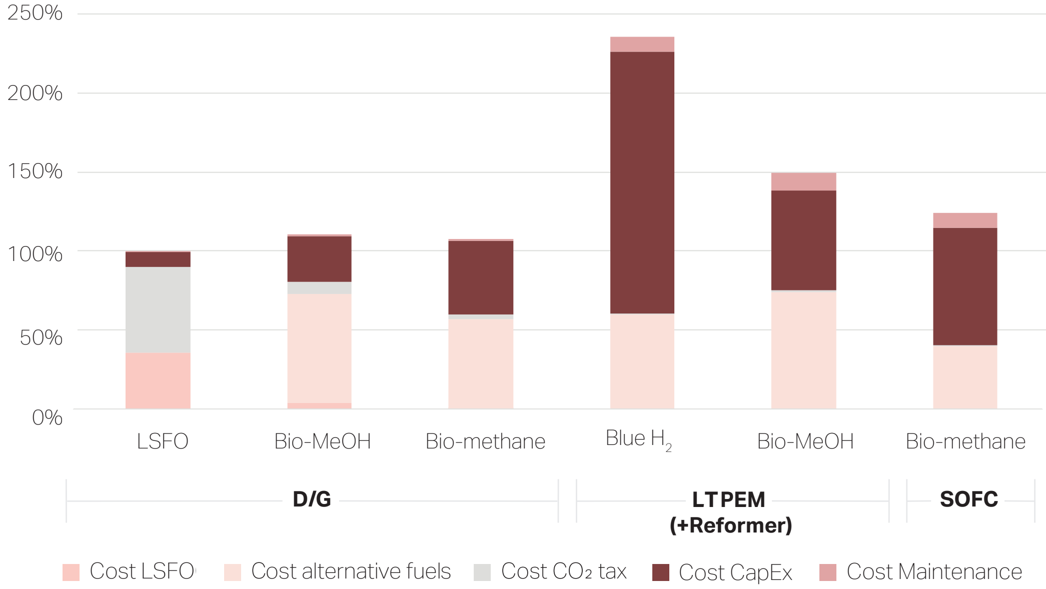
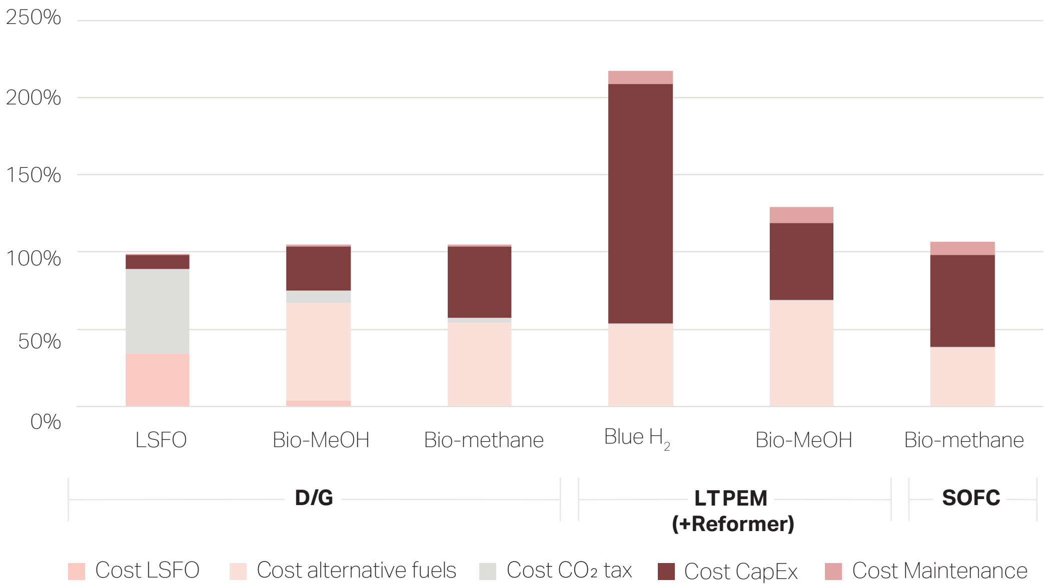
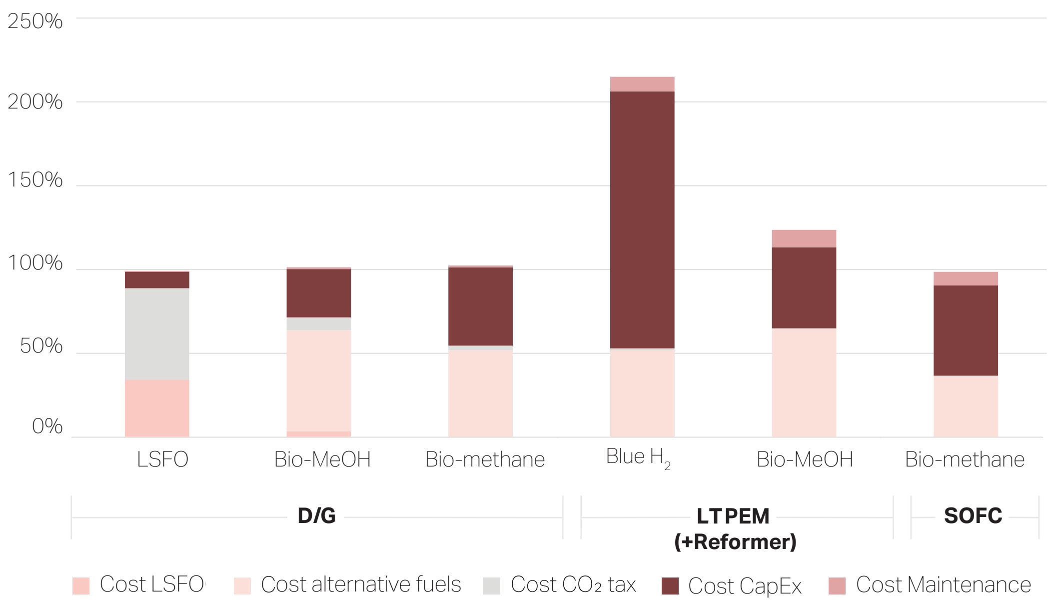


Figure 14B: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (bulk carrier) for the year 2030.



PV = present value, LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell, FO = fuel oil, CapEx = capital expenditure.

Figure 14C: Relative total cost of ownership comparison (TCO) for the shortlisted case studies (bulk carrier) for the year 2040.



PV = present value, LSFO = low-sulfur fuel oil, bio-MeOH = bio-methanol, D/G = diesel generator, H_2 = hydrogen, LT PEM = low-temperature proton-exchange membrane, SOFC = solid oxide fuel cell, FO = fuel oil, CapEx = capital expenditure.

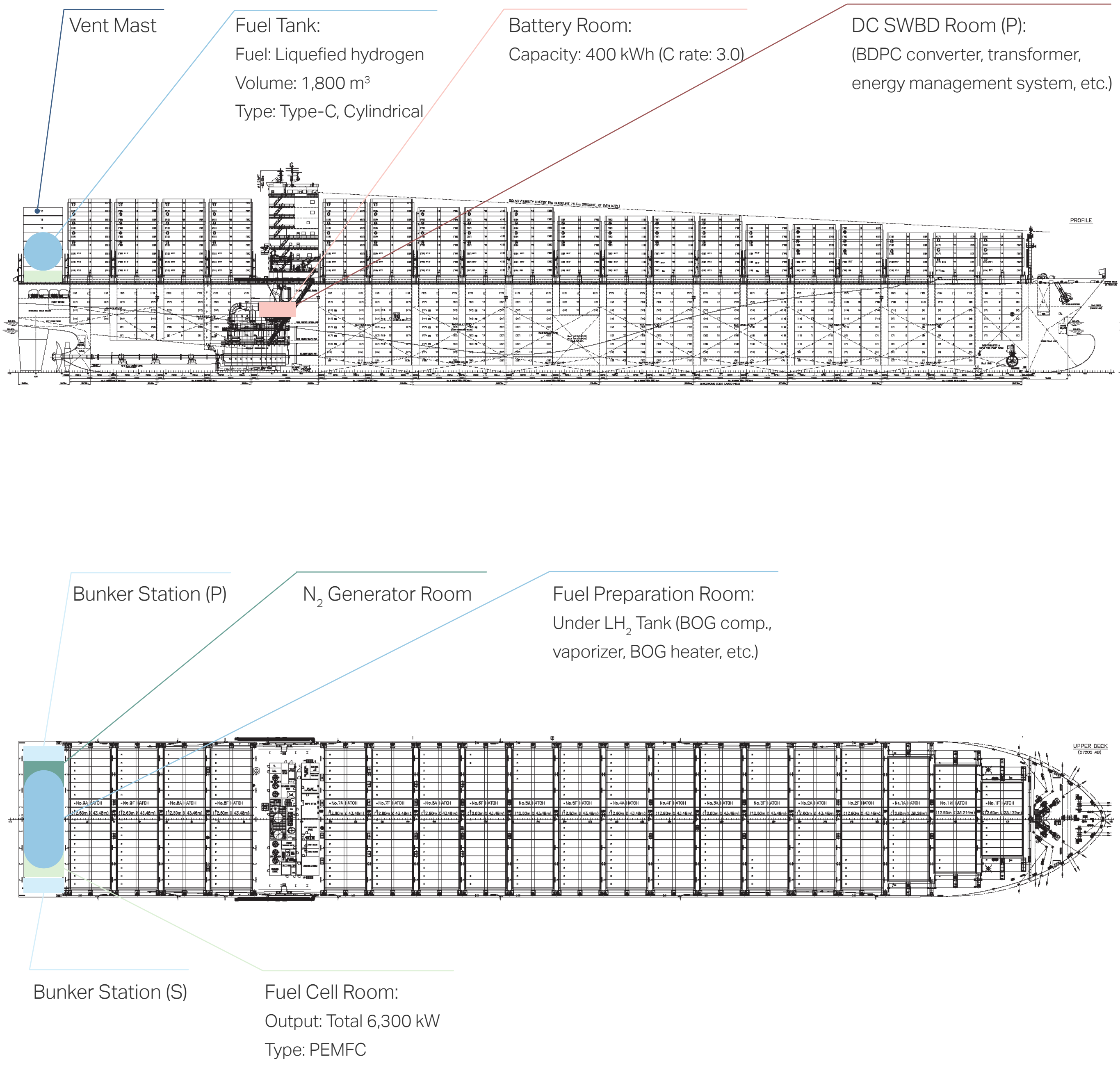
4.6 Physical integration desktop study

Along with the assessments described in the previous subsections, we carried out an integration study using a representative general arrangement for each ship type combined with one of the selected fuel cell technologies. The purpose of this study was to verify that the assumptions made during the calculations align with a realistic physical arrangement, by helping to visualize how fuel cell systems could be practically integrated into existing ship designs and aiding understanding of any consequences for existing commercial capabilities.

Here we present the results of our physical integration study for a container vessel using hydrogen-powered LT PEM fuel cells. The results of equivalent analyses describing a bulk carrier and a tanker, both with methane-powered SOFC, can be found in the Appendix (Sections A.5.4 and A.5.5). In the interests of time, we did not consider all possible fuel and ship type combinations in detail. The general arrangements considered in this integration study, along with the capacity of batteries and fuel systems used, can be considered consistent with the scenarios described in the numerical case studies discussed in the previous sections (Sections 4.1-4.5).

Our integrated hydrogen-LT PEM container ship design, described in Figures 15-18, confirms that introducing this specific fuel-cell-based setup on board this ship would not require large modifications to the general arrangement, and therefore should not affect ships' business models. We focus on some specific areas of the ship design in upcoming subsections.

Figure 15: Fuel cell integration (LT PEM and liquid hydrogen) on a container ship - general arrangment.



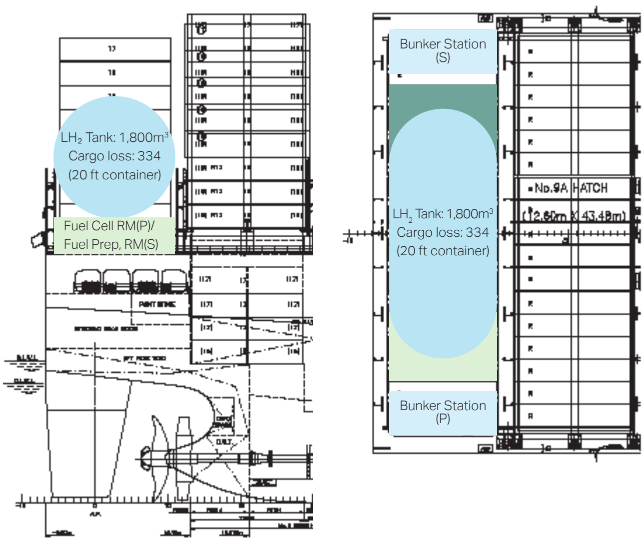
DC SWBD = direct current switchboard, PEMFC = proton-exchange membrane fuel cell, LH_2 = liquid hydrogen, BOG = boil-off gas, N_2 = nitrogen.

4.6.1 Fuel tank

The first step in our physical integration study was the design of fuel tanks. For liquid hydrogen and the container ship, this brought several complexities. Liquid hydrogen presents safety concerns and space requirements that make shipboard applications challenging. Given these safety concerns, we assumed that the fuel tank would be in the aft ship, as close as possible to machinery relevant to fuel gas supply and on the open deck. This enabled us to minimize cargo losses while reducing the risk of gas concentration, the hazardous area, and the limitation of reefer containers arrangement. The estimated cargo loss for this example is approximately 334 TEU.

We assumed that the hydrogen tank would be a Type C fuel tank with vacuum insulation and no reliquefication system. Fuel tank capacity was estimated at 1,800 m^3, which should be sufficient to cover 30 days of electrical load demand according to the operational data we received (see Appendix, Section A.1).

Figure 16: Fuel cell integration (LT PEM and liquid hydrogen) on a container ship - liquid hydrogen storage.



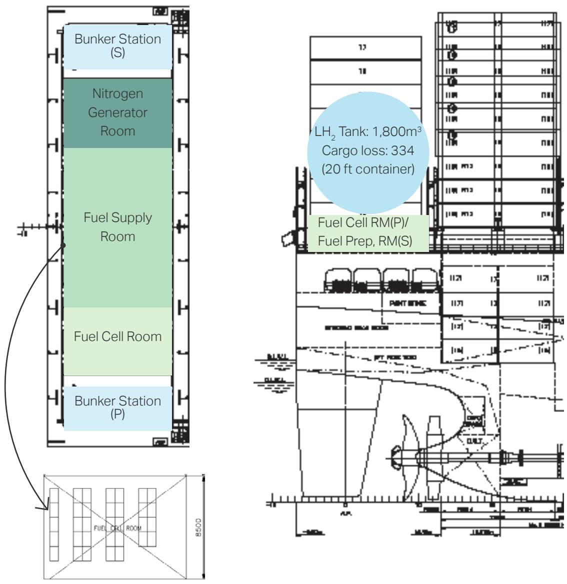
LH_2 = liquid hydrogen, RM = room.

4.6.2 Fuel cell room

Our next step was to ensure sufficient space is available on board for the fuel cell system itself: this was made possible by designing a fuel cell room that could accommodate the full capacity considered in our calculations (in this case, 6.3 MW). We estimated the size of each fuel cell by taking an average across the different suppliers involved in this project.

The fuel cell room would comply with existing class guidelines for fuel cells. Most classification societies regard the fuel cell space as a hazardous area, as a base case scenario. They might, however, consider the fuel cell space as non-hazardous after special consideration, on a case-by-case basis.[17]

Figure 17: Fuel cell integration (LT PEM and liquid hydrogen) on a container ship - fuel cell room.



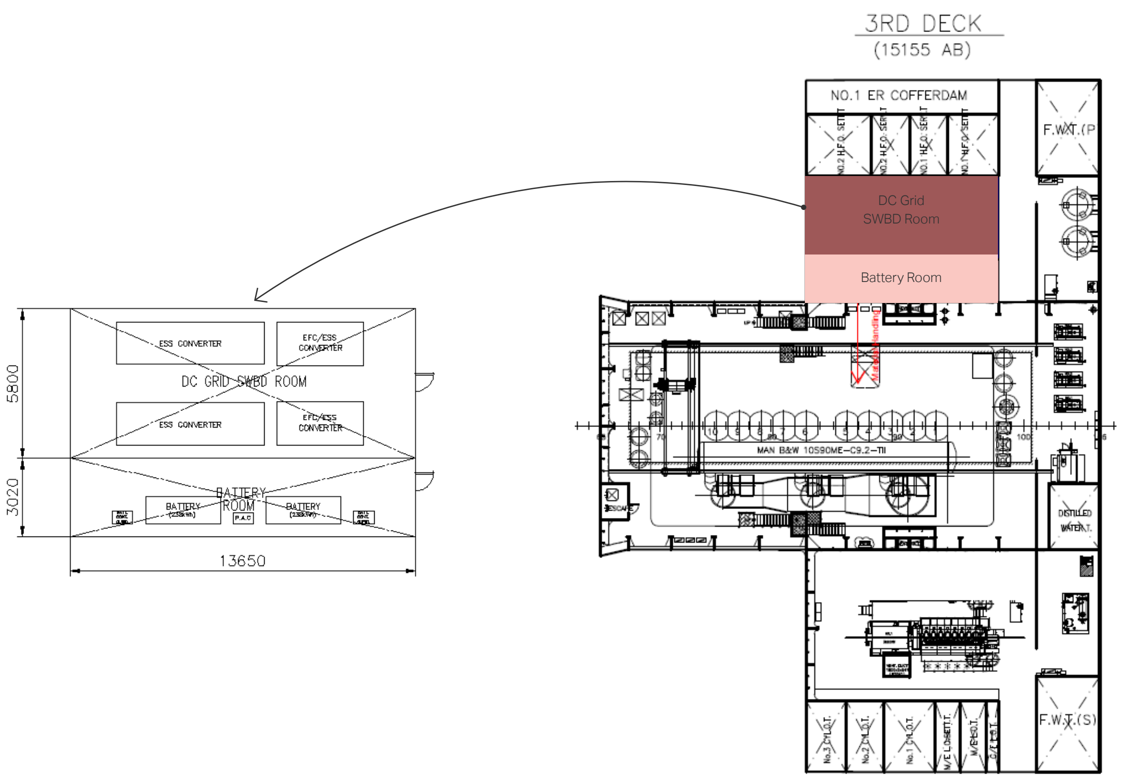
LH_2 = liquid hydrogen, RM = room.

4.6.3 Battery room

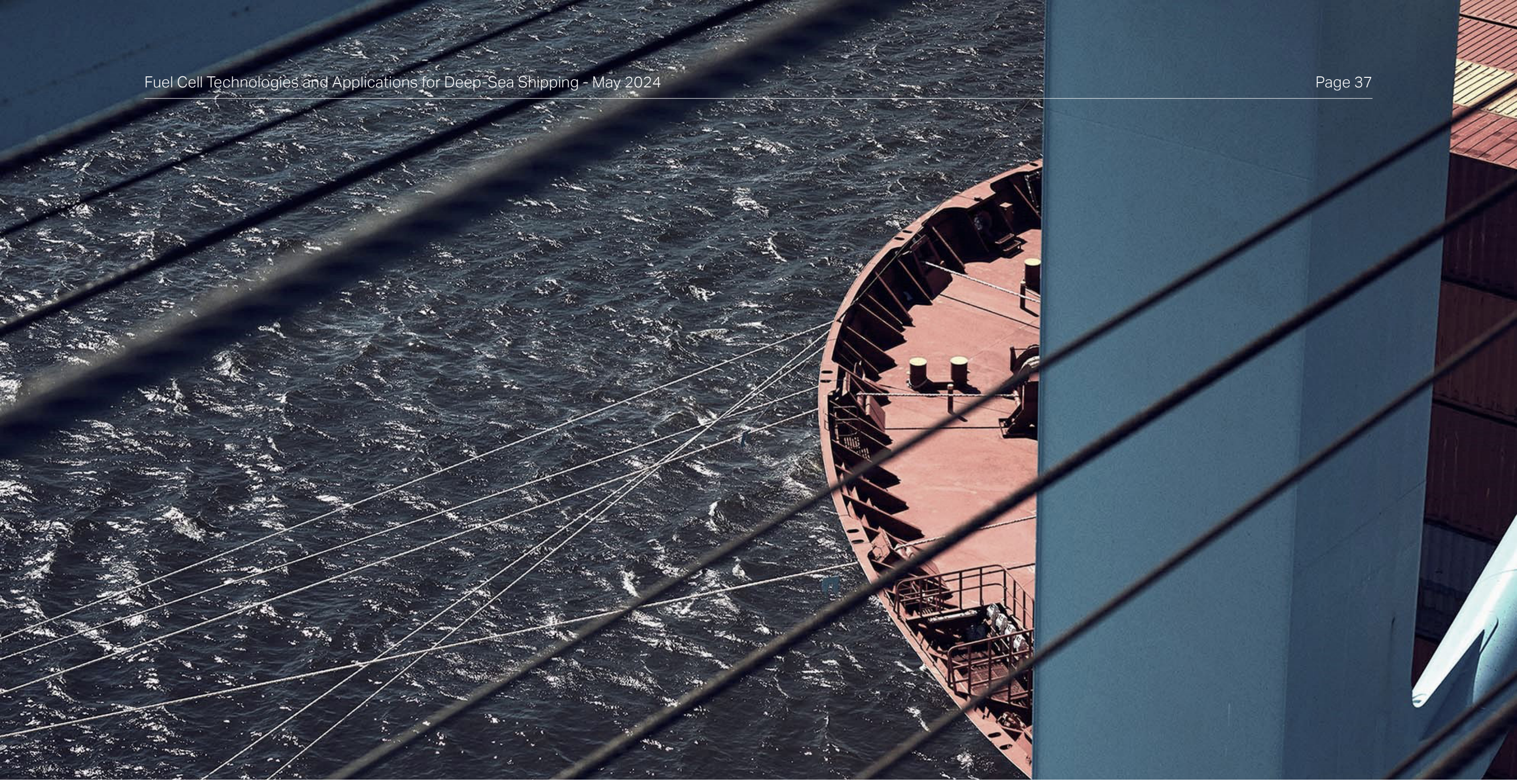
Significant battery capacity is likely to be necessary to support fuel cell systems. In this integration case, the batteries required to reach the desired capacity would fit in the room that is occupied by the existing D/G, which in this scenario would be replaced by the new energy converters. Air conditioning systems are accounted for to maintain the performance and designed lifetime of batteries.

This design would comply with existing safety guidelines for batteries. The assumed battery capacity in this case (LT PEM with liquid hydrogen) is 400 kWh. In the case of an incorporated reforming system, a larger-capacity battery is required to cover the long start-up time: for example, the assumed battery capacity is 3,000 kWh in the methanol/SOFC case.

Figure 18: Fuel cell integration (LT PEM and liquid hydrogen) on a container ship - DC grid and battery rooms.



DC Grid SWBD = direct current grid switchboard.



05. Deep dive: technology outlook for solid oxide fuel cells and ammonia

Using SOFC instead of conventional engines could improve the safety, emissions, and performance of ammonia-fueled vessels. As previously explained, this report does not include detailed technical and cost data for SOFC combined with ammonia – primarily due to the lack of available performance and operational data. However, knowing that ammonia will likely play a key role as a scalable maritime fuel, the outlook for combining SOFC with ammonia and its potential value in the medium to long term deserve some comments.

The solid oxide technology platform has been introduced already, including TCO in combination with methane. Considering the ammonia pathway ahead along with the growing maturity level of SOFC, this combination of a high-potential fuel cell with the scalable and cost-attractive ammonia fuel pathway could prove to be a promising option in the future.

The first trials with direct ammonia conversion on a small SOFC stack level were reported in 2009.[18] Recently, successful tests with a much larger 6kW SOFC stack tower were reported with efficiencies from 61-68%.[19] The 6kW technology platform is reported to be scaled up and tested at 100 kW during the first half of 2024.[20] Some EU-funded projects on ammonia and SOFC are also ongoing.[21] The MMMCZCS has participated in a recent project to study ammonia SOFC systems for maritime applications, funded by the Danish Energy Agency's Energy Technology Development and Demonstration Program (EUDP).[22]

Ammonia's entry to the maritime sector as a marine fuel in a two-stroke ICE is progressing – and will likely enter the market several years before ammonia-fueled SOFC. However, there are important differences between ammonia combustion and the additional technology benefits of SOFC in the medium to long term:

Efficiency: SOFC are capable of achieving efficiencies of 50-65% (as shown in Table 1), which could be as much as 10% above two-stroke engines and even further above four-stroke auxiliary engines (see Sections 2.1.3 and 3.1). This could lead to lower fuel consumption and operating costs, but also an overall lower amount of renewable power needed per vessel in the power-to-ammonia-to-power pathway. High efficiency also reduces the amount of fuel needed on board the ship. As the required fuel storage volume for ammonia is 3.6 times that of VLSFO,[20] reducing this requirement is important for the cargo capacity of the vessel.

Safety: Using ammonia as a shipping fuel presents safety hazards, and it is therefore crucial to understand and take steps to reduce these risks.[23] As SOFC use an electrochemical reaction that does not involve moving parts or combustion, their use could potentially mitigate some ammonia safety risks compared to ICE. Unlike engines, SOFC do not require high injection pressure, thereby also lowering the risk of ammonia leakages.

Emissions – both pollutants and CO_2-equivalent: Risks related to NO_x and N_2O emission levels in ammonia-fueled ICE systems are to be monitored in ongoing development.[24] For SOFC, this should not be a concern, as no thermal NO_x is generated in the stack itself. NO_x emissions created elsewhere in the system (e.g., after-treatment system for unconverted ammonia) could be managed by the same after-treatment technologies being developed for ammonia ICE, albeit with lower capacity requirements.

While there are still challenges to be addressed, such as the scaling of bunkering infrastructure and the development of safety standards and risk mitigation strategies, the use of SOFC with ammonia fuel presents a promising pathway towards an important role in sustainable and net-zero shipping.

06. Conclusions and next steps

This project aimed to provide insight into the latest developments in fuel cell technology for maritime applications, as well as this technology's potential for integration in the low-emissions ships of the future. Based on our realistic assumptions and the results presented here, fuel cells may be able to support the decarbonization of the shipping industry as auxiliary power sources, depending on ship characteristics, fuel choice, and policy incentives.

Importantly, fuel cell technologies are especially attractive if a carbon tax is in place; otherwise, they may struggle to compete on price with other options, such as conventional D/G. We judge that the introduction of a carbon tax is not unrealistic to expect, nor is a carbon price beyond 200 USD per tonne of carbon in the long term (see, for example, the International Energy Agency's 2022 World Energy Outlook report).[25] However, the impact of this carbon tax value on the overall business case makes it difficult to draw a firm conclusion about the financial feasibility of this technology within maritime applications at present.

Looking beyond business cases, our results indicate that fuel cells could improve the overall efficiency linked to alternative fuels and, in turn, reduce WTW GHG emissions from ships. Accordingly, we conclude that alternative energy converters such as fuel cells should not be excluded among technology options, as they have the potential to bring a significant contribution to decarbonization of shipping.

Although we were not able to capture the performance of all relevant fuel cell technologies in this report (e.g., alkaline fuel cells and high-temperature PEM were not accounted for), we do not expect that including these remaining systems would dramatically change our conclusions. Nevertheless, we recommend that further assessments focus on confirming the validity of these results for other fuel cell technologies, once sufficient data is made available to describe their marine systems.

In view of the potential positive impact on emissions and fuel demand reduction, we recommend that owners, charterers, and regulators should account for fuel cells in their medium- and long-term decarbonization strategies. We further recommend that a reassessment of fuel cells' role in the shipping industry should be undertaken in the future, as more information becomes available about technical performance and forecast costs. Lastly, we recommend that public or private investment should be encouraged to facilitate full-scale trial projects to test and demonstrate marine fuel cell systems.

07. The project team

This report was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners. Team members marked with an asterisk (*) were seconded to the MMMCZCS.

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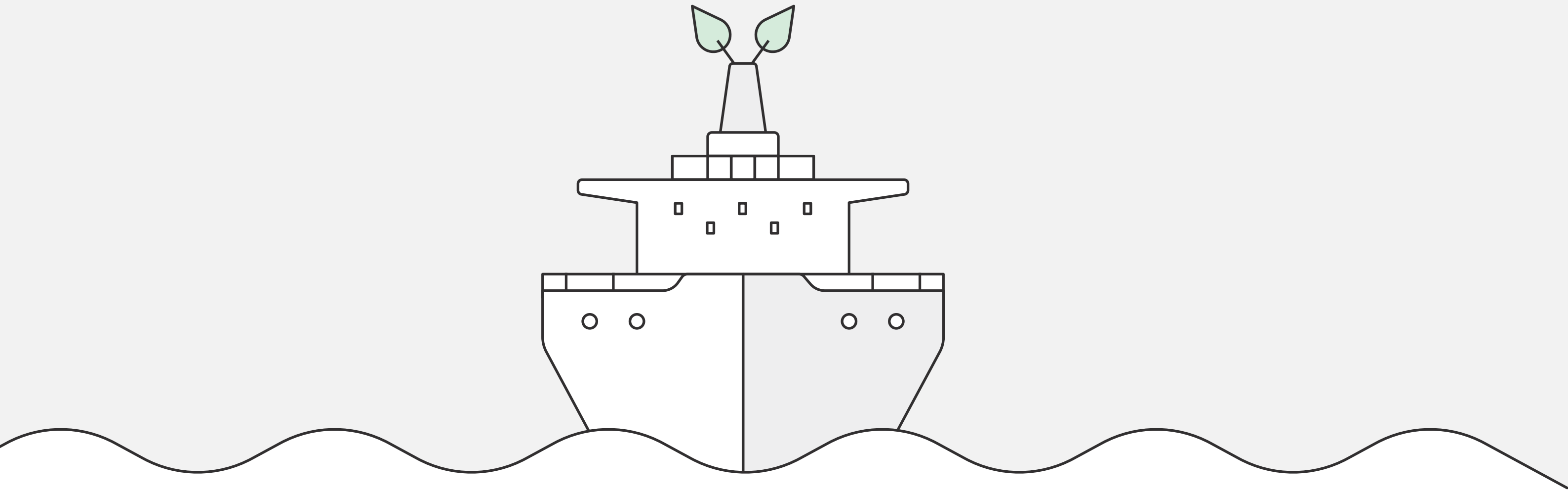

Abbreviations

AC	Alternating current
AFC	Alkaline fuel cell(s)
BOL	Beginning of life
D/G	Diesel generator(s)
DWT	Deadweight tonnage
EOL	End of life
EUDP	Energy Technology Development and Demonstration Program (Det Energiteknologiske Udviklings- og Demonstrationsprogram)
GHG	Greenhouse gas
HT PEM	High-temperature proton-exchange membrane
ICE	Internal combustion engine(s)
LT PEM	Low-temperature proton-exchange membrane
LR2	Long-range 2
LSFO	Low-sulfur fuel oil
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
PEM	Proton-exchange membrane
PEMFC	Proton-exchange membrane fuel cell(s)
SOFC	Solid oxide fuel cell(s)
TCO	Total cost of ownership
TEU	Twenty-foot equivalent unit
WHR	Waste heat recovery
WTW	Well-to-wake

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Appendix

A.1 Representative operational profiles

As briefly described in Section 3.1.1, MMMCZCS partners kindly shared operational profile data for the three ship types selected for inclusion in our case studies. These profiles (Figures 19-21) are expected to properly describe the average working conditions for the three ship types by showing onboard electrical power demand.

Figure 19: Operational profile for an LR2 tanker (five-minute intervals over three years).

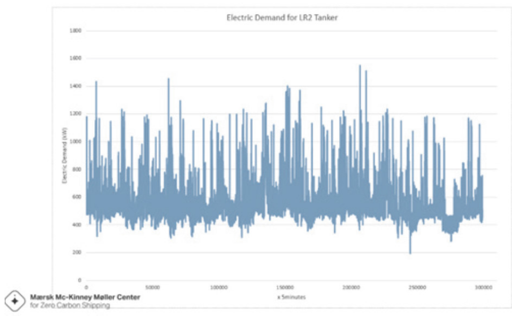


Figure 20: Operational profile for an 82,000 DWT bulk carrier (hourly intervals over three months).

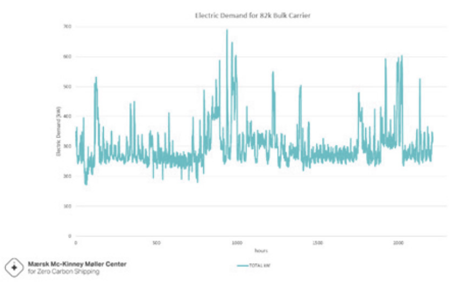
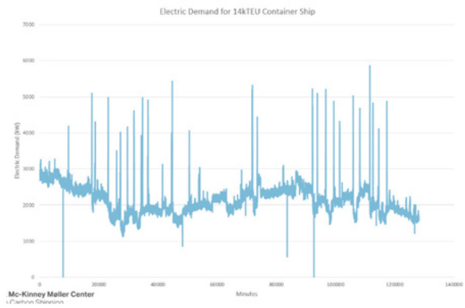


Figure 21: Operational profile for a 15,000-TEU container ship (one-minute intervals over three months).



While the interval and overall window varied across ship types, we considered that the provided granularity and timescale were sufficiently accurate for the related business model. For example, while the tanker data (Figure 19) had a much higher resolution than the bulk carrier data (Figure 20), this is not expected to be a problem, as electrical load is normally more stable for a bulk carrier.

A.2 Efficiency assumptions

A.2.1 Fuel cell efficiency

Fuel cell efficiency can be assessed at different levels, which we can summarize as follows (from highest to lowest efficiency):

1. Fuel cell stack efficiency represents the efficiency of the individual stacks that make up each fuel cell unit. This is the highest efficiency, as it is unaffected by supporting systems.

2. Fuel cell system efficiency includes additional losses due to individual components that are expected to be part of the future ‘integrated package’. Such components might include:
– DC/DC converters
– Control panel
– Air supply fan
– Ventilation fan for fuel cell cabinet

3. Total efficiency as installed on board (including utilities) refers to all additional systems required to ensure proper operation of the fuel cell system. This larger group of components could consist of, but is not limited to:
– AC/DC inverter
– Fuel supply pump
– Heat exchanger
– Glycol water pump (when required i.e., hydrogen and methane)
– Sea water pump
– Cooling water pump
– Air supply fan for fuel cell room
– Air supply fan for battery room
– Ventilation fan for fuel preparation room
– Water supply pump for reformer (when required i.e., methanol)

As briefly described in Section 3.1.2, several fuel cell suppliers provided performance-related information for the technologies used in our study. This performance information was anonymized and aggregated, resulting in average efficiency curves that were used during our analysis. These curves are shown in Figures 22 and 23. These figures show that different technologies are expected to operate at maximum efficiency at different loads, which is likely to affect how they are integrated on board.

Figure 22: Estimated efficiency curve for low-temperature proton-exchange membrane (LT PEM) fuel cell technology, as used in our calculations.

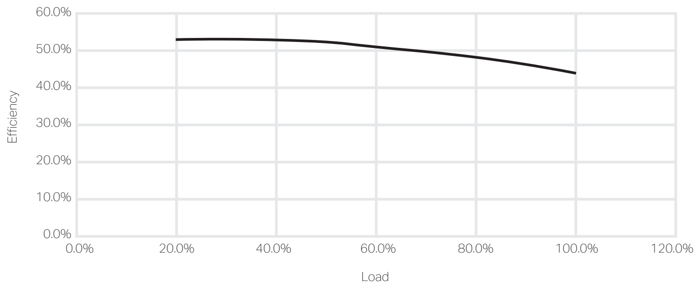
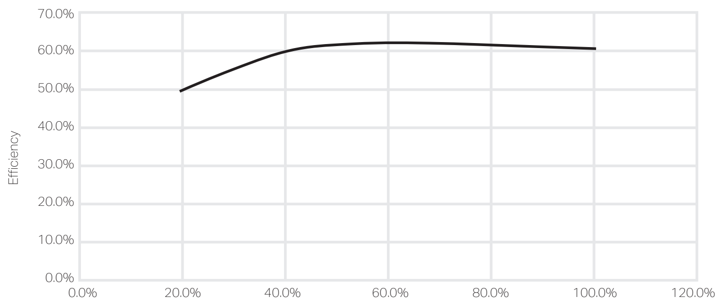


Figure 23: Estimated efficiency curve for solid oxide fuel cell (SOFC) technology, as used in our calculations.



In both cases, the curves shown include loss for DC/DC conversion. Further, fuel cell stacks’ performance is expected to degrade over time, resulting in beginning-of-life (BOL) efficiency and end-of-life (EOL) efficiency. The graphs represent an average value between BOL and EOL performance.

In terms of the three efficiency levels described in this section, Figures 22 and 23 represent efficiency level 2 for the fuel cell systems and fuel combinations considered in this report. Importantly, the exact scope of a ‘fuel cell system’ is a supplier-specific decision, which makes the resulting efficiency values hard to compare with absolute accuracy between technology suppliers. As a result, the curves should be understood as approximate estimates calculated in close collaboration with suppliers involved in order to achieve a sufficient level of detail for an 'apples to apples' comparison.

Losses in efficiency at efficiency level 3 (total efficiency as installed on board) are not captured in Figures 22 and 23. However, we accounted for these losses separately in our calculations, based on expert input.

A.2.2 Supporting systems efficiency - reformers

Steam reforming is required to reform methanol to hydrogen in the following chemical reaction:

$CH_3OH + H_2O \Rightarrow 3H_2 + CO_2 + \Delta H$
32.04 g/mol x 1 mol + 18.02g/mol x 1 mol ⇒
2.02g/mol x 3 + 44.01g/mol x 1 - 57.7kJ/mol

This reaction requires additional heat above 250°C. As a result, we assumed an overall 20% loss for the heating of methanol.

A.2.3 Supporting systems efficiency - WHR

We did not consider WHR as part of the fuel cell efficiency values for this study. However, this technology could be a potential source of future improvements.

A.2.4 Supporting systems efficiency - batteries

Please refer to the upcoming section on dynamic simulations.

A.3 Dynamic simulations

In addition to the details described in previous sections, it was important to evaluate the fuel cell technology on a higher system level, and not simply as stand-alone technology. One of the main aspects to consider (given the inherently different behavior of fuel cells and ICE) is how these systems would respond to the dynamic loading that each of the three operational cases (i.e., ship types) presents.

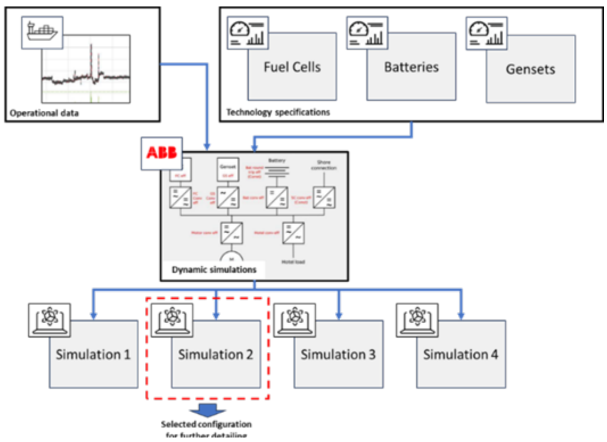
ABB, a mission ambassador of the MMMCZCS, took the lead on dynamic simulations work to address this knowledge gap. For the initial scaling of required sub-components, several system simulations were carried out to find optimal configuration and trade-off between performance and component cost. An important element of the simulations was to build a dynamic model, rather than treating the operational data as static averages. This is because there can be shorter peak loads during voyages that the auxiliary power system would not be capable of handling individually. To sum up, the simulation process can be broken down into the following steps (also summarized visually in Figure 24):

- Feed operational vessel data into a simulation

- Specify system configuration by combining initial assumptions with the main technology parameters shared by technology suppliers (e.g., fuel cell ramp-up time, battery charge/discharge, min/max load, stand-by time)

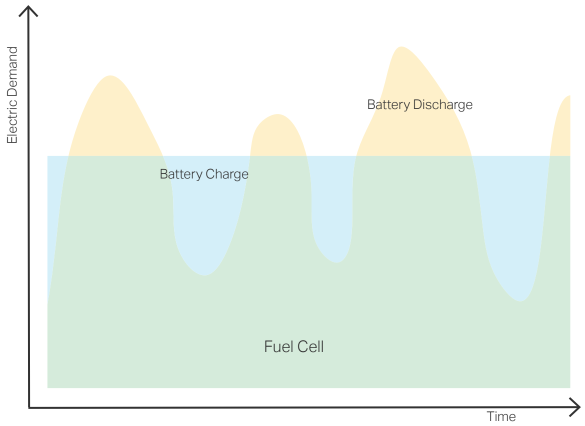
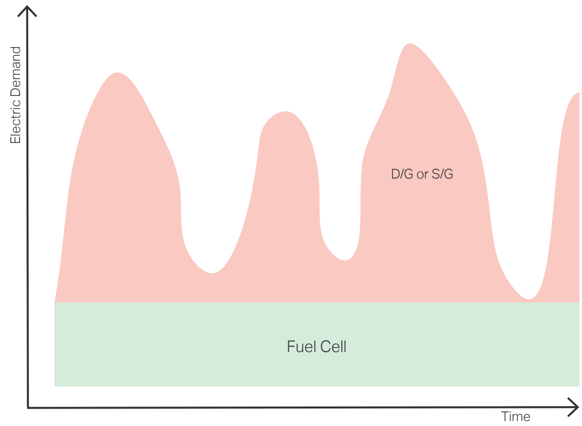
- Carry out and compare different simulation cases in order to find an optimum balance between performance and cost (based on the average reference figures collected within the project working group)

Figure 24: Dynamic simulation flow chart (source: ABB).



For the TCO assessment, we assumed that fuel cells would 'cooperate' with batteries as described in the 'average demand' scenario in Table 5. The only exception to this assumption is the additional 'minimum reefer demand' case for the container ship (see also Section 3.1.4).

Table 5: Summary of average versus minimum demand fuel cell system configuration scenarios.

<table>
<tr><th>Average demand</th><th>Minimum demand</th></tr>
<tr><td>Excess electricity from fuel cell can be charged to battery and the battery can cover excess demand for fuel cell.

</td>
<td>Fuel cell capacity shall cover minimum stable electric demand and excess demand shall be covered by D/G.

</td></tr>
<tr><td>Pros:
– If efficiency of the fuel cell is better than D/G, fuel consumption can be saved
Cons:
– Capacity of the battery will be bigger depending on the response of fuel cell</td>
<td>Pros:
– System configuration is very simple
Cons:
– Even if efficiency of the fuel cell is better than D/G, the fuel consumption saving is smaller due to small capacity of the fuel cell
– Even if emissions from the fuel cell are lower, emissions might be increased due to high emissions from low-load operation of D/G</td></tr>
</table>

D/G = diesel generator, S/G = shaft generator

A.4 Ship grid integration diagrams

Diagrams in this section (Figures 25-28) show how both different fuel cell technologies and D/G could be integrated into the ship grid for the container ship, where the original setup has the highest number of subcomponents. Fuel cell integration on the other ship types would be simpler but would follow the same design principles.

Figure 25: Ship grid integration for original diesel generators (container ship).

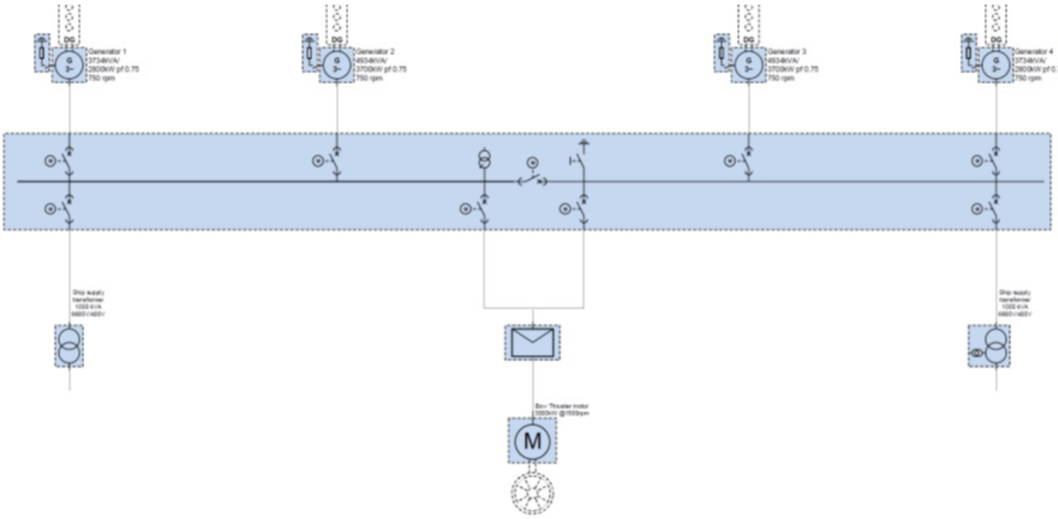


Figure 26: Ship grid integration for LT-PEM with hydrogen (container ship).

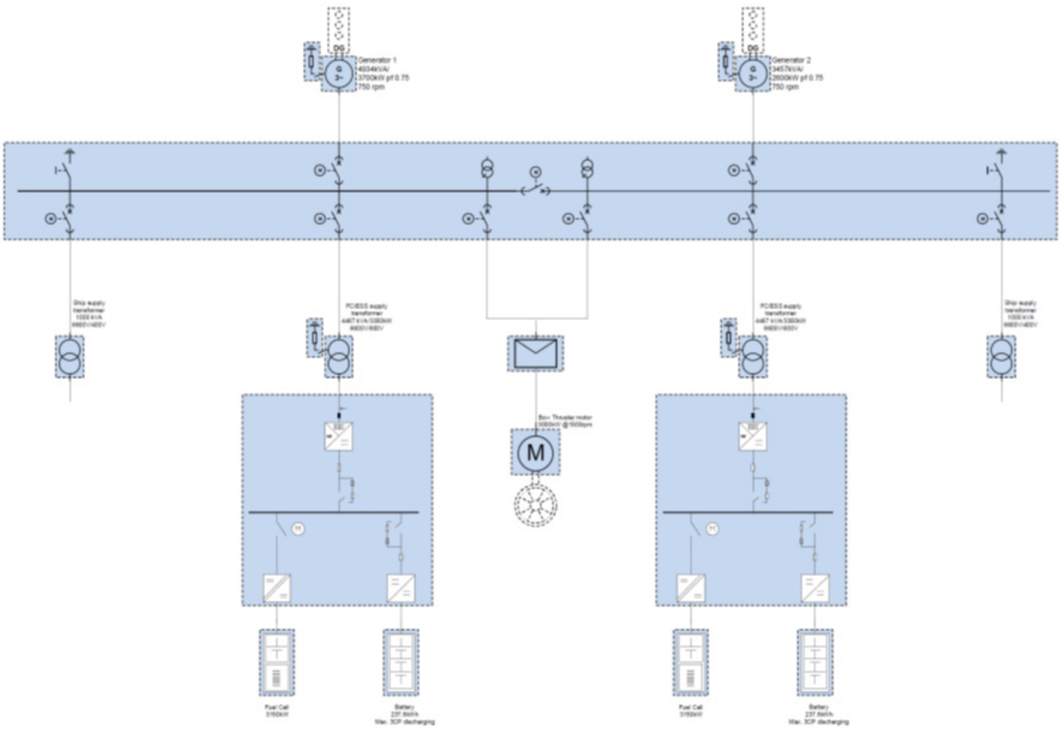


Figure 27: Ship grid integration for LT-PEM with bio-methanol and SOFC with bio-methane (container ship).

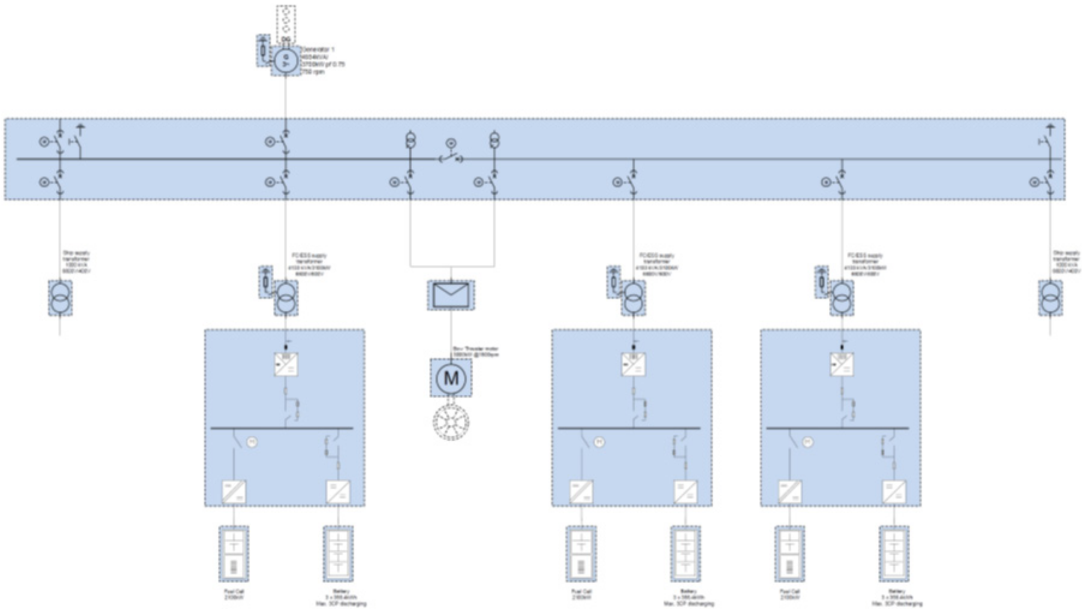
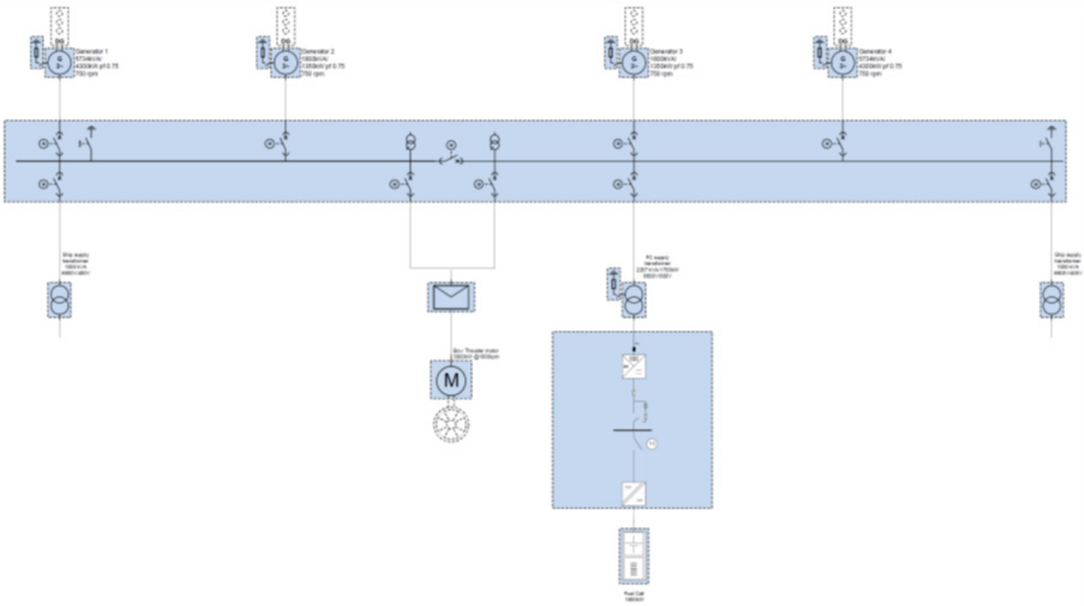


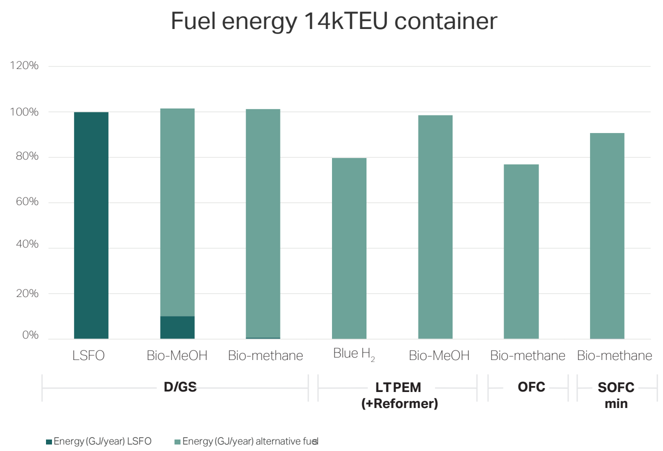
Figure 28: Ship grid integration for SOFC minimum with bio-methane (container ship).

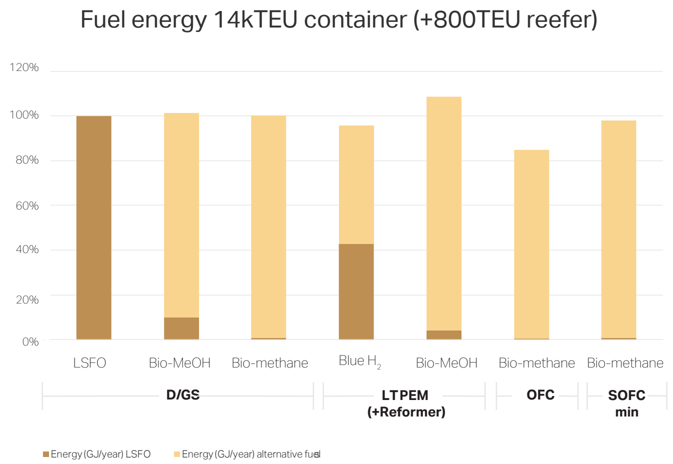


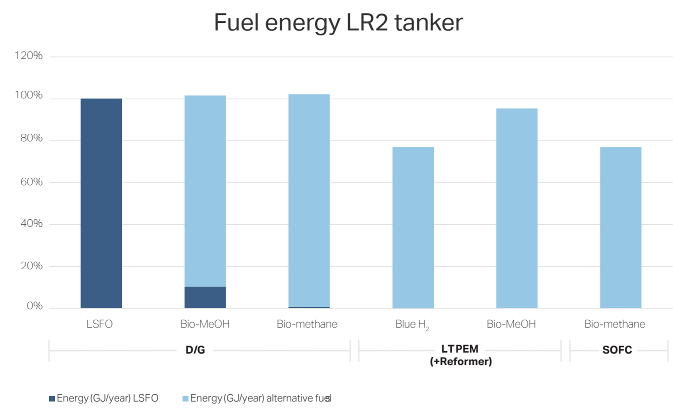
A.5 Additional results

A.5.1 Estimated onboard efficiency outlook

Figure 29: Relative onboard energy demand comparison for the shortlisted case studies (container ship, tanker).

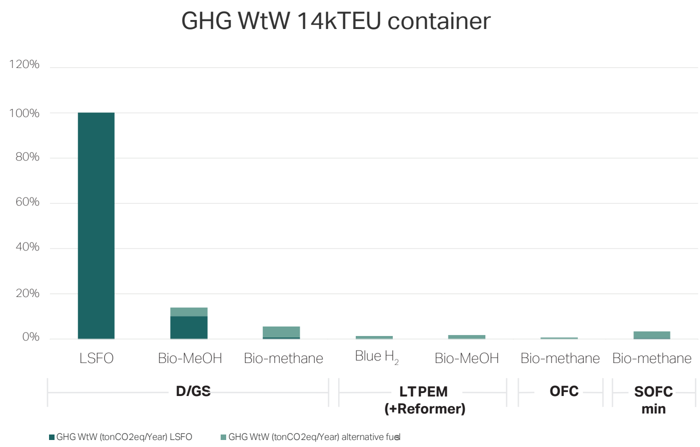


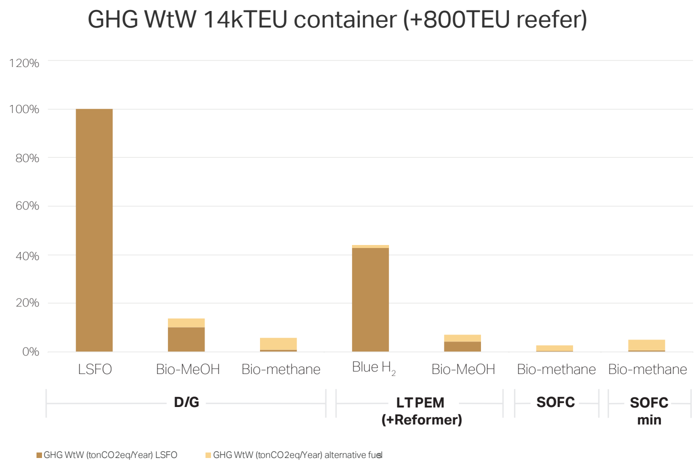


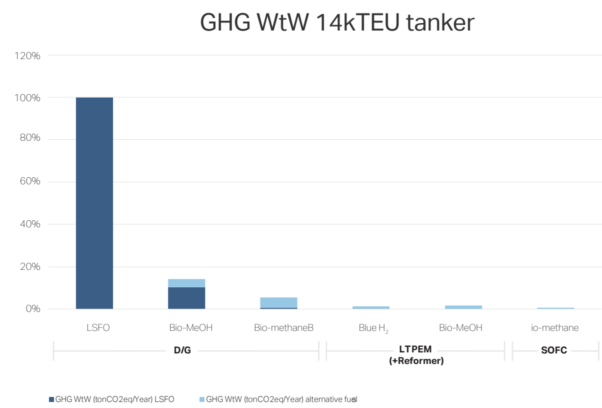


A.5.2 Estimated emissions outlook

Figure 30: Relative onboard GHG emissions comparison for the shortlisted case studies (container ship, tanker).







A.5.3 Estimated fuel cost outlook

Figure 31: Relative onboard estimated fuel costs comparison for the shortlisted case studies (tanker).

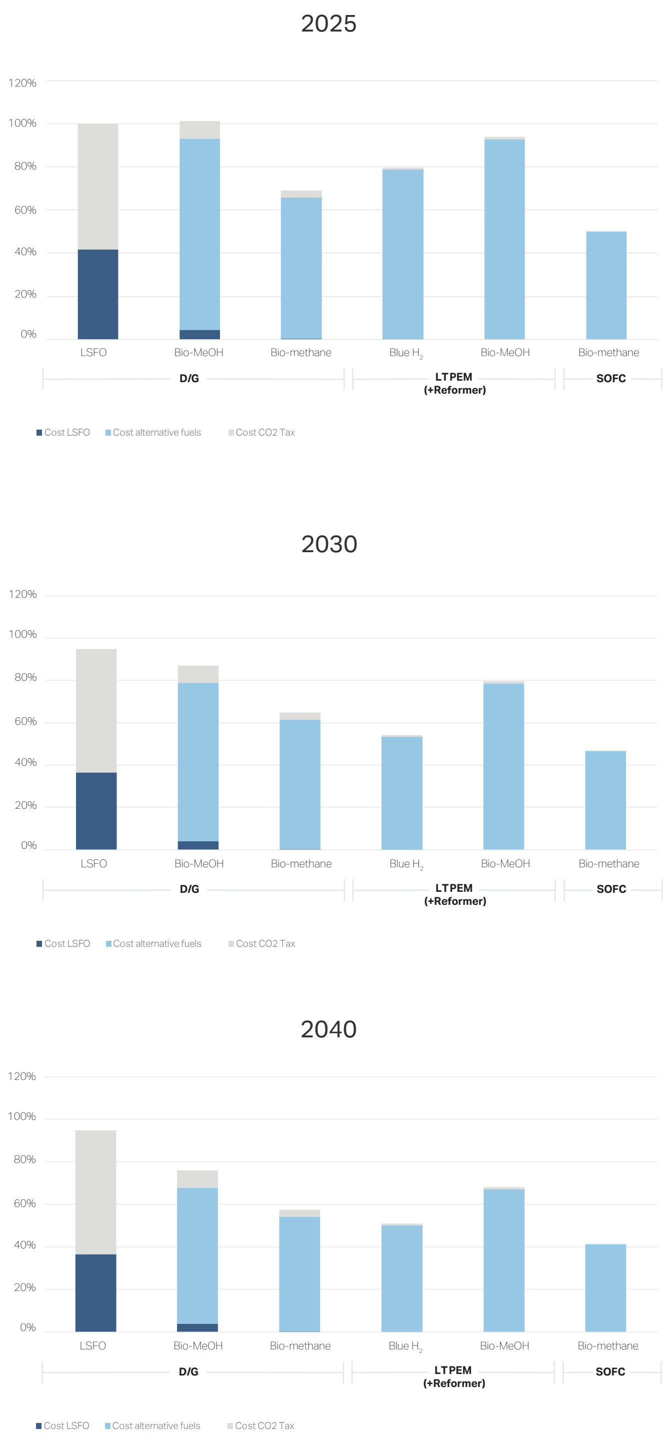


Figure 32: Relative onboard estimated fuel costs comparison for the shortlisted case studies (container ship).

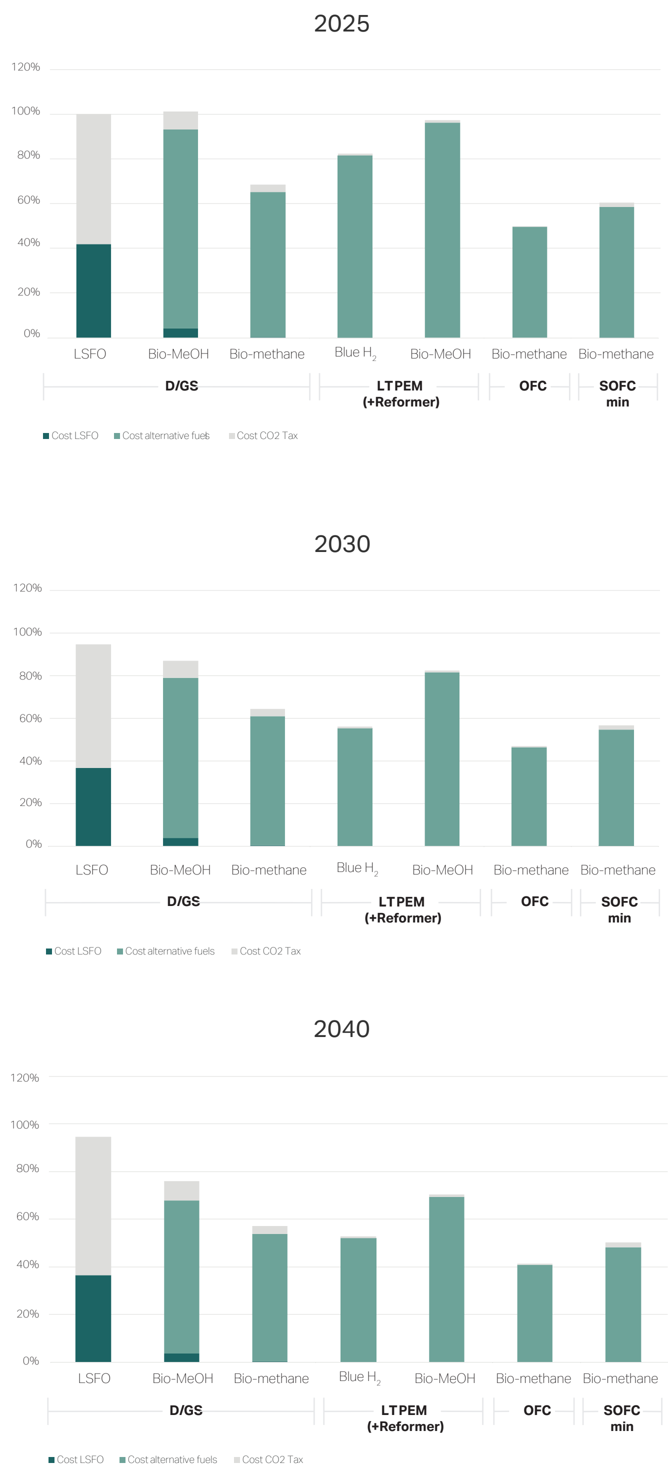
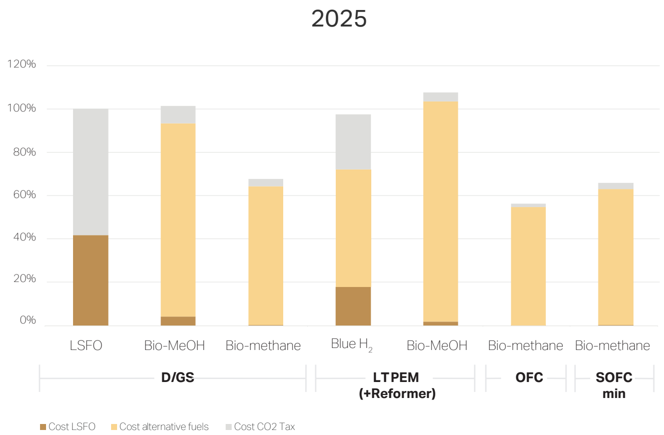
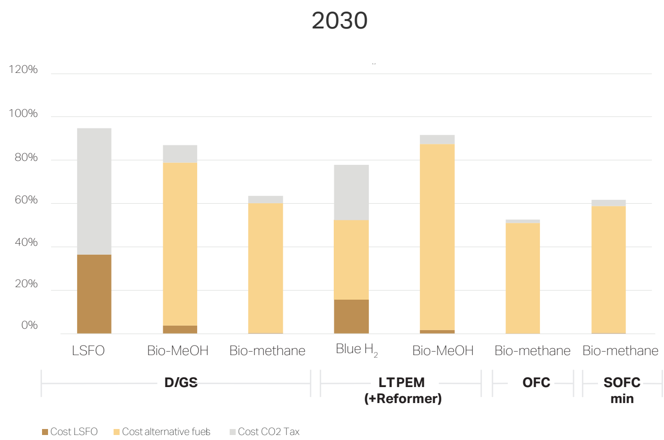
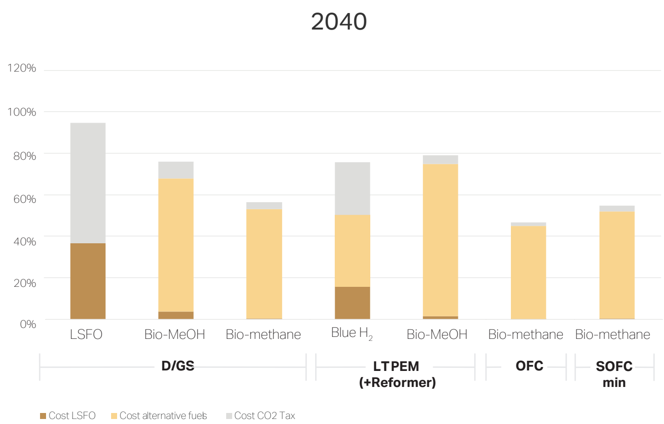


Figure 33: Relative onboard estimated fuel costs comparison for the shortlisted case studies (container ship, +800TEU reefer).







A.5.4 Physical integration – bulk carrier and SOFC (methane)

Figure 34: Fuel cell integration (SOFC and methane) on a bulk carrier - general arrangement.

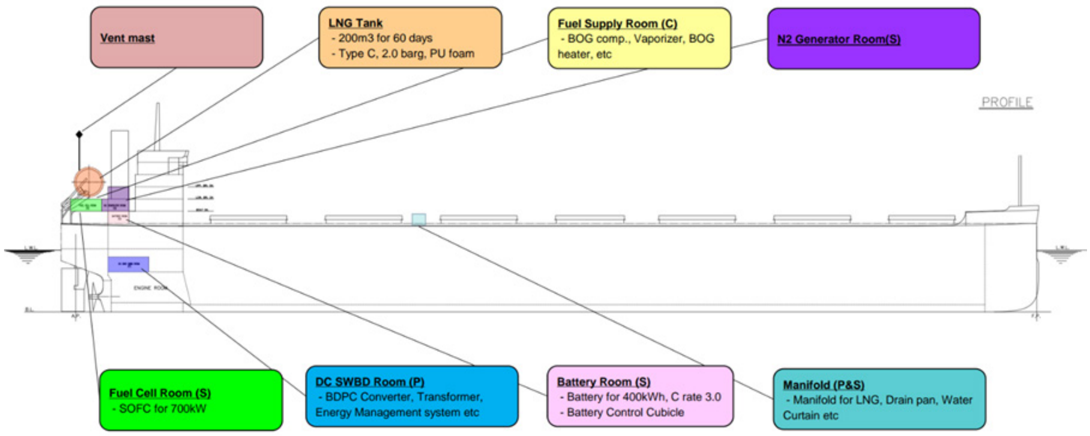


Figure 35: Fuel cell integration (SOFC and methane) on a bulk carrier – detail, lower bridge deck.

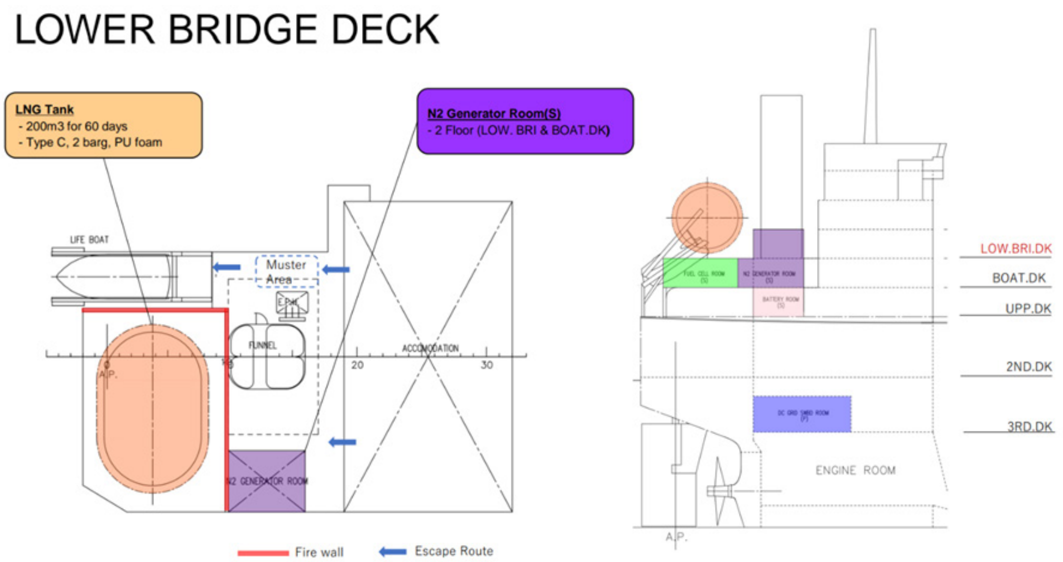


Figure 36: Fuel cell integration (SOFC and methane) on a bulk carrier – detail, boat deck.

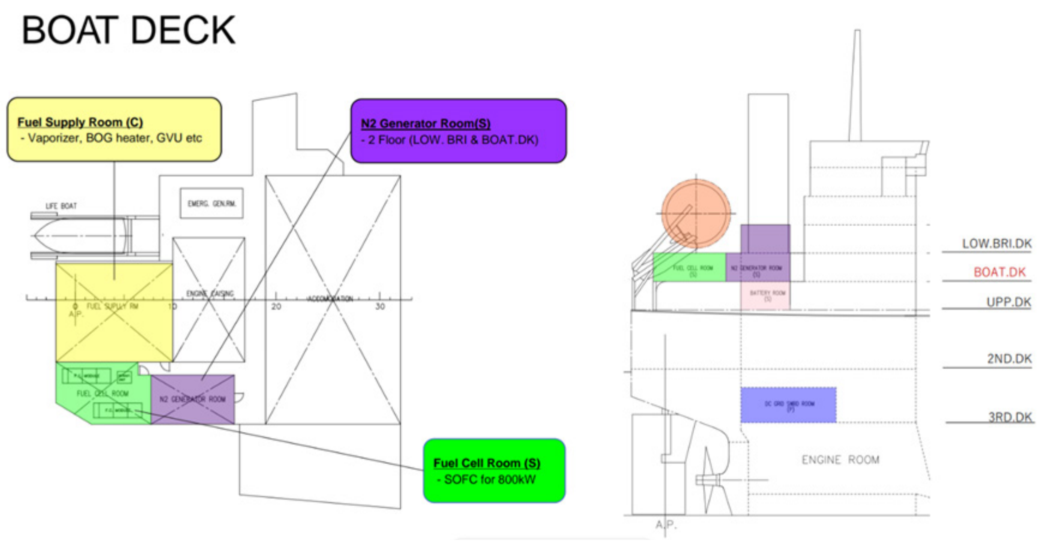


Figure 37: Fuel cell integration (SOFC and methane) on a bulk carrier – detail, upper deck.

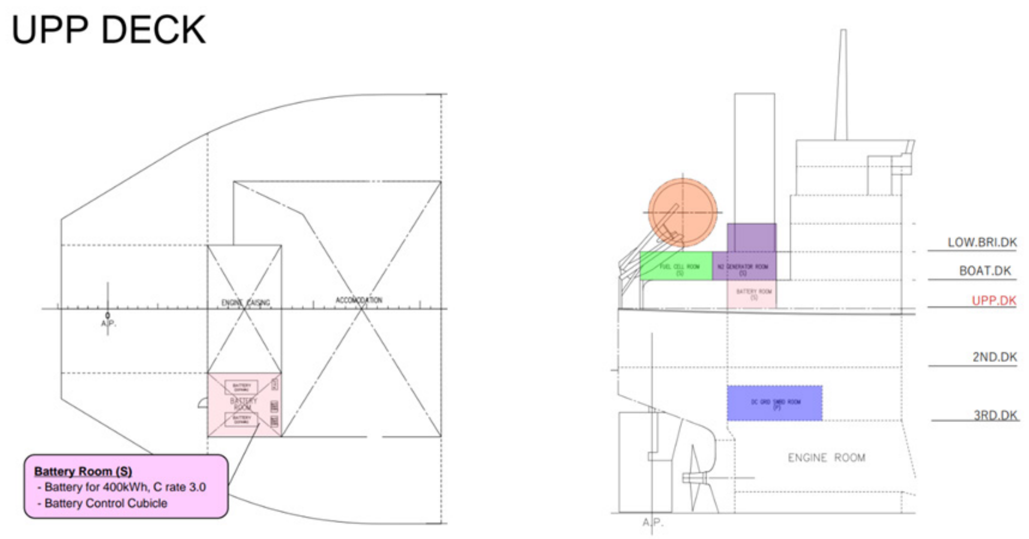
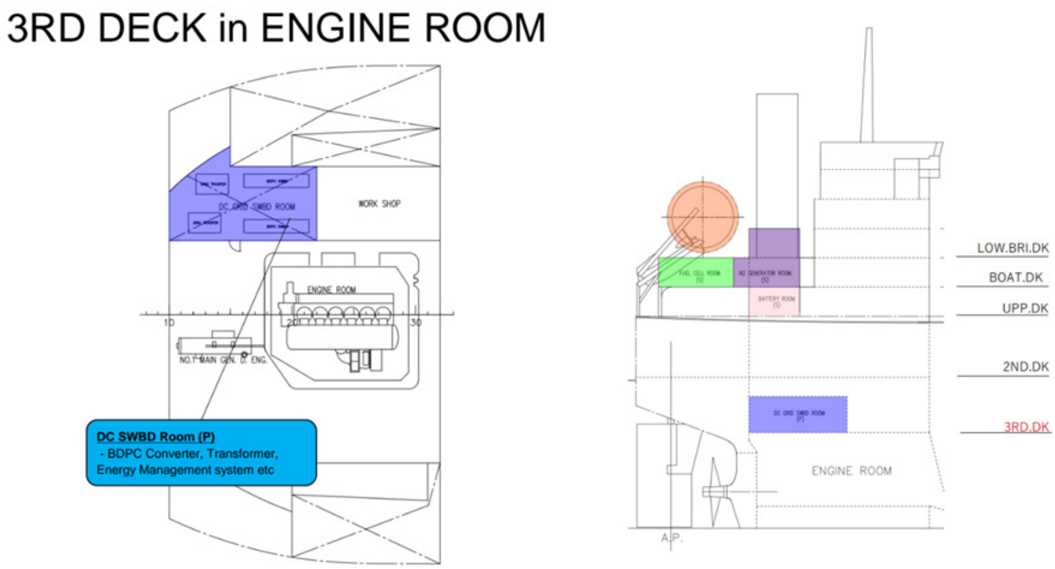


Figure 38: Fuel cell integration (SOFC and methane) on a bulk carrier – detail, 3rd deck in engine room.



A.5.5 Physical integration – tanker and SOFC (methane)

Figure 39: Fuel cell integration (SOFC and methane) on a tanker – general arrangement.

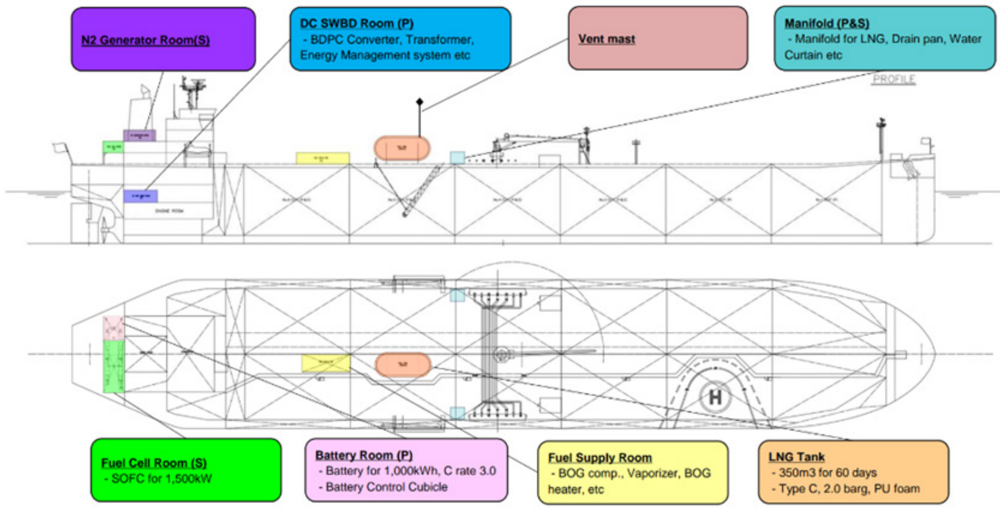


Figure 40: Fuel cell integration (SOFC and methane) on a tanker – detail, A-deck.