A methanol impact tool for yachts

Assessing the impact of using methanol as an alternative fuel on the design, emissions and costs of yachts

M.J.W. Kries

SDPO.20.040.m

Delft University of Technology

TU Delft

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by

M.J.W. Kries

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DE VOOGT
NAVAL ARCHITECTS

Preface

This thesis is my final work to complete the Master Marine Technology at the Delft University of Technology. This past year I have researched alternative fuels which could be implemented in superyachts. I have discovered the environmental importance of using alternative fuels and what could be achieved with them. Methanol is particularly interesting and has several great properties to be a potential yacht fuel. During my time at De Voogt I also discovered the beautiful world of superyachts and the possibilities they offer. This research could not have been completed without the support of several people, who I would like to thank beforehand.

I am very proud of this research and could not have done it without the excellent supervision I have received. Giedo, thank you for supervising me and this research on behalf of De Voogt Naval Architects. I enjoyed our many meetings and chats, both on the methanol topic but also on a higher societal level. When I got stuck or wasn't sure what to do you had the ability to ask the right questions and keep the focus on the essence of the research. I have learned a lot from you this year, both technical and personal, thank you for that. Giedo, Aaron, Bram and Ronno, thank you all for your help, allowing me to participate in the GMM project and giving the tours in the shipyard. During the COVID period your efforts helped to make me feel part of De Voogt.

Next I would like to thank my Delft student colleagues at De Voogt. During my time at De Voogt our group has grown to quite a large number. I enjoyed discussing and just chatting together, from home and when possible at the office.

Hans and Austin, thank you for the supervision on behalf of the TU Delft. I appreciate your guidance, the meetings we have had and your constructive feedback during these meetings. This helped improve the overall quality of this thesis.

These last words of appreciation will go to my family. My parents, brother and sister and my girlfriend, thank you for continuous and unconditional support and always being available for help. Especially this last year with you Mairin, which was a bit of a roller coaster, your help and support helped me to complete this thesis, keep me motivated and you made working from home that much better. Thank you for everything.

M.J.W. Kries
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Summary

Superyachts are large emitters of greenhouse gases, as well as other emissions such as NO_x, SO_x and PM. In order to meet the climate goals set by the IMO, to reduce GHG emissions by 50% in 2050, alternative fuels are being investigated. Methanol is one of these alternative fuels which shows great potential. Methanol can be produced completely carbon neutral from biomass or captured CO_2, contains no sulphur, can be stored in liquid form at atmospheric pressure and temperature and can be used in both fuel cells and combustion engines. There are currently no yachts sailing on methanol but methanol has already been implemented in several other ships. Both yacht builders and owners do show interest in the implementation of methanol on yachts, which makes researching its impact on a yacht very relevant. The yachting sector is only a small fraction of the entire shipping industry and therefore only has a small influence on large scale availability of fuels. Since it is unclear which alternative fuel will become the standard on the long term in the yachting industry, it is of interest to also investigate the impact over a longer period of time or of several pathways. Previous research is generally limited to emissions and costs related to those alternative fuels on a limited range of ship types which do not include yachts. The impact of methanol on the design, emissions and costs is still largely unknown for yachts. This led to the main research question of this thesis: *What is the net impact of methanol as a fuel for existing and new yachts on costs, emissions and design for several pathways?*

In order to determine the impact of methanol, several topics are investigated: the properties of methanol, the rules & regulations regarding methanol, the design impact of the storage of methanol, the environmental impact of using methanol and the impact on costs. In order to determine this impact for several yachts, a design impact tool has been developed which can be used from the early design stages. The tool uses the properties of a (diesel) yacht to determine several power and fuel volume related requirements for the implementation of methanol. The tool also determines the amount of volume that is available in the yacht for the storage of methanol in a basic tank arrangement. Together these form the properties of the yacht with the implementation of methanol. From these methanol yacht properties, the emissions and costs of such a yacht can be determined. These results are then combined in a pathway analysis to determine differences in impact of several future pathways, which was done for a smaller 50 m yacht and a large 100 m yacht.

From the results of this research it was concluded that using methanol as fuel for yachts generally has a positive impact on emissions, compared to a diesel yacht. Methanol offers SO_x free emissions, a reduction of PM emissions and NO_x emissions equal to that of diesel without the necessity of after treatment. CO_2 emissions slightly increase with fossil methanol but can be net zero if renewable methanol is used. The impact of methanol on costs is considered negligible in terms of converters and storage as compared to a diesel yacht. Fuel costs of fossil methanol are slightly higher than fossil diesel, while renewable methanol fuel costs are lower than renewable diesel and 5 times higher than fossil methanol. The impact of methanol on the design is relatively large. Compared to diesel, approximately 2.3 times the amount of fuel is required for an equal range. The double bottom is not considered a feasible location for the storage of methanol. A significant amount of interior area is occupied by the fuel tanks and the surrounding cofferdams. Therefore retrofitting an existing yacht with methanol is not considered feasible. For new designs, methanol is considered a feasible option.

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Introduction

The IMO regulations are becoming progressively stricter: the sulphur cap outside Sulfur Emission Control Areas (SECAs) has decreased from 3.5% to 0.5% at the start of 2020, multiple possible future ECAs are being considered, a total annual greenhouse gas (GHG) reduction by 50% by 2050 (compared to 2008) and efforts to phase out the GHG emissions entirely are pursued. The 2050 target of the IMO is shown in Figure 1.1 (right figure) together with superyacht fleet growth scenarios and their impact on the global warming potential of the fleet, as well as the global warming potential of superyachts of different sizes (left figure). This requires the maritime sector to improve efficiencies and investigate alternative fuels and energy conversion options. One alternative fuel is methanol, the simplest alcohol, which has great potential as a marine fuel. Methanol can be produced completely carbon neutral from biomass or renewable electricity and captured CO_2, contains no sulphur, can be stored in conventional fuel storage tanks with relatively few modifications (compared to LNG, liquid hydrogen and ammonia) and can be used in both fuel cells and modified combustion engines. Therefore, methanol can be implemented in both new ships and in retrofitting existing ships. The latter is of significant importance because of the long lifetime of ships, especially luxury yachts. Because of these relatively long lifetimes, it is not sufficient to only build new ships that have low to zero emissions as this would take many decades before a large percentage of the superyacht fleet is less polluting. This means that retrofitting existing ships is required to reach the IMO climate goals for 2050. As with all new technologies, the cost of implementation is higher than more mature technologies. However, superyacht owners are interested in more efficient yachts with a lower impact on climate, eco-systems and human health and can also afford these new technologies. This gives the superyacht industry the ability to push development and implementation of more environmentally friendly solutions.[1] Yacht owners are also more likely to sail to areas which have stricter emission regulations enforced by local governments, such as the Norwegian fjords or other natural heritage sites and dense tourist destinations. Therefore lower emission solutions are also more appealing to yacht owners.

Methanol, together with LNG are found to be the most mature alternative fuels, from a technology readiness (TRL) perspective, to substitute conventional fossil diesel by Lloyd's Register and UMAS (2020). Rules and regulations for their use as fuels currently exist and vessels are already using these fuels. Ammonia and hydrogen have greater barriers to overcome regarding safety, storage and bunkering infrastructure and there are currently no rules and regulations for the use of these fuels specifically. Therefore, especially on the short term, methanol and LNG are the more realistic options for pathways towards a zero emission future. Both LNG and methanol can be produced from fossil, biomass and renewable electric feedstocks. The volumetric energy density (of the fuel only) of methanol is around 2/3 of LNG, therefore more volume of methanol is required for the same energy content. However, the storage of methanol is much easier as methanol can be stored in conventional diesel tanks with only a few modifications, whereas LNG requires special cryogenic double walled tanks with less space

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[1] Feadship is also involved in the Green Maritime Methanol project. This project aims to investigate the feasibility of methanol as a sustainable alternative transport fuel in the maritime sector. The consortium consists of shipowners, shipbuilders, naval architects, engine suppliers as well as methanol suppliers, ports and the Methanol Institute.

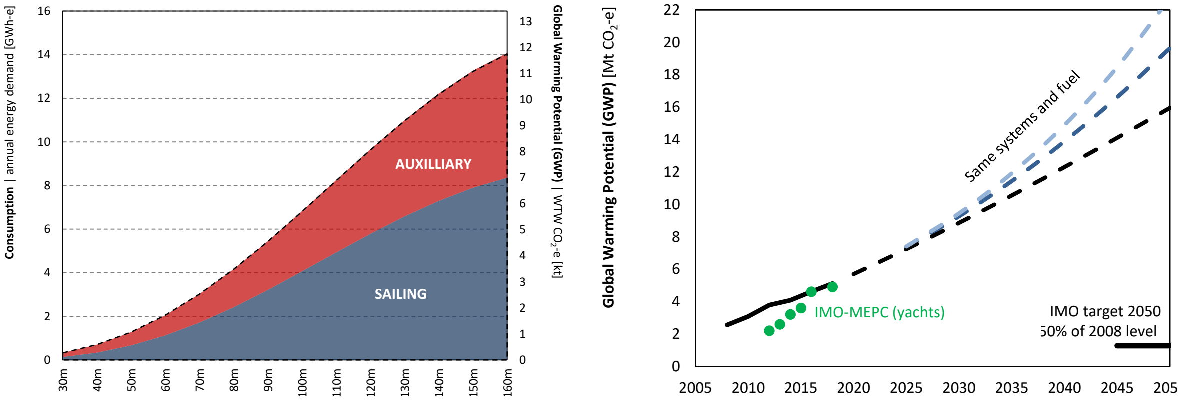

Figure 1.1: Global warming potential [kt CO_2-e] of superyachts of different lengths [m] (left) and global warming potential [Mt CO_2-e] (right) (G. Loeff, De Voogt Naval Architects).

efficient shapes and good insulation to keep the natural gas in its liquid form. Especially for retrofitting and for yachts, the fact that methanol can be stored in conventional diesel tanks of any shape is a large benefit. Because of these reasons, methanol can be regarded as the most favourable alternative fuel for the yachting industry. Therefore, this research focuses on methanol. For completeness, information on other fuels is given in Appendix B.

There are already several vessels sailing that use methanol as fuel, such as the RoPax Stena Germanica.[2] Next to that global shipping company Maersk announced the first carbon neutral feeder vessel by 2023 with the plan of operating the vessel on carbon neutral e-methanol or sustainable bio-methanol from day one.[3] There are currently no yachts using methanol as fuel, but yacht builders and owners are interested in its implementation on yachts. Therefore researching the impact of using methanol fuel on yachts is very relevant.

1.1. Problem statement

General feasibility studies regarding methanol in ships, and also yachts, have been performed. These feasibility studies are generally very high level with a low amount of detail. The main focus of these studies in general is on the economical feasibility, emissions and availability and sometimes also on the implementation on ships. The practical implementation on ships in these studies is limited to the current fuel capacity, the efficiency of the energy converter and the lower LHV of methanol as compared to diesel fuels. The general conclusion of these studies is that the current fuel capacity as it is with diesel is not sufficient enough to maintain the ships range. Therefore, the use of methanol greatly reduces the range of the vessel or the fuel capacity should increase to maintain the range. Harmsen et al. (2020) states that for a short sea freight vessel (Ro-Ro), the range decreases from 10,504 nm to 4,572 nm for a switch from MGO to methanol. For a 67 m luxury yacht, which has a fuel capacity of around 170 m^3, the range decreases from 6,000 nm to 2,612 nm for a switch from MGO to methanol. These decreases in range arise from the lower energy content and density of methanol compared to MGO, which equals to a factor of 2.30 in terms of energy per m^3 (MGO over methanol). For this yacht to maintain transatlantic range (around 3,500 nm plus a 20% margin), an additional 102 m^3 of fuel tank volume is required, which is an increase of 61% over the original fuel capacity. This however, does not have to be the only conclusion of using methanol on ships. Other energy converters can increase the efficiency, reducing the required fuel capacity. Vessels, including yachts, usually have void spaces which may be utilised as additional fuel tanks or alternative tank layouts (with possibly a larger fuel capacity) may be realised. Some cost comparison studies between alternative fuels have considered alternative energy converters such as fuel cells but these studies have not yet considered yachts.

Another category which is left out consistently is retrofitting ships, except for the methanol projects that focus on the application of methanol on an existing ship. In order to reduce the impact of the yachting

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[2] Stena Line Germanica methanol fuelled ferry
[3] Maersk carbon neutral liner vessel on methanol

industry on the climate the entire fleet should decrease its environmental impact and not just the yachts that are newbuild. The superyacht fleet (over 30 m) counted almost 5000 yachts in 2018 (Superyacht Times, 2019). If the current fleet growth is continued, the amount of superyachts will be doubled by 2050 (see Figure 1.2). This means that half of the fleet in 2050 already has been build today because superyachts are rarely being scrapped, especially Feadships. Therefore, retrofitting should be taken into account as this is a very important and big part of the total impact of the fleet.

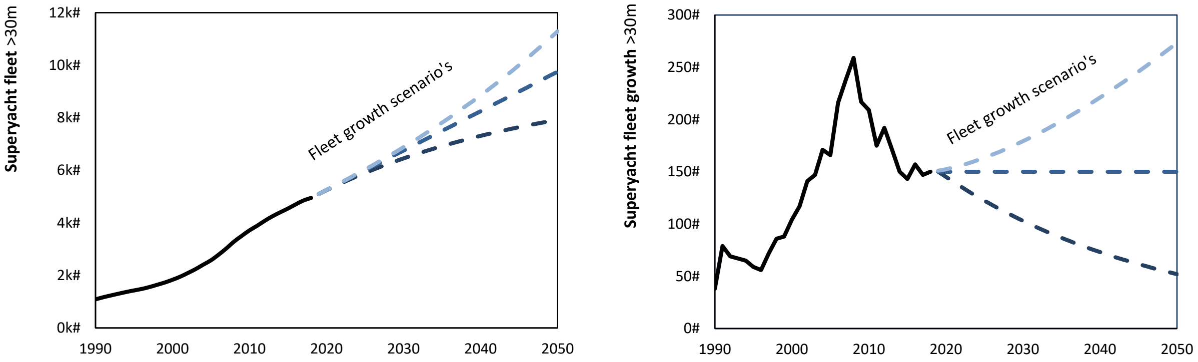


Figure 1.2: Fleet size and fleet size growth of superyachts (G. Loeff, De Voogt Naval Architects). Based on data from Superyacht Times (2019).

Finally, not much is known about the more detailed impact of using methanol as an alternative fuel for yachts on safety and environmental impact, as well as operational and capital expenses such as fuel costs, costs of energy converters and storage of the fuel.

To summarise the problem statement:

- Studies regarding methanol as fuel for ships and yachts are generally high level. These studies lack the level of detail to realistically determine the impact methanol has on a yacht, both in terms of range and design impact.
- Currently existing yachts, will form approximately half of the superyacht fleet in 2050. Therefore, in order to decrease the environmental impact of the superyacht fleet, retrofitting cannot be neglected.
- A more detailed assessment of the impact of methanol as a fuel on safety, environmental impact and costs has not been done, particularly for yachts.

1.2. Research questions

As is discussed in the problem statement, there is a knowledge gap in the impact of methanol on yachts. This is particularly true for the impact of methanol on the design and costs of yachts. From the problem statement the following main research question can be determined to reduce this gap in knowledge.

- What is the net impact of methanol as a fuel for existing and new yachts on costs, emissions and design for several pathways?

To answer the main research questions, several sub questions have to be answered. The sub questions are:

- What are the power and energy requirements of yachts throughout their operational profile?
- What are feasible fuel storage options for a methanol fuelled yacht, considering safety and rules and regulations?
- Which energy converters are feasible options for a methanol fuelled yacht and how do they perform in terms of costs and emissions?

- What are possible pathways of existing and new yachts towards a zero (GHG) emission future of a methanol fuelled system?
- How do these pathways perform in terms of costs and emissions for different cases based on existing Feadships?

1.3. Research objective

Since there currently is no method to estimate the impact of methanol on a yacht, the goal is to develop one. The problem consists of two parts. On the one hand, there is the need to evaluate the impact of methanol on a yacht in terms of design and feasibility. On the other hand, there is a need to evaluate different pathways with methanol, in order to determine which pathways are feasible (and which are not) and how each pathway influences the impact on emissions and costs. A pathway is a possible upgrade path of fuel and converter combinations between now and 2050. A more detailed description of the pathways can be found in chapter 7. The research objective is therefore to develop a design tool to determine the impact of methanol in different configurations. This design tool can then be used to evaluate the different configurations in different pathways. With the design tool, the pathways will be evaluated for a few yachts in a case study. As a yacht is very complex to design, especially regarding space and volume, the focus of this method is on the correct implementation of methanol in a realistic storage and conversion system. The number of pathways will be limited.

From the problem statement and research objective the requirements for the method and the design tool can be determined. These requirements are split in requirements for the method and for the design tool.

The method should:

- Be able to visualise and explore the impact of several pathways on costs, emissions and design.
- Be applicable to a wide range of yachts, both newbuild and existing.
- Include a means to determine the impact of methanol in several configurations.
- Take into account basic trends in costs and properties of fuel and components.

The design tool should:

- Be usable in the early stages of the design process.
- Be usable for both retrofitting and newbuilding.
- Be usable by a researcher or design specialist, to assist in assessing the impact.
- Run in a short amount of time (seconds) so that parameters can “interactively” be changed by the user.
- Contain a database of fuels and components (engines, generators, fuel cells, cofferdam), with a possibility to add other fuels and components. The database includes the properties of the fuels and components.
- Correctly take safety measures such as a cofferdam into account.
- Take into account additional space and volume, if available, for the storage of additional fuel.

The outputs of the design tool should:

- Reasonably accurately estimate the resistance, range, costs and emissions, with an accuracy of 10-20%, to be used in the analysis of the pathways.
- Give technically feasible and safe designs of the fuel storage and conversion system that fit within the boundaries of the yacht.
- Visually present the fuel storage and energy conversion system configuration (2D).

- Be able to be compared to a conventional diesel baseline yacht design.

Outside the scope:

- The focus of the design tool and method is on assessing the impact of methanol in terms of design impact, costs and emissions. A quantified analysis of safety is outside the scope of this thesis.
- An extensive analysis of a great number of pathways, as the focus is on the implementation of methanol. A few likely and relevant pathways will be analysed initially.
- The implementation of other alternative fuels. This may be a feature in the future.
- The use of 3D designs as input or output.
- The automatic generation and optimisation of configuration design layouts (it is not meant as a packing tool).

1.4. Outline research

After the introduction of the problem, research objective and research questions in this first chapter, a literature review of the alternative fuel methanol and possible energy converters is presented in chapter 2. In this chapter the properties, safety, production processes and availability of methanol are first discussed, after which the energy converters capable of using methanol are reviewed.

Chapter 3 focuses on the design requirements, resulting from rules and regulations. The impact of these rules & regulations as well as the properties of methanol itself are discussed in chapter 4. An alternative solution to the cofferdam required in the rules and regulations is also discussed. After that, an analysis of the space available in a yacht for potential storage of methanol fuel and several tank layouts is done for three existing Feadship yachts. From this analysis, the method used to determine the tank properties in the design tool is determined. The impact of the large methanol volume on the design is also discussed, together with a method to reduce this impact. The retrofitting case is discussed in more detail in this chapter in light of the design impact and costs.

The design tool is discussed extensively in chapter 5. In this chapter the tool is first discussed in general, after which the different modules of the tool are discussed in detail. The focus is on the methods, parameters and values that are used in the design tool as well as the data flow.

A validation of the design tool's modules is done in chapter 6. Here the available space and resistance prediction are validated.

The properties and considerations of the four pathways that are assessed in this research are discussed in chapter 7.

In chapter 8 the pathways are applied to two yacht designs and the results are discussed. For each yacht case study the possible design configurations, tank layouts and their impact are determined. After the design impact assessment, the results of the four pathways are stated and discussed. Both emissions and costs for each yacht and each pathway are covered in this chapter.

The perspective of methanol is discussed in chapter 9. In this chapter the possibilities, opportunities and lessons learned, as well as the difficulties and unanswered questions of methanol are discussed.

The conclusions and recommendations are presented in chapter 10.

2

Literature review

This chapter contains a literature review regarding methanol and its use as a fuel for ships. The literature contains a review of the physical properties, safety, production processes, global availability of methanol as well as possible energy converters using methanol as fuel.

2.1. Physical properties

Methanol is the simplest alcohol and has the chemical formula of CH_3OH. It is colourless, flammable and liquid at ambient temperatures. Methanol is mainly used in the petrochemical industry as a solvent or building block for other chemicals. About 35% is used for the production of formaldehyde production, which has a very wide range of industrial applications. Other uses of methanol are the production of fuel additives, MTBE, acetic acid, methyl and vinyl acetates and other chemicals (Dalena et al., 2018).

The molecular weight of methanol is equal to that of oxygen, however, its density is much higher. This is because density is dependent on the surrounding molecules. The characteristic OH group makes methanol a polar molecule. Due to this OH-group, hydrogen bonding occurs between methanol molecules (or other polar molecules) which results in the formation of quasi-super molecules or cyclic

Table 2.1: Properties of Marine Gas Oil (MGO) and methanol. Data from Ellis and Tanneberger (2015), unless denoted by superscripts: 1 - Volger (2019), 2 - World Fuel Services (2017).

Property	Unit	MGO	Methanol
Chemical formula	-	$C_{12}H_{26}$-$C_{14}H_{30}$	CH_3OH
Physical state at SATP	-	Liquid	Liquid
Physical state at storage conditions	-	Liquid	Liquid
Storage temperature	°C	15	15
Storage pressure	bar	1.0	1.0
Density (SATP)	kg/m^3	-	682^1
Density (15°C)	kg/m^3	855.6-890^2	795.5
Boiling temperature (1 bar)	°C	175-650	65
Dynamic Viscosity (40°C)	cSt	2.72-3.5	0.58
Gravimetric LHV	MJ/kg	42.7	19.9
Volumetric LHV	MJ/l	36.5-38.0	15.8
Volumetric LHV_{fuel}/LHV_{MGO} ratio	-	1.0	2.35
Lubricity WSD	μm	280-400	1100
Vapour density (air=1)	-	>5	1.01-1.1
Flash point	°C	>60	9-12
Auto-ignition temperature	°C	250-500	440-470
Explosive limits	%	0.3-10	6.0-36.0

tetramers. This makes methanol liquid at STP, infinitely miscible with water and is also the reason why methanol does not mix well with hydrocarbons (Verhelst et al., 2019). In Table 2.1 a number of relevant properties of methanol and MGO, which is often used as fuel for yachts, are given for comparison.

2.2. Safety and hazards of methanol

The safety and hazards regarding methanol will shortly be discussed in this section. Hazards such as ingestion and inhalation are discussed and methanol is also compared to other chemicals in terms of the amount of accidents. Methanol vapour is discussed separately as this could be a relatively larger risk on ships in the confined engine room of a yacht.

2.2.1. Toxic effects and effects on human health

Methanol causes acute toxic effects from ingestion, inhalation of high concentrations of methanol vapour and absorption through the skin of methanol liquids. Humans and primates are uniquely sensitive to methanol poisoning, while methanol is less toxic to non-primate animals. Almost all available methanol toxicity information for humans is related to acute exposure. Not much is known about the effects of chronic exposure (Ellis and Tanneberger, 2015). Another problem to be considered is that methanol smells like normal drinking alcohol (ethanol) (Carl Roth, 2019). Next to being toxic, methanol is also a very flammable liquid, as its flash point is below ambient temperatures.

Although methanol is dangerous and toxic, this is also true for other fuels such as gasoline and diesel (substitutes). In many respects alcohol fuels can be regarded safer than gasoline. The major issue is toxicity in terms of ingestion, skin or eye contact, or inhalation. Methanol poisoning from direct ingestion takes 10-48 hours to cause symptoms but the cure is well understood. Skin or eye contact and inhalation are of lower concern as long as it does not persist for hours. Toxicity of alcohol fuels is comparable or in many cases better than that of common gasoline or diesel. Methanol fires are invisible in sunlight, but extinguished with water (for pure methanol). Widespread methanol usage is expected to lead to a reduction in deaths, fires and property loss of 90-95% versus gasoline (Verhelst et al., 2019).

Compared to other chemicals, methanol is involved in much less accidents as can be seen in Figure 2.1. In descending order (of the selected chemicals in this report), ammonia is involved in most accidents, followed by hydrogen, natural gas and methanol. Accidents are the release of a substance, explosions and fires accounting for 50%, 30% and 20% of the accidents respectively (Dräger, 2011). As methanol was not used as a fuel for ships when this source was published, the number of accidents relative to the other chemicals may change when the use (and distribution) of methanol as shipping fuel increases. However, with the information stated in this section, methanol can be considered less dangerous than other chemicals. Combined with the primary risk of methanol such as ingestion or inhalation, for which rules and regulations are being developed to contain the methanol as much as possible, it is not very likely that the relative share of methanol in the total accidents will change much.

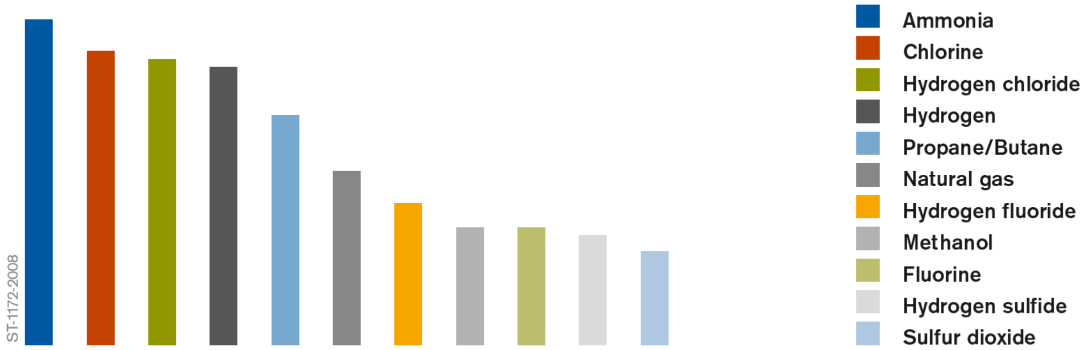


Figure 2.1: Chemicals involved in accidents in descending order (MARS database 1984-2004). Image from Dräger (2011).

2.2.2. Methanol vapour

Pure methanol vapour has a density slightly higher than that of air (see Table 2.1) and is formed above the boiling point of methanol (65°C). With a relative density of 1.1, methanol vapour would slowly sink to the floor. However, it is unlikely that a pure methanol vapour would form. It is much more likely that a mixture of air and methanol would form in the case of a small leakage for example. The vapour/air mixture at 20°C has a relative density of 1.01 (International Labour Organization and World Health Organization, 2018). This means that the mixture nearly has an equal density to that of normal air and is naturally buoyant in air. In locations where methanol vapour may occur, such as the engine room or fuel tanks, the airflow therefore needs to be controlled and directed to a safe location to get rid of the vapour mixture. Not much information about the exact behaviour of methanol vapour in air is found in the literature, therefore the chance and impact of a methanol leakage should be carefully investigated to accurately assess the risk related to methanol vapour.

2.3. Methanol production

Methanol can be produced from many different feedstocks. The production methods of methanol from the following feedstocks is discussed in this section:

- Natural gas
- Coal
- Biomass
- CO_2 and renewable electrolysis

Most of the methanol is currently produced from natural gas, which is a fossil fuel. In order for methanol to become a renewable fuel, the methanol must be produced in a renewable way. The production efficiency of methanol is higher than that of ethanol or synthetic hydrocarbons. Most production processes result in crude methanol containing residual gases and a significant amount of water. To purify the methanol, distillation or dehydration is required, which amounts to a significant part of the cost. Currently no crude methanol is available on the market, but there may be an opportunity to use this in for example fuel cells which require a mixture of methanol and water. This way, part of the purification costs can be bypassed (Verhelst et al., 2019). The energy density of this mixture will however be much lower than of pure methanol resulting in more mass and volume to be stored or transported to deliver an equal amount of energy. Using crude methanol may or may not have an advantage depending on the difference in price between crude methanol and purified methanol.

Methanol can be produced by chemical processes, which bypasses the biomass limits that other biofuels have. It is also being advanced as the most interesting power-to-x fuel, where excess energy from the grid is converted to fuel for later use and easier storage, because it is the cheapest liquid (at SATP) “electrofuel” that can be produced (Verhelst et al., 2019). Next to that, methanol is an important feedstock for many other chemicals such as formaldehyde but also other chemicals which have a wide range of applications. Therefore, methanol offers a way for many sectors to reduce their environmental impact, when bio-methanol or e-methanol (from CO_2 and renewable electricity) is used. This may also increase the appeal of using methanol and developing renewable methanol production related technology, such as carbon capture technology.

2.3.1. Natural gas

About 90% of all available methanol is produced from natural gas. The production of methanol from natural gas can be summarised in three steps: the production of synthesis gas, the conversion of the synthesis gas (syngas) into crude methanol and the distillation of the crude methanol until the desired purity is achieved. Syngas is a mixture of hydrogen (H_2), carbon-monoxide (CO) and carbon-dioxide (CO_2). The syngas is mainly produced by steam reforming (SR) and autothermal reforming (ATR) of natural gas, but it can also be produced by partial oxidation (PO) of methane or other carbon-based materials such as coal, heavy oils, biogas. The chemical reactions for each of the syngas production methods are given in the equations below: Equation 2.1 to Equation 2.4 (Dalena et al., 2018).

Steam reforming:

$$\mathrm{CH_4 + H_2O \rightleftharpoons CO + 3\,H_2} \tag{2.1}$$

Autothermal reforming (ATR):

$$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O \tag{2.2}$$

Water-gas shift occurring with ATR:

$$CO_2 + H_2 \rightleftarrows CO + H_2O \tag{2.3}$$

Partial oxidation:

$$CH_4 + \frac{1}{2}\,O_2 \longrightarrow CO + 2\,H_2 \tag{2.4}$$

The carbon-monoxide and carbon-dioxide within the syngas can then be converted to methanol through hydrogenation. This occurs through the following reactions (Equation 2.5 and Equation 2.7).

Hydrogenation of CO:

$$CO + H_2 \rightleftarrows CH_2O \tag{2.5}$$

$$CH_2O + H_2 \rightleftarrows CH_3OH \tag{2.6}$$

Hydrogenation of CO_2:

$$CO_2 + 3\,H_2 \rightleftarrows CH_3OH + H_2O \tag{2.7}$$

In Table 2.2 the carbon and thermal efficiency of the methanol synthesis process is shown. The indirect methanol synthesis as described above contains the syngas generation from methane (reforming), the methanol production (hydrogenation) and the purification of the crude methanol. The syngas generation accounts for 60% of the capital cost of the process. In the direct methane to methanol process methanol is produced by the direct partial oxidation of methane to methanol. The carbon efficiency is the percentage of carbon in the feed that is contained in the useful end product. The thermal efficiency is the fraction of the LHV of the feed to the process that is retained by the useful products. The main reason for the difference in efficiencies is the reaction selectivity. In the indirect methanol process almost no carbon is lost due to irreversible side-reactions and around 99% is converted to methanol during methanol synthesis (de Klerk, 2015).

Table 2.2: Efficiency of the indirect and direct methanol synthesis from natural gas (de Klerk, 2015).

Process	Overall process efficiency	
	Carbon (%)	Thermal (%)
Direct methane to methanol	35	28
Indirect methanol synthesis	65-68	51-54

2.3.2. Coal

Methanol can also be produced from coal. This method for producing methanol is mostly used in China. This methanol is not exported, but used locally in China as a blender or alternative to gasoline (Ellis and Tanneberger, 2015). China is considered one of the biggest producers of methanol, primarily from coal. This take up of methanol production is partly because in order to obtain valuable coal mining permits: companies have to provide a use for that coal, which led to the construction of very large methanol plants (Verhelst et al., 2019).

The production process of methanol from coal happens through the same general steps as that of natural gas. The coal is first converted to biogas (CH_4 and CO_2), syngas (H_2, CO_2 and CO), pure hydrogen and alkaline gases in a gasifier. The char gasification reaction is given in Equation 2.8 below, which in combination with the CO_2 formed in the water gas shift (WGS) from before forms the syngas. With the syngas, the production path of methanol from it is the same as for the production of methanol from natural gas (see Equation 2.5) (Dalena et al., 2018).

Char gasification reaction:

$$C + H_2O \longrightarrow CO + H_2 \tag{2.8}$$

2.3.3. Biomass

The amount of biomass that is available is substantial. In Figure 2.2, an estimate of the amount of biomass residue worldwide which could be used as a renewable feedstock is shown. The amounts are in exajoules per year, where 1 EJ is equal to approximately $2.8 \cdot 10^8$ MWh. There are several conventional and new processes for the production of bio-methanol, such as pyrolysis, gasification, biosynthesis, electrolysis and photo electrochemical processes. Pyrolysis is more suitable for the large scale production of methanol for diesel engines, whereas gasification is preferred for the production of gaseous fuels. New techniques such as photo electrochemical and electrolysis have been proven to have potential for the lab scale production of methanol but still require further research before it may be used in large scale production (Shamsul et al., 2014). Thermochemical processes are the better option because of the larger amount of feedstock that can be transformed and the faster conversion rate (Dalena et al., 2018). In Figure 2.2, an overview of the energy potential per biomass category is shown.

Methanol can be produced from biomass, such as solid waste or any carbon containing resource, with the same process as coal: gasification. The gasification allows the conversion of solid biomass into gaseous mixtures with the help of gasifying agents such as air/oxygen, steam and flue gases. This process is done with high temperatures in the presence of oxygen with the aim to lower tar content and increase the amount of hydrogen in the syngas. With biomass, the resulting syngas is not always of the quality that is required for the production of methanol. One of the biggest problems is the formation of tar and char through the reduction of carbon oxides. Tar is particularly unwanted because it may cause the formation of tar aerosols and polymerisation into more complicated structures which reduce the hydrogen production. Adding a catalyst in the gasifier, reduces the tar content of the products significantly. To gasify the biomass, it has to be pulverised to particle sizes of 100 μm which is a process that requires significant energy consumption. Torrefaction (mild pyrolysis) is the process of combustion in the range of 200-300°C in anaerobic conditions of biomass. This process makes it easier to grind the biomass, which makes the grindability comparable to that of coal. The power consumption of the grinding process is hereby reduced by 80-90% in comparison to raw biomass. This results in a much environmentally friendlier production of syngas than when coal is used (Dalena et al., 2018).

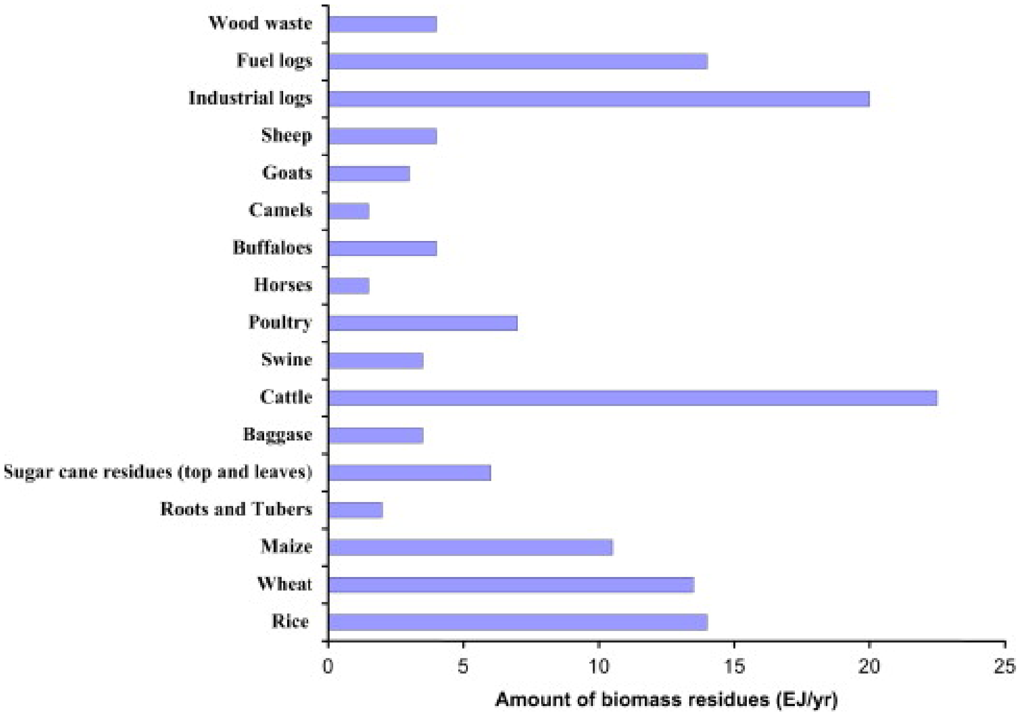


Figure 2.2: Amount of energy (in EJ/year) in biomass residues per category. Image from Shamsul et al. (2014).

For the production of methanol from biomass, similar thermal efficiencies are found as efficiencies for the production of methanol from methane, and are around 55%. This efficiency includes the gasification, cleaning and distillation (Lücking, 2017).

Examples

A few examples of methanol production plants that produce methanol from biomass are listed below:

- Chemrec (Sweden) produces methanol through the gasification of black liquor (Ellis and Tanneberger, 2015).
- Enerkem is a methanol plant in Canada, which produces methanol since 2015 from municipal solid waste (MSW) otherwise destined for landfill. The plant is designed to process over 100,000 tons of unrecoverable waste (Hobson and Márguez, 2018).
- BioMCN is based in the Netherlands and produces methanol from biogas from multiple sources (MSW, anaerobic digestion plants, etc.). From 2006 to 2015 they produced methanol from glycerine, but switched to biogas from 2015 onward. In 2017, BioMCN produced almost 60,000 tons of methanol (Hobson and Márguez, 2018).

2.3.4. CO_2 and renewable electrolysis

Methanol can be produced through the hydrogenation of CO_2. Since the CO_2 molecule is very stable a great amount of energy, optimised reaction conditions and a high stability and activity catalyst are required to convert the carbon dioxide into a value added chemical such as methanol. The reaction is shown in Equation 2.9 below:

$$\mathrm{CO_2 + 3\,H_2 \rightleftarrows CH_3OH + H_2O} \tag{2.9}$$

The carbon dioxide can be captured from any natural or industrial source, human activities or air. The required hydrogen in this method can be produced through the electrolysis of water, but there are also other sources of H_2 (i.e. biomass pyrolysis or gasification). The electrolysis can be done with a renewable source of electricity such as wind, solar, waves, tidal energies. The electrolysis reaction is shown in Equation 2.10 below:

$$\mathrm{2\,H_2O \xrightarrow{\Delta,\,electricity\,or\,\mathit{h\nu}} 2\,H_2 + O_2} \tag{2.10}$$

The use of CO_2 as a feedstock for the production of methanol has many advantages. CO_2 is cheap and abundant as well as non-toxic, non-corrosive and non-flammable which makes it safe to use and handle. It offers mitigation of the greenhouse effect by means of recycling the greenhouse gas (Dalena et al., 2018). The capture of CO_2 from air requires 2 to 4 times more energy than CO_2 capture from flue gases. Strong bases can scrub CO2 from the atmosphere, but the regeneration of these bases is very energy intensive. More energy efficient materials to extract CO_2 from the atmosphere are under development, which could lower the capturing cost in the future (Brynolf et al., 2018). The costs associated with the capturing of carbon from different sources are shown in Table 2.3. The CO_2 capture efficiencies are also shown in this table. The capture efficiency is defined as the amount of CO_2 that is captured from the flue gases.

Examples

A few examples of methanol production plants that produce methanol with renewable electricity are listed below:

- The CRI George Olah methanol plant in Iceland started production in 2013 and now produces about 4,000 tons of methanol per year. This plant recycles CO_2 from the Svartsengi geothermal power station. This geothermal power station also supplies power for the electrolysis of water to produce the required hydrogen (Hobson and Márguez, 2018).
- Liquid Wind is currently developing a facility in Sweden to produce methanol. They will use wind generated electricity to electrolyse water into hydrogen and oxygen. This will be done with Nel's

Table 2.3: Capture efficiency and associated costs of carbon dioxide. Capture efficiencies are from Taljegard et al. (2015)), capture costs are from Brynolf et al. (2018).

CO_2 Source	Capture efficiency [%]	CO_2 capture cost [€/tCO_2]	
		Short-midterm (to 2030)	Long term (2030+)
Natural gas power plant	90	20-60	10-60
Coal power plant	90	30-170	10-100
Petroleum refining	75	60-140	30-90
Cement industry	85	70-150	30-50
Iron & steel production	75	50-70	30-60
Ammonia production	85	<20	<20
Bioethanol production, biogas upgrading	100	<20	<20
Pulp and paper industry[a]	-	21-47[a]	-
Ambient air	-	-	20-950

[a] Capture cost from Taljegard et al. (2015)

hydrogen modular electrolyser. Waste CO_2 will be captured from large CO_2 emitters such as the pulp and paper industry. Using a Haldor Topsoe reactor, the hydrogen and CO_2 is converted into methanol.

2.4. Methanol availability and supply

Methanol is one of the most (top 5) shipped chemicals worldwide and has been stored, transported and handled safely for over a 100 years. Over 95 billion litres are manufactured yearly (Hobson and Márguez, 2018). Methanol is therefore available worldwide in most large ports. For example, in Rotterdam and Antwerp, there are large storage terminals for bulk chemicals including methanol. Methanol is mainly used as a chemical feedstock for the petrochemical industry, but is increasingly used as a fuel (blended or pure) mostly in China. Ellis and Tanneberger (2015) stated that the annual methanol demand is expected to grow from 61 million metric tons (MMT) in 2012 to 146 MMT in 2022. In 2018 the worldwide methanol production was around 78 million MT, while the production capacity was around 122 million MT (Chatterton, 2019). According to IHS, the uptake for methanol as a marine fuel is projected to reach 150,000 MT per year by 2020 (Methanol Institute, 2019).

In Figure 2.3, the global terminal/port locations for methanol and their capacities (in metric tons), if known, are shown (data from Chatterton (2019)).

The production and supply chain for methanol produced from natural gas and delivered to the ship's fuel tank are similar to that of LNG, where the fuel is produced near the feedstock location, transported to large storage hubs, from there transported to local storage and then supplied to the ship's fuel tank through a bunker vessel (or truck). Up to the penultimate step (local storage), the production and transport steps are the same as for the methanol destined for the chemical industry, and infrastructure for this already exists. According to the UN classification system, methanol is a class 3 flammable liquid, and tank requirements are similar to that of other flammable liquids of the same class such as ethanol, gasoline and petroleum distillates (Ellis and Tanneberger, 2015). In Figure 2.4 this production and transportation supply chain is shown.

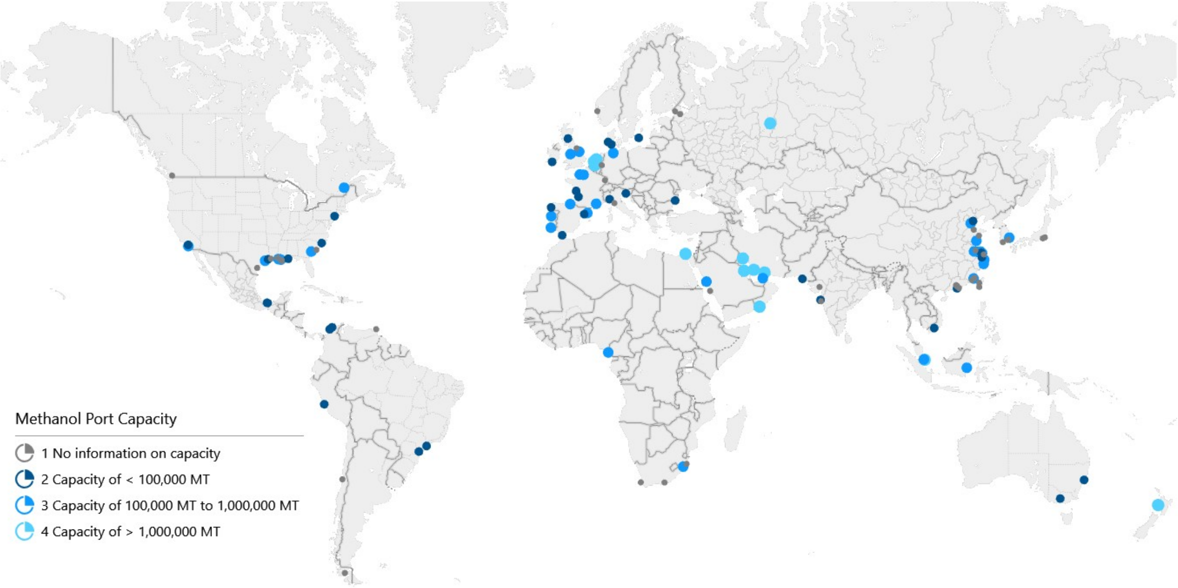


Figure 2.3: Global methanol availability in ports, with methanol storage capacities if known. Data from Chatterton (2019).

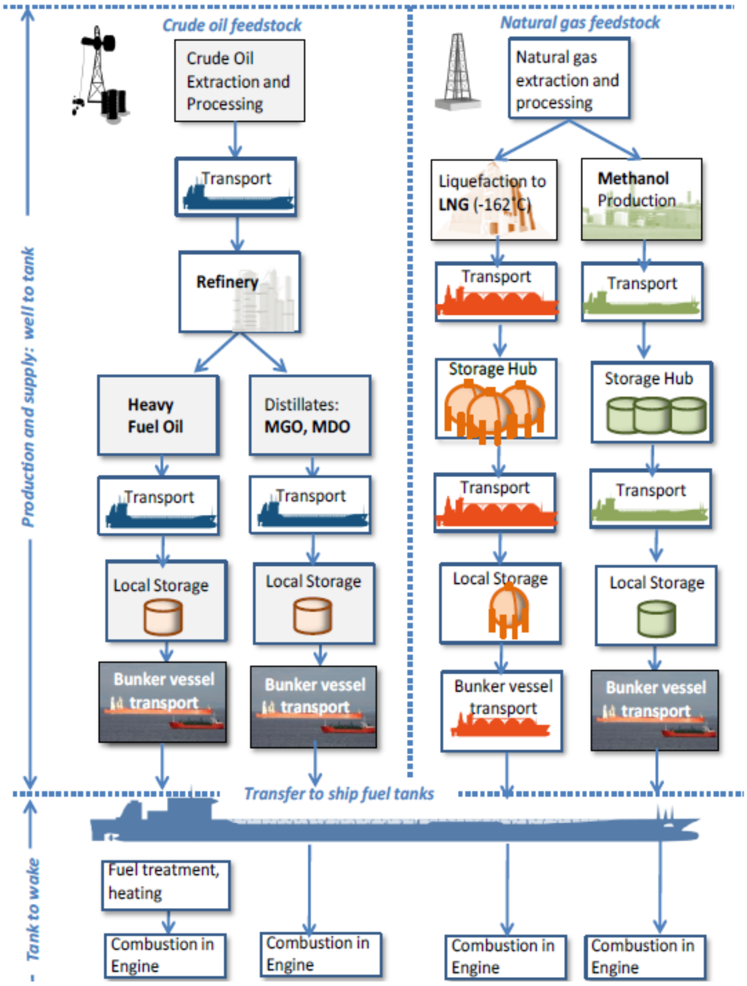


Figure 2.4: Production and supply chain of methanol and LNG from natural gas and conventional marine fuels from crude oil. Figure from Ellis and Tanneberger (2015).

2.5. Energy converters

In this section the energy conversion of methanol from fuel to usable energy is discussed. Methanol can be used in pure form, but also in blends with other alcohols, conventional fuels or water with varying implications for the energy converter. The converters discussed in this section are:

- Spark ignited internal combustion engines
- Compression ignited internal combustion engines
- PEM fuel cells
- Direct methanol fuel cells
- Solid oxide fuel cells

Other fuel cells were also found in the literature research but were often not associated with using methanol as fuel or with the application on ships. Gas turbines were also considered as they can deliver large powers in a relatively small package, due to their high power density. Microturbines, delivering smaller powers, are also becoming increasingly more popular. However, gas turbines generally have a higher fuel consumption due to the lower efficiency. Therefore, gas turbines were excluded for this research.

2.5.1. Internal combustion engines

One of the energy converters that can be used in combination with methanol is the internal combustion engine (ICE). Internal combustion engines inject the fuel into the cylinder which is then ignited through a spark (spark ignition) or through compression (compression ignition). Both ignition methods are further discussed in the following sections. Through this process, energy contained in the fuel is converted to pressure and heat, which moves the piston which in turn drives a crankshaft. Experimental results with methanol fuelled ICEs are also discussed, as well as engine material considerations and cold starting with methanol.

In combustion systems, methanol improves the brake thermal efficiency (BTE), while also emitting significantly lower SO_x, NO_x and PM than complex hydrocarbon fuels. Methanol can be used as engine fuel in several ways. In spark ignition engines, as pure methanol or as a blend component or as a separately injected fuel (dual fuel). In compression ignition engines as a separately injected fuel or as port injected fuel.

Methanol can be blended for use in (mostly) unmodified engines. There are multiple ways to blend methanol with other fuels and various ratios. Binary blends are a mix of methanol with another fuel such as gasoline. Ternary blends are a mix of methanol with another alcohol and another fuel. In order for methanol to blend with diesel, an emulsifier is required. Methanol-water blends have been found to have reduced NO_x emissions compared to pure methanol (Verhelst et al., 2019). The formation of NO_x depends heavily on temperature, thus by adding inert water to the fuel mix, NO_x emissions can be reduced (Maritime Knowledge Centre et al., 2018). Not much is known about blending methanol with marine diesel fuels. Especially heavy fuel oils (HFO) and marine diesel oils (MDO) are very different from diesels used in land transportation. However, the more refined marine gas oil (MGO) is more similar to the automotive diesel fuels and can likely also be blended with methanol in combination with an emulsifier.

Spark ignition

Spark ignition engines are usually smaller engines with lower power outputs. As mentioned before, methanol can be used in an SI engine as a separate fuel stream. This would mainly be used as an octane booster when required. However, having two separate fuel streams creates a more sophisticated engine design and engine management system. On the other hand using methanol as pure or blended fuel requires only one fuel stream and one injector. This method requires the least amount of modifications to the engine. Some modifications to the fuel injector may be required.

The methanol in a spark ignition engine can be ignited by a sparkplug or a glowplug. A sparkplug generates a spark which ignites the fuel while a glowplug is a hot surface which triggers the ignition of the fuel when it comes in contact with the surface. SI engines that do not use the lean burn concept (lower fuel/air ratio than stoichiometric), have peak efficiencies far below a direct injection compression ignition diesel engine (Maritime Knowledge Centre et al., 2018).

Several properties of methanol make it a good fuel for spark ignition engines. These properties include the high octane number, wide range of flammability limits and high flame speed and are shortly discussed. Methanol is, like other alcohols, very knock resistant with a research octane number (RON) of around 109 (compared to 15-25 for diesel and 80-98 for gasoline). The octane number is a standard measure for the auto-ignitability of a fuel, where a higher octane number implies a higher allowable compression before the fuel auto-ignites (i.e. low auto-ignitability). When (part of) the fuel ignites spontaneously, and not because of the propagation of the flame caused by the spark plug, the unwanted effect called knock occurs (Maritime Knowledge Centre et al., 2018).
Alcohol fuels in general have a wider range of flammability limits compared to gasoline, which is the range of ratios of fuel to air in which the fuel-air mixture can be ignited by an ignition source. This allows for the use of leaner fuel mixtures (less fuel per unit of air) which can theoretically result in higher thermal efficiencies of the engine (Maritime Knowledge Centre et al., 2018).
The flame speed of methanol is also higher than that of conventional fuels. This results in faster combustion of the fuel mixture which allows a more optimised combustion timing. This could also lead to an increase in efficiency. This precise timing of the combustion is not possible for compression ignition engines because they depend on the auto ignition of the fuel (Maritime Knowledge Centre et al., 2018).

Compression ignition

Most larger engines use the compression ignition (CI) concept to ignite the fuel. CI engines compress the fuel to a point where the fuel spontaneously ignites. Methanol has a very low cetane number (CN), which results in very poor auto-ignition capabilities. Most CI engine methanol concepts therefore use a high CN fuel, mostly diesel, to auto-ignite and thereby also igniting the methanol. Methanol can be mixed with diesel, but this requires an emulsifier or co-solvents, because they do not mix well without. Using a blend has the advantage that only one fuel injector is needed, which limits the amount of modifications required. A dual fuel approach however is more common, which allows the methanol and diesel to enter the engine separately. There are multiple ways of introducing the fuel to the engine. The two main options are direct injection (DI) and port fuel injection (PFI).

The direct injection requires a custom cylinder head with separate injectors, one for methanol and one for diesel (or other pilot fuel), or a custom injector which is capable of injecting both the pilot fuel and methanol together. Direct injection has the advantage that the methanol injection can be timed such that premixing with the compressed air is limited, eliminating the possibility of knock. These injectors inject the methanol at high pressures in the cylinder (500-600 bar), requiring a high pressure fuelling system (Verhelst et al., 2019).

The second option, PFI, introduces the methanol into the engine's intake ports. This method is very interesting for retrofitting because it requires less modifications to the engine. Here, a lower pressure methanol fuelling system can be used. Knock, due to end gas auto-ignition can be an issue with PFI, which requires a lowered compression ratio or a limited methanol-air ratio at higher loads. PFI can therefore result in lower performance compared to DI (Verhelst et al., 2019).

Another option is glow plug ignition, which reforms the methanol inside the engine. This would eliminate the need for a pilot fuel. The glow plug triggers surface ignition of methanol relatively easy. This is thought to be due to the reforming of methanol into CO and H_2, where the hydrogen easily (pre-)ignites and acts as a pilot fuel for the rest of the methanol (Verhelst et al., 2019).

In yachts, the propulsion system is usually diesel-direct or diesel-electric, with multiple diesel generator sets (high speed CI diesel engines with a generator). The generators have an efficiency of around 96% (50-110% rated power) (Leroy-Somer, 2018). The diesel engines (for a 575 kW engine on EN590 fuel; 200 g/kWh at 100% power) have an efficiency of around 42% (MTU, 2018), which results in a combined efficiency of approximately 40%.

Experimental results

In most cases, a slight decrease in efficiency (compared to normal diesel operation) is observed in performed experiments at low loads and a slight increase at high loads. At low loads, the premixed (with PFI) methanol-air mixture can approach the flammability limits leading to higher emissions of

Table 2.4: NO_x, PM, SO_x and (unburned) CH_4 emissions of medium speed engines (250-1200 rpm) for diesel (<0.1% sulphur), methanol and LNG. Methanol and LNG are used in dual-fuel (DF) engines. The values are given in g/kWh. Data from Harmsen et al. (2020).

Engine/fuel	Diesel Tier II	Diesel Tier III	Methanol DF Tier II	Methanol DF Tier III	LNG DF Tier III
Emission control technology	Engine out	SCR or EGR	Engine out	SCR or methanol-water	Engine out (DI) or SCR (DI)
NO_x limit	8.6-12.4	2.2-3.0	8.6-12.4	2.2-3.0	2.2-3.0
NO_x	8.0-11.5	2.0-2.7	~5	2-3	2-3
PM	0.23	0.23	0.03	0.03	0.02
SO_x	0.36	0.36	0.007	0.007	0.009
Methane	0.0036	0.0036	n.a.	n.a.	5.7

unburned fuel, decreasing the efficiency. At high loads, the faster and cooler combustion of methanol enables higher efficiencies (Verhelst et al., 2019). Experiments done by the Ghent University, on a modified CI engine with PFI of methanol, report an increase in efficiency of 12% maximum (Sileghem, 2020).

Compared to normal diesel operation, NO_x emissions are generally lower with methanol. This decrease depends on the engine load and the achieved methanol fraction, and ranges from 6% to over 50%. This decrease is mainly attributed to the cooling effect of methanol (high heat of vaporisation/latent heat), resulting in lower in-cylinder temperatures and therefore reducing thermal NO_x formation, and to the faster combustion of methanol (higher flame speed), which reduces the duration of high in-cylinder temperatures resulting in a shorter time where NO_x can be formed (Verhelst et al., 2019). Experiments done by the Ghent University, on a modified CI engine with PFI of methanol, report a decrease in NO_x emissions of 60% on average (Sileghem, 2020).

Next to NO_x, the formation of soot or particulate matter (PM) is also reduced by up to 80%. This is mainly because methanol contains no carbon-carbon bonds and aromatics, as is the case with diesel fuels. The methanol is also premixed with air (in the PFI case) which prevents locally fuel-rich zones. Its high heat of vaporisation usually increases ignition delay giving the pilot fuel, which is more likely to cause soot formation, more time to fully evaporate and mix well with air (Verhelst et al., 2019). Experiments done by the Ghent University, on a modified CI engine with PFI of methanol, report a decrease in soot emissions of 78% on average (Sileghem, 2020), in line with the reductions stated by Verhelst et al..

To compare the emissions of methanol with conventional diesel and LNG, engine emissions (tank to wake), such as NO_x, PM and SO_x, are shown in Table 2.4. The diesel emissions are based on a 0.1% sulphur fuel. For the methanol and LNG engines, the most common technologies are used: dual-fuel with a 2% diesel pilot injection. The NO_x limit is also given and is a function of the maximum engine speed. The Tier II NO_x limit is determined by: $44 \cdot n^{-0.23}$ g/kWh, where n is the engine rpm. The Tier III NO_x limit is determined by: $9 \cdot n^{-0.2}$ g/kWh, where n is the engine rpm (Harmsen et al., 2020).

Engine material considerations

Both metals and elastomers (e.g. in seals and fuel lines) can be attacked by methanol, if chosen improperly. The polarity of methanol causes dry corrosion, but corrosion can be increased by ionic impurities in the fuel. Alcohol fuels, including methanol, can be extremely aggressive towards magnesium, aluminium and copper. Steel and other ferrous metals are only slightly affected by methanol. In practice, for components in frequent contact with methanol, often austenitic stainless steel is used or other metals coated with a zinc or nickel alloy. For high level methanol blends (or pure), alcohol compatible elastomer classes have to be used, in for example seals and fuel lines (Verhelst et al., 2019).

Cold starting with methanol

Cold starts with high level methanol blends or pure methanol are challenging due to its properties: the lower energy density requires more mass to evaporate to release the same amount of energy; the higher latent heat requires more energy to evaporate the methanol, which reduces the temperature; and its low stoichiometric air-to-fuel ratio results in a higher required vapour pressure to obtain a stoichiometric mixture. Furthermore, it is a single component fuel: there are no components in the mixture with different properties which could assist the ignition in cold starts. Methanol is also electrically conductive, which can cause short circuiting between spark electrodes if not all fuel has evaporated, as may be the case with cold starts. Compared to ethanol, methanol does however start much faster and easier and almost as quickly as gasoline. With noble metal spark plugs, methanol has a tendency to pre-ignite. This however, can be effectively eliminated with lower electrode temperatures (Verhelst et al., 2019).

2.5.2. Fuel cells

Next to internal combustion engines, fuel cells are also able to use methanol as fuel. The following fuel cell types are discussed in this section:

- Proton exchange membrane fuel cells (PEMFC)
- Direct methanol fuel cells (DMFC)
- Solid oxide fuel cells (SOFC)

Fuel cells are promising energy converters. Due to the absence of combustion in the energy conversion process, no NO_x, soot and SO_x is formed when used with methanol. Efficiencies are high, ranging from 40 to 60 percent for most fuel cell types. These efficiencies are expected to become even higher in the future. Currently fuel cells are not used that often in maritime applications, especially with higher power requirements that many ships have. This is related to the current pricing of fuel cells and their short lifetimes and service intervals making it a very expensive technology as well as the relatively low energy density (compared to ICEs). A big advantage of the fuel cell, especially for luxury yachts, is its silent operation as there are no moving parts in the FC which could cause vibrations through the ship.

A fuel cell converts the chemical energy in the fuel to electrical energy through an electrochemical reaction between fuel and oxygen (or another oxidising agent). A fuel cell consists of an anode and a cathode which are separated by an electrolyte (membrane), which only lets ions through. This creates a flow of electrons (i.e. an electrical current), from the anode to the cathode.

There are many different types of fuel cells, with Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC) being the most promising for the shipping industry (de Vries, 2019). In Table 2.5 an overview of different fuel cell types are given, with the most relevant properties. A few of the most relevant fuel cells for methanol are shortly discussed in the following sections.

Low Temperature Proton Exchange Membrane (LT-PEMFC)

Low temperature PEM fuel cells use hydrogen as fuel and operate between 50-100 °C. The temperature is required to remain below 100 °C, as the water based electrolyte needs to remain liquid. The use of methanol in a PEMFC requires the reforming of methanol to hydrogen, which can be done by a reformer. PEMFCs require a very high purity of the hydrogen (de Vries, 2019). The electrodes can be poisoned by carbon monoxide and sulphur, which reduces the efficiency of the FC. PEMFCs have a relatively high power density (Tronstad et al., 2017). A schematic overview of the PEMFC is given in Figure 2.5. In this figure one can see the flow of hydrogen ions and the flow of electrons through the electrolyte and from the anode to the cathode respectively.

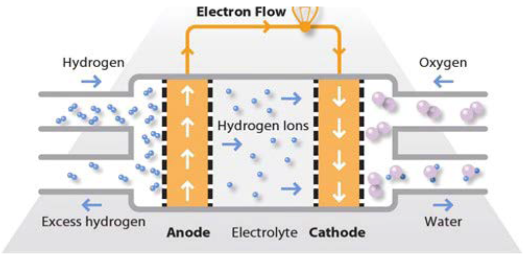


Figure 2.5: Schematic overview of the PEMFC. Figure from: Tronstad et al. (2017).

High Temperature Proton Exchange Membrane (HT-PEMFC)

HT-PEMFC operate similarly to their low temperature counterpart, but can operate at a higher temperature (up to 200 °C), because they do not use a water based electrolyte. The reaction and fuel are the same as that of the LT-PEMFC. The HT-PEMFC is less sensitive to CO and sulphur poisoning than the LT-PEMFC and has similar efficiencies. Due to the higher operating temperature however, it is possible to harvest some additional energy with a heat recovery system (Tronstad et al., 2017). The higher operating temperature also allows the internal reforming of methanol to hydrogen.

Table 2.5: Properties of different fuel cell types. Fuels that can be used are: hydrogen (H), high purity hydrogen (HP), methanol (M), LNG (L), diesel (D). FC sizes are: small (S), medium (M) and large (L). When a heat recovery system (HRS) can be used, the upper limit of the efficiency is achieved with HRS. References: 1 - Tronstad et al. (2017), 2 - Abderezzak (2018).

FC type	Operating temperature [°C]	Efficiency [%]	Fuel	Module power range [kW]	Size	Start-up time	Response time	lifetime [hr]	Ref
LT-PEMFC	50-100	50-60	H	Up to 120	S	Instantly	Very fast	8000	1,2
HT-PEMFC	<200	50-60	L, M, D, H	Up to 30	S				1
DMFC	50-120	20	M	Up to 5	S	Instantly	Very fast	-	1,2
SOFC	500-1000	60-85 (HRS)	L, M, D, H	20-60	M	Hours	Slow	>30000	1,2
AFC	20-90	50-60	HP	Up to 500	S	Minutes	Rel. quick	5000	1,2
PAFC	<200	40-80 (HRS)	L, M, D, H	100 - 400	L	1-3 hours	Very fast	>40000	1,2
MCFC	600-700	50-85 (HRS)	L, M, D, H	Up to 500	L	Hours	Size depending	>1000	1,2

An example of a HT-PEMFC is the H3 5000W made by SerEnergy. The fuel cell operates at 160 °C and produces 5 kW per module. The H3 unit has a built in methanol reformer, which reforms the methanol to hydrogen. The FC uses a mixture of 60% methanol and 40% water as fuel and reaches an efficiency of around 45% (between 10-70% of its output power) and around 42% (100% power) (Kildedal, 2019; SerEnergy, 2019). It has been used on the Viking Line Mariella for 90 kW auxiliary power (3x6 modules), and is also installed for providing 35 kW (7 modules) of propulsion power on the MS Innogy (Kildedal, 2019).

Direct Methanol Fuel Cell (DMFC)

A direct methanol fuel cell operates directly on methanol without first having to reform to hydrogen, due to the catalysts on the electrodes. This type of fuel cell is good for delivering small amounts of power over long durations (up to 5 kW). The DMFC operates between 50-120 °C. However, the efficiency is low compared to other FC types and methanol crossover is a major challenge (Tronstad et al., 2017). A schematic overview of the DMFC is given in Figure 2.6. Here one can see the methanol molecules transferring hydrogen ions through the electrolyte and exiting the fuel cell as carbon dioxide. The oxygen coming into the fuel cell reacts with the hydrogen ions to form water that exits the fuel cell. Due to the very limited amount of power that this type of fuel cell can deliver, it is not further considered in this research.

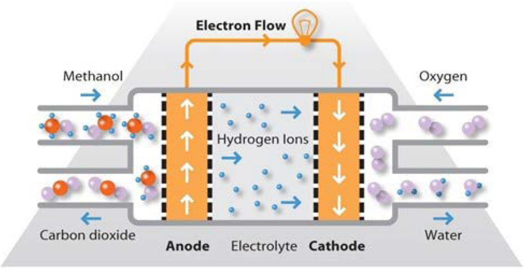


Figure 2.6: Schematic overview of the DMFC. Figure from: Tronstad et al. (2017).

Solid Oxide Fuel Cell (SOFC)

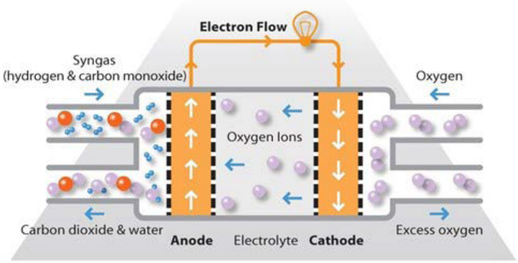


Figure 2.7: Schematic overview of the SOFC. Figure from: Tronstad et al. (2017).

Solid oxide fuel cells operate at high temperatures between 500-1,000 °C. This type of fuel cell has a large flexibility towards fuel choice. Hydrogen, LNG, methanol and even hydrocarbons such as diesel can be used as fuel for this fuel cell. Within the fuel cell, the fuel is reformed to syngas (H_2 and CO) through the high operating temperature. The solid oxide fuel cell has a high efficiency of around 60%, but this can be as high as 85% or higher if a heat recovery system is used (Tronstad et al., 2017). A schematic overview of the SOFC is given in Figure 2.7. In this figure the syngas that is formed by the high temperature in the SOFC enters the fuel cell, reacts with oxygen ions and exits the fuel cell as carbon dioxide and water. Oxygen enters the fuel cell at the cathode side to supply the needed oxygen ions. Excess oxygen exits the fuel cell on the cathode side. As the operating temperature of the SOFC is so high, the purity of the fuel is less important resulting in less decreases in efficiency caused by poisoning of the electrodes. The downside of this type of fuel cell is the slow reaction and start up time (see Table 2.5). This slow reaction time has a relatively small impact when the SOFCs are used to provide auxiliary power for a yacht, as this power demand is rather constant.

2.6. Literature review conclusion

The literature review covered a wide range of methanol related topics, which are summarised below:

- The density and energy content of methanol are lower than that of diesel, resulting in more methanol volume to contain an equal amount of energy.
- Safety aspects of methanol were also discussed, such as methanol vapour which is buoyant in air.
- Methanol can be produced from natural gas, coal, biomass and CO_2 combined with renewable electrolysis. Methanol produced from biomass and renewable CO_2 can lead to significant reductions in greenhouse gas emissions from well-to-wake.
- Methanol is globally available in most large ports.
- Methanol can be used in both internal combustion engines as in fuel cells. High temperature PEM fuel cells were found to be feasible for yachts next to internal combustion engines. Both energy converters are available, are being build and have efficiencies comparable to diesel internal combustion engines conventionally used on yachts.
- Fuel cells suffer from shorter lifetimes with a decreasing efficiency over its lifetime and from high capital costs.
- Methanol fuelled internal combustion engines were found to be on par with diesel engines in terms of costs and efficiency.
- The difference in emissions between methanol and diesel come primarily from the properties of the fuel itself, which results in slightly higher CO_2 emissions, no SO_x emissions and lower PM emissions for methanol.
- The NO_x emissions for methanol and diesel fuelled ICEs are comparable, but methanol ICEs do not require after treatment to meet the IMO Tier-III NO_x levels while diesel ICEs do.
- Only with fuel cells is a further reduction in NO_x and PM emissions possible. Fuel cells can also lower the overall emissions since their efficiency is slightly higher than that of ICEs. SOFCs are still in development and not found to be commercially available. When SOFCs become a feasible option, their properties can be added to the database and used in the design impact tool.

3

Regulational differences from diesel

There are many design aspects to consider when designing a yacht that uses methanol as fuel, which are different from a diesel yacht. Some aspects regarding the rules and regulations, such as inerting tanks with nitrogen and double walled piping, are too detailed and considered to have less impact on the design, for the level of detail in this research. However, other aspects such as the required cofferdams, the relatively large space the tanks use and which tank layouts are feasible all have a large impact on the design and on the results of the design tool. This chapter describes the cofferdam in more detail, which is a difference in rules & regulations between methanol and diesel that has the most impact on the design. In chapter 4 the implications of the cofferdam and its impact on the design of a yacht are discussed.

3.1. Cofferdams

Cofferdams are a required safety feature in the current rules and regulations. The function of a cofferdam is stated in the IMO CCC6 (2019) guidelines:

> 2.2.3.2 Cofferdam is a structural space surrounding a fuel tank which provides an added layer of gas and liquid tightness protection against external fire, toxic and flammable vapours between the fuel tank and other areas of the ship.

The primary function of a cofferdams therefore is to serve as a secondary gas and liquid tight barrier between the stored methanol and other spaces in the yacht, in order to prevent the contents of the fuel tank from spilling into another area that is not designed to safely contain methanol as a consequence of a single leak while also protecting the tank against external hazards such as a fire. A cofferdam is therefore an accepted solution to separate the methanol fuel tanks from other spaces. For most other spaces this cofferdam is required between methanol fuel tanks and most other spaces. An exception to this is when the methanol tanks are adjacent to the bottom shell plating or fuel preparation spaces (Lloyd's Register, 2019). In the more recent CCC6 guidelines (5.3.2) this exception has been extended to also include all shell plating below the lowest possible waterline and other fuel tanks containing methanol (IMO CCC6, 2019). It is most likely that this will be adopted by the classification societies.

The dimensions of the current cofferdams are determined by the accessibility of the cofferdam because they have to be able to be inspected by a person. IMO CCC6 (2019) states:

> 5.11.6 For safe access, horizontal hatches or openings to or within fuel tanks or surrounding cofferdams should have a minimum clear opening of 600 X 600 mm that also facilitates the hoisting of an injured person from the bottom of the tank/cofferdam. For access through vertical openings providing main passage through the length and breadth within fuel tanks and cofferdams, the minimum clear opening should not be less than 600 X 800 mm at a height of not more than 600 mm from bottom plating unless gratings or footholds are provided. Smaller openings may be accepted provided evacuation of an injured person from the bottom of the tank/cofferdam can be demonstrated.

In order to facilitate openings in the structure of the cofferdam of 600 by 600 mm horizontally and 600 by 800 mm vertically the cofferdam itself should be larger than these dimensions. Discussions with A. Speets (Specialist, Structural Engineering at De Voogt Naval Architects) resulted in the following practical consequences and guidelines for cofferdams construction on yachts:

- In longitudinal direction the cofferdams are preferably aligned with the yacht's frames and floors.
- In transverse direction the cofferdams are preferably aligned with the yacht's girders.
- For an opening of 600 by 600 mm, the width of the cofferdam should not be less than 700 to 750 mm. If the frame spacing is less, then the cofferdam should be two frames wide.
- If stiffeners are inside the cofferdam, there should at least be a clear width of 400 mm and clear height of 600 mm. For large stiffeners this may result in a larger width or height of the cofferdam. The height of the cofferdam will likely be around 800 mm.
- Including cofferdams inside the double bottom is unrealistic, especially for smaller yachts. Without cofferdam, the double bottom is already complex and small in terms of accessibility and construction. Adding a cofferdam of this size in the double bottom will significantly increase the constructional complexity and decrease accessibility.

From the points above, it is clear that the double bottom is not a feasible location for methanol tanks with cofferdams. Also, as the cofferdam is required between the fuel tank and other spaces, it is therefore required above the fuel tank which is where most of the volume in the double bottom is. This means that up to 40% and more of the volume in the double bottom is occupied by the cofferdam, depending on the height of the double bottom and shape of the hull. Therefore, the double bottom is not only unfeasible from a constructional point of view but also very inefficient from a volume point of view. Furthermore, a minimum width of 700 mm and a minimum height of 800 mm will be used in this thesis as dimensions of the cofferdam (see Table 4.1). Next to these dimensions, the double bottom will not be used as possible location for the methanol tanks in the design tool, as will be discussed further in 4.2.

Next to the dimensions of the cofferdam, there are several other requirements from IMO CCC6 (2019) of which a few relevant requirements are shortly highlighted below:

6.4.2 Cofferdams should be arranged either for purging or filling with water through a non-permanent connection. (...)

11.4.3 For fire integrity, the fuel tank boundaries should be separated from the machinery spaces of category-A and other rooms with high fire risks by a cofferdam of at least 600 mm, with insulation of not less than A-60 class.

13.3.12 Double bottoms, cofferdams, duct keels, pipe tunnels, hold spaces and other spaces where methyl/ethyl fuel may accumulate should be capable of being ventilated to ensure a safe environment when entry into the spaces is necessary.

15.3.2 Liquid leakage detection should be installed in the protective cofferdams surrounding the fuel tanks, in all ducts around fuel pipes, in fuel preparation spaces, and in other enclosed spaces containing single-walled fuel piping or other fuel equipment.

15.7.1.6 Permanently installed gas detectors should be fitted in cofferdams and fuel storage hold spaces surrounding fuel tanks.

Next to the IMO CCC6 guidelines, the rules for methanol fuelled ships from Lloyd's Register (2019) also contain relevant rules with respect to cofferdams, of which a few are stated below:

6.3.2 All tank connections, fittings, flanges and tank valves shall be enclosed in a cofferdam or a space meeting the requirements of a cofferdam.

6.4.1 Cofferdams or spaces meeting the requirements of cofferdams shall safely contain leakage from fuel tanks, tank connections, fittings, flanges and tank valves without this leakage spreading to other spaces.

6.4.3 Cofferdams shall be protected from external heat sources.

6.4.4 Cofferdams and pump rooms shall be considered hazardous and shall be arranged with continuous liquid and vapour detection. Liquid detection may be achieved through liquid level monitoring.

6.4.6 Cofferdams shall be provided with a suitable means of removing fuel.

8.4.1 A permanently-installed system of methanol vapour detection providing an alarm with an audible signal and visual indication shall be fitted in: all enclosed spaces containing fuel supply piping and equipment or consumers, e.g. machinery spaces, cofferdams, fuel processing rooms, valve rooms.

As can be seen in the rules stated above, there are several rules focused on the detection and containment of any possible leaks of methanol in both liquid and vapour states. This containment is also important because, as stated in 2.2.2 Methanol vapour, methanol vapour is near buoyant in air which complicates the process of forcing methanol vapour to a safe location where it does not form a risk to anyone. All in all, the cofferdam provides additional safety in the form of a secondary barrier surrounding the methanol tank. The cofferdam does however uses valuable interior space. This impact on the design and tank layout is further discussed in chapter 4.

4

Design impact of methanol

Using methanol as fuel has several implications for the design of a yacht. This is due to the properties of methanol itself but also due to the rules & regulations as discussed in chapter 3, which both differ from conventional diesel yachts. There are a number of factors that have a large impact on the design and on the results of the design impact tool. Therefore, the following items are discussed in this chapter:

- The cofferdam and an alternative to the cofferdam
- Possible tank layouts
- The impact of the large methanol volume and tank layouts
- Implications of this impact for the retrofitting case

These items that impact the design result in design considerations and choices made for the design tool and are further elaborated in this chapter.

4.1. Cofferdam design impact

With these rules & regulations and guidelines stated in 3.1 Cofferdams, the function and purpose of a cofferdam is clear. A cofferdam is a rather bulky safety measurement that provides an added layer of protection and containment between the fuel tanks and other spaces. As space is very valuable and scarce on board of yachts, having the required cofferdams in areas which could be used for other purposes is not very desirable (although cofferdams may be water filled and therefore have a double function but this shall then be specially considered in risk based studies). Therefore, an alternative solution that has an equivalent level of safety but requires less space than the current cofferdam may be very beneficial, especially in yachts. Such an alternative cofferdam, that deviates from current rules and regulations, may be approved through the risk-based design principle (Lloyd's Register, 2018). This will be discussed further in the next section (4.1.1 Alternative cofferdam design).

4.1.1. Alternative cofferdam design

As mentioned before, the current rules and regulations require a cofferdam surrounding the methanol containing fuel tanks. The size of the current cofferdam, that follows from the requirements (see 3.1 Cofferdams), is a large problem on yachts particularly and when considering refitting a yacht with methanol tanks. On large commercial vessels, the size of the cofferdam can be small compared to the dimensions of the ship. On yachts however, especially smaller yachts, the dimensions of the cofferdam can be relatively large and use valuable space and volume that could otherwise be used for accommodations or luxury area. An alternative, smaller, design of the cofferdam would be very beneficial and if the cofferdam is small enough may even allow the double bottom to still be used for fuel tanks. For designs that deviate from the existing rules and regulations, or for novel or complex designs where the current rules and regulations do not apply, a risk based technique can be used. This technique is described in the Lloyd's Register (2018) Risk Based Design document and requires a detailed risk assessment of

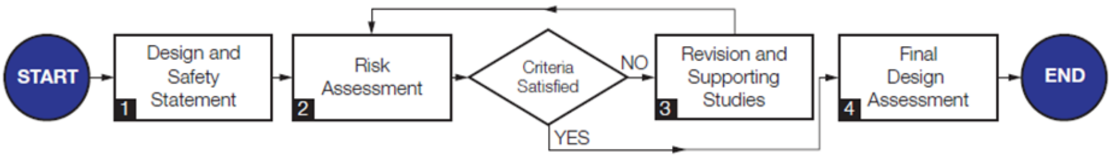


Figure 4.1: Process diagram of the generic process for risk based designs from Lloyd's Register (2018).

the design. Before accepting a risk based design, Lloyd's Register will have to be satisfied that the hazards of a technology or system are robustly identified and the immediate consequences are mitigated to an appropriate level. This comes down to the designer actively demonstrating equivalent safety as the rules and regulations from which is deviated. The generic process for risk based designs is shown in Figure 4.1. A complete risk based design assessment is not within the scope of this research. Nevertheless, it is interesting to assess the impact that an alternative cofferdam design could have on the design of a yacht.

The requirement that the cofferdam is required to be inspected from the inside by a person has the largest impact on the size of the cofferdam. If another solution for this can be found and the cofferdam would not have to be inspected by person, the size of the cofferdam could be greatly reduced. In the rules and regulations for the classification of ships using gases or other low flashpoint fuels (Lloyd's Register, 2020), it is stated that for LNG fuelled ships where the LNG is stored in type C independent tanks, no secondary barrier is required. The cryogenic type C tank that contains the LNG already has a secondary barrier (which also acts as insulation to maintain the low fuel temperature). Since the space between the inner and outer wall of the type C tank usually contains a vacuum space combined with insulating material, this space cannot be inspected by a person from the inside. The state of the tank is monitored by sensors within the tank and double wall. As methanol does not have to be stored at cryogenic temperatures and has a, although still low, higher flashpoint methanol may be considered less hazardous. A similar approach, where several methanol vapour and liquid detectors and other safety instruments are fitted inside the cofferdam, may therefore also be accepted for the cofferdams surrounding methanol tanks. These sensors would then allow similar capabilities of inspecting the state of the tank and cofferdam as the LNG type C tanks.

Next to the inspection and containment capabilities, the cofferdam should also protect the tank from external fires and other hazards. As required in the IMO CCC6 (2019) methanol guidelines, A-60 class fire protection is required in cofferdams. An A-60 class fire protection insulation is required to protect against cellulosic fires for at least 60 minutes. The thickness of A-60 fire protection generally varies from 20 to 60 mm, depending on the thermal insulation properties of the fire protection. This fire protection should fit within the alternative cofferdam while also providing enough room for tank connections, valves and sensors. Alternatively the connections to the tank and valves, which should be enclosed in a cofferdam (see rule 6.3.2 of the Lloyd's Register rules for methanol fuelled ships in 3.1 Cofferdams), may also be enclosed in a box that offers the same protection as a cofferdam in order to allow the rest of the cofferdam to be smaller than the valves and tank connections.

Structural feasibility of such a small cofferdam is also of importance. This cofferdam would have to be constructed on the outside of the tank which means that the methanol tanks would have to be located in a space which has enough clearance around the tank. This clearance reduces the effectiveness of the smaller cofferdam. Alternatively the cofferdams may be constructed first, after which the methanol tank is constructed from the inside. This may be a possible alternative since the methanol tank spaces are very large and give enough space for the construction of a tank. The cofferdams can then be constructed against the bulkheads (aft and in front of the tank) and the tanks can then be constructed against the cofferdams. Although there may be some possibilities for the construction of such a small cofferdam, this will definitely be a design challenge.

As the dimensions of the alternative cofferdam are of main interest in this thesis, a minimum width and height of 100 mm is assumed to be reasonable dimensions for the alternative cofferdam considering the aspects described above and is therefore used in this thesis (see Table 4.1). The main goal of

Table 4.1: Minimal dimensions of normal and alternative cofferdams.

Cofferdam type	Minimum length (mm)	Minimum width (mm)	Minimum height (mm)
Normal cofferdam	700	700	800
Alternative cofferdam	100	100	100

the alternative cofferdam is to show that the normal cofferdam uses a great amount of space which is particularly important on smaller yachts and to show what reduction of lost space an alternative cofferdam with much smaller dimensions could give. The alternative cofferdam is applied in the case studies of the yachts in chapter 8.

4.2. Available space and tank layouts

Space is extremely valuable on board of yachts, especially luxury area, as this is the space the client wants and pays for (Cozijnsen, 2019). Other areas such as technical areas and crew accommodations are supporting areas for the owner and guests and the functioning of the yacht. Therefore, any additional space required for the storage and conversion of energy results in an increase in technical area which, assuming the dimensions of the yacht remain constant, results in a decrease of luxury area. Other areas such as crew areas, which area generally close to technical areas, can also be influenced by an increase in technical area. However, as crew area is generally already minimised, the removal of crew area where it is required for fuel storage will likely result in the addition of crew area at another location where it will again result in a loss of luxury area. This means that the space and volume available for the storage of fuel is limited.

In the literature regarding methanol as fuel, the available volume for fuel is assumed to be equal to the fuel capacity installed on existing ships and yachts and cofferdams are not taken into account in the fuel capacity (Harmsen et al. (2020) for example). However, the installed fuel capacity on the original yacht was determined for a required range and range speed using MGO as a fuel. If a yacht is designed or refitted with methanol as fuel, the volume available for fuel storage is not necessarily equal to the volume that would be available (or installed) for the storage of MGO and other solutions may be found.

The fuel tanks of diesel yachts are usually located in the double bottom. Since the requirements of fuel tanks for methanol are different from diesel, both in terms of volume and in terms of rules & regulations, the arrangement and method of storage should be investigated. Therefore, this section contains:

- An analysis of possible tank layouts for existing Feadships.
- Principle tank layout options derived from this analysis.

In 4.2.1 an analysis of the 2D general arrangements (GAs) of three existing Feadships is done in order to investigate where space and volume is available and in which quantities, for the storage of methanol and what tank layouts are feasible. After the conclusions from the tank layout analysis of the existing yachts, the general idea behind the tank layout that is used in the design tool of this research is described in 4.2.2 Tank layout principle.

4.2.1. Possible methanol tank layout analysis of existing Feadships

Fuel on yachts is conventionally stored in the double bottom and sometimes in the wing tanks. Next to fuel, the double bottom generally contains tanks for fresh water, grey water and lubrication oil, as well as void spaces. On smaller yachts there are usually less voids, but on larger yachts the voids may contribute to a significant part of the double bottom. Whether the yacht has a low or high maximum speed also has an influence on the available hull volume for fuel, since a higher top speed results in a larger technical area (e.g. engine room) for a yacht of the same GT. If the engine room is larger, the volume left in the hull for tanks becomes smaller if other areas remain constant.

To determine which volumes in the hull are available for possible storage of methanol and what tank layouts may be feasible, the GA (general arrangement) drawings of three yachts are analysed in detail. Here a feasible tank layout is one which stores methanol effectively and is possible (and realistic) in terms of construction, arrangement and stability. In order to determine feasible tank layouts that could

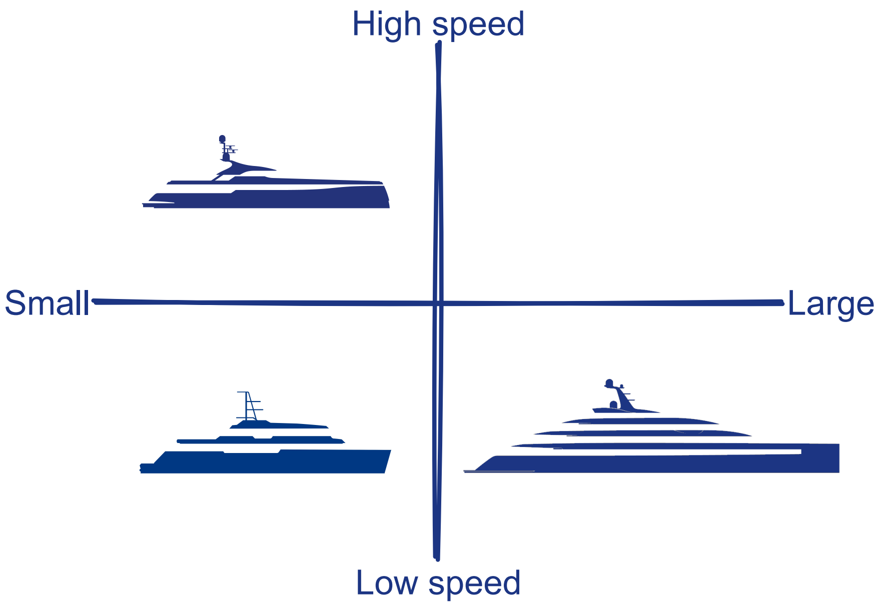


Figure 4.2: Yacht analysis matrix showing the two categories: size and maximum speed.

be applied to a wide range of yachts, the yachts which are analysed have different characteristics. Two categories considered to have an influence on the available volume and tank layouts are maximum speed and size, where a large yacht is longer than 70m and a fast yacht has a Froude number higher than 0.4 at its maximum speed. The two categories result in four possible combinations as can be seen in Figure 4.2. The maximum speed is considered to be of main influence for small yachts particularly because small yachts already have limited space available with a lower maximum speed. In large yachts, the maximum speed is considered to have a smaller impact as there is generally much more space available. Therefore, three yachts are analysed in the next sections:

- A large low speed yacht
- A small low speed yacht
- A small high speed yacht

For each yacht, two tank layouts are drawn in the GA and the achieved methanol volume is determined. The tank layouts are a double bottom tank layout and a single or two tank layout. Since the drawings are 2-dimensional, the exact tank volume cannot be determined. Instead, the volume has to be estimated by using the cross sectional areas of the tanks at several frames to approximate the average tank cross sectional area, which can then be multiplied by the length of the tank to find an approximate tank volume. In the creation of tank layouts one important aspect of the current regulations is incorporated. Of the current regulations, the cofferdam is considered to have the largest impact on the general arrangement and tank layout. The rules and regulations require a cofferdam where the methanol tank is not adjacent to the shell plating below the (lowest possible) waterline, another methanol tank or the fuel preparation space, as described in 3.1 Cofferdams. The minimal dimensions of the cofferdams are shown in Table 4.1, where the normal cofferdam dimensions are used in this analysis.

To assess the quality of a tank layout, a usage factor is defined in Equation 4.1. This is the factor of methanol volume in the total volume of the tank construction which includes the cofferdam.

$$f_{usage} = \frac{V_{methanol}}{V_{methanol} + V_{cofferdam}} \tag{4.1}$$

A high usage factor indicates an efficient tank layout because a relatively small amount of the volume is used by the cofferdam and a large amount of volume is occupied by the fuel tank itself. It is however, important to keep in mind that the usage factor is purely a geometric volume factor. No practical construction aspects are included in this factor. Therefore, it is very well possible that a tank layout with a nonzero usage factor is in reality not feasible to construct. This would mean that the actual usage factor of one of the tank layouts could be 0, particularly for methanol tanks in the double bottom.

Large low speed yacht

The yacht analysed in the large and low speed yacht category has waterline length of around 100 m and a Froude number at maximum speed around 0.3. This yacht has a frame spacing that is larger than the minimum cofferdam length. This allows the cofferdam to span a single frame length. This large yacht has a high double bottom. Through a range calculation (see 5.1.5 Required fuel capacity) it was determined that over 800 m^3 of methanol is required to maintain the range at the original range speed. Two tank layouts are drawn in order to analyse feasible tank layouts, which are described below.

Tank layout 1 | Double bottom: Because the required methanol volume is high, a first tank layout was drawn in the 2D drawings to determine the volume available in the double bottom (including wing tanks that have a higher tank top height than the double bottom) if it was used entirely for methanol fuel tanks and cofferdams. The total volume of methanol that could be stored in the double bottom (including wing tanks) was estimated to be approximately 730 m^3. By adding a methanol tank inside the engine room of around 110 m^3, a total of 840 m^3 was achieved. While this layout makes optimal use of the shell plating below the waterline (and thereby not requiring a cofferdam other than in front, aft and above the methanol tanks), the double bottom is not very efficient in storing fuel because of the curved hull and deadrise angle. A very large part of the double bottom volume is consumed by the required cofferdam separating the tank top and the methanol tank. Because the entire double bottom is used by methanol tanks (and cofferdams) in this layout, other volumes have to be used for other tanks such as water and lubrication oil tanks. Another disadvantage is the constructional difficulty. The double bottom is a curved and confined space which may make it difficult to construct a cofferdam inside.

Tank layout 2 | Two tanks: A second layout, that is considered easier to construct, includes tanks that span several frame lengths in the longitudinal direction, span the entire width of the yacht and have a height up to the (lowest possible) waterline. The methanol tanks are surrounded by cofferdams on top, fore and aft of the tank. This layout consists of two of these large tanks. With two large tanks, one around midship and one in the aft, the required methanol tank volume can be achieved. By using two larger tanks, the methanol can be stored more efficient than in the double bottom. This layout is also considered to be easier to construct. With a single large tank, the usage percentage would be the highest, compared to a layout with two (or more) tanks. This is because each tank has to be fully surrounded by cofferdams (except for shell plating below the lowest possible waterline).

The usage factors resulting from the tank layouts are shown in Table 4.2.

Small low speed yacht

The yacht in the small and low speed category has a waterline length of around 50 m and a Froude number at maximum speed around 0.3. This yacht has a frame spacing that is smaller than the minimum cofferdam length. This requires the cofferdam to span two frame lengths. The double bottom height in the small yacht is lower than that of the large yacht. Through a range calculation (see 5.1.5 Required fuel capacity) it was determined that around 200 m^3 of methanol is required to maintain the range at the original range speed.

Tank layout 1 | Double bottom: For this small yacht, the volume in the double bottom was also determined. Because of the much lower double bottom, the cofferdams use a relatively high fraction of the volume (compared to the large yacht). With the cofferdams included, only around 20 m^3 of methanol tank volume could be realised in the double bottom, which is only around 10% of the required methanol volume.

Tank layout 2 | Two tanks: The second layout consists of two larger tanks, one around midship and one close to the aft of the yacht. The tanks again span several frame lengths, span the full width and a height up to the waterline, as described in the second tank layout of the Large low speed yacht. With this layout, the required methanol volume can be reached.

The usage factors resulting from the tank layouts of the small low speed yacht are shown in Table 4.2.

Small high speed yacht

The yacht in this category has a waterline length of approximately 45 m and a Froude number at maximum speed around 0.65. The frame spacing of this yacht is equal to the minimum cofferdam length, which requires the cofferdam to span one frame length. The double bottom height in this small yacht is lower than that of the large yacht. Next to the lower double bottom height, the double bottom does not span the entire length of the yacht. Through a range calculation (see 5.1.5 Required fuel capacity) it is determined that around 40 m^3 of methanol was required to maintain the range at the original range speed.

Tank layout 1 | Double bottom: For this small yacht, the volume in the double bottom was also determined. Because of the much lower double bottom which does not span the entire length of the yacht, the cofferdams use a relatively high fraction of the volume (compared to the large yacht). With the cofferdams included, only around 25 m^3 of methanol tank volume could be realised in the double bottom. This would mean that all other non-fuel tanks have to be relocated and results in a decrease in range or range speed.

Tank layout 2 | Single tank: As this high speed yacht has a waterjet, it is not feasible to locate a methanol tank around the aft of the yacht. Therefore this layout consists of only a single tank around the midship. The yacht is designed for a high maximum speed and therefore has a low draft. Therefore, the height of the double bottom is lower than for most yachts. In order to create a larger tank volume, the height of the tank has to be increased to above the waterline which then requires cofferdams at both sides of the tank (next to the cofferdams on top, in front and aft of the tank). This increases the complexity of the tank construction. If the height of the tank (including cofferdam) is increased to the height of the deck above, only a few frame lengths are required to reach the required methanol capacity.

The usage factors resulting from the tank layouts of the small high speed yacht are shown in Table 4.2.

Methanol tank layout conclusions

From the analysis of the general arrangements, designing several tank layouts and the resulting usage factors (see Table 4.2) some conclusions can be drawn. The first conclusion is that, with the current cofferdam dimensions, the double bottom is not a feasible location for methanol tanks, for all but the largest yachts. This is because a cofferdam is required in the location where most of the volume is in the double bottom. Next to the limited volume available for methanol tanks, the construction of the tanks and cofferdams inside the double bottom is believed to be rather difficult (see 3.1 Cofferdams).

The second conclusion that can be drawn from this analysis is that one to a few larger tanks spanning several frame lengths, the entire width of the yacht and with a height up to the lowest possible waterline (or possibly above the waterline for yachts with a very small draft) are more volume efficient (i.e. a higher methanol volume to total volume ratio). These layouts are also considered to be easier to construct than tanks and cofferdams in the double bottom only. The downside of this layout is that a significant part of the tank deck has to be sacrificed, which is where technical or crew areas usually are located. Next to that, tank volume that is conventionally located within the double bottom is now relocated to the larger tanks which are largely not in the double bottom. This leaves the double bottom emptier than usually and raises the centre of gravity of the fuel tanks.

Table 4.2: Methanol tank usage factor of the tank layouts according to Equation 4.1 for three Feadships.

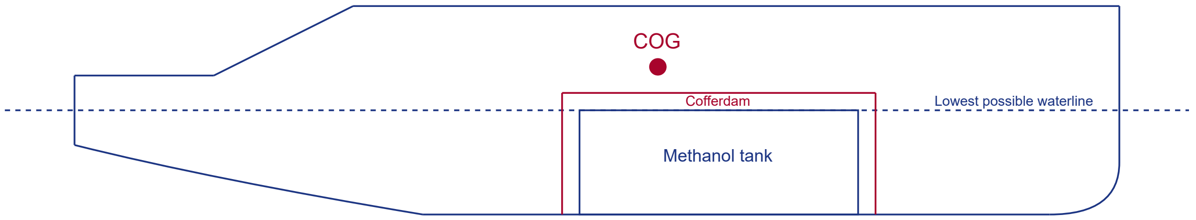
Tank layout	f_{usage} Large low speed yacht	f_{usage} Small low speed yacht	f_{usage} Small high speed yacht
Double bottom tanks	0.48^a	0.20^a	0.25^a
Midship tank	-	-	0.50
Midship & aft tanks	0.65	0.55	-

^{a} Usage factor only for the part of the required volume that fits in the double bottom. See the descriptions of the tank layouts of the different yachts.

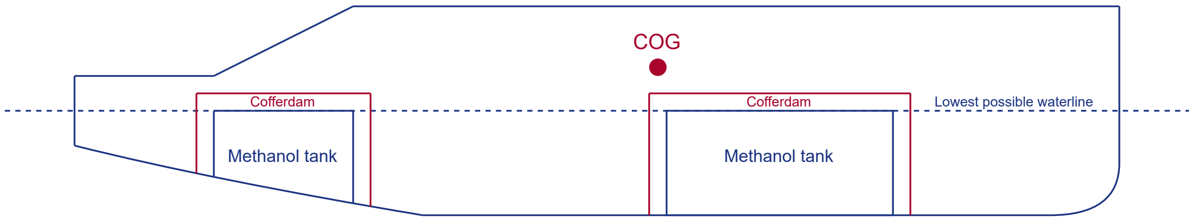
4.2.2. Tank layout principle

The process of designing a tank arrangement is of course an iterative design process done by a naval architect. However, from the conclusions of the tank layout analysis (see 4.2.1 Methanol tank layout conclusions) a few guidelines for the principle design solution of the methanol tanks can be determined. Not only the construction of a methanol tank in the double bottom is complicated and not really feasible but the double bottom is also a highly inefficient location to place the methanol tanks. The principle design solution is to only design tanks that have a height up to the lowest possible waterline. This relocates the required cofferdams on top of the tank from inside the double bottom to the top of the tank, which height is up to the waterline for most yachts. This allows the tanks to be higher and adjacent to more shell plating (below the waterline) and therefore more methanol volume can be stored (for a tank of equal length) relative to the volume used by cofferdams. This tank layout principle is shown schematically in Figure 4.3.

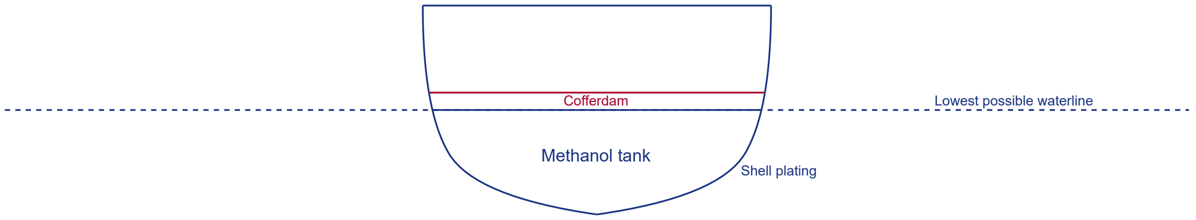
From the second conclusion of the analysis, it can be derived that a small amount of separate tanks is more favourable than a high amount of separate tanks because each individual tank that is not next to the shell plating or another methanol tank is required to have cofferdams on all sides. With each separate tank (i.e. not adjacent to another methanol tank) added, the volume efficiency of the storage of methanol becomes lower and relatively more volume is lost to the cofferdams. Therefore, the amount of separate tanks is kept to a minimum in the design tool. From a volume efficiency standpoint, it is desirable to have only a single large tank (which is of course divided into smaller tanks for trim and free surface effect reasons). In order for such as large tank to have minimal impact on the trim of the yacht, the tank's COG (centre of gravity) should be as close to the COG of the yacht as possible. As one single cluster of tanks decreases the trimming capabilities, a single tank is not a good solution when the tank cannot be placed close to the COG of the yacht. For most yachts, the engine room is often located around the centre of the yacht or slightly aft of the centre. As a consequence, the central



(a) Central methanol tank with cofferdams.



(b) Central and aft methanol tanks with cofferdams.



(c) Transverse cross section of a methanol tank.

Figure 4.3: Schematic representation of the tank layout principle with one and two methanol tanks, as well as a cross section.

methanol tank is located in front of the engine room and likely slightly in front of the COG of the yacht. To account for this situation, a second tank can be located more aft in the yacht (i.e. a location between the aft of the yacht and the engine room). This double tank layout offers a greater ability to adjust the yacht's trim in different load cases. The actual effect on trim and tank volume efficiency of designing a yacht with one or two tanks is investigated in chapter 8 Case study.

To summarise, the principle tank layout and design consists of the following guidelines (see Figure 4.3):

- The tank arrangement consists of one or two large methanol tanks (divided into smaller tanks).
- The tanks are surrounded by cofferdams on all sides except when the tank is adjacent to the shell plating below the lowest possible waterline or another methanol tank.
- The tanks are adjacent to the shell plating below the waterline, except for the fore and aft ends of the tank and the top of the tank. Therefore, the tanks span from the keel to the lowest possible waterline in terms of height. This way, optimal use is made of the fact that no cofferdam is required between the methanol tank and the shell plating.
- In the case of one large tank, the tank is located as close to the COG of the yacht as the arrangement allows (or the arrangement can be adjusted to the location of the tank).
- In the case of two large tanks, the fore tank (which is usually larger) is located in front of the COG of the yacht but still as close to it as the arrangement allows. The somewhat smaller aft tank is located aft of the COG of the yacht in a location that gives enough trimming capabilities (and is in a favourable location for the GA).

4.3. Impact of the large volume and tank layout

Methanol tanks are considerably larger in volume than conventional diesel tanks. This is a direct consequence of the physical properties of methanol (see Table 2.1) and of the rules & regulations (see 3 Regulational differences from diesel). Combine this with the fact that the double bottom is generally not suitable for methanol storage (as is discussed earlier this chapter), this results in quite a large volume that has to be placed elsewhere (largely outside the double bottom). This impact is discussed in this section and is not equal for the two categories considered in the main research question:

- New yacht designs
- Retrofitting existing yachts

The impact of the large methanol tanks on the design of a yacht can be reduced by reducing the required fuel volume (and therefore the size of the tanks) or by increasing the available space in the yacht. The latter option is significantly more challenging for existing yachts and is therefore discussed separately from new yachts. The following three options are discussed in the next sections:

- Reducing the required fuel volume for both categories
- Increasing the available space for new yachts
- Increasing the available space for existing yachts

4.3.1. Reducing the required fuel volume

For both categories, to reduce the size of the methanol tanks one could decrease the required range, range speed or a combination of the two. However, this will leave a considerable tank volume that is most likely still larger than the diesel volume. More importantly, a decrease in range is highly undesirable. Diesel is widely available throughout the world but the availability of alternative fuels, such as methanol (but also others), is currently much more limited (see Figure 2.3). Methanol is mostly available in larger ports, which can be problematic as superyachts often sail to natural heritage sites or popular tourist destinations which can be in more remote locations. The combination of a lower availability, smaller range and more remote destinations is therefore not a very good one. When an owner or future owner of a yacht considers an alternative fuel with the intention to reduce the environmental footprint of the yacht, he or she may not want to be limited in that way. Unless the availability of one or more alternative fuels becomes much better in the future, decreasing the range is not desirable.

4.3.2. Increasing the available space for new yachts

A future owner of a superyacht is buying interior space packaged in the shape of a yacht. When an alternative fuel such as methanol is considered, it is desirable to keep the interior space equal in order to deliver a comparable package to the owner. This way the value of the yacht to the owner is not decreased by a loss in interior space. To keep the interior space equal, the additional increase in space required for the methanol systems (as compared to a diesel yacht) can be compensated by an increase in the dimensions of the yacht. The option to increase the dimensions of the yacht is considered to be a more attractive and more realistic option for new designs than for existing yachts (see 4.3.3). Increasing the breadth or depth of the yacht has an impact on the roll stability of the yacht, which may or may not be an issue. Increasing the length of the yacht has a much smaller impact on roll stability, assuming that the draught does not change, as well as not changing much to other areas of the yacht which would be the case if the breadth of the entire yacht would be increased. This last point is especially beneficial if an interior design already has been made.

Increasing the length also has a small influence on resistance, reducing the wave making resistance while increasing the frictional resistance. This results in slightly less propulsion power required at high speed, while increasing the power demand at low speeds. However, the impact on resistance is less relevant than the impact on the design of the yacht. The auxiliary power will stay approximately the same since the interior area and volume, on which the auxiliary power primarily depends, remains equal.

For a new yacht, increasing the length is not a physical constructional task but only impacts the design and naval architecture side. Next to that, it is not uncommon for a yacht's length to increase during the design phase (up to the contract design). Therefore, there are no costs associated with increasing the length of a new yacht.

All in all, increasing the length to compensate for the area lost by methanol systems is considered applicable for new designs. Such a length increase has been illustrated in Figure 5.3 and is used in the design impact tool (see 5.2.5 Length increase calculation).

4.3.3. Increasing the available space for existing yachts

As with a new design, the dimensions of an existing yacht can be increased to compensate for the volume of the methanol system and keep the interior space equal. For refitting one might argue that increasing the length by adding a midship section could be the most effective and least complicated method with the smallest impact on the yacht, as this does not have such a large impact on the rest of the yacht and its interior compared to increasing the breadth for example. If the breadth of the yacht is increased, this would have to be done over the entire length of the yacht and not just a small section. Increasing the length could technically be possible. There are however significant drawbacks in terms of design impact and in terms of costs.

In terms of design, the impact of increasing the length is large because of several reasons:

- Adding a midship section does not only impact the hull but also the superstructure as the yacht's length is increased at a location where the superstructure is.
- The length is most likely not increased by the full length of the methanol tank(s), which means that crew or technical area has to be relocated from the original location (where the methanol tank is placed) to a another.
- The interior design has to be adapted to the added few metres of length. The relocation of the area where the methanol tank is placed requires at least a few changes to the GA and may trigger a whole series of small (or large) changes throughout the entire yacht from the technical and crew areas to the luxury areas.

In terms of costs, the impact of increasing the length is large because of the following reasons:

- Docking time will likely be rather long, compared to a normal refit, due to the many changes that are required to the yacht. A longer docking time will increase the costs of the retrofit.

- Construction of the midship section, separating the yacht in two parts and adding the midship section all require a significant amount of labour and will result in high costs.
- Removing part of the interior around where the section is added, removing interior where the methanol tanks are going to be installed as well as other areas that are impacted due to required changes in the GA again require a significant amount of labour.
- Construction of methanol tanks and cofferdams in the hull can be a complex task. Not only is there not a lot of space for the workers to construct the tanks and cofferdams, there may also be significant changes to the original hull required (e.g. moving bulkheads, girders or tanktops) in order to make space for the tanks.
- All fuel piping needs to be replaced with double walled piping. Next to that, a inerting system needs to be installed to be able to inert the piping, tanks and cofferdams, as well as other changes that may be required by the rules & regulations.

Considering the stated design and cost impact, increasing the length of an existing yacht is not as feasible as for a new yacht design as there are many additional aspects to consider compared to a new yacht. The magnitude of the impact of the aspects stated above on the design and costs is not known, however this impact is likely very large. Especially the costs associated with increasing the length are likely very high. Unless the owner is absolutely determined to retrofit the yacht to a methanol fuelled system and can accept the high costs, it is probably not the best solution. Therefore, increasing the length is not considered an option for existing yachts in this research and in the methanol impact tool.

4.4. Evaluating the retrofitting option

A great amount of arguments why the impact on design and costs of retrofitting is large (as stated in the previous section, see 4.3.3) are not specific to the increase of length of the yacht. These arguments also hold for retrofitting a yacht to a methanol fuelled system in general. When an existing yacht is retrofitted to methanol but the length of the yacht is not increased this has other implications for the design and costs.

In terms of design impact, installing the methanol tanks and cofferdams always use more space than diesel tanks (with the tank layouts discussed in 4.2.2). If the length is increased there is no net loss of interior space but the GA still needs to be rearranged slightly. If the length is not increased, a significant amount of interior space is lost to the tanks. This interior space is usually occupied by technical and crew areas and have to be relocated, as they are usually indispensable areas. This means that installing a methanol system eventually comes at the cost of luxury area. Whether the length is increased or not, both result in significant changes to the design and GA.

In terms of the impact on costs, retrofitting to a methanol fuelled system will also result in quite some docking time when the length of the yacht is not increased as this also requires significant changes to the interior and the hull at the location of the methanol tanks. The docking time will likely be shorter than when the length is increased. Without the length increase there is still a large amount of interior space that needs to be removed and constructed elsewhere in the yacht in order to construct the methanol tanks and cofferdams. As required by the rules & regulations, all fuel piping needs to be replaced by double walled piping and an inerting system needs to be added. All these changes add to the cost of the retrofit.

In conclusion it can be stated that the impact of retrofitting to a methanol fuelled system on the design and costs for existing yachts is large, which raises the question whether retrofitting is actually a good option with methanol. Not only would the costs of such a retrofit likely be very high, the impact on the design (GA) of the yacht itself will be vast. Therefore, retrofitting yachts with methanol is not considered to be a feasible option with the tank layouts considered in this research. Retrofitting yachts with methanol may become a better option if a more compact solution is found (and accepted by classification societies) for the cofferdam that would allow the methanol tanks to be placed in the double bottom. However, as this is currently not the case, retrofitting existing yachts with methanol is not included in the case study of this research.

4.5. Design impact conclusion

The impact of several methanol related factors on the design of a yacht was assessed in this chapter. The cofferdam required by the rules & regulations takes up a significant amount of volume. Therefore, an alternative cofferdam design was discussed that has smaller minimum dimensions.

The general arrangements of three existing Feadships were analysed in order to determine the amount of space that is available for methanol tanks and the required cofferdams. To do this, two tank layouts were drawn in the GAs of the yachts: a double bottom layout and a layout with a single or two large tanks. It became clear the the double bottom is not a feasible location for methanol tanks, especially on smaller yachts. It was also found that the cofferdams required by the rules and regulations have a large impact on what principle tank layouts are feasible. The cofferdams are relatively large compared to the tanks, particularly for smaller yachts. Therefore, it is desirable to keep the amount and size of cofferdams to a minimum. This can be done by keeping the amount of separate tanks to one or two, and by making optimal use of the shell plating below the lowest possible waterline. The methanol tanks have to be increased in height up to the lowest possible waterline in order to be effective and feasible.

By using methanol as fuel, the required fuel volume to achieve a certain range is also larger than with diesel. As the methanol tank layouts consist of one or two large tanks surrounded by cofferdams which cannot be placed in the double bottom only, they use interior space which is valuable. It is argued that decreasing the range is not desirable in light of the global availability and the general sailing areas of superyachts. Therefore, to keep the interior area of the yacht equal, the dimensions of the yacht can be increased for new yachts. For refitting, this is not considered a good option and the impact of methanol in terms of design and costs are both very large. Therefore, methanol is considered to be currently unsuitable for retrofitting existing yachts.

5

Design impact tool

The impact of using methanol on a yacht consists of the impact on the design, emissions and costs. The properties of the yacht have to be processed to get the required output to determine this impact. For this processing of the yacht's properties a design impact tool is required. The properties of the fuel storage, such as the required methanol volume and the way in which this volume is stored within the boundaries of the yacht, but also the propulsion and auxiliary power have to be determined from the input. This information can then be used to determine the impact on the design and to calculate the emissions and costs. With the design impact tool and the resulting emissions and costs, several pathways are researched in chapter 8. The validation of the design tool is presented in chapter 6.

The design tool is intended to be used by a researcher or design specialist. With the tool, the researcher or design specialist can assess what the impact of switching to methanol as fuel would be for one or more designs. With the help of the design tool the design specialist can assess what the impact of methanol is on the design, emissions and costs when asked to investigate this for a new (concept) design, a variation on an existing design or for an already existing yacht. A researcher on the other hand could potentially use the tool to asses the impact on costs and emissions for a range of yachts and to determine pathways for the future.

The design tool is developed to comply with the design requirements, as presented in 1.3 Research objective. The tool consists of 4 major modules: power & energy, available space, emissions and costs. These modules and their subcomponents are discussed in detail in this chapter. A schematic representation of the design impact tool can be seen in Figure 5.1. Next to the four modules, the input, database, output, options and the length increase iteration are also shown in this figure. Several design choices made in the tool are discussed in the previous chapter 3. In this chapter, the different modules

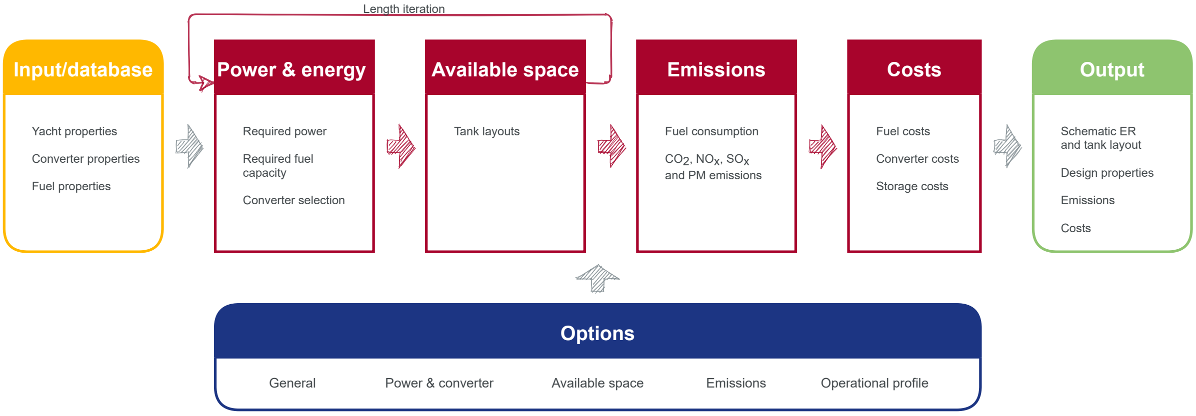


Figure 5.1: Schematic overview of the design impact tool.

are discussed:

Input processing:

- Power & energy - Required propulsion power
- Power & energy - Required auxiliary power
- Power & energy - Converter selection
- Power & energy - Fuel selection
- Power & energy - Required fuel capacity
- Available space - Tank layouts
- Available space - Length increase

Output generation:

- Emissions - Total fuel consumption
- Emissions - CO_2 emissions
- Emissions - NO_x, SO_x and PM emissions
- Costs - Fuel costs
- Costs - Converter costs
- Costs - Fuel storage costs

All parameters of the design tool, which can be changed, are shown in Appendix C. The yacht specific parameters are shown in Table C.2, the converter parameters from the database are shown in Table C.3, the fuel parameters from the database are shown in Table C.1 and the design tool parameters and options are shown in Table C.4.

5.1. Power and fuel capacity requirements

In order to determine the impact of methanol on a yacht, the required power and fuel capacity are required in order to determine the energy converters and fuel consumption. With these properties the impact on costs and emissions can then be determined. To do this, the power demand is split into propulsive power and auxiliary power and the required fuel capacity is determined through a range calculation. It is assumed that the propulsion power and auxiliary power are supplied by different energy converters, as is common in yachts (main engines for propulsion and separate generator sets for auxiliary power). The methods to determine the following properties are discussed in this section:

- Required propulsion power
- Required auxiliary power
- Converter selection
- Fuel selection
- Required fuel capacity

5.1.1. Required propulsion power

In order for the design impact tool to be usable in a wide range of design stages, it is desirable to be able to determine the propulsion power through multiple methods. First, the resistance of the hull has to be determined. The resistance can be determined in an early design stage through the Holtrop & Mennen method, which is discussed further in Holtrop & Mennen resistance prediction method. The resistance can also be determined through model towing tests and CFD calculations, which are both more accurate than the Holtrop & Mennen resistance calculation. Further in the design process a CFD resistance calculation is usually performed. As both the model tests and CFD calculations are outside the scope of this research, an option is added to the design tool to manually enter the yachts resistance at different ship speeds if they are known through other methods.

If the required propulsion power is known, the energy converter has to be determined to deliver this power. This process is elaborated on in 5.1.3 Converter selection.

Holtrop & Mennen resistance prediction method

The Holtrop & Mennen resistance prediction method was first published in 1978 and updated in 1982 (Holtrop and Mennen, 1982). This method is based on regression analysis of model experiments and full scale data. The method is useful to estimate the resistance (and propulsion power) with a limited amount of parameters available that describe the shape of the hull.

For predicting the hull resistance, the Holtrop & Mennen method requires the parameters shown in Table 5.1. With the required parameters, an estimate for the resistance can then be calculated. An example of a Holtrop & Mennen propulsion power estimate is shown in Figure 5.2.

Table 5.1: Required parameters for the Holtrop & Mennen resistance prediction method.

Parameter	Unit	Description
L_{WL}	m	Length of the waterline
B_{WL}	m	Breadth at the waterline
T	m	Draft
Δ	m^3	Displaced volume
C_M	-	Midship coefficient $({}^{A_m}/_{B_{wl}\cdot T})$
C_{WP}	-	Waterplane area coefficient $({}^{A_{wp}}/_{L_{wl}\cdot B_{wl}})$
A_T	m^2	Immersed transom area
$A_{B,T}$	m^2	Bulb transverse area (if present)
h_B	m	Centre of bulb area above keel line (if present)
lcb	%	Longitudinal centre of buoyancy (% of L_{wl} forward of ${}^{L_{wl}}/_2$)
n_{bt}	-	Number of bow thrusters
D_{bt}	m	Bow thruster tunnel diameter
D_p	m	Propeller diameter
Z_p	-	Number of propeller blades
P/D	-	Pitch/diameter ratio of the propeller
Afterbody	-	Shape of the afterbody (Pram, Normal, V-shaped, U-shaped)
Appendages	-	The surface areas of appendages

Propulsion power calculation

With the estimated or entered resistances, the required propulsion power can be determined at different speeds. Although there are some yachts that have diesel-electric propulsion systems, most have diesel-direct propulsion systems. With a direct drive, the required propulsion power can be calculated according to Equation 5.1 (Klein Woud and Stapersma, 2003).

$$P_b = R_t \cdot SM \cdot \eta_H \cdot \eta_O \cdot \eta_R \cdot \eta_S \cdot \eta_{trm} \cdot \frac{1}{MCR} \cdot v \qquad (5.1)$$

Where P_b is the break power (required) (W), R_t is the ships total resistance (N), SM is the sea margin, η_H the hull efficiency ($\eta_H = {}^{1-t}/_{1-w}$, from Holtrop & Mennen), η_O the propeller open water efficiency, η_R the relative rotative efficiency (from Holtrop & Mennen), η_S the mechanical shaft efficiency, η_{TRM} the transmission (gearbox) efficiency, MCR the maximum continuous rating of the converter and v the ship speed in m/s. The values of these constants are shown in Table 5.2. As can be seen in this table, there are different sea margins. The resistance (and power) at maximum speed in calm water conditions is usually used to determine the power and number of main engines (i.e. a sea margin of 1.0). For the range calculation, or fuel volume required calculation, a 10% margin on the break power is added (Schouten, 2017). In all other calculations, such as the yearly fuel consumption, a slightly higher sea margin of 1.15 is used to account for non-ideal conditions Magnussen (2017). The MCR constant is usually 1.0 because the power of the converters in the database are given in continuous power.

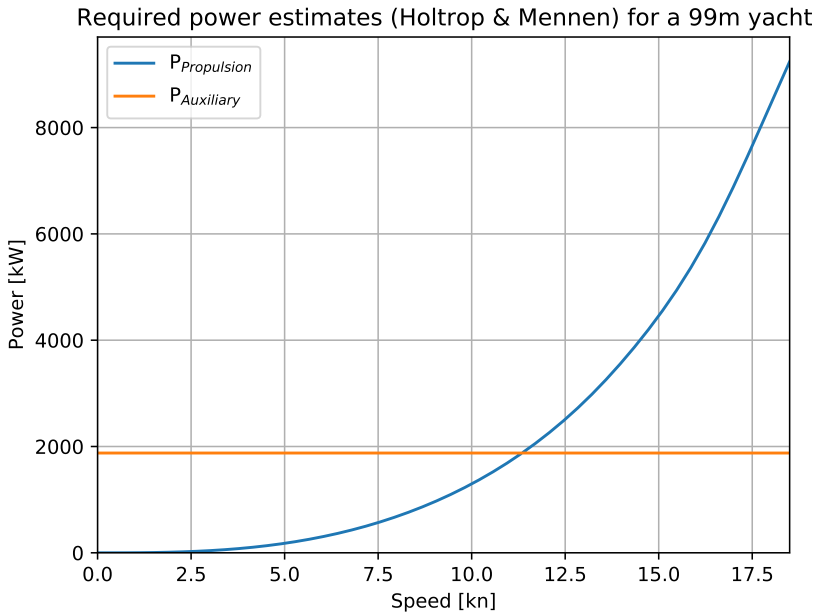


Figure 5.2: Example of required power estimates for propulsion and auxiliary power for a 99m yacht. The propulsion power is determined from the parameters of Table 5.1, the auxiliary power is estimated from the gross tonnage of the yacht (described in 5.1.2 Required auxiliary power).

The power for propulsion can also be partially generated by fuel cells. The power required for propulsion is generally too high to be fully delivered by fuel cells as they require much more space than ICEs and such a large amount of fuel cells would be very expensive. If this option is desired, a speed up to which the fuel cells should provide propulsion power, in addition to providing auxiliary power, is used to determine the required power through Holtrop & Mennen for the fuel cells. This fuel cell power for propulsion (not auxiliary FC power) is then subtracted from the propulsion power for the main engines, which may lead to less powerful or fewer main engines that are required.

In order to determine the fuel consumed in a year for propulsion of the yacht, the propulsion power in different operations in the operational profile has to be known (see 5.4.2 Total fuel consumption). With the speeds associated with the different operations in the operational profile, the resistance and thereby the propulsion power can be determined with the Holtrop & Mennen method. As mentioned before, in these calculations a sea margin of 1.15 is used.

Table 5.2: Constants used in the propulsion power, range and fuel consumption calculations. References: 1 - Magnussen (2017), 2 - Schouten (2017), 3 - generalised from De Voogt data.

Constant	Value	Description	Ref
SM_C	1.00	Sea margin - calm water - used to determine converters (P_b at V_{max})	3
SM_R	1.10	Sea margin - range - used in range calculation	2
SM	1.15	Sea margin - used for all other calculations	1
η_O	0.61	Propeller open water efficiency	3
η_S	0.99	Mechanical shaft efficiency	3
η_{TRM}	0.98	Transmission efficiency - gearbox	2
MCR	1.0	Maximum continuous rating converter	3
S_{app}	7.4%	Surface area of appendages (% of the wetted area of the hull)	2
$1 + k2$	7.28	Form factor for appendages	2

5.1.2. Required auxiliary power

The auxiliary power is defined as all power except for the propulsion power. Power consumers such as stabilisers and tunnel thrusters are therefore also included in this category. The installed generator power can be estimated by a regression formula based on the installed generator powers of 66 existing Feadships. The relation between the installed generator power and several other yacht parameters has been assessed. The clearest trend is seen with the gross tonnage of the yacht (see Figure A.1). This trend can also be explained: auxiliary power is for the largest part consumed by HVAC systems, which is constantly required in luxury yachts for both the interior materials and comfort on board. The installed (and consumed) power of HVAC systems primarily depends on the volume of the spaces which require conditioning of the air and GT is a measure of volume. This regression formula (Equation A.1) is used to calculate the required auxiliary power to be installed.

When the required auxiliary power is known, the energy converters have to be determined to deliver this power. This process is elaborated on in 5.1.3 Converter selection.

In order to determine the fuel consumed in a year for auxiliary power, the auxiliary power in different operations in the operational profile has to be known. The different operations in the operational profile are: in harbour, for anchor, in service, sailing at maximum speed, sailing fast (range speed or above), sailing slow (below range speed) and manoeuvring. The definitions of these operations can be found in Table 5.3. The different auxiliary powers in the operational profile are defined as a factor of the total installed generator power. These factors are determined from available load list data for 13 Feadships by comparing the estimated auxiliary power in different scenarios with the installed generator power of the yacht (see Figure A.2).

5.1.3. Converter selection

Once the required propulsion power has been determined, a selection of the energy converter providing this power can be determined. The database (see 5.3 Database) contains multiple main engines and their properties. The main engines can be selected in two ways: by manual selection or automatically. The automatic selection of the main engines is done based on the highest load percentage (required power/delivered power) of the engine, given a minimum and maximum number of engines. For the manual selection a list of all the engines in the database that can deliver the required power (number of engines required between the given minimum and maximum of engines), ordered from highest to lowest load percentage, can be selected from. The propulsion power can also be delivered partially by fuel cells as mentioned in 5.1.1 Propulsion power calculation.

Similar to the propulsion power, the converter that provides the auxiliary power is chosen. This is done by (automatically) selecting a converter from the database containing several generator sets and fuel cells. The auxiliary power can also be provide by fuel cells.

The properties of the converter configuration, consisting of a converter for propulsion power and a converter for auxiliary power, are used by the design tool to determine the fuel consumption, emissions and costs (see 5.4 Emissions and 5.5 Costs).

5.1.4. Fuel selection

As the design tool is intended to the use with multiple fuels, a fuel has to be chosen from the database. By default, methanol is selected as fuel unless the baseline option is used, in which case diesel (EN590) is used as fuel. The properties of the chosen fuel(s), such as the storage density and lower heating value, will be used for further calculations and have several consequences which are discussed below.

There is a very limited amount of converters using methanol as fuel. Almost all methanol engines currently available are modified diesel engines and only a single methanol PEM fuel cell for marine application is available (other PEM fuel cells are also available but require methanol to hydrogen reformers). This results in an unrealistic comparison when comparing methanol configurations to diesel configurations, as only a few methanol engines with limited power ranges are available. Given that most methanol engines are converted (or derived from) diesel engines, it is therefore assumed that all engines in the database can be converted to methanol operation in order to overcome the lack of methanol fuelled converters and cover the same power range as diesel engines.

The relevant properties, such as the specific fuel consumption (SFC) of the converter are converted from the original fuel of the converter to the selected fuel. For the conversion of the SFC, there are two aspects to account for. Firstly, there is a difference in lower heating value (LHV) of the fuels. Secondly, literature sources (Verhelst et al., 2019) report that an engine converted from diesel to methanol has a slightly higher efficiency at higher engine loads and a slightly lower efficiency at lower loads, estimated to be in the order of a few percents. However, after corresponding with P. Molander (ScandiNAOS AB) who stated from experience that the efficiency of their methanol compression ignition engine is almost identical to a diesel engine. It is therefore assumed that the change in efficiency, by converting the properties of a diesel engine to methanol, is negligible. As the ScandiNAOS methanol engine is in the power range of 400 to 500 kW, it is currently unknown how methanol engines in other power ranges will compare to diesel engines. The SFC of the converter can be calculated according to Equation 5.2.

$$SFC_{chosen} = SFC_{original} \cdot \frac{LHV_{original}}{LHV_{chosen}} \tag{5.2}$$

Where SFC is the specific fuel consumption in g/kWh and LHV the lower heating values of the original and chosen fuel in MJ/kg.

5.1.5. Required fuel capacity

In order to achieve the range distance that is required, there has to be enough fuel capacity on board. In order to determine this fuel capacity that is required, a range calculation is done. Within De Voogt Naval Architects it is standard to use 85% of the nominal power of a single generator as constant auxiliary load for the range calculation, as well as an SFC tolerance of 5% which is included to account for possible uncertainty or deviations of the reported SFC of the engine (Schouten, 2017).

Given a required range, the required fuel volume can be calculated with the properties of the chosen converters and fuels and the required propulsion power at range speed (including a 10% sea margin, see Table 5.2). The required fuel volume is calculated by Equation 5.3 to Equation 5.8. First the range duration is determined:

$$t_{range} = \frac{d_{range,req}}{v_{range}} \tag{5.3}$$

Where t_{range} is the duration of the range in hours, d_{range} the range distance in nm and v_{range} the range speed in knots. The required delivered energy is then calculated according to Equation 5.4 and Equation 5.5.

$$E_{prop} = P_{prop} \cdot t_{range} \tag{5.4}$$

$$E_{aux} = P_{aux} \cdot t_{range} \tag{5.5}$$

Where E is the energy in kWh and P the required power in kW. With the required energy and the specific fuel consumption (SFC) of the converters, the required fuel mass can be calculated according to Equation 5.6 and Equation 5.7.

$$m_{fuel,prop} = (1 + tol_{SFC}) \cdot SFC_{main\ engines} \cdot \frac{E_{prop}}{1000} \tag{5.6}$$

$$m_{fuel,aux} = (1 + tol_{SFC}) \cdot SFC_{generator/FC} \cdot \frac{E_{aux}}{1000} \tag{5.7}$$

Where m_{fuel} is the fuel mass in kg, tol_{SFC} the tolerance in specific fuel consumption of 0.05 (5%) (Schouten, 2017) and SFC the specific fuel consumption of the converters in g/kWh. The SFC is determined by calculating the load percentage of the converters with the required number of converters to deliver the required power, with a minimum of two main engines running for redundancy (Schouten, 2017). With this percentage and the fuel properties, the SFC can be determined from the data in the database (see Fuel selection). With the fuel mass known, the fuel volume is calculated by dividing the mass by the storage density of the fuel (Equation 5.8).

$$V_{fuel} = \frac{m_{fuel,total}}{\rho_{fuel}} \tag{5.8}$$

Where V_{fuel} is the required fuel volume in m^3 and ρ_{fuel} is the density of the fuel in kg/m^3. This required fuel volume can then be compared to the available fuel volume as described in 5.2 Available space. If the required range cannot be achieved with the available volume, the achievable range can also be calculated from the available volume. This can be calculated by performing the above calculation in reverse (Equation 5.8 to Equation 5.3).

5.2. Available space

In this section the methods to determine the properties of the methanol tanks and cofferdams are described. The length of a methanol tank including cofferdams can also be limited, in which case the determined tank and cofferdam properties describe the maximum space and volume that is available for fuel storage.

As determined in 4.2 Available space and tank layouts, the double bottom is not a feasible location for methanol tanks and cofferdams. The principle design solution (see 4.2.2 Tank layout principle) of one or two large tanks is used in this research in order to approximate the available space in the yachts and resulting tank volume for methanol in a more realistic way than in previous research found in the literature research.

Determining the fuel volume that is available in a yacht is not an easy process. The tank layout is the result of an iterative design process. In order to estimate the this volume, the tank layout and volume calculation have to be simplified since a full 3-dimensional tank layout and volume calculation is outside the scope of this research.

A tank layout with one or two larger tanks is considered to be the most applicable to a range of yachts and more feasible to construct, as is stated in 4.2.1 Methanol tank layout conclusions. To further simplify the calculation, a constant cross sectional area throughout the length of the tank and cofferdam is assumed. Therefore, using the actual average cross sectional area of the tank and cofferdam gives the most accurate results. For a tank around the midship, the midship area may be used as a first approximation, but because the tank occupies the entire cross section up to the lowest possible waterline the cross sectional area of the tank is slightly smaller than that. Because the midship area is usually the largest cross sectional area of the ship, this also results in a higher tank and cofferdam volume than it would using the average cross sectional area of the tank. For a more accurate estimation of the tank volume, the cross sectional area at the central frame of the tank can be used (e.g. determined from the linesplan of the hull), assuming that the cross sectional area varies linearly in longitudinal direction.

There are two basic tank layouts which are found to be practical, constructible and efficient in terms of methanol volume to total tank volume (including cofferdams) ratio. The first layout (method 1) consists of a single large methanol tank (which consists of two or more individual tanks for redundancy, reducing the free surface and for some flexibility in loading conditions and trim). The second layout (method 2) consists of two large tanks. Since the method requires the cross sectional area of the tanks to estimate the volume, the exact position of the tanks is not important for the volume calculation, as long as the cross sectional area accurately describes the average cross sectional area of the tank.

As mentioned before, the design of a tank layout is an iterative process which requires the input of a designer. One or two larger tanks which are not entirely in the double bottom but also above the double bottom have a significant impact on the interior and the arrangement of a yacht. Especially for refitting, this is a problem that has many factors. It may be desirable to align the tank with an existing watertight bulkhead, or an existing division in the interior. Therefore, the fore and aft frames of the tanks (including cofferdams) can be specified, which are then used to determine the available tank volume. The size of the tank(s) can also be determined by specifying the required volume. Four calculation methods, which consist of a tank layout choice and a cofferdam choice, are incorporated in the available tank volume calculation, which are explained below.

5.2.1. Method 1 – Single tank with normal cofferdams

For the first method, normal cofferdams as described in 3.1 Cofferdams are used. These cofferdams surround the tank completely except for where the tank is adjacent to the shell plating below the lowest possible waterline. Since these cofferdams are required to be inspectable from the inside, there are minimum dimensions for the cofferdam. For construction purposes, the cofferdams should extend to a full frame length. If the frame spacing is smaller than the minimum length of the cofferdam, an additional frame is required in the longitudinal direction. From this length and the cross sectional area, the volume of the cofferdam in front and aft of the tank can be determined. For the cofferdam above the tank, the breadth of the yacht (at the lowest possible waterline) is multiplied with the minimum height of the cofferdam and the total length of the tank (including the fore and aft cofferdams) to find the volume.

If the required volume is specified, then the required length of the tank is determined from the cross sectional area of the tank. If the aft and fore frames are specified between which the tank and cofferdams can be placed, then the available tank volume is determined by first subtracting the two cofferdams (front and aft of the tank). With this specified tank volume, the achievable range can then be determined.

5.2.2. Method 2 – Two tanks with normal cofferdams

For method 2, the same method is used for determining the size of the cofferdams as with method 1. The difference is the added second tank. This requires a cross sectional area of the second tank.

For this method, the fore and aft frames of the first tank (including cofferdams) have to be specified. The size of the second tank can then be determined by either specifying the required volume and subtracting the volume of the first tank, or by also specifying the fore and aft frames of the second tank (including cofferdams). For the latter option, the actual tank volume may be smaller or larger than the required volume and an achieved range can subsequently be calculated.

5.2.3. Method 3 – Single tank with alternative cofferdams

Method 3 and 4 deviate from the first two methods because here it is assumed that the alternative cofferdams are not required to be inspected from the inside by a person. Therefore, the size of the alternative cofferdams is smaller (see Table 4.1). Furthermore, it is assumed that the inner walls of the cofferdams, adjacent to the methanol tank, do not have to be aligned to the ships frames. Instead it is assumed that the cofferdam is aligned to the frames and on the outside of the tank, where the tank itself is not aligned to the frames (which is, for this calculation, equivalent to the cofferdam being placed inside the tank and the tank being aligned to the frames which may also be a feasible option). The size of the tank is then calculated in the same way as method 1, which also uses a single methanol tank.

5.2.4. Method 4 – Two tanks with alternative cofferdams

Method 4 uses the same approach to the alternative cofferdams as method 3. The outer plating of the transverse cofferdams is aligned to the yacht's frames but the inner cofferdam plating adjacent to the methanol tank is not. The size of both tanks is then calculated in the same fashion as method 2, which also uses two separate methanol tanks.

5.2.5. Length increase calculation

As described in 4.3 Impact of the large volume and tank layout, it may be desirable to keep the interior area equal. For this purpose, the length of the yacht can be increased. The additional space of the methanol system required in the yacht is primarily used by the methanol tank(s) and cofferdams. Therefore the increase in dimensions required is determined from the tank and cofferdam properties. As the tanks have a height up to the lowest possible waterline (as described in 4.2.2 Tank layout principle) and most yachts have one deck below the waterline, the methanol tanks and cofferdams occupy (at least) one deck of interior space throughout the length of the tank and cofferdams. By increasing the length of the yacht, interior space is created on all decks (including the deck where the tank is located). Assuming that the width of all decks (including the decks in the superstructure) is equal throughout the length of the methanol tanks, cofferdams and the added length as an approximation, the length of the tanks and cofferdams can be equally distributed over the number of decks. See Figure 5.3 for a schematic drawing of this length increase. The length of the yacht is increased around midship, where

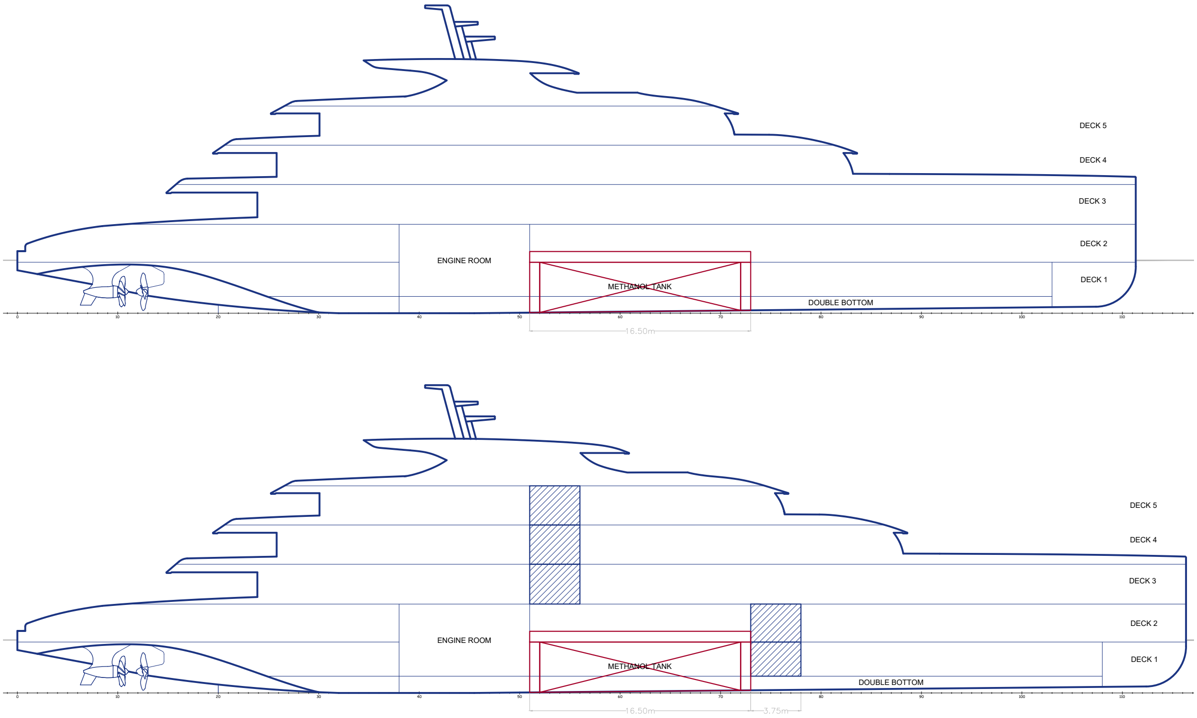


Figure 5.3: Schematic drawing of a length increase of a yacht with 5 decks. The lower drawing has an increased length to add interior area (blue) to compensate the tank and cofferdam area (red). The width of all decks is assumed equal, which means that the length of the tank has to be distributed over all 5 decks.

the central tank is located. From a constructional point of view, the added length therefore needs to be aligned to the frame spacing.

Iteration

In order for the interior area to remain equal to the interior area with a conventional diesel configuration, the length is increased. Since the breadth of each deck is assumed to be equal to the waterline breadth, the interior area is equal when the total length of the tank(s) and cofferdams is divided over all decks. The required length increase can thus be calculated by dividing the total tank and cofferdam length by the number of decks. This is of course not done if diesel is chosen as fuel (in the case of the baseline design and pathway).

An increase in yacht length has an impact on the resistance of the yacht. In order to assess this impact, an iteration over the power and energy requirement (5.1 Power and fuel capacity requirements) and the available space (5.2 Available space) is done. The resistance is redetermined with the following assumptions and simplifications for this relatively small increase in length ($< 10\%$):

- Only the waterline length and the displacement parameters of the Holtrop & Mennen calculation (see Table 5.1) are changed.
- The other parameters of the Holtrop & Mennen calculation are kept constant, which are parameters such as B_{WL}, T, C_M and C_{WP}.
- The length (L_{WL}) is increased by the total length of the tank(s) and cofferdams divided by the number of decks of the yacht (including the decks in the superstructure).
- The displaced volume (∇) is multiplied by the same factor as the length is increased ($L_{WL,new}/L_{WL,old}$).

An increased length may lead to a decrease in resistance at maximum speed (and therefore possibly less powerful main engines), but also an increase in resistance at range speed. This results in a new and larger required fuel volume to achieve the required range, which in turn can result in a different tank size (tanks are aligned to the yacht's frame length). If the tank size (length) needs to be increased, this again results in a loss of interior area which has to be compensated by lengthening the yacht, this time by the length increase (as compared to the previous length) again divided by the number of decks. The iteration stops when no new increase in length is required and therefore the fuel volume and tank size is sufficient to reach the required range while also keeping the interior space equal. As the length increase, like the methanol tank itself, is aligned to the frame spacing of the yacht and the interior space is kept at least equal to the original interior space, the interior space resulting from the iteration is never less than the original interior area (often slightly increased).

5.3. Database

The database contains information of the yacht design, which is used as input, as well as the properties of the main engines, generator sets, fuel cells and of the fuels. The parameters for each of these are shown in Table C.2, Table C.3, Table C.1 and Table C.4. These properties are used by the different modules in the design tool.

5.4. Emissions

The emissions that a yacht emits in a year are dependent on several factors. The method in which the yearly emissions are determined is discussed in further in the following sections:

- Operational profile
- Total fuel consumption
- CO_2 emissions
- NO_x, SO_x and PM emissions

The way in which the yacht is used has a considerable influence on the yearly emissions. Most yachts are mostly in port or for anchor which means that only the generators are running and the fuel consumption is less than if the yacht is sailing at a high speed. This use of the yacht is defined in the operational profile which is discussed in 5.4.1 Operational profile. Which energy converters are chosen influences emissions both directly and indirectly. The efficiency of the converter determines the fuel consumption and therefore the emissions and the type of converter can also influence (some of) the emissions (e.g. fuel cells). Finally, the fuel that is used also has a large impact on the emissions of the yacht. CO_2, SO_x and PM emissions are mostly dependent on respectively the carbon and sulphur content of the fuel. Sulphur in the fuel will result in sulphur-oxides and PM being emitted. NO_x on the other hand is primarily a result of high combustion temperatures, which is why fuel cells emit (almost) no NO_x.

5.4.1. Operational profile

The operational profile of a yacht has a large influence on the yearly fuel consumption and the resulting total emissions. If a yacht spends most time in a harbour or for anchor, it uses less fuel and has fewer emissions than if a yacht is cruising or sailing at high speed a large amount of time because then additional fuel is burned for propulsion next to the auxiliary power that is almost always required. For the design tool, the operational profile is defined for each operation as a combination of a percentage

Table 5.3: Description of different operations in the operational profile, the associated average speed (which is used to determine the propulsion power and consumption) and the associated auxiliary power (as determined in 5.1.2 Required auxiliary power).

Operation	Definition	Average speed (kn)	Auxiliary power scenario
Harbour	Yacht is within known harbours	0	Harbour
Anchor	$v < 2.5$ kn and outside known harbours	0	Anchor
Service	Yacht is within Feadship service locations	0	0
Maximum speed	$v > \frac{1}{2}(v_{max} + v_{range})$ kn	$((v_{range} + v_{max})/2 + v_{max})/2$	Sailing with guests
Cruise fast	$v_{range} \leq v < \frac{1}{2}(v_{max} + v_{range})$ kn	$((v_{range} + v_{max})/2 + v_{range})/2$	Sailing with guests
Cruise slow	$2.5 \leq v < v_{range}$ kn	$(2.5 + v_{range})/2$	Sailing with guests
Manoeuvring	2% of time	5	Manoeuvring

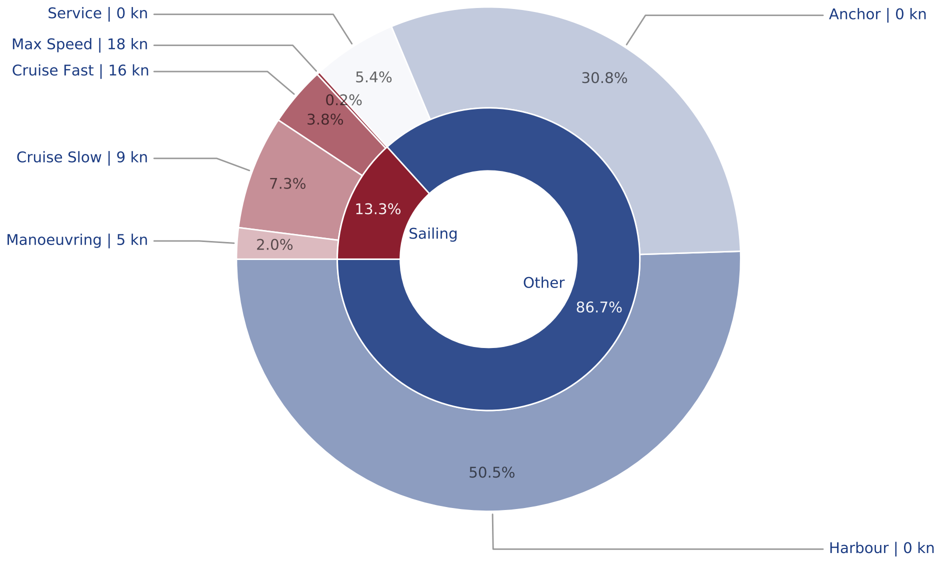


Figure 5.4: An example of an operational profile.

of the time performing this operation, an associated speed (to calculate the propulsion power, see 5.1.1 Required propulsion power) and an associated auxiliary power (see 5.1.2 Required auxiliary power). The definition of the different operations, associated speeds and associated auxiliary powers are shown in Table 5.3. The percentage of time performing each operation can be determined for an existing yacht from AIS data or approximated based on the intended use of a yacht design. The average speeds of each operation are the average of the upper and lower bound of the definition of the operation. An example of an operational profile is shown in Figure 5.4.

5.4.2. Total fuel consumption

The total yearly fuel consumption is determined from the operational profile, the selected converters and fuel. For each category in the operational profile, the fuel consumption for propulsion and auxiliary power is determined. The fuel consumption for propulsion power is determined by calculating the required power for the associated speed in the operational profile with the Holtrop & Mennen method (see 5.1.1), this time with a sea margin of 1.15 as described in 5.1.1 Propulsion power calculation. With this propulsion power and the fuel properties, the optimal number of converters to supply this power can be determined from which the specific fuel consumption (SFC) of the converters can be determined. The SFC and required power result in a fuel consumption per hour (kg/h). Combined with the total time of the category in the operational profile this results in a yearly total fuel consumption for propulsion power in that category. In the same way, the auxiliary fuel consumption can be determined. The required auxiliary power is given in the operational profile. This power combined with the optimal number of auxiliary converters again results in an hourly fuel consumption. Multiplied by the hours per year in this category of the operational profile, this results in the yearly fuel consumption for the auxiliary power.

From the yearly propulsive fuel consumption and the auxiliary fuel consumption, both the fuel costs (see 5.5.1 Fuel costs) and the emissions. The determination of the different emissions is discussed below.

5.4.3. CO_2 emissions

CO_2 emissions are one of the emissions that contribute to global warming on a large scale. It is therefore important that these emissions should be estimated by the design tool. The CO_2 emissions only depend on the fuel that is used in the converters and the amount of fuel that is used. The CO_2 emissions do not depend on the type of converter (e.g. combustion engine or fuel cell). The fuel consumption for propulsion and auxiliary power are added together and multiplied by the well-to-tank and tank-to-wake CO_2 emission factors per MJ of fuel (CO_2 g/MJ). These emission factors can be found in Table 5.4. The CO_2 emission factors from Ellis and Tanneberger (2015) are for fossil fuels.

Renewable methanol has the same chemical composition as fossil methanol and therefore the same CO_2 tank to wake emissions. The CO_2 tank to wake emissions of renewable diesel could be slightly different from fossil diesel as fossil diesel is a mixture of hydrocarbons resulting from the refining process of crude oil. Diesel synthetically produced from renewable feedstocks likely to be a cleaner fuel consisting of fewer different compounds (a more narrow range of hydrocarbons) as well as fewer contaminating particles from the crude oil [ref???]. The CO_2 tank to wake emissions of renewable diesel are however, for this thesis, considered equal to that of fossil diesel and could be considered an upper bound to the actual CO_2 emissions of renewable diesel. The CO_2 well to wake uptake (negative emissions) of the renewable fuels are assumed to have equal magnitude as their tank to wake emissions in order for the fuels to be fully renewable, including the production and distribution processes of the fuels. Often in the literature, the well to wake CO_2 emissions are not exactly equal to the tank to wake emissions because of the emissions during the production and distribution process. However, in order for a fuel to be truly renewable there should be no net CO_2 emissions. It is therefore assumed, in this thesis, that renewable fuels have net zero CO_2 emissions.

5.4.4. NO_x, SO_x and PM emissions

NO_x, SO_x and PM are also important emissions which have a more local impact on the environment. These emissions are not only dependent on the fuel that is used, as is the case with CO_2, but also on the converter that is used. NO_x emissions depend mostly on the temperature in the combustion chamber (for combustion engines), while SO_x and PM depend more on the sulphur and particles in the fuel. The NO_x emissions are given for both IMO Tier II and Tier III regulations. The Tier III emissions are equal for methanol as they comply with IMO Tier III regulations without after treatment (Ref: Patrik Molander ScandiNAOS). Diesel ICEs do require after treatment to comply with Tier III. The NO_x, SO_x and PM emissions in ICEs for renewable diesel are assumed equal to those of fossil diesel, although in reality they may be different because fossil and synthetic (renewable) diesel are have different chemical compositions. NO_x emissions could be higher if the cleaner synthetic diesel burns at a higher temperature in the combustion chamber while SO_x and PM emissions could be lower because synthetic diesel is not produced from crude oil. . For fossil and renewable methanol these emissions are equal as they have the same chemical composition. Emissions other than CO_2 for fuels used in fuel cells (both PEMFC and SOFC) are extremely low (negligible), as stated in Darrow et al. (2015). NO_x, SO_x and PM emissions for fuel cells are therefore assumed zero in this thesis. The emission factors for NO_x, SO_x and PM are given in Table 5.4.

Table 5.4: Emission factors in g/MJ of fuel from different feedstocks in both internal combustion engines (ICE) and fuel cells. The subscripts next to the fuel denote the feedstock of the fuels: F = fossil, R = renewable. The -II and -III of the NO_x emissions denote the respective IMO NO_x regulations. References: 1 - Ellis and Tanneberger (2015), 2 - Brynolf (2014).

Emissions	ICE				Fuel cells				Ref
	MGO$_F$	MGO$_R$	Methanol$_F$	Methanol$_R$	MGO$_F$	MGO$_R$	Methanol$_F$	Methanol$_R$	
$CO_{2,WTT}$	14.2	-74.1	28.55	-69.1	14.2	-74.1	28.55	-69.1	1
$CO_{2,TTW}$	74.1	74.1	69.1	69.1	74.1	74.1	69.1	69.1	1
$NO_{x,TTW}$-II	1.5	1.5	0.28	0.28	0	0	0	0	2
$NO_{x,TTW}$-III	0.28	0.28	0.28	0.28	0	0	0	0	2
$SO_{x,TTW}$	0.047	0.047	0	0	0	0	0	0	2
PM_{TTW}	0.011	0.011	0.0043	0.0043	0	0	0	0	2

5.5. Costs

The design impact tool also assesses the costs associated with using methanol as fuel as compared to a conventional yacht using diesel. The precise impact on the costs caused by switching to methanol is very difficult to determine as this cost difference consists of many different factors. This cost difference depends on factors such as the costs of components in the methanol fuel and propulsion system, costs associated with the construction of the methanol tanks, a possible decrease in value because of possibly lost interior space and methanol fuel costs but the costs that are diesel related (and thus not required for a methanol yacht) also have to be subtracted from the original cost of the yacht. As a full detailed costs analysis of a methanol yacht and its components is outside the scope of this research, the cost analysis is limited to a few factors that are believed to have the largest impact on the costs, which are:

- Fuel costs (operational expenses)
- Converter costs (capital expenses)
- Fuel storage costs (capital expenses)
- Costs associated with (not) increasing the length of the yacht (capital expenses)

The factors stated above are described in more detail in the following sections. The capital expenses related to the methanol system, consisting of converter and storage costs, will be expressed as a percentage of the total value of the yacht (presented in 8 Case study). This yacht value is a parameter in the database. As the costs for the storage of fuel and costs for the converters is an estimate, this yacht value does not have to be an exact value. A rough estimate of the approximate value of the yacht is enough to give an estimate of the relative costs of the methanol system compared to the total value of the yacht.

5.5.1. Fuel costs

Fuel costs are an important factor to consider when determining the financial impact of using methanol as fuel. The fuel costs are determined from the yearly fuel consumption (MWh) as determined in 5.4.2 Total fuel consumption. To find the total yearly fuel costs, the consumption can be multiplied by the fuel price per MWh. In the pathway analysis (see 7 Pathways) there is a linear trend in fuel price taken into account. The upper and lower limit of the fuel price for the years 2020 and 2050 are given in the database containing the fuels and their properties. With the linear trend between the prices in these years, the fuel price at any year within the interval can be determined. To find the upper and lower limit of the fuel costs in a certain year, the yearly fuel consumption is multiplied by the fuel price limits in that year. The limits of the fuel costs are determined for both the fossil and renewable variant of the fuel that is used, in order to compare them.

5.5.2. Converter costs

The costs for converters consist of the cost of the converters used for propulsion power and of the converts used for auxiliary power. The converters considered in this research are internal combustion engines and fuel cells. As discussed in 5.1.1 Propulsion power calculation fuel cells are only suitable for a small fraction of the power required for propulsion. Therefore, the main propulsion power is provided by internal combustion engines. For auxiliary power both generator sets (internal combustion engines with alternators) and fuel cells possible. This section discusses the following costs related to the converters considered in this research:

- Main engine costs
- Generator set costs
- Fuel cell costs
- Trends in converter costs

An overview of the cost values found in the literature review can be found in Table 5.5. As the cost values which were found in the literature research are based on low to medium speed internal combustion engines, they are less applicable for yachts which tend to use high speed engines. Therefore, more applicable cost information of ICEs from Feadship (confidential) is used which can be found in Appendix C Table C.5. An indication of the cost of after treatment can also be found in Table C.5 (confidential). The conversion costs from a base diesel engine to a methanol engine are approximately equal to the cost of after treatment (SCR) for diesel engines (P. Molander, ScandiNAOS). For fuel cells the literature value from Brynolf (2014) is used in the design tool.

Table 5.5: Price per kW of main engines, generator sets and fuel cells. Prices are given in Euro's (a €0.90 per $1.00 rate is used to determine the price in euro's). References: 1 - Brynolf (2014), 2 - Lloyd's Register and UMAS (2020).

Converter type	Converter cost diesel [€/kW]	Converter cost methanol [€/kW]	Ref
Main engines	630	648	1
	531	531	2
Generator sets	225	225	2
PEM fuel cells	3,600	3,600	1
	1,620	1,620	2

Main engine costs

The propulsion power is provided by the main engines, which are internal combustion engines. To determine the costs of main internal combustion engines, a small literature search was done first. The price per kW found in two literature sources is shown in Table 5.5. These values however, are for larger marine (two-stroke) engines that run at a lower rpm. This kind of engine is, while being more efficient but also larger and more expensive, often not used on yachts. The main engines installed on most yachts are the more compact high-speed four-stroke engines. These engines are less efficient than the larger slow to medium speed engines, but they also have a lower price and are smaller. In order to give a more representative cost estimate of the main engines for a yacht, an indication of the engine cost was given by B. Boon (De Vries, Feadship), which is shown in Table C.5. Because this indication is the most representative of the engine cost for a yacht, this value is used in this research to determine the main engine costs.

Next to the base engine, combustion engines often require after treatment to comply with the IMO Tier-III NO_x regulations. An indication for the cost of an after treatment unit (SCR) was also given by B. Boon, which is also shown in Table C.5. In order to determine the cost of a methanol engine, P. Molander from ScandiNAOS (builder of methanol engines) was contacted. The price of a methanol engine is approximately equal to that of a diesel engine with after treatment. A conversion of a diesel engine to methanol operation therefore costs approximately as much as the after treatment of a diesel engine. However, a methanol engine does not require any after treatment in order to meet the Tier-III NO_x emission requirements. Therefore, the cost of a methanol engine is approximately equal to the cost of a diesel engine (including after treatment). The main engine costs are determined according to Equation 5.9.

$$TCC = P_i \cdot price/kW + n_c \cdot C_{AT} + n_c \cdot C_c \tag{5.9}$$

Where TCC is the total converter cost, P_i is the installed total power [kW] of the converters (main engines in this case), $price/kW$ the price per kW of installed power of the converters, n_c the number of converters, C_{AT} the cost of after treatment per converter (only for diesel engines) and C_c the conversion cost per engine (only for methanol engines).

Generator set costs

The auxiliary power can be provided by generator sets, which consists of an internal combustion engine and an alternator that converts the mechanical energy generated by the engine into electrical energy (alternating current). One of the literature sources also stated the price per kW for a four-stroke auxiliary engine. Next to that, B. Boon (De Vries, Feadship) also gave an indication of the price of a generator set (see Table C.5). As with the main engines, diesel generator sets also require after treatment to comply with the IMO Tier-III emission limits. For methanol generators, the same conversion and after treatment costs as for the main engines are assumed. The generator costs are also calculated according to Equation 5.9.

Fuel cell costs

The auxiliary power, but also a small part of the propulsion power (as described in 5.1.1 Propulsion power calculation) can also be provided by fuel cells. The price of fuel cells, including a reformer for

PEM fuel cells, in the literature shows a large variation from \$1,800/kW (Lloyd's Register and UMAS, 2020) to \$4,000/kW (Brynolf, 2014). Data from SerEnergy (supplier of methanol HT-PEMFCs with internal reformers) suggests an even higher price (see Table C.5). Since there is no combustion in fuel cells, no NO_x after treatment is required. For the price of fuel cells in this research, the price of \$4,000/kW (€3,600/kW) from Brynolf (2014) is assumed. The costs of fuel cells can be calculated according to Equation 5.10.

$$TCC = P_i \cdot price/kW \tag{5.10}$$

Where TCC is the total converter cost, P_i is the installed total power [kW] of the converters (fuel cells in this case) and $price/kW$ the price per kW of installed power of the converters (€3,600/kW).

Cost trend

Since energy converter technology is continuously being developed, it can also be expected that the cost of these converters can change over time. Internal combustion technology, which has been used as main energy converter in the maritime industry for a long time, is not likely to reduce in costs, but particularly the newer technologies such as fuel cells (e.g. PEMFCs and SOFCs) may reduce in costs over the coming decades. Because of this, it is possible to apply a multiplication factor of the price for each converter technology and fuel. For simplicity this factor assumes a linear trend between the value in 2020 and 2050, which is discussed in more detail in 7.2.3 Converter price.

5.5.3. Fuel storage

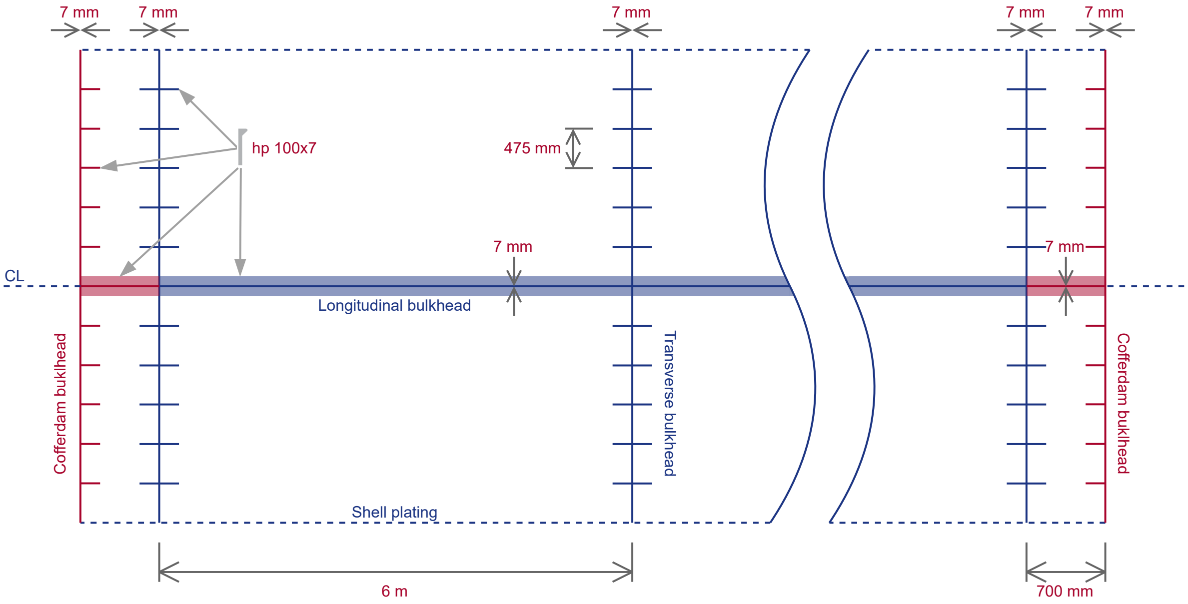
Next to the fuel costs and the cost of the converters, the costs associated with the storage of methanol will also have an influence on the total cost difference with a diesel yacht. Not only is over twice the fuel volume required (to achieve the same range distance), the tank layout is also different and additional safety measures (e.g. a cofferdam) are required. Brynolf (2014) states that the storage costs can be estimated by a price per GJ of energy content in the fuel: \$30/GJ for diesel and \$50/GJ for methanol. That research is however more focused on larger commercial vessels and these values may not be as applicable to yachts.

It is a complex task to determine the actual costs of a fuel storage system, not only for methanol but also for diesel. Both systems are (partly) an integral part of the construction of the hull (for diesel the double bottom) which makes it difficult to determine the cost of material and labour to construct the tanks independently. Next to that the cost of tanks also depends on the piping, required gauges and other instruments. In order to give an indication of the costs of fuel storage in this research, an estimate is based on the steel weight of the tanks (including cofferdams for methanol). The double bottom is usually where diesel tanks are located but it is not a suitable location for methanol tanks (as discussed in 4.2.1 Methanol tank layout conclusions). Since most of the construction of diesel tanks in the double bottom is part of the construction of the hull and double bottom, its costs are assumed to be negligible compared to the construction of methanol tanks. In order to determine the cost of the methanol tanks and cofferdams, their steel weight has to be determined. The steel weight is determined from the dimensions of the tanks and cofferdams as calculated in 5.2 Available space. The following assumptions, resulting from discussions with A. Speets (Specialist, Structural Engineering at De Voogt Naval Architects), are used in the storage cost calculation and are also shown in Figure 5.5:

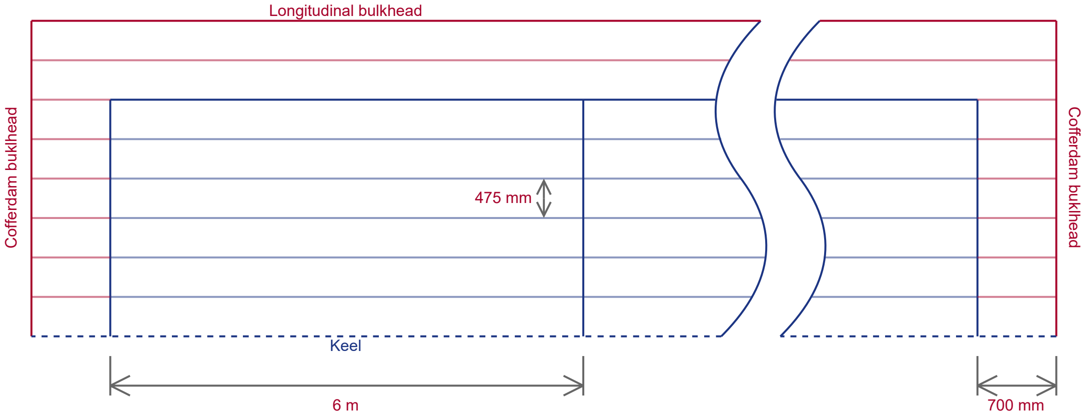
- The cost of diesel tanks is negligible compared to the cost of methanol tanks.
- The shell plating of the hull is excluded from the steel weight calculation.
- A steel density (mild steel) of 7,850 kg/m^3 is used.
- All plating of the tank and cofferdam is assumed to be 7 mm thick.
- Longitudinal stiffening of plates and girders every 475mm in height is assumed by hp100x7 profiles with a weight of 8.86 kg/m.
- Every 6 meters in length (and the fore and aft end of the tanks), a transverse bulkhead (7mm) is placed. The bulkhead is also stiffened with hp100x7 profiles spaced every 475mm.
- The tanks are divided on the centerline by a longitudinal bulkhead (7mm).

- The tanktop (7mm, stiffened) spans the breadth and length of the tank at the lowest possible waterline.
- The cofferdams surrounding the fuel tank consist of a transverse bulkhead (7mm, stiffened), a longitudinal bulkhead inside the cofferdam (7mm, stiffened) and a top plate (7mm, stiffened) that spans the breadth and length of the tank plus cofferdam length.

With these assumptions, an estimate of the additional steel weight of the tank can be calculated from the dimensions of the methanol tanks. The calculated steel weight can be used to estimate the construction costs of the tanks. Jármai and Farkas (2014) present specific material costs k_m (\$/kg) and specific fabrication/labour costs k_f (\$/min). The specific steel cost is in the range of 1.0 to 1.3 \$/kg, aluminium in the range of 3.0 to 3.5 \$/kg and stainless steel in the range of 6.0 to 7.1 \$/kg. Jármai and Farkas present an extensive method to calculate the fabrication costs (labour) based on the time it takes to process the material including: welding, cutting, flattening and painting. This level of detail in the cost calculation is outside the scope of this research. However, they also present a specific cost ratio $\frac{k_f}{k_m}$ (kg/min) with values based on the location of labour, where a higher ratio means a higher labour cost.



(a) Horizontal cross section of the methanol tank and cofferdam below the top cofferdam.



(b) Longitudinal cross section of the methanol tank and cofferdam at the centreline.

Figure 5.5: Schematic representation of the tank steel weight calculation principle.

For Western Europe they present a value of 1.5 to 1.0 kg/min. Using the upper range of the specific steel cost of 1.3 $/kg and multiplying this by the $\frac{k_f}{k_m}$ ratio of 1.5 kg/min, this results in a specific labour cost of 1.95 $/min. As a detailed fabrication time calculation is outside the scope, a processing or fabrication time of 1.0 min/kg is assumed. By multiplying the steel weight with this processing time, a fabrication time is calculated. This fabrication time based on the steel weight can then be multiplied by the specific labour cost to find a total labour cost. Additionally, to account for the complexity and difficulty of the construction of the cofferdams, required for methanol tanks, the labour time (and indirectly the costs) is multiplied by a complexity factor: 1.2 for normal cofferdams and 1.5 for alternative cofferdams.

5.5.4. Costs associated with the optional increase of the yacht's length

As mentioned before, the storage of methanol is not in the same location as conventional diesel tanks. The double bottom is a very convenient place for (diesel) fuel tanks because the double bottom is required by the rules & regulations and large enough for the required fuel capacity, which results in no additional decrease in luxury or crew area. Since the double bottom is not a feasible area for methanol tanks and cofferdams, these tanks do require additional space in locations where it decreases luxury or crew area. This leaves two options:

- Increasing the yacht's dimensions to account for the loss in interior area caused by methanol tanks.
- Keeping the dimensions of the yacht the same.

In order to keep the yacht's value equal to the owner in terms of luxury area, the design of the yacht can be lengthened as discussed in 4.3 Impact of the large volume and tank layout. This way there is no loss of interior area which could decrease the value of the yacht. Increasing the length of an existing yacht to account for the larger methanol tanks would be extremely costly, as discussed in 4.3, and is therefore not a feasible option. For a new design, increasing the length is not a physical constructional task but only impacts the design and naval architecture side. Next to that, it is not uncommon for a yacht's length to increase during the design phase (up to the contract design). Therefore, the costs associated with an increase in length are not taken into account in this research.

The second option, where the dimensions of the yacht are kept equal, has other implications for the yacht. If the yacht's length cannot be increased (as is the case for refitting existing yachts) or it is not desired by the owner to increase the length, the methanol tanks and cofferdams take up valuable space inside the yacht. This will result in a decrease in value of the yacht, if this value is based on the luxury area. However, this would have to be a conscious decision of the owner and therefore the decrease in value may be subjective depending on the wishes of the owner. The owner may consider the benefits of an alternative fuel at the expense of luxury area in a negative way or the owner may not. The decrease in value of the yacht, based on a decrease in luxury area is not included in the design tool.

5.6. Design tool conclusion

In order to produce the required results to answer the main research question, a design impact tool has been developed in this research. This chapter described the different modules of the design tool and discussed the methods and calculations. The design tool consists of five modules:

- Power & energy
- Available space
- Database
- Emissions
- Costs

The design tool is used to determine the impact of using methanol on the design and layout, as well as determining the emissions and costs of several pathways.

The propulsion power required is determined by the Holtrop & Mennen method which is combined with the speed associated with each operation in the operational profile. The installed propulsion power is determined by combining the Holtrop & Mennen method with the required maximum speed. The required installed auxiliary power is determined through a regression formula based on existing Feadships. The required auxiliary power for each operation in the operational profile is determined by using a load factor based on existing yachts. With the propulsion and auxiliary power known, energy converters are chosen from the database. The chosen energy converters are then used in a range calculation to determine the required energy to be stored to reach the required range.

With the required fuel capacity the properties of the tank layout can be determined. Two tank layouts are implemented: a single methanol tank layout and a double methanol tank layout, with the option to chose the smaller alternative cofferdam. The tank and engine room layout is also visualised. This module is primarily used to determine the design impact, the optional length increase of the yacht and the costs of the tank layout.

With the properties of the configuration of the yacht, consisting of a tank layout and converter selection, the emissions and costs are determined. The emissions are determined from an operational profile dependent fuel consumption and the chosen converters. The fuel costs are also determined from this fuel consumption. Other costs are also determined such as the costs of the tanks and cofferdams and the costs of the converters.

6

Design tool validation

There are currently no existing yachts using methanol as fuel. The design tool and its results can therefore not directly be validated. The validation is therefore done on the level of the different modules of the design tool. The available space and power & energy modules process the input to estimate and determine unknown properties of the yacht if it would use methanol as fuel. Therefore, these modules are validated in this chapter. The emissions and costs modules then use these methanol yacht properties and determine emissions and costs based on values found in the literature. Therefore, these modules are not further validated. In this chapter the following modules are validated:

- Available space - Tank layout properties
- Available space - Tank layout feasibility
- Power & energy - Holtrop & Mennen resistance and power prediction

6.1. Tank layout properties

The tank layout methods, described in 5.2 Available space, are a simplified calculation and not a full 3D modelling of the tanks. Therefore the actual volume of the tanks, when build, will deviate from the volume calculated with these methods. To validate that the methods are a sufficiently accurate simplification of a real tank, the volume is also determined from actual AutoCAD 2D GA drawings (3D models of the hull were not available) of the yacht. Since the AutoCAD drawings are 2D and transverse cross sections not available at every frame, the tank volumes determined from these drawings are also not a perfect representation of the actual volume and have to be determined as accurate as possible.

In Table 6.1 the volumes and deviations are shown for a tank around midship, on a yacht with a midship area of 53.24 m^2 and a waterline breadth of 15.50 m. A methanol tank (12 frames) including surrounding cofferdams (top, aft and fore), with a total of 14 frames, are drawn in the 2D general arrangement. By combining the longitudinal and transverse cross sections, the volume of the tank and cofferdams is determined as accurate as possible. The design tool uses an average cross sectional area of the tank of 48.90 m^2 (determined from AutoCAD) to determine the tank and cofferdam volumes. Therefore the volume of both the fore and aft cofferdams is equal for the design tool output while these volumes

Table 6.1: Tank layout properties validation for a single methanol tank around midship. Volumes are given in [m^3].

Method	V_{tank}	$V_{cofferdam}$	$V_{cofferdam,top}$	$V_{cofferdam,aft}$	$V_{cofferdam,fore}$
AutoCAD 2D GA	467.52	188.91	110.99	39.98	37.95
Design tool	479.16	193.78	113.92	39.93	39.93
Deviation from AutoCAD	+2.5%	+2.6%	+2.6%	-0.1%	+5.2%

are not equal for the AutoCAD drawing. Both the methanol tank volume and the total cofferdam volume is overestimated by the design tool by approximately 2.5%. The aft cofferdam is only slightly underestimated, while both the top and fore cofferdam are overestimated in volume.

6.2. Tank layout feasibility

The tank layout calculations are based on the analysis of possible methanol tank layouts of three existing yachts (see 4.2.1 Possible methanol tank layout analysis of existing Feadships). The properties of these tanks and their feasibility in terms of design and arrangement need to be assessed. The tank layouts resulting from the design tool also have an impact on trim and draught. The feasibility of these tank layouts is determined in chapter 8 for several yachts. The tank and cofferdams are shown in the schematic layouts in chapter 8. From these schematic layouts it can be seen that there is no overlap of tanks or cofferdams with the engine room and the tanks layouts appear feasible.

6.3. Holtrop & Mennen resistance and power prediction

The design tool determines the required power in two steps: first the resistance is estimated by the Holtrop & Mennen method (see Holtrop & Mennen resistance prediction method) which is then used to determine the required power through a simplified calculation using several efficiencies (see Propulsion power calculation). Both are validated in this section.

The Holtrop & Mennen method is already quite an old resistance prediction method, first published in 1978, based on an equally old set of data from model experiments and full-scale data. The method was updated in 1982 to give more accurate predictions at higher Froude numbers (above 0.5). However, the regression is not purely based on yacht models and the method may therefore be less accurate for yachts as when the method and coefficients are tuned to yacht models only. As computational power has increased significantly since the publication of the Holtrop & Mennen method, CFD calculations have become much more common and give more accurate results.

In order to validate the resistance and power prediction used in the design tool, CFD calculation and model test results that are available of 3 Feadships (the same yachts as analysed for the available space) are compared to the predictions of the design tool. For all yachts, the latest CFD calculation or model test results are used. The error percentages of the Holtrop & Mennen resistance predictions and the break power predictions for the yachts are shown in Table 6.2.

The Holtrop & Mennen method has the following applicability limits:

- The approximation is valid for seawater (1.025 ton/m^3) of 15 °C, for calm water.
- Cross-sectional area of the bulb must be less than 20% of the midship sectional area.
- Midship coefficient between 0.5 and 1.0.
- L$_{WL}$/B ratio between 3.5 and 9.5.
- LCB between -5% and +5% of Lwl/2.

Table 6.2: Errors of the total resistance (Rt) and break power (Pb) of the Holtrop & Mennen method compared to the results from CFD calculations or model tests. The L$_{WL}$/B ratio, midship coefficient (C_M) and the prismatic coefficient (C_P) of the yachts are also stated.

Yacht	L_{WL}/B	C_M	C_P	Speed	Error Rt (%)	Error Pb (%)	Reference
Large low speed	6.4	0.81	0.67	V_{max}	-1.6	-4.6	Model
	6.4	0.81	0.67	V_{range}	-1.1	-7.6	Model
Small low speed	4.9	0.74	0.67	V_{max}	-18.8	-23.2	CFD
	4.9	0.74	0.67	V_{range}	-18.2	-19.4	CFD
Small high speed	6.0	0.63	0.72	V_{max}	+3.1	+4.0	Model
	6.0	0.63	0.72	V_{range}	-20.5	-45.6	Model

- Prismatic coefficient between 0.40 and 0.93.
- Half angle of waterline entrance maximum 70°.
- Resistance coefficient of bow propeller between 0.003 and 0.012.

The three yachts that are used for this validation all have no bulb and a midship coefficient, L_{WL}/B ratio, LCB and prismatic coefficient within the limits stated above.

Large low speed yacht: As can be seen from Table 6.2, the H&M predictions for resistance and power of this yacht are close to the model test values. The resistance and power predictions for both speeds are within 5% of the model test value, except for the power estimation at range speed which is underestimated by over 7%. The wetted hull area is underestimated by 6.2% and the appendage area is underestimated by 38%. The appendage area is partly underestimated by the underestimated wetted hull area (which is multiplied by 7.4% to find the appendage area Schouten (2017)), and partly because this factor of 7.4% is lower than the 11% that it actually is for this yacht.

Small low speed yacht: Both resistance and power predictions for this yacht are underestimated by the H&M method by 20-25%. After investigating the estimations made by the resistance prediction method, it was found that both the wetted area of the bare hull and the appendage surface area were underestimated. The wetted area of the hull is estimated by an equation of the Holtrop & Mennen method and is underestimated by 10.7%. The appendage area is estimated by multiplying the estimated wetted area by 7.4% from Schouten (2017) (see Table 5.2) and is underestimated by 50.4%. This is partly because the wetted hull area is underestimated and partly because this 7.4% is lower than the approximately 13% that it is for the actual yacht.

Small high speed yacht: The resistance and power predictions for this yacht are close to the model test at high speed. At range speed however, the resistance is underestimated by 20%. The power prediction is underestimated even more at 45%. The error difference between the propulsion and resistance at range speed is likely due to the waterjet propulsion system of this yacht: a waterjet is significantly less efficient at low speeds than a propeller. At high speeds, the waterjet is comparable to a propeller in efficiency, which explains the insignificant error difference between power and resistance at high speed for this yacht. After also investigating the wetted hull area and appendage area for this yacht, it was found that the wetted hull area was underestimated by 5% and the appendage area overestimated by 90% (appendage area is approximately 4% of the wetted hull area for the actual yacht).

6.3.1. Manual input of wetted area

As previously stated, the wetted area of the hull and the appendages is not accurately estimated by the Holtrop & Mennen method and by the 7.4% of the wetted hull for the appendage area. Therefore, the design tool was updated with an option to manually provide the wetted hull area and/or appendage area. The errors in resistance and power prediction, when the actual wetted areas of the yachts are used, area shown in Table 6.3.

Large low speed yacht: Using the actual wetted area of the hull and appendages does not improve

Table 6.3: Errors of the total resistance (Rt) and break power (Pb) of the Holtrop & Mennen method compared to the results from CFD calculations or model tests, with the actual wetted areas of the yachts. The L_{WL}/B ratio, midship (C_M) and prismatic (C_P) coefficients of the yachts are also stated.

Yacht	L_{WL}/B	C_M	C_P	Speed	Error Rt (%)	Error Pb (%)	Reference
Large low speed	6.4	0.81	0.67	V_{max}	+9.6	+6.2	Model
	6.4	0.81	0.67	V_{range}	+11.7	+4.2	Model
Small low speed	4.9	0.74	0.67	V_{max}	-4.2	-8.8	CFD
	4.9	0.74	0.67	V_{range}	+2.6	+1.7	CFD
Small high speed	6.0	0.63	0.72	V_{max}	-1.3	-0.5	Model
	6.0	0.63	0.72	V_{range}	-25.3	-48.1	Model

the resistance estimates which were already close to the model values. Since the wetted areas were underestimated by the Holtrop & Mennen method, using the actual wetted areas increases the resistance to the point where the resistance is now overestimated by around 10%. Only the power prediction at range speed has improved, to an overestimation of 4.2%, by using the actual wetted areas as this value was previously underestimated by over 7%. As yachts generally only sail at maximum speed for a very small percentage of the time (see Figure 5.4), a power prediction that is closer to the model test at range speed is preferred over a closer power prediction at maximum speed. Therefore, the actual wetted areas are used for this yacht in the case study in chapter 8.

Small low speed yacht: Setting the wetted hull area to that of the actual yacht therefore still underestimates the appendage area. When both the wetted hull area and appendage area are set to that of the real yacht, the errors in total resistance and break power become smaller: +2.6% and +1.7% respectively at range speed and -4.2% and -8.8% respectively at maximum speed. The range speed estimates are close to the actual CFD calculations of the yacht. The maximum speed estimate of the resistance is within 5% of the CFD calculation, while the power estimate is still underestimated by 8.8%. However, these estimates are already closer to the CFD results than without the actual wetted areas. Therefore, the actual wetted areas are used for this yacht in the case study in chapter 8.

Small high speed yacht: When setting both areas to that of the actual yacht, the resistance and power estimates at maximum speed become even closer to the model test values: -1.3% and -0.5% respectively. At range speed, the resistance and power estimates become slightly worse: -25.3% and -48.1% respectively. Following the same reasoning as for the large low speed yacht, the actual wetted areas are used for the case study of this yacht.

6.4. Validation conclusion

Although the exact volume of the methanol tanks and cofferdams is difficult to determine, an attempt was made to validate the tank and cofferdam properties as determined by the design tool by determining this volume with the help of 2D general arrangement drawings in AutoCAD. The difference in tank volume and total cofferdam volume is approximately 2.5%. The difference between the design tool and 2D GA volumes of the individual cofferdams varies from cofferdam to cofferdam, ranging from -0.1% to +5.2%. The total cofferdam volume however has a difference of 2.6%. The tank layouts as presented in chapter 8 also appear feasible in terms of layout and general arrangement. For future development, a more realistic and accurate method would be to implement a method to use 3-dimensional hull shapes and generate 3D tank layouts. This would allow a more accurate determination of the tank and cofferdam properties.

The resistance and power prediction methods were also validated. Although the three yachts were within the limits of the Holtrop & Mennen method, there were significant errors in the predicted resistance compared to model and CFD results. This error could partly be attributed to an error in estimated wetted hull and appendage areas. The design tool was subsequently updated with an option to manually provide these wetted areas. The result of using the actual wetted areas of the yachts varied. For the low speed large yacht, the error in resistance increased but the error in break power improved (for range speed). For the low speed small yacht both the resistance and power estimations improved at both speeds. The resistance and power estimations of the high speed small yacht improved slightly at maximum speed but at range speed the error increased. As the error in required power for this third yacht is over 45% at range speed partly due to the waterjet propulsion system, this yacht is excluded from chapter 8. The case study of this yacht can be found in Appendix D.

As the required power is determined from the resistance by propulsion and transmission efficiencies (see 5.1.1), this is a very simplified method as every yacht has different propulsive efficiencies depending on the hull and propeller properties. The required power prediction could be improved by adding more detail to this calculation such as the Wageningen B-series data to estimate propeller efficiencies at different speeds. Adding different propulsion options such as waterjets would improve the range of yachts on which the design tool could be applied (e.g. the third high speed yacht).

7

Pathways

The term pathway is a returning term in energy transition literature, including the maritime sector. The term pathway in itself is a very broad term, which means: (1) “a way that constitutes a path” such as a road; (2) “[a] way of achieving a specified result”; or (3) “a course of action” according to the English dictionary (Rosenbloom, 2017). Also in literature related to ships and their emissions there is often spoken of pathways, for example LLoyd’s Register and UMAS (2019). These pathways have the purpose of determining the environmental (and sometimes economical) impact of a path consisting of using an alternative fuel over a certain time period or to determine which alternative fuels could be used to ensure a zero emissions future.

These pathway analyses are very important to determine the success of an alternative fuel (or an alternative energy converter). The pathway analysis can be used to not only determine the impact or costs at a single moment in time, but to investigate how this impact (or these costs) change over time by incorporating several changeable parameters. These parameters can be anything that could be of interest (within realistic or expected boundaries of course) to change such as fuel prices, converter prices, fleet size, converter efficiencies, fuel availability and many others. The ability to explore and determine changes over time makes pathways very relevant, especially in this time of much needed change in order to meet for example the IMO climate goals.

For the purpose of this research, the definition of a pathway is narrowed down to the following: a pathway is an upgrade path which a yacht can follow within a set timeframe, where the upgrade path consists of one or more configurations of the power generation system on board. The configurations are limited to the choice of fuel, a tank layout and energy converters of the yacht.

The goal of the pathway analysis is to analyse the impact of different configurations on costs and emissions. Both fossil and renewable energy sources are included in the costs and emissions analysis of the pathways. The pathways will be compared to a baseline which consists of a conventional diesel engines and generators with MGO as fuel. In this section, the different aspects of the pathways are further elaborated on.

7.1. Pathway properties

7.1.1. Number of pathways

4 pathways will be analysed in terms of costs and emissions. The choice for a small number of pathways comes from the emphasis on the impact of methanol on a yacht in a more general sense. It is therefore considered to be less important to analyse a great number of pathways, which would be more useful if one would want to know which year would be the best year to do a refit in terms of overall costs and environmental aspects. Such an analysis could be considered an optimisation of the pathway. However, the main goal of this research is to do a more general determination of the impact that using methanol as fuel has on the emissions and costs in different configurations (fuel and converter options). For this purpose, 4 pathways (next to the diesel baseline diesel pathway 0) is considered to be sufficient.

7.1.2. Time span

The pathways will consider the period from 2020 to 2050. This time span is chosen because 2050 is also the target year of the IMO greenhouse gas reduction goals. These goals state that the IMO is pursuing at least a 50% reduction of GHG emissions by 2050 next to a 40% reduction by 2030. The period of 2020 to 2050 is a time span of 30 years. Cozijnsen (2019) reported that Feadships usually have a larger refit after 15 to 20 years, while smaller refits are done more frequently. A change in power generation configuration (fuel and converters) could be considered as a large refit. Therefore, a single change in configuration (choice of converters and fuel) will be considered. Combined with the chosen configuration at the start of the pathway (in 2020), this limits the amount of configurations in a single pathway to 2.

7.2. Trends included

The different pathways are most useful to assess the impact of methanol on the costs and environment when there are some variables or properties that change throughout the 2020 to 2050 period. The following trends, which are discussed in this section, are included in the pathway analysis:

- Fuel price
- Converter efficiency
- Converter price

7.2.1. Fuel price

The first trend that is included is a change in fuel price. In order to not overcomplicate the pathway model a simple linear trend is used to describe the evolution of the price of different fuels from different feedstocks. The prices found in the literature for fossil, bio and renewable methanol are shown in Figure 7.1. The prices for renewable diesel (E-diesel) and fossil MGO are also shown in Figure 7.2. As can be seen in both figures, the price estimates show a large variation in the non-fossil feedstock prices. Not only long term price estimates show a large variation, also the near future (2020-2030) price estimates do so. In the pathway model, an upper and lower bound of the fuel price is used, similar to the upper and lower bounds given in the literature. The renewable fuel price estimates from Lloyd's Register and UMAS (2020) are the most conservative price estimates and the only estimates

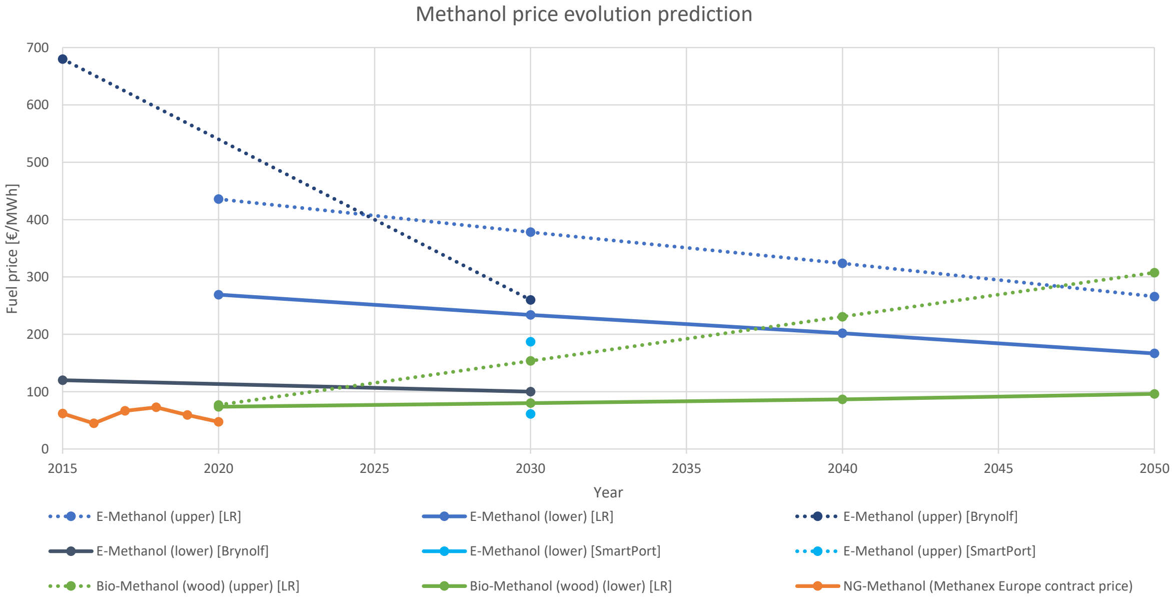


Figure 7.1: Fuel price evolution predictions of methanol from different feedstocks and different literature sources. LR: Lloyd's Register and UMAS (2020), Brynolf: Brynolf et al. (2018), SmartPort: TNO (2020), Methanex: Methanex (2020)

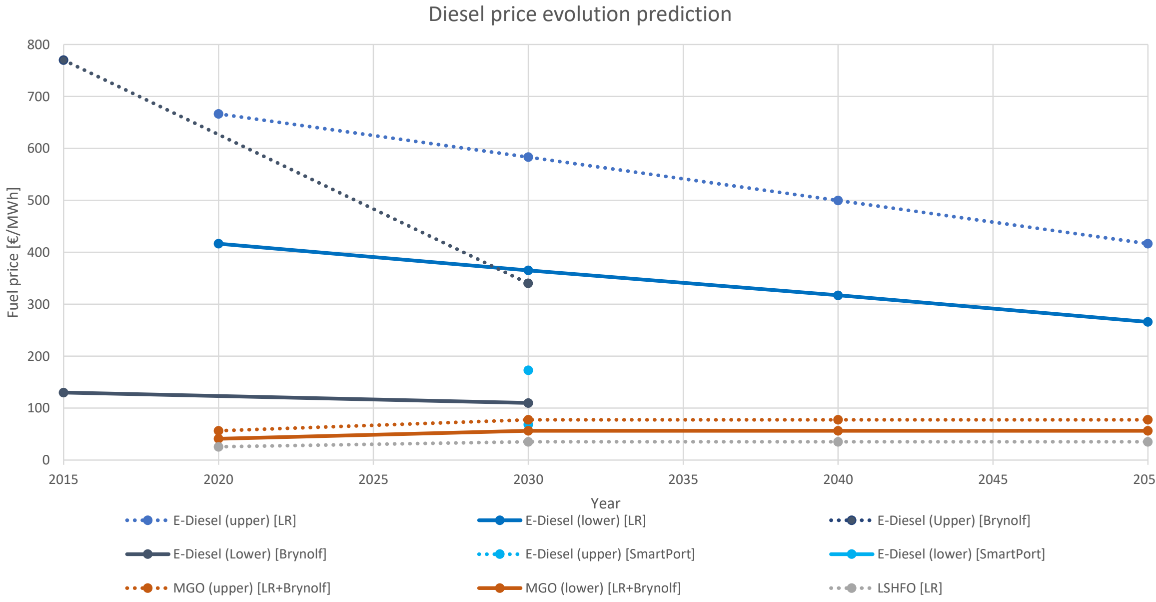


Figure 7.2: Fuel price evolution predictions of diesel from different feedstocks and different literature sources. LR: Lloyd's Register and UMAS (2020), Brynolf: Brynolf et al. (2018), SmartPort: TNO (2020).

found in the literature that span the entire duration of the pathways (2020-2050). Therefore these price estimates are used for the renewable price estimates of diesel and methanol. Lloyd's Register and UMAS (2020) did not estimate the fossil MGO price but only the fossil HFO price, which shows a slightly increasing trend between 2020 and 2050 as can be expected as fossil feedstocks are being depleted. Brynolf (2014) states that the price of fossil MGO is approximately 1.6 to 2.2 times the price of HFO. For the fossil MGO price, both literary sources are combined by using the HFO price estimates from Lloyd's Register multiplied by the factor of 2.2 from Brynolf (2014). For the fossil methanol price in 2020, historical price data from Methanex (2020) is used. The lower price limit is chosen as the lowest yearly averaged Europe contract price between 2015 and 2020 and the upper price limit is chosen as the highest yearly averaged Europe contract price between 2015 and 2020. The same trend as is used for the fossil diesel (MGO) price, is then applied to the fossil methanol 2020 price limits.

The fuel prices used in the pathway model in this thesis are shown in Table 7.1. The upper and lower bounds of the fuel prices, also result in an upper and lower bound of the yearly fuel costs (OPEX). The actual fuel costs will most likely be somewhere between this upper and lower boundary, but this is completely dependent on the evolution of both fossil and renewable fuel prices over the next decades.

Table 7.1: Fuel prices in €/MWh used in the pathway model in this thesis. For fossil methanol, an equal increase in price is assumed as found in the literature for fossil diesel (MGO).

Fuel	Feedstock	Price 2020		Price 2050	
		Lower limit	Upper limit	Lower limit	Upper limit
Diesel	Fossil	41	56	56	78
Diesel	Renewable	417	666	266	417
Methanol	Fossil	45	79	61	110
Methanol	Renewable	269	436	167	266

7.2.2. Converter efficiency

Another trend that is included is a change in the properties of the different converters. This is mainly relevant for fuel cells. Since fuel cells are still a very new technology, especially the HT-PEMFCs and SOFC considered in this research, it is likely that gains will be made in the efficiency of these converters. The gains in combustion engine efficiency using diesel are likely to be very minimal, and are deemed negligible. Since the use of methanol in an ICE is not very common and methanol has some benefits over conventional diesel (e.g. consists of a single molecule) it is likely that some small gains will be made in efficiency by fine tuning the engine to the use with methanol. For example, Volger (2019) states that the efficiency of methanol ICEs will increase from 40% in 2020 to 50% in 2050 and (methanol) LT-PEMFC efficiency increases from 55% in 2020 to 75% in 2050.

However, the efficiency changes presented by Volger (2019) appear rather high and there is a very large uncertainty regarding developments in these technologies and which gains in efficiency might be made. Therefore, as a worst case scenario, the efficiency of the converters is assumed constant at the 2020 efficiency values (i.e. no change in efficiency). The yearly fuel costs and emissions resulting from this pathway analysis will therefore form an upper limit to both and any future increases in efficiency of (some of) the converters will decrease the fuel cost and emissions of the pathway(s) using these converters.

7.2.3. Converter price

There are currently only a few methanol engines available. Methanol engines are mostly modified diesel engines and thus the price includes the base engine and the conversion costs. A methanol engine does not require after treatment, which reduces the total costs of the engine and after treatment. Therefore, a methanol engine is currently approximately as expensive as a diesel engine of the same power. However, more methanol engines may be expected in the coming years which can reduce the price of a methanol ICE. Fuel cells may also be expected to reduce in price over the coming decades as the technology matures. In order to implement this possible trend in price of the converters, a simple multiplication factor is applied. This factor is a linear function between a given value in 2020 and a value in 2050. The multiplication factor in 2020 is set to 1.0. If one expects the price of for example fuel cells to have decreased by 15% in 2050, the multiplication factor in 2020 is 0.85. Depending on the year when the converters are installed in the yacht (i.e. 2035 when there are two major refits between 2020 and 2050), the multiplication factor for that year can be determined from the linear trend between the two values.

As is the case with converter efficiency, the possible change in cost of these converters over the next decades is highly uncertain. Therefore, the cost of converters is also assumed constant over the period considered in this pathway analysis. The resulting estimate of the converter cost can be considered an upper limit and the actual cost may turn out to be lower than this estimate.

7.3. Chosen pathways

In this section, a short description of each pathway is given and the reasoning behind the converter and fuel choice as well as the scenario the pathway represents are described. The chosen pathways are:

- Pathway 0. The baseline pathway, using diesel ICEs from 2020 to 2050.
- Pathway 1. Using methanol ICEs from 2020 to 2050.
- Pathway 2. Using methanol ICEs and FCs from 2020 to 2050.
- Pathway 3. Using diesel ICEs from 2020 to 2035 and methanol ICEs from 2035 to 2050.
- Pathway 4. Using methanol ICEs from 2020 to 2035 and methanol ICEs and FCs from 2035 to 2050.

7.3.1. Pathway 0 - Baseline diesel ICE

The baseline scenario represents the conventional yachts (see the schematic Figure 7.3). Both the propulsion power and the auxiliary power demands are provided by internal combustion engines using diesel (MGO) as fuel. The baseline scenario keeps this configuration from 2020 to 2050. As the baseline pathway uses diesel (MGO) as fuel, this pathway is expected to have higher NO_x, SO_x and PM emissions than the pathways using methanol as fuel.

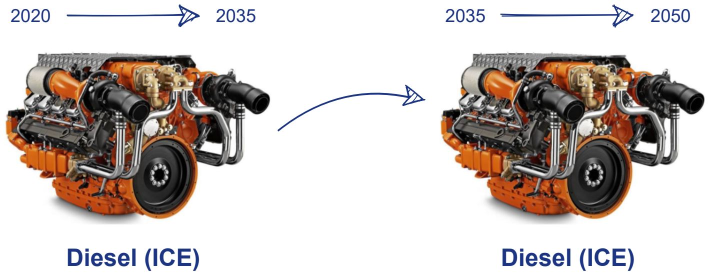


Figure 7.3: Pathway 0 - Baseline. Diesel internal combustion engines.

7.3.2. Pathway 1 - Methanol ICE

The first methanol pathway (see Figure 7.4) consists of to methanol converted internal combustion engines or internal combustion engines that are developed and build specifically for methanol, once they become (more) available, for the generation of propulsion and auxiliary power. This pathway keeps this configuration throughout the entire time span (2020 to 2050). This first methanol pathway is considered to have the least impact on the design and arrangement as the converters (methanol ICEs) have an equal size as diesel ICEs (or even are just modified diesel engines), which cannot be said for fuel cells. This pathway therefore represents a realistic and feasible methanol scenario without too much adjustments to the energy conversion system and is likely the first methanol configuration to be implemented. This pathway is expected to perform similarly to the baseline pathway in terms of costs, but offer lower NO$_x$, SO$_x$ and PM emissions.

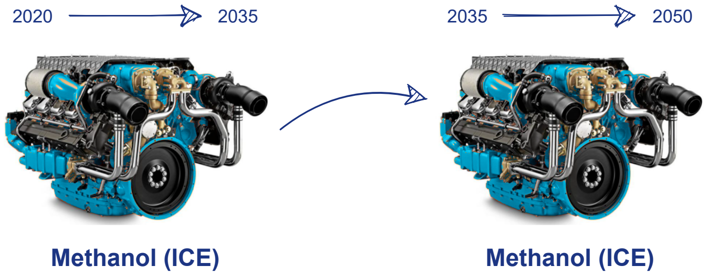


Figure 7.4: Pathway 1 - Methanol. Methanol internal combustion engines.

7.3.3. Pathway 2 - Methanol ICE+FC

In the second pathway (see Figure 7.5 the propulsion power is generated by the internal combustion engines running on methanol and the auxiliary power is generated by methanol fuel cells. This pathway uses this combination (ICE+FC) throughout the 2020 to 2050 time span. This pathway represents the scenario that fuel cells are either too expensive, too inefficient, do not have a long enough lifetime, are too large or a combination of these in order to deliver the full required power for auxiliary and

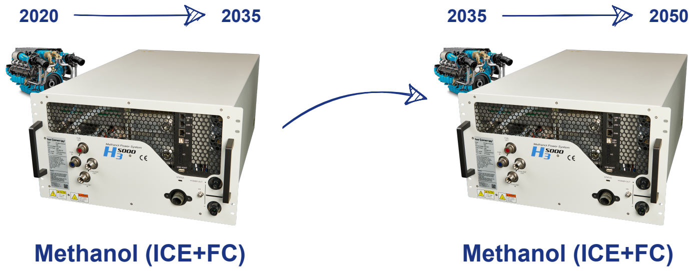


Figure 7.5: Pathway 2 - Methanol. Methanol internal combustion engines (propulsion power) and fuel cells (auxiliary power).

propulsion power. The fuel cells do however offer a much cleaner energy conversion than ICEs in terms of emissions, which can appeal to yacht owners, as well as a potentially higher efficiency that may increase between 2020 and 2050. If fuel cell prices decrease, efficiencies and lifetimes increase, this pathway can offer significant advantages compared to the methanol ICE configuration of pathway 1. Especially in the close future however, fuel cells are a very expensive alternative to ICEs and although they offer similar (to slightly higher) efficiencies, they are not yet on par with ICEs in terms of power density, price and lifetime.

7.3.4. Pathway 3 - Diesel ICE to methanol ICE

Pathway 3 is the only pathway of the four that postpones the transition from diesel to methanol to halfway 2020 and 2050 (Figure 7.6). From 2020 to 2035, regular diesel ICEs are used for the generation of propulsion and auxiliary power. From 2035 to 2050 methanol fuelled ICEs are used. This pathway represents the scenario that a yacht owner is not yet willing to switch to an alternative fuel. This can have many reasons such as availability of the fuel throughout the world, fuel prices which may be higher (and remain so for the first time span) and other costs associated with the switch to methanol which together may not justify the environmental advantages for the owner. As methanol converters develop and methanol becomes more available after a few decades then a switch to methanol may be more beneficial, hence the methanol configuration in the second time span (2035-2050). This pathway is expected be in between the baseline pathway 0 and pathway 1 in terms of costs and emissions.

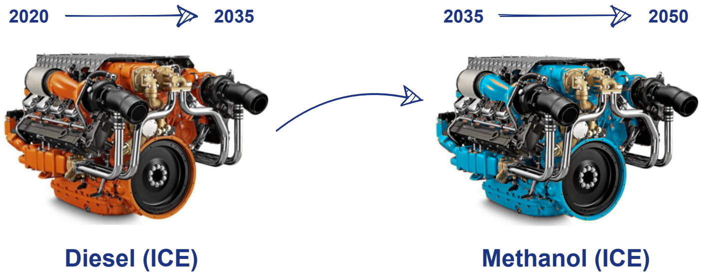


Figure 7.6: Pathway 3 - Diesel to methanol. Diesel internal combustion engines to methanol internal combustion engines.

7.3.5. Pathway 4 - Methanol ICE to methanol ICE+FC

The fourth pathway (Figure 7.7) uses methanol ICEs for the generation of propulsion and auxiliary power for the first period (2020-2035) and switches to fuel cells for the generation of auxiliary power for the second period (2035-2050). This pathway is between pathway 1 and pathway 2 and represents the scenario that fuel cells are not yet a feasible solution right from the start. This could have various reasons such as the price of fuel cells, efficiency, power density or lifetime. The switch to fuel cells is made in 2035, when it is expected that fuel cells have developed quite a bit to the point that they are a more feasible option. This pathway is expected to have lower total emissions than the other pathways, with the exception of pathway 2 which uses fuel cells throughout the entire time span, but at a higher capital cost than the pathways that use internal combustion engines from 2020 to 2050.

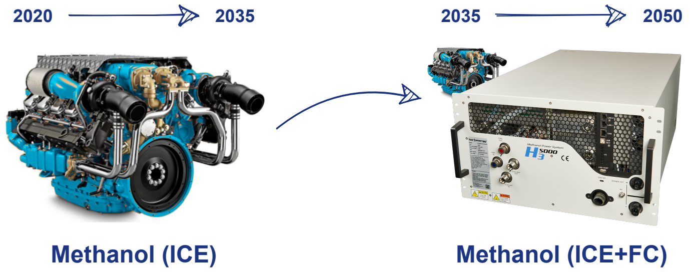


Figure 7.7: Pathway 4 - Methanol. Methanol internal combustion engines to methanol internal combustion engines (propulsion power) and methanol fuel cells (auxiliary power).

7.4. Pathways conclusion

In order to represent a few realistic future scenarios, 4 pathways that use methanol as fuel (at least for half of the pathway) were created. Next to the methanol pathway a diesel baseline pathway was created to which the methanol pathways could be compared. The baseline pathway represents the business as usual case where conventional fossil diesel is used in internal combustion engines (a renewable diesel case is also added to the baseline). The methanol pathways consist of a pathway using methanol internal combustion engines throughout the entire pathway, a pathway using methanol ICEs for propulsion power and HT-PEMFCs for auxiliary power throughout the entire pathway, a pathway delaying the switch to methanol by using diesel ICEs for the first half and methanol ICEs for the second half and a pathway that uses methanol ICEs for the first half and methanol ICEs for propulsion power and HT-PEMFCs for auxiliary power the second half. All pathways in this research could lead to a zero GHG emission yacht when renewable methanol (or renewable diesel) is used.

8

Case study

With the case study of several yachts, the main research question is answered: *what is the impact of methanol as fuel for existing and new yachts on costs, emissions and design for several pathways?* The goal of this case study is therefore to assess this impact of using methanol for a range of yachts, and to determine whether there is a difference in impact for yachts that have different sizes and design speeds.

A case study is done for three yachts to determine the impact of using methanol on the design and layout of the yacht. Different tank layout and converter options are investigated and their consequences discussed. In this these case studies, a configuration and tank layout for each yacht is chosen which is then used to determine the fuel costs and emissions between 2020 and 2050 of the pathways discussed in chapter 7 Pathways. The capital cost of the converters and methanol tanks of each pathway are also determined and related to the value of the yacht. This chapter contains the following case studies and pathways:

- Yacht A - Case study. The design options & impact and a trim impact assessment.
- Yacht B - Case study. The design options & impact and a trim impact assessment.
- Pathway 0 - Baseline diesel ICE. Emissions and costs of yachts A and B.
- Pathway 1 - Methanol ICE. Emissions and costs of yachts A and B.
- Pathway 2 - Methanol ICE+FC. Emissions and costs of yachts A and B.
- Pathway 3 - Diesel ICE to Methanol ICE. Emissions and costs of yachts A and B.
- Pathway 4 - Methanol ICE to Methanol ICE+FC. Emissions and costs of yachts A and B.

The third yacht (yacht C) is not shown in this chapter as this yacht is considered outside the limits of the design tool and therefore the results are less reliable and accurate. The resistance and propulsion power prediction for this yacht at lower speeds were found to be particularly inaccurate (see section 6.3). This is partly due to an incorrect resistance prediction by the Holtrop & Mennen method and partly due to the waterjets which are not implemented as a propulsion method in the design tool. Nevertheless, one may be interested in an indication of the impact of methanol on a small high speed yacht. The results of the case study for yacht C can be found in Appendix D.

An assessment of the impact of the tank layout on trim is not part of the design impact tool. However, since the tank layouts of the methanol tanks are very different from conventional diesel tank layouts, which are typically spread over the double bottom, it is desirable to estimate the magnitude of the impact on trim. The design tool does provide the required information for the user to check this trim impact manually. When stability information of the original diesel reference yacht is available, the centre of gravity and actual weight of the methanol tank(s) following from the design tool can be used to determine the effect of the methanol tanks on trim and draught. This is done for yacht A and yacht B.

8.1. Yacht A - Large low speed yacht

The first case study is done for a relatively large yacht that has a low Froude number at maximum sailing speed. The particulars of yacht A, such as the main dimensions, maximum and range speeds and required range, are shown in Table 8.1. The operational profile of the this yacht is shown in Figure 8.1. This operational profile is based on AIS data of the reference yacht. The operational profile is used to determine the yearly fuel consumption of the different pathways. For yacht A, most of the time is spend in a harbour or in port which make up 87% of the operational profile together with the time in service. The rest of the time the yacht sails, mostly at a speed between 2.5 knots and cruising speed (i.e. cruise slow in the operational profile). Only a very small percentage of time is sailed at a speed close to the maximum speed.

Table 8.1: Main particulars of yacht A.

Property	Value	Unit
L_{WL}	99.35	m
B_{WL}	15.50	m
T_{design}	4.25	m
Δ	3607	t
v_{max}	18.5	kn
v_{range}	15.0	kn
$Fn_{v_{max}}$	0.305	-
$range_{req}$	5200	nm

With the properties of the yacht, the design tool determines the power and energy requirements for the converters and storage of fuel (see 5.1 Power and fuel capacity requirements). The power required for propulsion and auxiliary power in different scenarios in the operational profile are shown in Table 8.2.

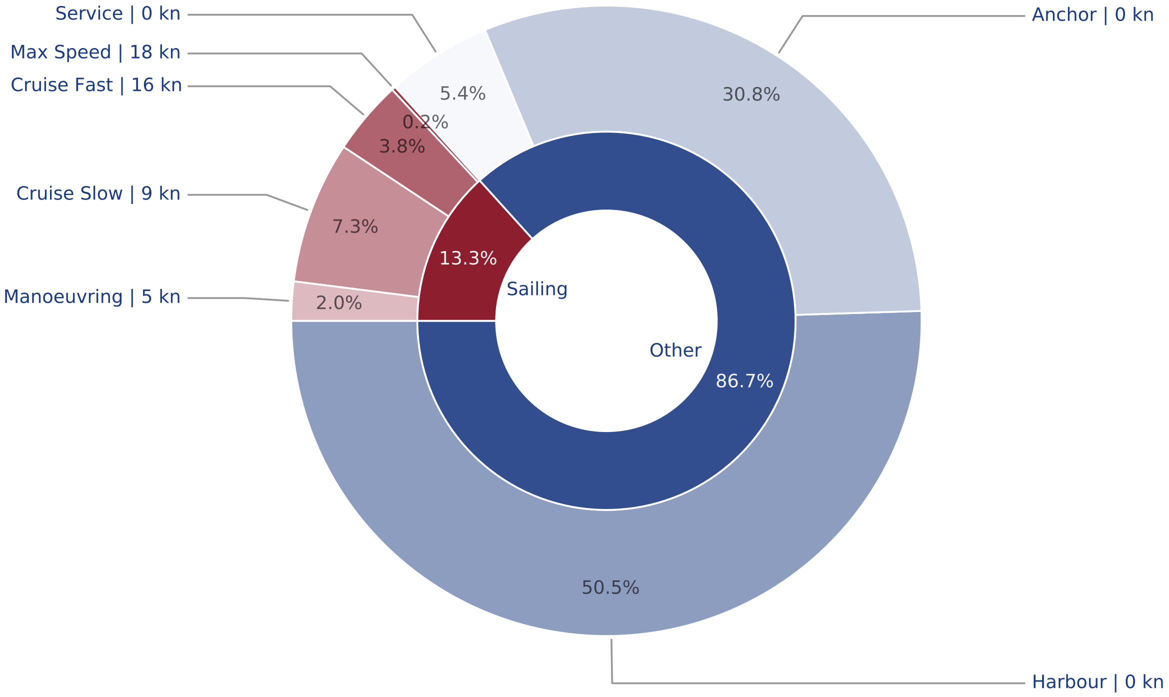


Figure 8.1: Operational profile of yacht A. The average speeds used in the fuel consumption calculation are shown next to the operation. The percentages show the amount of time in a year that is spend in this operation.

Table 8.2: Required propulsion and auxiliary power (in kW) determined from the properties of yacht A (before the length increase iteration).

Power	Propulsion		Auxiliary					
Scenario	v_{max}	v_{range}	Installed	Sailing guests	Sailing crew	Manoeuvring	Harbour	Anchor
P_{req}	8187	3993	1877	743	541	1495	583	579

8.1.1. Design - options & impact

In order to determine the design impact of methanol for this yacht, the two tank layouts (1 tank and 2 tanks) are both reviewed, as well as the converter choice. In Table 8.3 the required fuel volume, the achieved fuel volume and the usage factor of the tank(s) are shown. The required fuel volume given in this table is determined through the range calculation (see 5.1.5) after the length increase iteration (see 5.2.5). The achieved fuel volume is determined through the available space calculation (see 5.2) also including the length increase iteration as is done for the required fuel volume. The usage factor of the tank is determined through Equation 4.1 and represents the storage efficiency of the tank. A high usage factor represents a high methanol volume over total tank volume (including cofferdams) ratio.

The impact of using methanol in combination with ICEs or fuel cells on the required fuel volume can clearly be seen in Table 8.3. The required methanol volume is around 2.3 times the required diesel volume, which is in line with the LHV difference between both fuels. Using fuel cells for the auxiliary power slightly decreases the required volume, as the efficiency of the used HT-PEMFCs is only slightly higher (42 - 45% compared to approximately 40%). The required fuel volume for two tanks is a little higher than for the one tank configuration. This is because two tanks are less efficient in terms of volume in storing the fuel as relatively more cofferdam volume surrounds the tanks. Therefore, the ship's length is increased more in the length increase iteration step (5.25 m compared to 4.50 m), resulting in a higher fuel consumption because the resistance at range speed has increased. The achieved fuel volume is also shown for both tank layouts and are rather close to the required fuel volume. The single tank has a higher usage factor of 0.743 compared to the 0.685 of the two tank configuration, which is a slight decrease of 8% in storage efficiency compared to the single tank configuration. Both methanol tanks lose around 30% of volume to the cofferdams surrounding the tanks.

When looking at the alternative cofferdam configurations (second values in the table) one can see that the required fuel volumes are equal to that of the normal cofferdam layouts (first values). The achieved fuel volumes are slightly closer to the required fuel volumes than the normal cofferdam layouts for the single tank layouts but not for the double tank layouts. The fuel tanks with alternative cofferdams are smaller (shorter in length) than the normal cofferdam layouts (see Figure 8.3, Figure 8.4, Figure 8.5 and Figure 8.6) but offer more fuel volume. This change in achieved volume is because the alternative cofferdams use less volume than the normal cofferdams but since the tanks are aligned to the ship's frames it can occur that reducing the tank length by another frame length results in an achieved fuel volume that would be less than the required fuel volume. That the alternative cofferdams use less volume can also clearly be seen from the usage factors which are close to 1 with only 4 to 5% of the total tank volume being used by the alternative cofferdams. This is much less than the 30% of the normal cofferdams.

The diesel baseline and methanol configurations and tank layouts options are shown in Figure 8.2, Figure 8.3, Figure 8.4, Figure 8.5 and Figure 8.6 on the next pages. The engines and fuel cell configurations are determined with the number of main engines set to 2, the number of generator sets between 2 and 4 (determined based on required power and optimal load percentage) and the number of fuel cells between 1 and 14 (determined as the generator sets). The top views for the alternative cofferdam configurations are very similar to the normal cofferdam configurations and are therefore not shown.

When comparing Figure 8.3 to Figure 8.2 it is clear that the methanol tank volumes are significant

Table 8.3: Required tank volume ($V_{fuel,req}$) following from the range calculation and the achieved fuel volume (V_{fuel}), after the length increase iteration (Δ_l). For the usage factor (Equation 4.1) the first value is with normal cofferdams and the second with alternative cofferdams.

Configuration	1 tank				2 tanks			
	$V_{fuel,req}$ [m^3]	V_{fuel} [m^3]	f_{usage} [-]	Δ_l [m]	$V_{fuel,req}$ [m^3]	V_{fuel} [m^3]	f_{usage} [-]	Δ_l [m]
MGO - ICE	424^a	440^a	1.000^a	0	-	-	-	0
MeOH - ICE	966/966	990/980	0.743/0.960	4.50/4.50	964/964	969/979	0.685/0.950	5.25/5.25
MeOH - ICE+FC	959/959	990/980	0.743/0.960	4.50/4.50	957/957	969/979	0.685/0.950	5.25/5.25

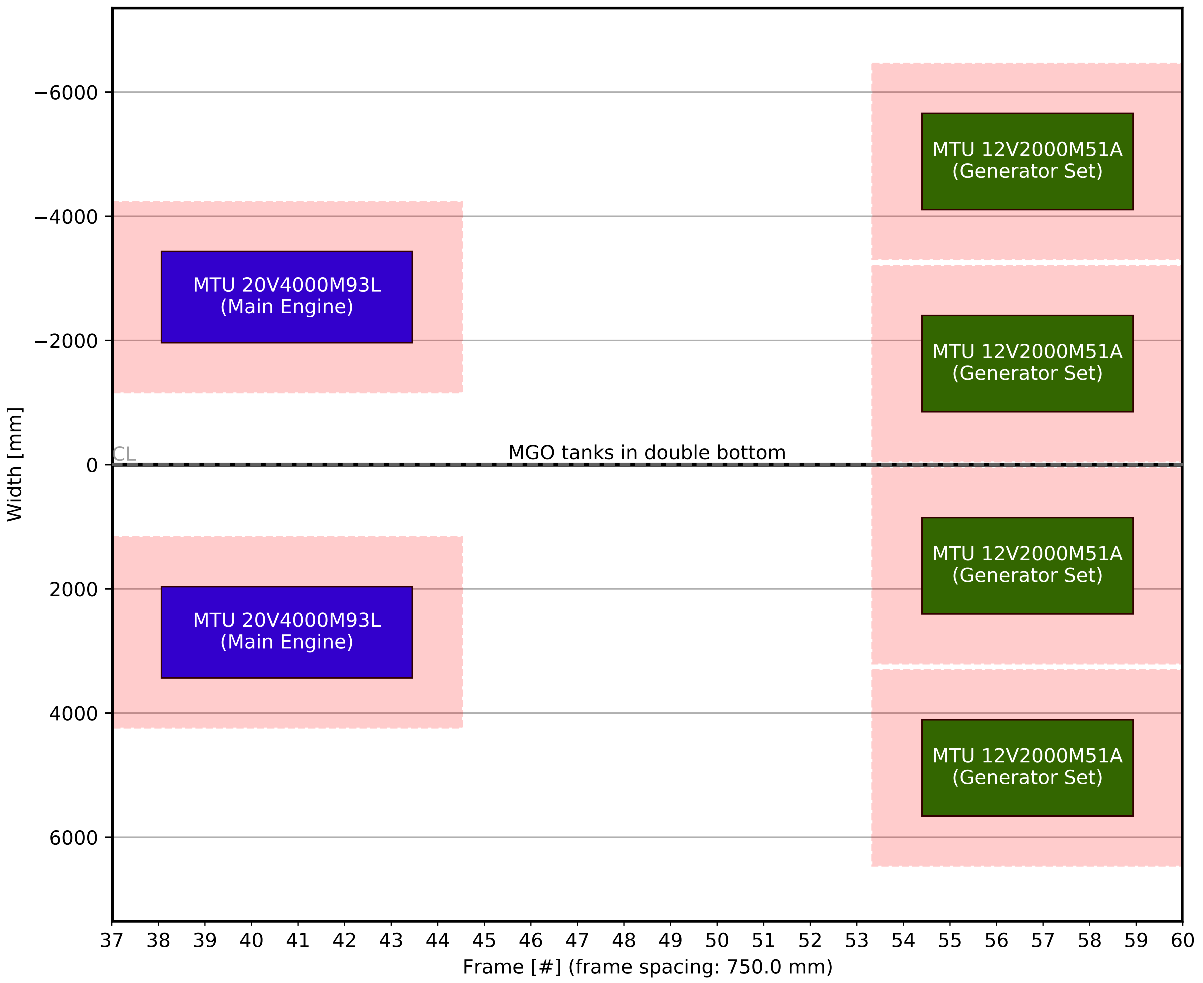
^{a} Diesel tanks are in the double bottom and no length iteration is done.

and occupy a large amount of interior space. Especially since diesel is stored in the double bottom and therefore doesn't occupy any interior space. With methanol however, this option is not considered feasible in terms of construction of the tanks and cofferdams. For this relatively large yacht, with a single tank, the minimum dimensions of the normal cofferdam are not that large compared to the dimensions of the tank. For the two tank layout of Figure 8.4 the share of cofferdams in the total tank volume becomes larger, which was also shown in Table 8.3 by the lower usage factor. In general the tanks become less efficient in storing methanol when the tank dimensions become smaller relative to the cofferdam dimensions. This can be seen in the aft tank of Figure 8.4. That the tanks become smaller relative to the cofferdam dimensions is also a direct consequence of an increase in amount of (separate) tanks. Reducing the dimensions of the cofferdam partly remedies this effect, which is done in the alternative cofferdam layouts.

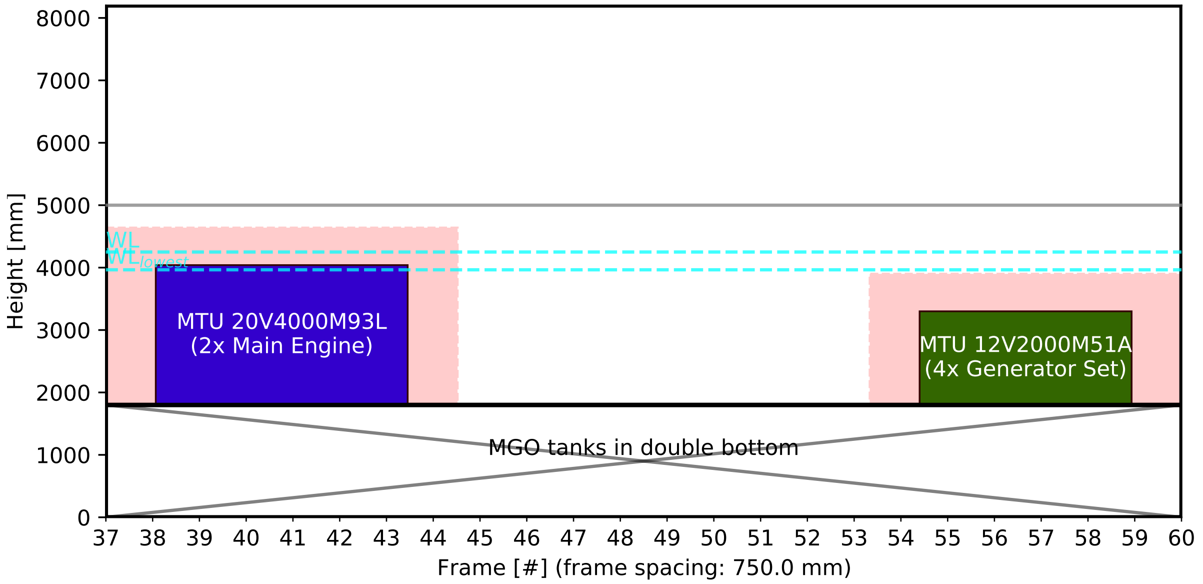
Since the hull of most yachts shapes upwards towards the aft, to make room for the propeller and improve the propeller inflow, the tank located to the aft of the yacht has a smaller height than the tank around the midship. This is visualised in the layout figures as a rectangular tank with a height from the lowest possible waterline down to halfway between this waterline and the keel but in reality this tank follows the bottom shell plating (the tool only uses an average cross sectional area). Because the (average) height of this aft tank is smaller than the central tank, this aft tank is even less efficient in storing methanol than the central tank. This aft tank therefore occupies relatively more interior area than the central tank does per unit fuel volume. This can also be seen in Table 8.4. A significant increase in interior area occurs when switching from a one tank layout to a two tank layout: +20.8% and +14.6% for normal cofferdams and alternative cofferdams respectively.

Table 8.4: Interior area usage (A_{int}) for the diesel reference layout, the one tank methanol layout and the two tank methanol layout all using ICEs only and the required length increase (Δ_l) to keep the interior area equal. The diesel reference layout has tanks in the double bottom which do not require interior area.

Tank layout	Total				Central tank			Aft tank		
	V_{fuel} [m^3]	f_{usage} [-]	A_{int} [m^2]	Δ_l [m]	V_{fuel} [m^3]	f_{usage} [-]	A_{int} [m^2]	V_{fuel} [m^3]	f_{usage} [-]	A_{int} [m^2]
MGO - DB	440	1.000	0	0	-	-	-	-	-	-
MeOH - 1 tank	990	0.743	337	4.50	990	0.743	337	-	-	-
MeOH - 1 tank - Alt cofferdams	980	0.960	314	4.50	980	0.960	314	-	-	-
MeOH - 2 tanks	969	0.685	407	5.25	660	0.718	232	309	0.623	174
MeOH - 2 tanks - Alt cofferdams	979	0.950	360	5.25	724	0.957	233	255	0.931	128

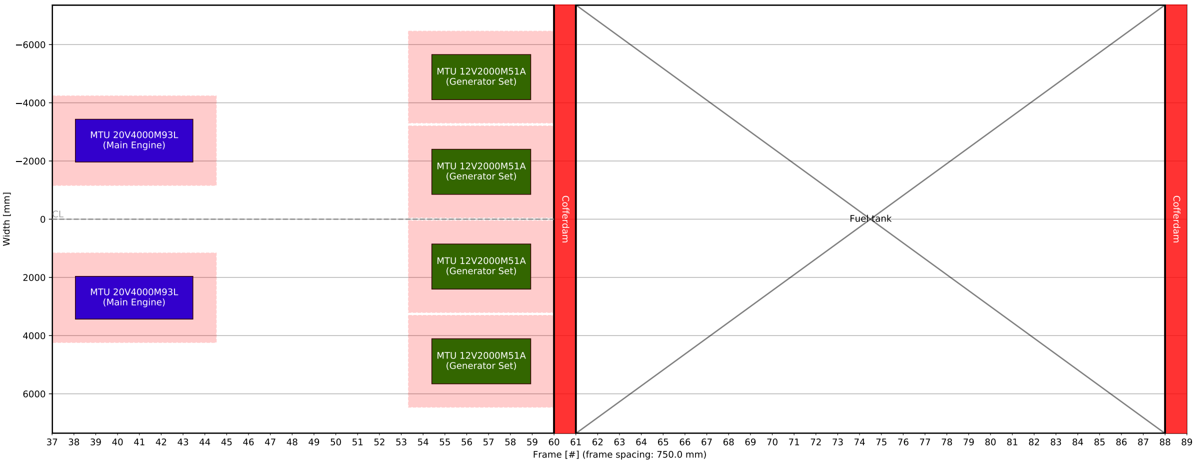


(a) Top view of the diesel baseline layout with ICEs for propulsion and auxiliary power.

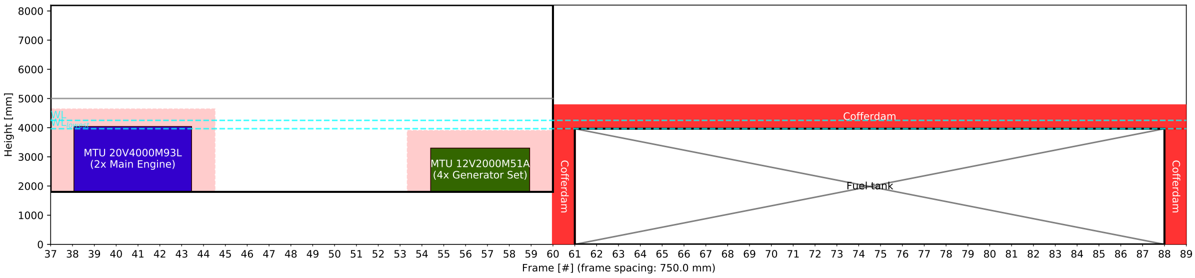


(b) Side view of the diesel baseline layout with ICEs for propulsion and auxiliary power.

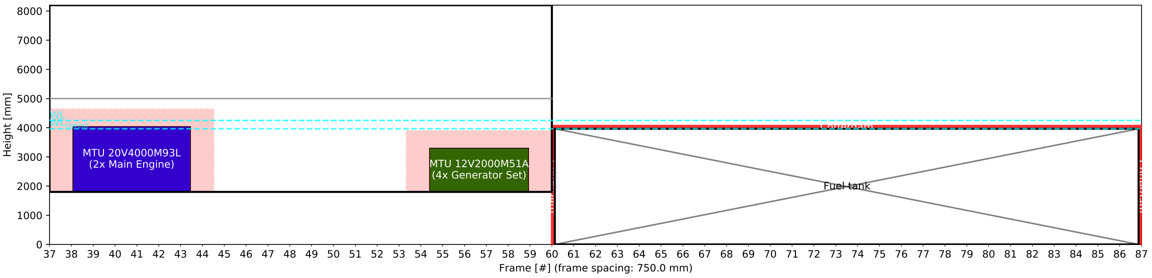
Figure 8.2: Schematic layout of the diesel baseline with MGO tanks in the double bottom.



(a) Top view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

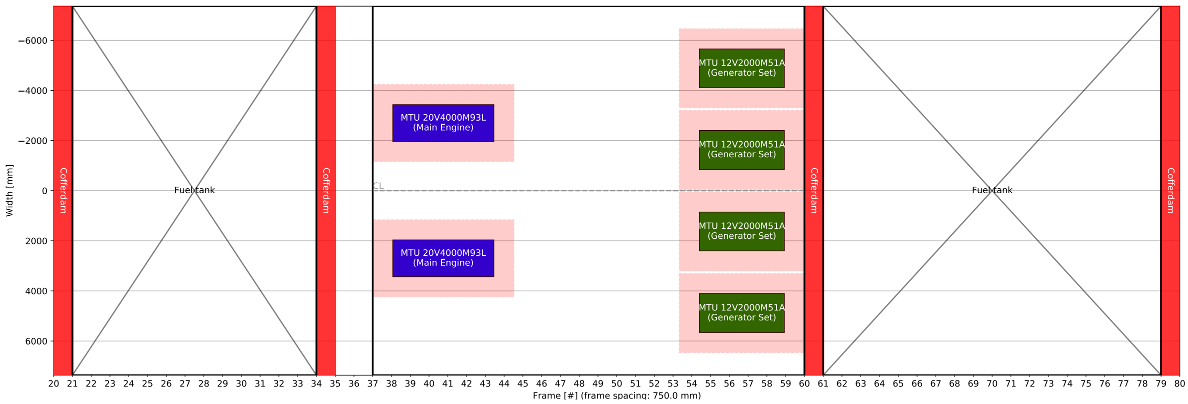


(b) Side view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

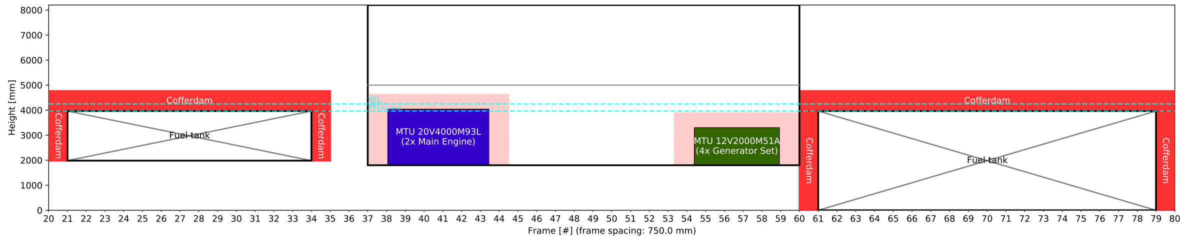


(c) Side view of the methanol layout with ICEs for propulsion and auxiliary power and alternative cofferdams. Top view is very similar to Figure 8.3a but with smaller cofferdams.

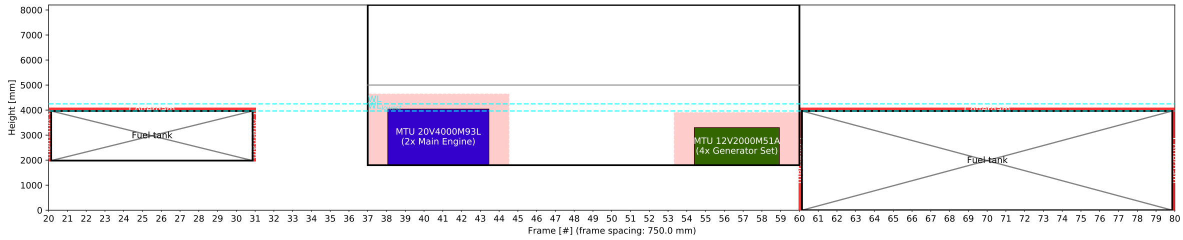
Figure 8.3: Schematic layouts of the ICE methanol configuration with one tank.



(a) Top view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

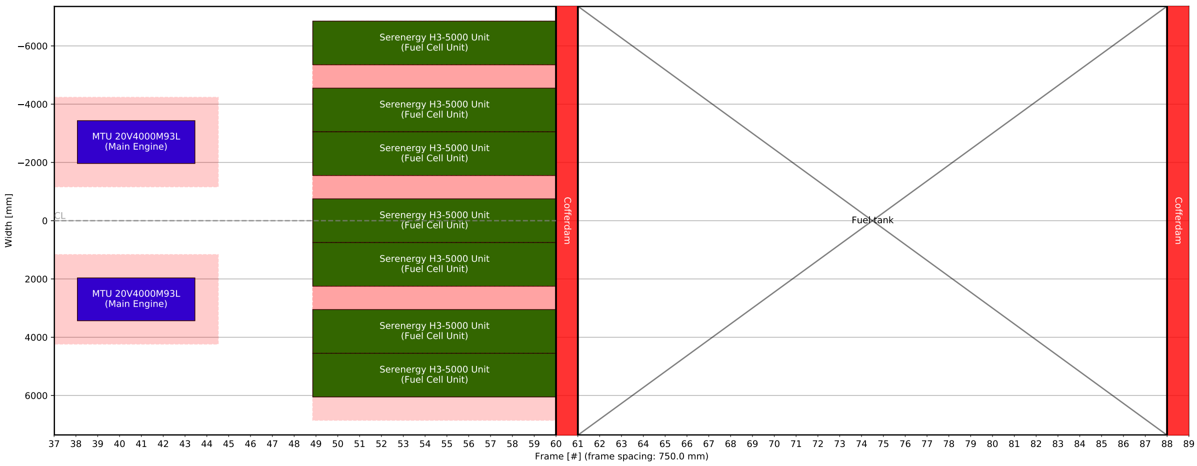


(b) Side view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

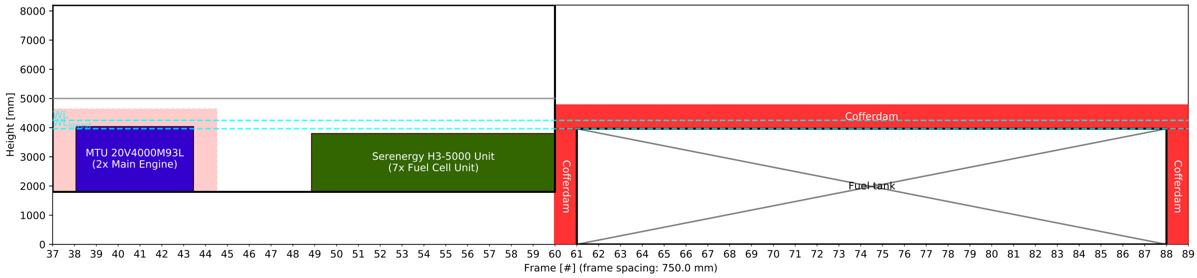


(c) Side view of the methanol layout with ICEs for propulsion and auxiliary power and alternative cofferdams. Top view is very similar to Figure 8.4a but with smaller cofferdams.

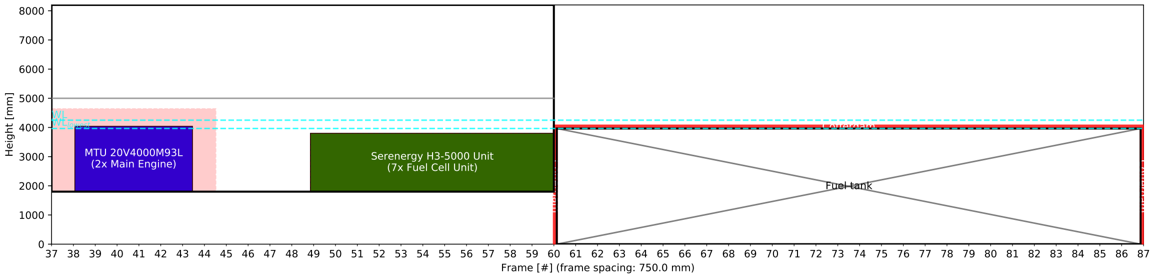
Figure 8.4: Schematic layouts of the ICE methanol configuration with one tank around midship and a second tank in the aft of the yacht.



(a) Top view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.

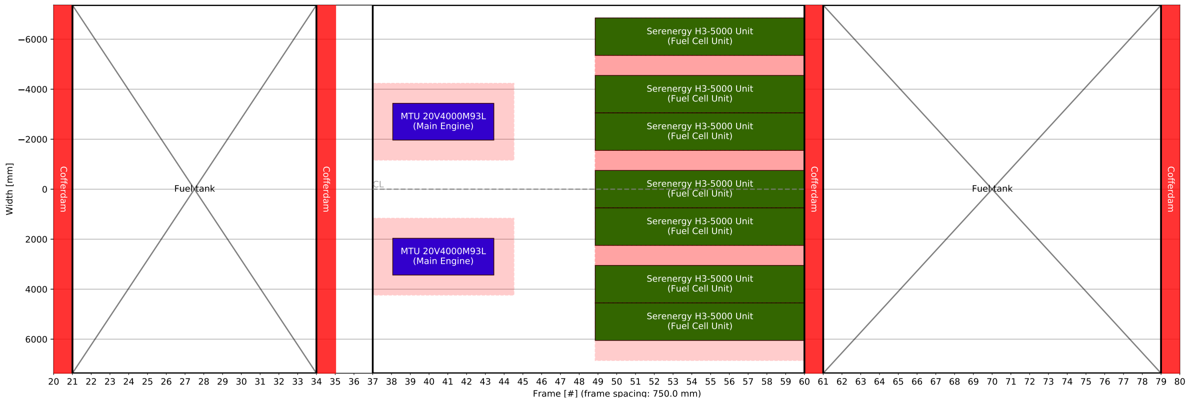


(b) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.

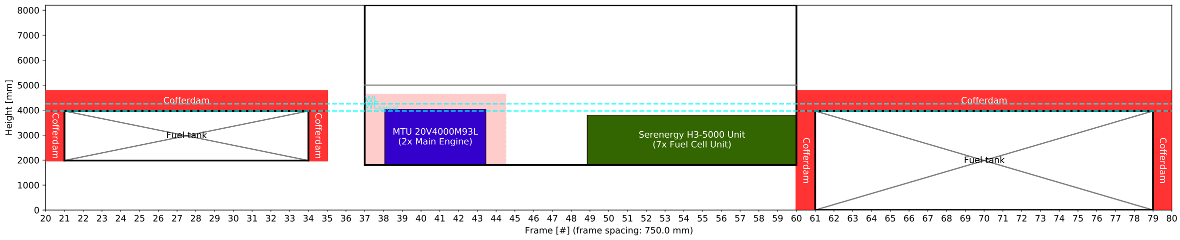


(c) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and alternative cofferdams. Top view is very similar to Figure 8.5a but with smaller cofferdams.

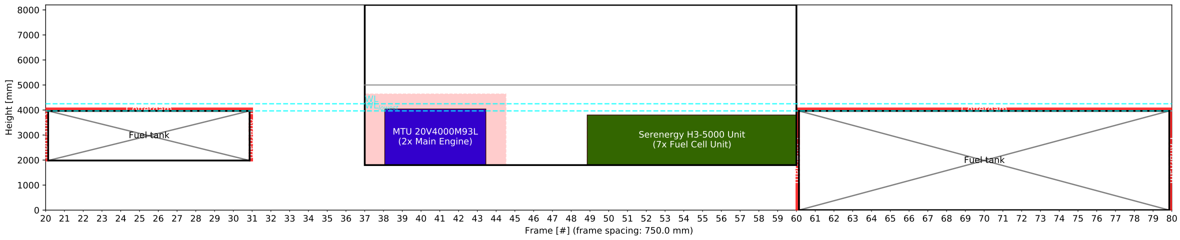
Figure 8.5: Schematic layouts of the ICE+FC methanol configuration with one tank.



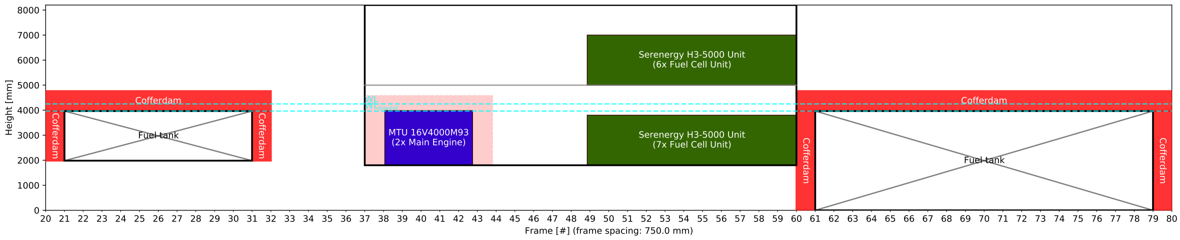
(a) Top view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.



(b) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.



(c) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and alternative cofferdams. Top view is very similar to Figure 8.6a but with smaller cofferdams.



(d) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for propulsion (up to 12 knots) and auxiliary power and normal cofferdams. The fuel cells also provide propulsion power up to 12 knots: 1999 kW propulsion + 1877 kW auxiliary. Therefore the main engines have to deliver less power: 6188 kW (6240 kW installed).

Figure 8.6: Schematic layouts of the ICE+FC methanol configuration with one tank around midship and a second tank in the aft of the yacht.

Trim

As stated before, having the least amount of tanks possible is beneficial from a volumetric efficiency point of view. However, having a tank layout with two tanks does have a large benefit which is also very important in the design of a yacht: trimming capabilities. In order to determine the impact of the methanol tank layouts on trim, the properties of the tank layout of yacht A are combined with stability booklets of the original diesel reference yacht. This is done by first subtracting the diesel fuel mass and COG from the yacht and then adding the methanol fuel mass at the COG of the methanol tanks. The change in trim and draught is then determined from the difference in weight and LCG location between the methanol layout and the diesel layout, which is then multiplied by the moment required to change the trim [t m/cm] and the ton per cm immersion respectively to find the new trim and draught. It is also checked whether it is possible to trim the yacht to its original trim with the water ballast available on board the original yacht and what the COG of the water ballast would have to be. The results of this trim analysis are shown in Table 8.5.

From Table 8.5 it is clear that in all cases the draught increases and the trim changes. The draught increase ranges from 31.6 cm (+7.4%) for the full loaded condition (98% fuel) to 3.2 cm (+0.8%) for the light loaded condition (9.8% fuel). However, the length increase iteration as applied in this research is not taken into account in this draught and trim analysis. When the ship's length is increased, it is likely that both the (design) draught and the ton/cm immersion will change, resulting in a methanol draught that is closer to the original draught. The trim change is rather large for the layout with 1 tank. The original yacht has a negative trim (aft has a larger draught than the front). By using only a single methanol tank in front of the engine room, which LCG is located in front of the LCG of the yacht in this case, the yacht is trimmed forward resulting in a less negative trim. For the full load, the yacht is trimmed forward significantly (+44.8%, i.e. less negative trim). This amount of change in trim cannot be compensated by locating all water ballast at the required LCG since this location is not within the yacht. However, it is up to the naval architect to determine whether this change in trim is an issue (the yacht is still trimmed more aft than in half loaded condition. In general the 1 tank layout, although this tank consists of a few smaller tanks, offers very limited options to change the trim. The 2 tank layout offers much more trim options and may offer very similar trim options, depending on the exact LCGs of the tanks and the volume/weight distribution between the two tanks.

In conclusion, although a single tank is preferred because it offers more fuel volume at a smaller loss of interior, two tanks are preferred because it offers much more trim options. The trim options with a single tank are severely limited, while a two tank layout can eliminate this problem. The two tank layouts (in combination with ICEs and ICEs+FCs) will be used for the pathway analysis of this yacht.

Table 8.5: Draft [m] and trim [m] of the original diesel yacht, the methanol 1 tank layout and the methanol 2 tanks layout. The required location of the LCG of available water ballast to cancel the trim change is also shown [m from aft].

Property	Full loaded condition			Half loaded condition			Light loaded condition		
	MGO	1 tank	2 tanks	MGO	1 tank	2 tanks	MGO	1 tank	2 tanks
Draught (mean) [m]	4.285	4.601	4.597	4.122	4.281	4.278	3.965	3.997	3.996
Trim [m]	-0.297	-0.164	-0.280	-0.068	-0.042	-0.074	-0.262	-0.260	-0.261
LCG_{req} water ballast [m]	-	-40.384	49.462	-	0.773	72.755	-	9.922	35.978

8.2. Yacht B - Small low speed yacht

The second case study is done for a smaller yacht that has a low Froude number at maximum sailing speed. The particulars of this yacht B, such as the main dimensions, maximum and range speeds and required range, are shown in Table 8.6. The operational profile of the this yacht is shown in Figure 8.7. This operational profile is based on AIS data of the reference yacht. The operational profile is used to determine the yearly fuel consumption of the different pathways. The operational profile of this yacht is different than the operational profile of yacht A. Yacht B has a relatively large sailing time and time spend in harbour. Of the time spend sailing also a relatively large percentage of time is spend sailing close to the maximum speed of the yacht, as the maximum speed of this yacht is relatively low.

Table 8.6: Main particulars of yacht B.

Property	Value	Unit
L_{WL}	49.26	m
B_{WL}	10.10	m
T_{design}	3.35	m
Δ	854	t
v_{max}	14.5	kn
v_{range}	11.0	kn
$Fn_{v_{max}}$	0.339	-
$range_{req}$	4500	nm

With the properties of the yacht, the design tool determines the power requirements for the converters and the energy storage requirements of the fuel (see 5.1 Power and fuel capacity requirements). The power required for propulsion and auxiliary power in different scenarios in the operational profile are shown in Table 8.7.

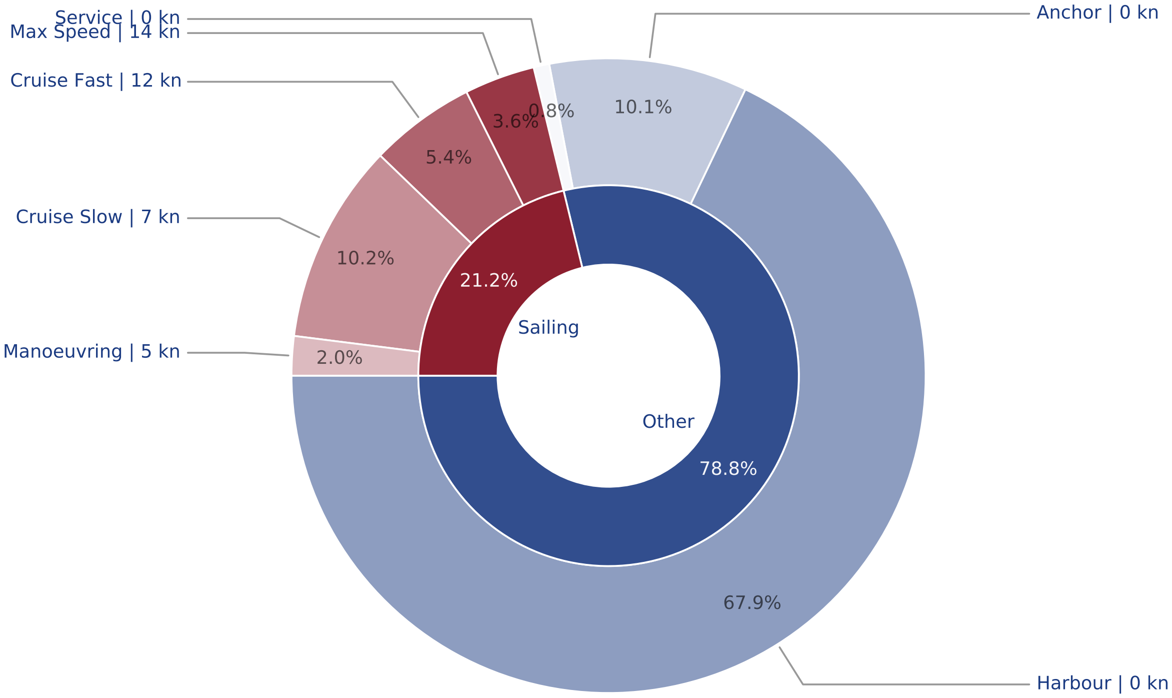


Figure 8.7: Operational profile of yacht B. The average speeds used in the fuel consumption calculation are shown next to the operation. The percentages show the amount of time in a year that is spend in this operation.

Table 8.7: Required propulsion and auxiliary power (in kW) determined from the properties of yacht B (before the length increase iteration).

Power	Propulsion		Auxiliary					
Scenario	v_{max}	v_{range}	Installed	Sailing guests	Sailing crew	Manoeuvring	Harbour	Anchor
P_{req}	1849	578	449	305	270	442	264	265

8.2.1. Design - options & impact

In order to determine the design impact of methanol for this yacht, the two tank layouts (1 tank and 2 tanks) are both reviewed, as well as the converters and their impact on the design. In Table 8.8 the required fuel volume, the achieved fuel volume and the usage factor of the tank(s) are shown. The required fuel volume given in this table is determined through the range calculation (see 5.1.5) after the length increase iteration (see 5.2.5) to keep the interior area equal to the diesel baseline. The achieved fuel volume is determined through the available space calculation (see 5.2) also including the length increase iteration as is done for the required fuel volume. The usage factor of the tank is determined through Equation 4.1 and represents the storage efficiency of the tank. A high usage factor represents a high methanol volume over total tank volume (including cofferdams) ratio which means that the cofferdam volume is relatively small compared to the tank volume usable for fuel.

The impact of using methanol in combination with ICEs or fuel cells on the required fuel volume is again, like yacht A, clearly seen in Table 8.8. The required methanol volume is around 2.3 times the required diesel volume, which is in line with the LHV difference between both fuels. Using fuel cells for the auxiliary power slightly decreases the required volume, as the efficiency of the used HT-PEMFCs is only slightly higher (42 - 45% compared to approximately 40%).

The usage factors for both the one tank and two tanks layout are significantly lower for yacht B than for yacht A (see Table 8.3). Yacht B has a single methanol tank usage factor of 0.601 compared to a usage factor of 0.743 for yacht A with the same tank layout, a decrease of 19%. An even larger decrease in usage factor between yacht B and yacht A is seen for the two tank layout of 27%. This decrease in usage factor, and therefore fuel storage efficiency, can be explained by the relation between the required minimal cofferdam dimensions and the frame spacing of the yacht. Yacht A has a frame spacing that is larger than the minimal cofferdam width which means that a single frame width can be used for the transverse cofferdams surrounding the tank. For yacht B the frame spacing is less than the minimum cofferdam width, resulting in a cofferdam that spans two frames as can be seen in Figure 8.9. This decreases the usage factor significantly. Next to that, the height of the cofferdam above the tank has a fixed minimum height. When the height of the lowest possible waterline decreases, the height of the cofferdam becomes relatively large compared to the height of the tank, which also results in relatively more volume that is used by the cofferdam instead of the storage of fuel. The usage factor therefore depends mostly on the height of the lowest possible waterline and on the frame spacing of the yacht in relation to the minimum cofferdam width, both of which generally decrease with smaller yachts.

Table 8.8 also shows a significant reduction in usage factor when two tanks are used instead of one. A usage factor of 0.601 for one tank and 0.503 for two tanks which is a decrease of 16%. For the same fuel volume that is stored, 16% more total volume (including cofferdams) is used by the 2 tank layout compared to the single tank layout. The usage factor would be even lower if more separate tanks were used. The effect of using two separate tanks is also seen on the length increase that is required to keep the interior area equal (or at least equal since the length increase is rounded up to whole frame lengths). With one tank the length increase is 3.0 m which is a 6.1% increase in waterline length, while with two tanks this length increase becomes 3.5 m which is a 7.1% increase in waterline length for approximately the same fuel volume. For yacht B in general, the cofferdams use a very large part of the total volume with 40% for the single tank and 50% for the two tank layout being used by the

Table 8.8: Required tank volume ($V_{fuel,req}$) following from the range calculation and the achieved fuel volume (V_{fuel}), after the length increase iteration (Δ_l). The usage factor is also shown for the tank layouts. The first value in each column is when normal cofferdams are used, the second with alternative cofferdams. ^{a} Diesel tanks are in the double bottom and no length iteration is done.

Configuration	1 tank				2 tanks			
	$V_{fuel,req}$ [m^3]	V_{fuel} [m^3]	f_{usage} [-]	Δ_l [m]	$V_{fuel,req}$ [m^3]	V_{fuel} [m^3]	f_{usage} [-]	Δ_l [m]
MGO - ICE	86^a	93^a	1.000^a	0	-	-	-	0
MeOH - ICE	194/194	198/205	0.601/0.938	3.00/2.50	193/194	194/200	0.503/0.919	3.50/3.00
MeOH - ICE+FC	186/187	186/193	0.594/0.937	3.00/2.50	185/187	186/192	0.497/0.918	3.50/2.50

cofferdams. Alternative cofferdams offer a solution for this storage inefficiency, requiring less than 10% of the total volume for cofferdams. In general the use of alternative cofferdams results in a decrease in length increase required, especially for the two tank layout.

The diesel baseline and methanol configurations and tank layouts options are shown in Figure 8.8, Figure 8.9, Figure 8.10, Figure 8.11 and Figure 8.12 on the next pages. The engines and fuel cell configurations are determined with the number of main engines set to 2, the number of generator sets between 2 and 4 (determined based on required power and optimal load percentage) and the number of fuel cells between 1 and 10 (determined as the generator sets). The top views for the alternative cofferdam configurations are very similar to the normal cofferdam configurations and are therefore not shown.

When comparing Figure 8.9 to Figure 8.8 it is clear that the methanol tank volumes are significant and occupy a large amount of interior space. Especially since diesel is stored in the double bottom and therefore doesn't occupy any interior space. With methanol however, this option is not considered feasible in terms of construction of the tanks and cofferdams. For this smaller yacht one can see that the cofferdams use a significant amount of space relative to the fuel volume, for a single tank configuration. This is the result of the minimum dimensions of the normal cofferdam which are quite large compared to the dimensions of the tank as well as the fact that two frame lengths are required for the transverse cofferdams. For the two tank layout of Figure 8.10 the share of cofferdams in the total tank volume becomes even larger, which was also shown in Table 8.8 by the lower usage factor. In general the tanks become less efficient in storing methanol when the tank dimensions become smaller relative to the cofferdam dimensions. This can be seen in the aft tank of Figure 8.10. That the tanks become smaller relative to the cofferdam dimensions is also a direct consequence of an increase in amount of (separate) tanks. Reducing the dimensions of the cofferdam partly remedies this effect, which is done in the alternative cofferdam layouts.

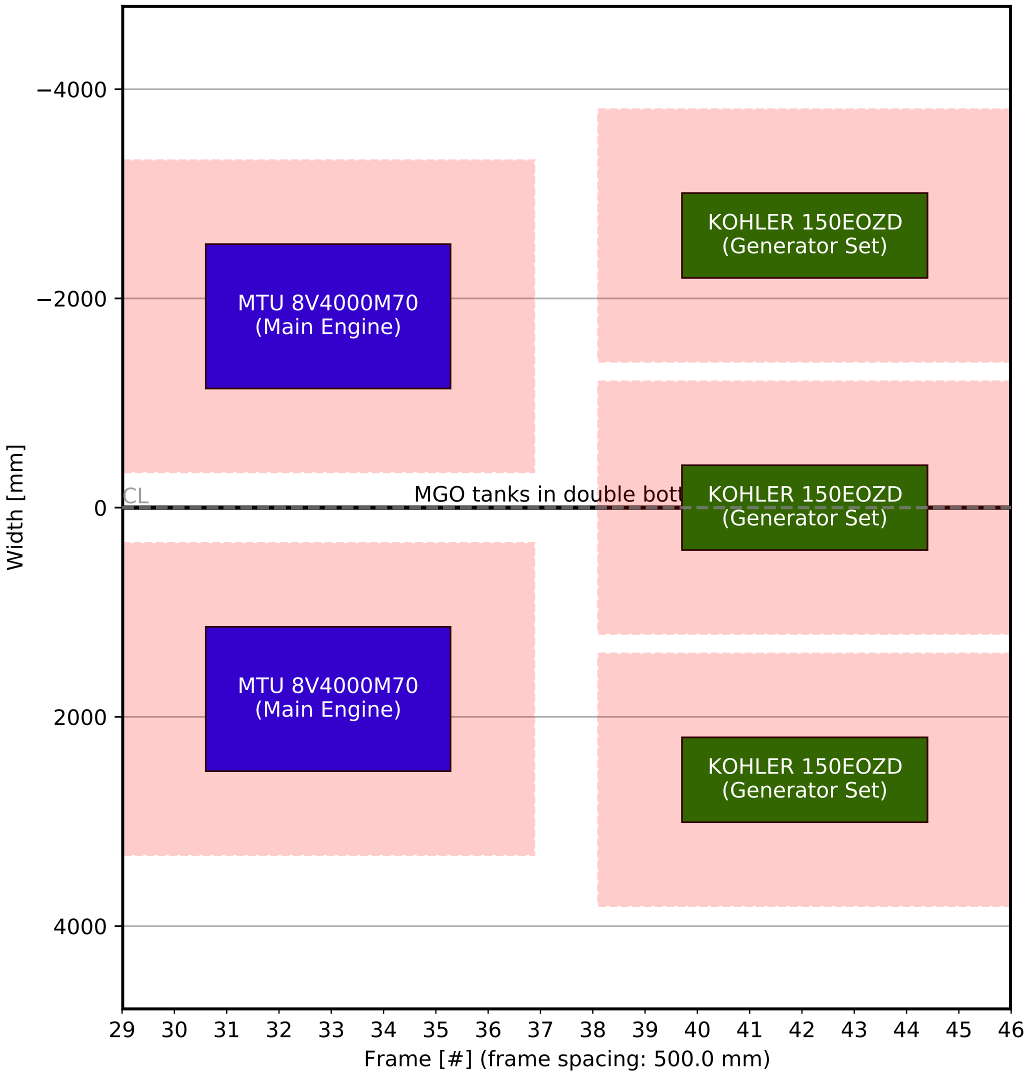
Since the hull of most yachts shapes upwards towards the aft, to make room for the propeller and improve the propeller inflow, the tank located to the aft of the yacht has a smaller height than the tank around the midship. This is visualised in the layout figures as a rectangular tank with a height from the lowest possible waterline down to halfway between this waterline and the keel but in reality this tank follows the bottom shell plating (the tool only uses an average cross sectional area). Because the (average) height of this aft tank is smaller than the central tank, this aft tank is even less efficient in storing methanol than the central tank. This aft tank therefore occupies relatively more interior area than the central tank does per unit fuel volume. This can also be seen in Table 8.9. A significant increase in interior area occurs when switching from a one tank layout to a two tank layout: +33% and +11% for normal cofferdams and alternative cofferdams respectively.

The HT-PEM fuel cell units in Figure 8.11 and Figure 8.12 do not fit in the engine room when longitudinally oriented as they overlap with the main engine. These FCs are long units delivering 300 kW per unit. However, these units consist of 10 racks next to each other with each rack containing 6 modules of 5 kW. The units do not necessarily have to consist of 10 racks next to each other. If instead a few 3 or 4 rack wide units are chosen, these units will fit inside the engine room in length direction. These 300 kW fuel cell units can also be rotated by 90° and placed in transverse direction which then allows

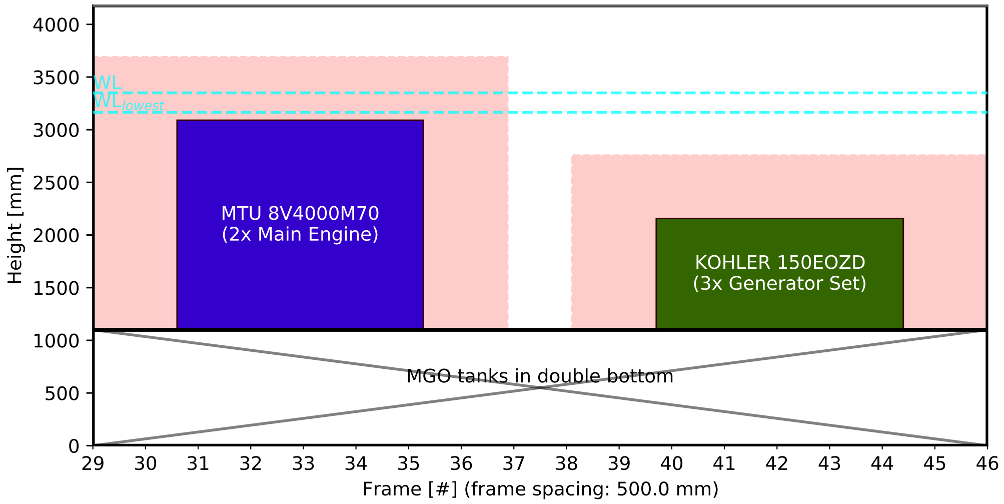
Table 8.9: Interior area usage (A_{int}) for the diesel reference layout, the one tank methanol layout and the two tank methanol layout all using ICEs only and the required length increase (Δ_l) to keep the interior area equal. The diesel reference layout has tanks in the double bottom which do not require interior area.

Tank layout	Total				Central tank			Aft tank		
	V_{fuel} [m^3]	f_{usage} [-]	A_{int} [m^2]	Δ_l [m]	V_{fuel} [m^3]	f_{usage} [-]	A_{int} [m^2]	V_{fuel} [m^3]	f_{usage} [-]	A_{int} [m^2]
MGO - DB	93	1.000	0	0	-	-	-	-	-	-
MeOH - 1 tank	198	0.601	106	2.50	198	0.601	106	-	-	-
MeOH - 1 tank - Alt cofferdams	205	0.938	91	2.50	205	0.938	91	-	-	-
MeOH - 2 tanks	194	0.503	141	3.50	105	0.514	66	90	0.490	76
MeOH - 2 tanks - Alt cofferdams	200	0.919	101	3.00	146	0.930	66	54	0.891	35

two fuel cell units to be placed as is required according to the required power calculation. The rotation of these units is not part of the design impact tool as this has no influence on the outcome and is only for visualisation purposes. However, for this yacht it is determined that two fuel cell units of 300 kW would fit in the engine room (in transverse direction) next to the main engines. With the two fuel cells in Figure 8.11 and Figure 8.12, there is enough spare power by the fuel cells to also provide propulsion power (next to the required auxiliary power) for speeds up to 7.5 knots. When the fuel cells are distributed differently throughout the engine room than in these figures, a third 300 kW fuel cell unit may fit in the engine room. With three fuel cell units, a speed of 10 knots can be reached by fuel cell power alone, which is almost the range speed.

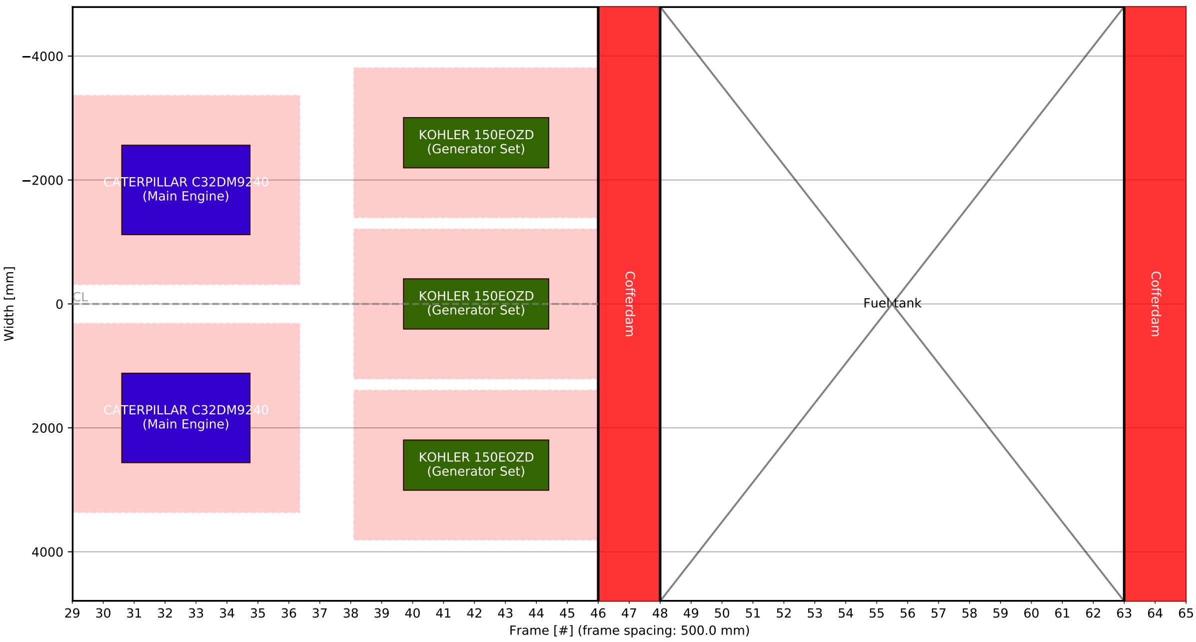


(a) Top view of the diesel baseline layout with ICEs for propulsion and auxiliary power.

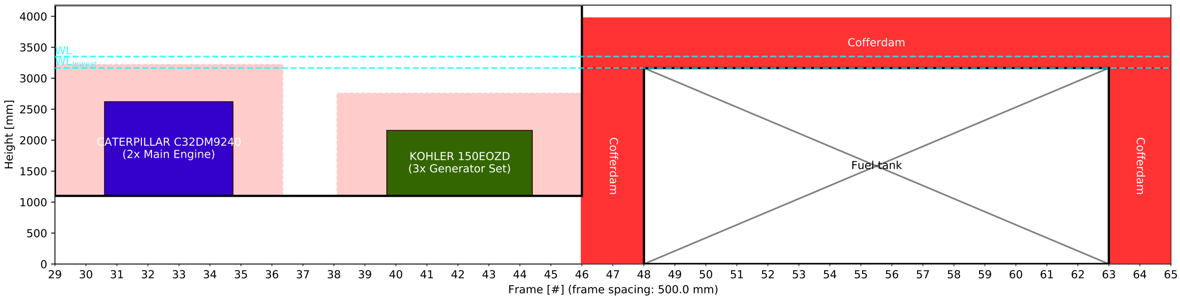


(b) Side view of the diesel baseline layout with ICEs for propulsion and auxiliary power.

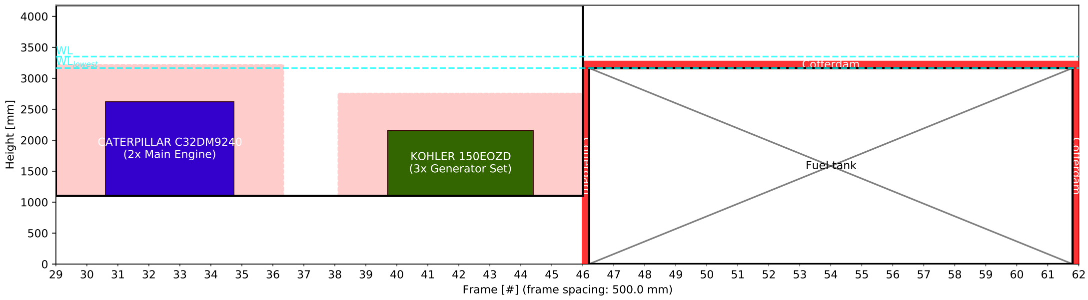
Figure 8.8: Schematic layout of the diesel baseline with MGO tanks in the double bottom.



(a) Top view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

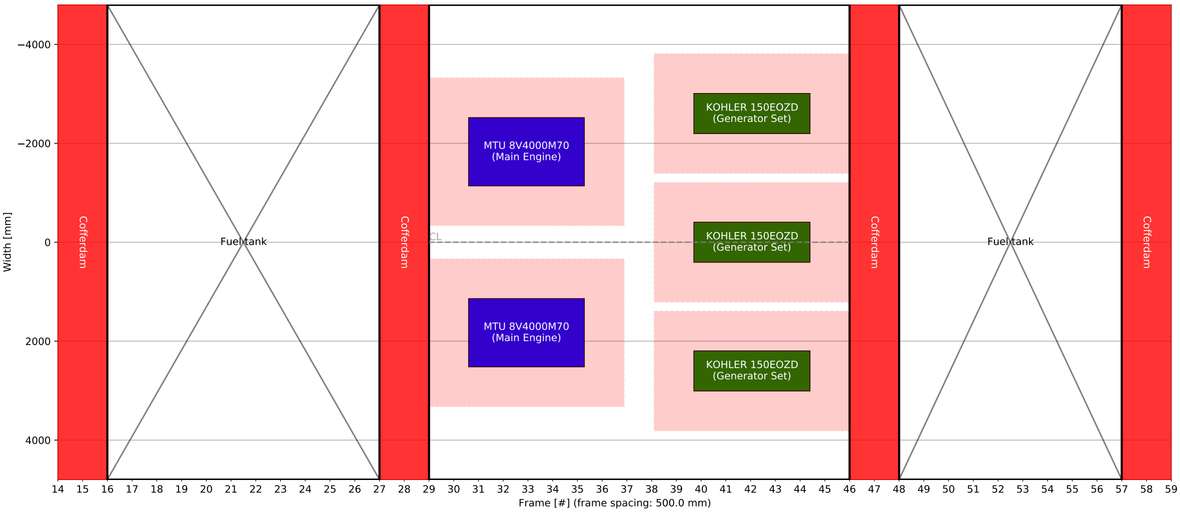


(b) Side view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

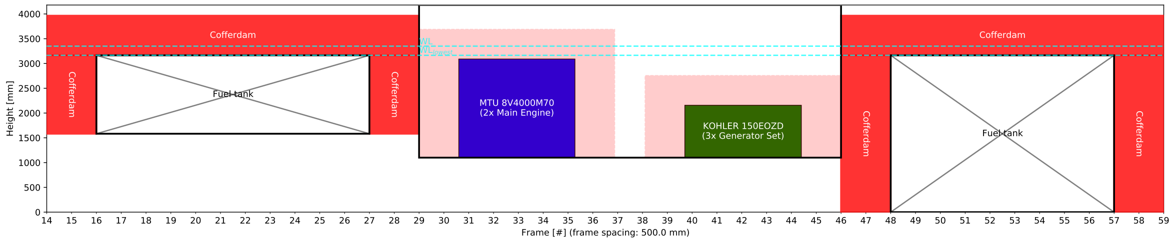


(c) Side view of the methanol layout with ICEs for propulsion and auxiliary power and alternative cofferdams. Top view is very similar to Figure 8.9a but with smaller cofferdams.

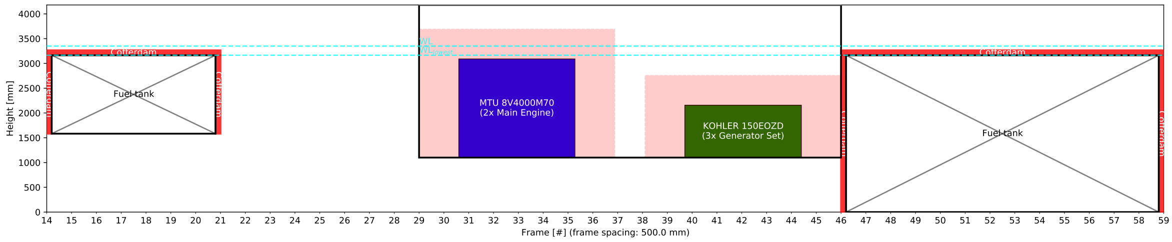
Figure 8.9: Schematic layouts of the ICE methanol configuration with one tank.



(a) Top view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

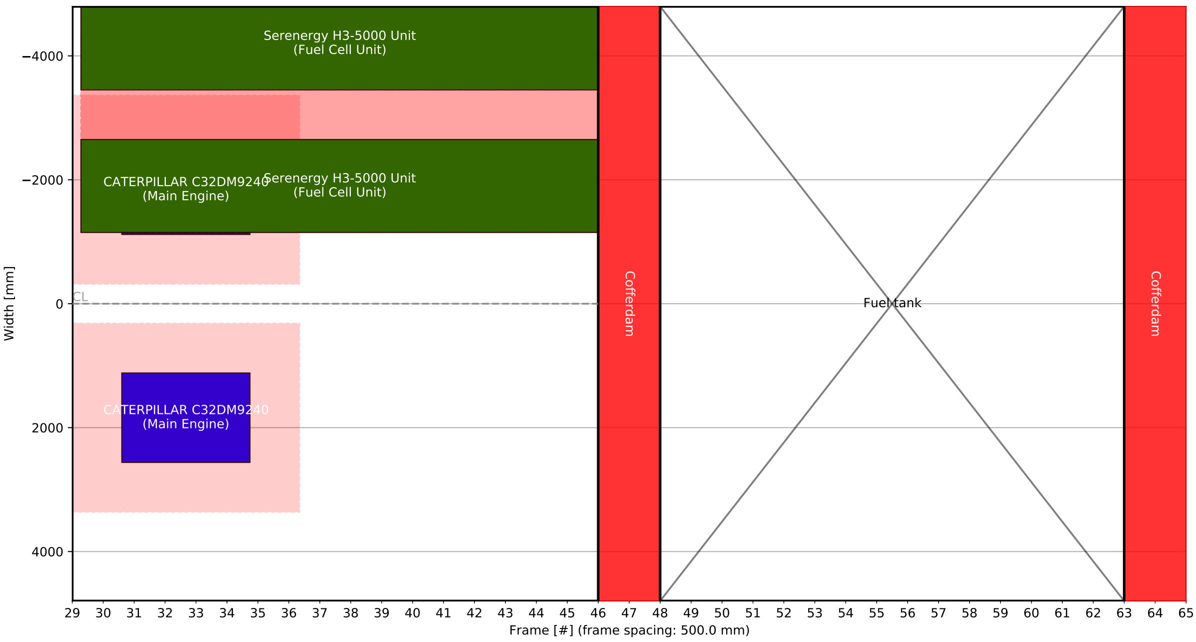


(b) Side view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

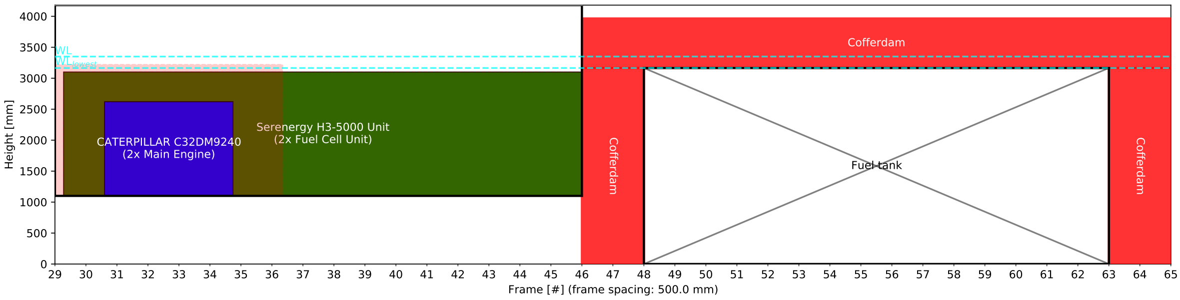


(c) Side view of the methanol layout with ICEs for propulsion and auxiliary power and alternative cofferdams. Top view is very similar to Figure 8.10a but with smaller cofferdams.

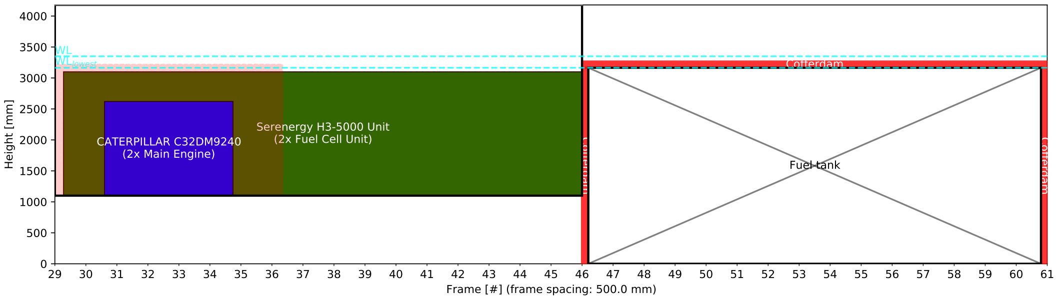
Figure 8.10: Schematic layouts of the ICE methanol configuration with one tank around midship and a second tank in the aft of the yacht.



(a) Top view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.

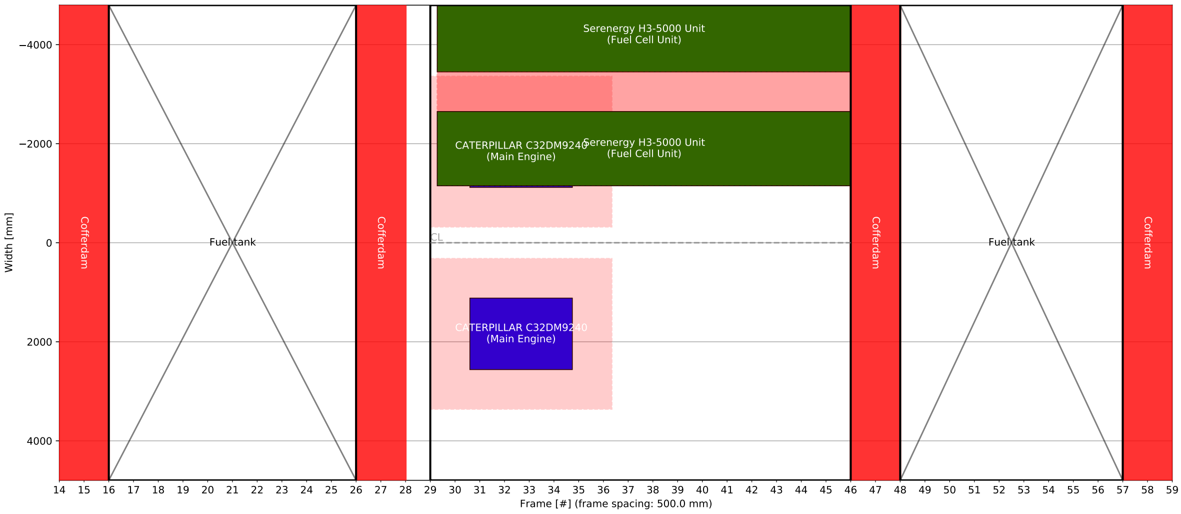


(b) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.

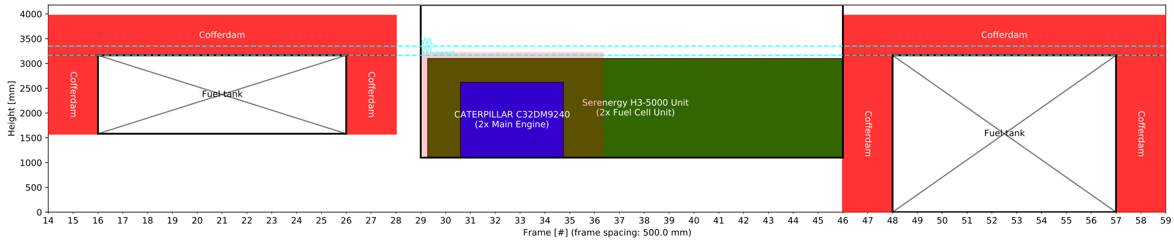


(c) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and alternative cofferdams. Top view is very similar to Figure 8.11a but with smaller cofferdams.

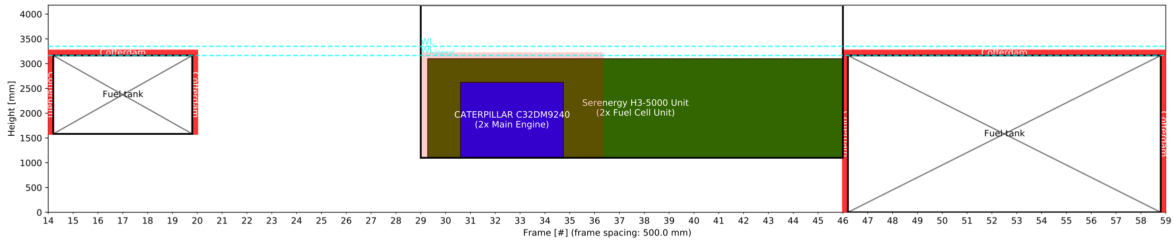
Figure 8.11: Schematic layouts of the ICE+FC methanol configuration with one tank.



(a) Top view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.



(b) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.



(c) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and alternative cofferdams. Top view is very similar to Figure 8.12a but with smaller cofferdams.

Figure 8.12: Schematic layouts of the ICE+FC methanol configuration with one tank around midship and a second tank in the aft of the yacht.

Trim

As was concluded for this yacht, having less separate tanks is beneficial from a volumetric efficiency point of view. However, having a tank layout with two tanks does have a large benefit which is also very important in the design of a yacht: trimming capabilities. In order to determine the impact of the methanol tank layouts on trim, the properties of the tank layout of yacht B are combined with stability booklets of the original diesel reference yacht. This is done by first subtracting the diesel fuel mass and COG from the yacht and then adding the methanol fuel mass at the COG of the methanol tanks. The change in trim and draught is then determined from the difference in weight and LCG location between the methanol layout and the diesel layout, which is then multiplied by the moment required to change the trim [t m/cm] and the ton per cm immersion respectively to find the new trim and draught. It is also checked whether it is possible to trim the yacht to its original trim with the water ballast available on board the original yacht and what the COG of the water ballast would have to be. The results of this trim analysis are shown in Table 8.10.

Table 8.10 shows that in all cases with methanol the draught increases and the trim changes when using methanol tanks compared to the original diesel yacht. The draught increase ranges from 14.9 cm (+4.4%) for the full loaded condition (98% fuel) to 1.5 cm (+0.5%) for the light loaded condition (9.8% fuel). However, the length increase iteration as applied in this research is not taken into account in this draught and trim analysis. When the ship's length is increased, it is likely that both the (design) draught and the ton/cm immersion will change, resulting in a methanol draught that is slightly closer to the original draught. The trim change is rather large for the layout with 1 tank. The original yacht has a negative trim (aft has a larger draught than the front). By using only a single methanol tank in front of the engine room, which LCG is located in front of the LCG of the yacht in this case, the yacht is trimmed forward resulting in a less negative trim. For the full load, the yacht is trimmed forward significantly (+32.5%, i.e. less negative trim). This amount of change in trim cannot be compensated by locating all water ballast at the required LCG since this location is not within the yacht (-5.971 m). However, it is up to the naval architect to determine whether this change in trim is an issue (the yacht is still trimmed more aft than in half loaded condition. In general the 1 tank layout, although this tank consists of a few smaller tanks, offers very limited options to change the trim. The 2 tank layout offers much more trim options and may offer very similar trim options, depending on the exact LCGs of the tanks and the volume/weight distribution between the two tanks. The two tank layout results in a very similar trim to the original yacht, within 0.3 cm change.

In conclusion, although a single tank is preferred because it offers more fuel volume at a smaller loss of interior, two tanks are preferred because it offers much more trim options. The trim options with a single tank are severely limited, while a two tank layout can reduce this problem. The two tank layouts (in combination with ICEs and ICEs+FCs) will be used for the pathway analysis of this yacht.

Table 8.10: Draft [m] and trim [m] of the original diesel yacht, the methanol 1 tank layout and the methanol 2 tanks layout. The required location of the LCG of available water ballast to cancel the trim change is also shown [m from aft].

Property	Full loaded condition			Half loaded condition			Light loaded condition		
	MGO	1 tank	2 tanks	MGO	1 tank	2 tanks	MGO	1 tank	2 tanks
Draught (mean) [m]	3.393	3.542	3.537	3.268	3.344	3.341	3.165	3.180	3.180
Trim [m]	-0.160	-0.108	-0.163	-0.230	-0.216	-0.231	-0.300	-0.299	-0.300
LCG_{req} water ballast [m]	-	-5.971	41.456	-	6.344	38.964	-	23.276	31.948

8.3. Pathway 0 - Baseline diesel ICE

Pathway 0 is the baseline to which the other pathways will be compared. It uses diesel as fuel with internal combustion engines to generate the required propulsion and auxiliary power. The general details of the pathways are described in 7 Pathways. The details of the baseline diesel pathway are given in 7.3.1 Pathway 0 - Baseline diesel ICE. The schematic representation of the configurations and tank layouts of the diesel baseline for the two yachts are shown in Figure 8.2 and Figure 8.8. These configurations and tank layouts are used in the design tool. With the design tool, the emissions of a yacht in a year and the costs are determined. Below is an overview of constant and variable parameters.

Constants:

- Yacht length
- Tank layout (single tank)
- Converter type (ICE)
- Converter configuration
- Converter efficiency (see 7.2.2)
- Converter price (see 7.2.3)

Variables:

- Fuel price (see 7.2.1)
- Operational profile (yacht specific)

8.3.1. Emissions

The CO_2, NO_x, SO_x and PM emissions are determined from the fuel consumption which depends on the operational profile of each of the yachts. These yearly emissions are shown in Figure 8.13. To put the emissions of the pathways into perspective, the CO_2 and NO_x are related to forest area and truck emissions respectively in Table 8.11.

As can be seen in Figure 8.13, the net CO_2 emissions of renewable diesel are zero while the other emissions are equal to the emissions of fossil diesel. The tank to wake emissions of renewable diesel are equal to that of fossil diesel but because the upstream (well to tank) emissions are negative, the net emissions of renewable diesel are much lower than the net emissions of fossil diesel.

The CO_2 and NO_x emissions of pathway 0 are related to forest area and the emissions of cars and trucks in Table 8.11. Especially for yacht A, the largest yacht, a large area of forest is required for the sequestration of CO_2 from the atmosphere in order to equal the CO_2 emitted by this yacht. When looking at the NO_x emissions of this same yacht A and comparing the emissions to the NO_x emissions of cars and trucks, the scale of NO_x emissions of a large yacht become clear. 48 diesel cars, driving continuously all year at 80 km/h, emit the same amount of NO_x as yacht A. Compared to heavy-duty trucks (of over 20 tonnes), this yacht emits the same amount of NO_x as 9 of these heavy-duty diesel trucks, again driving continuously at 80 km/h all year long. Although the NO_x emissions of the yachts using renewable diesel are equal to the NO_x emissions of fossil diesel (as assumed in Table 5.4), the environmental impact with respect to CO_2 emissions can be greatly reduced when using the renewable variant of the fuel at the cost of a higher fuel price (and reduced availability).

Table 8.11: CO_2 and NO_x emissions in perspective. The net CO_2 emissions are related to the forest area required to sequester the yearly CO_2 emitted by the yacht (data from Toochi (2018)). The NO_x emissions are related to the amount of diesel cars and heavy-duty diesel trucks (>20t), driving 80 km/h continuously, that emit an equal amount of NO_x (data from ICCT (2014); Velders (2013)).

Yacht	Fuel feedstock	CO_2 emissions		NO_x emissions		
		CO_2-WTW [t]	A_{forest} [km^2]	NO_x [t]	Cars	Heavy-duty trucks
A	Fossil	6420	14.65	20.4	48	9
	Renewable	0	0	20.4	48	9
B	Fossil	3088	7.05	9.79	23	5
	Renewable	0	0	9.79	23	5

8.3.2. Costs

The fuel costs over the entire period of pathway 0 are shown in Figure 8.14. Since there is no change in efficiency of the converters between configuration 1 and configuration 2 (see 7.2.2 Converter efficiency), the changing trend in fuel costs is purely caused by a decrease in fuel price. If the efficiency would change there would be a small decreasing jump in 2035 in fuel costs as at that year the configuration is refitted and a newer, more efficient engine may be installed. The gradual change in fuel costs is the result of a change in fuel price (see 7.2.1 Fuel price). The yearly fuel costs of renewable diesel are many times higher than for fossil diesel, especially in 2020 where renewable diesel is approximately 10 times as expensive. When looking at the yearly fuel costs in 2050, this difference becomes smaller. However, renewable diesel offers significantly less CO_2 emissions and likely also less other emissions.

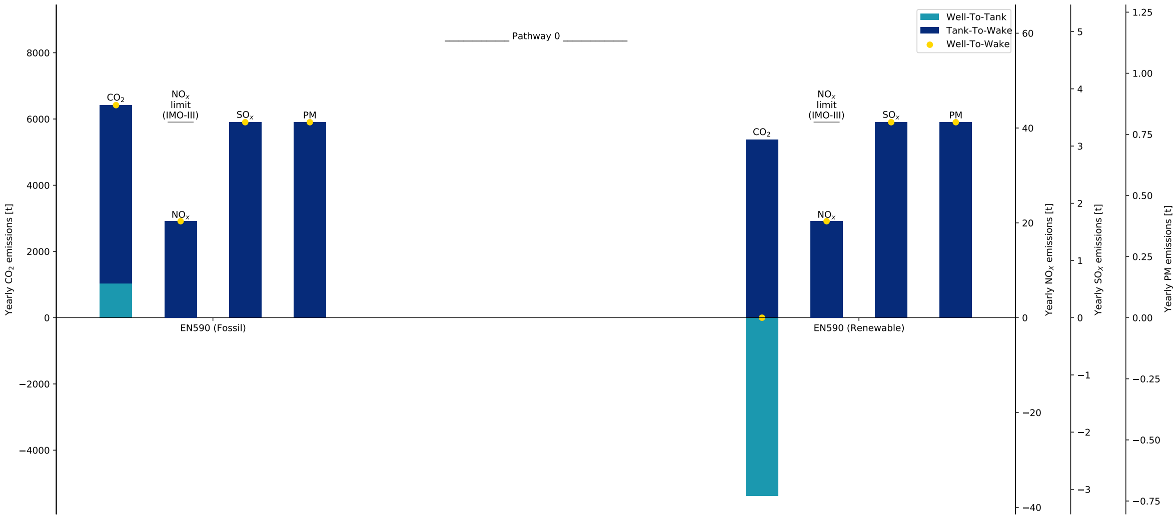
The costs of the converters for both propulsion and auxiliary power are shown in Table 8.12. The storage costs of diesel tanks in the double bottom are assumed to be equal to zero, as discussed in 5.5.3 Fuel storage. The costs of converters are also shown relative to the value of the yacht in Table 8.13 together with the relative costs of storage which is stated between brackets. The total relative costs range from around 1.7% to 3%. It can also be seen that the relative converter costs increase with decreasing yacht size, but the speed of the yacht is also of great influence.

Table 8.12: Costs of converters for propulsion and auxiliary power generation in million Euros and storage costs in Euros of pathway 0.

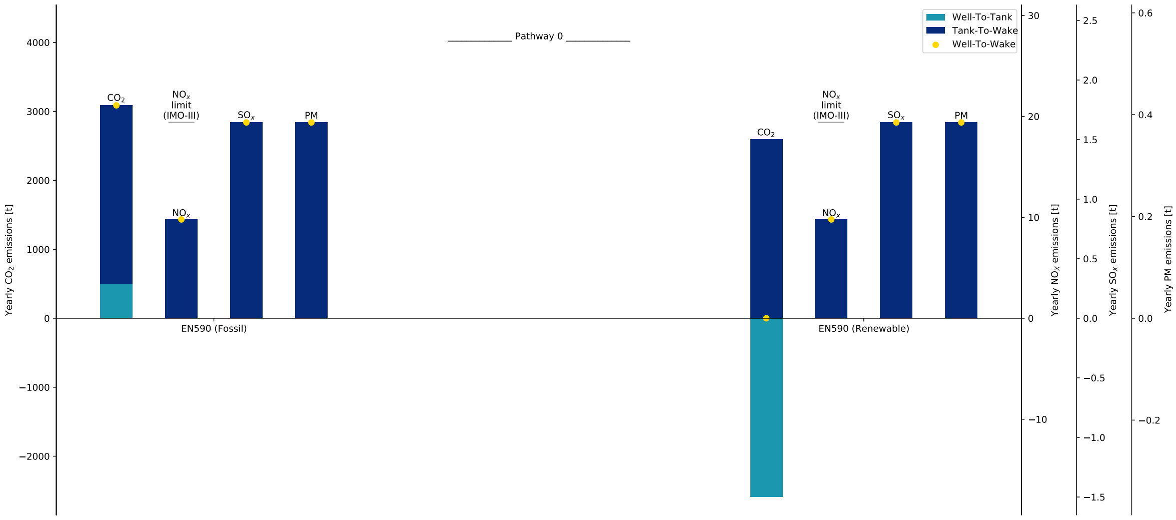
Yacht	Configuration 1					Configuration 2				
	Propulsion		Auxiliary		Storage	Propulsion		Auxiliary		Storage
	Type	Price [M€]	Type	Price [M€]	Price [€]	Type	Price [M€]	Type	Price [M€]	Price [€]
A	ICE	2.780	ICE	1.528	0.0	ICE	2.780	ICE	1.528	0.0
B	ICE	0.896	ICE	0.570	0.0	ICE	0.896	ICE	0.570	0.0

Table 8.13: Total converter costs and storage costs of pathway 0. The total costs (converters and storage) are expressed as a percentage of the yacht's value. The relative storage costs are given between brackets.

Yacht	Configuration	Converter costs [M€]	Storage costs [M€]	Yacht value [M€]	Relative costs [%]
A	ICE - Diesel	4.308	0.000	250	1.72 (0.00)
	ICE - Diesel	4.308	0.000	250	1.72 (0.00)
B	ICE - Diesel	1.466	0.000	50	2.93 (0.00)
	ICE - Diesel	1.466	0.000	50	2.93 (0.00)

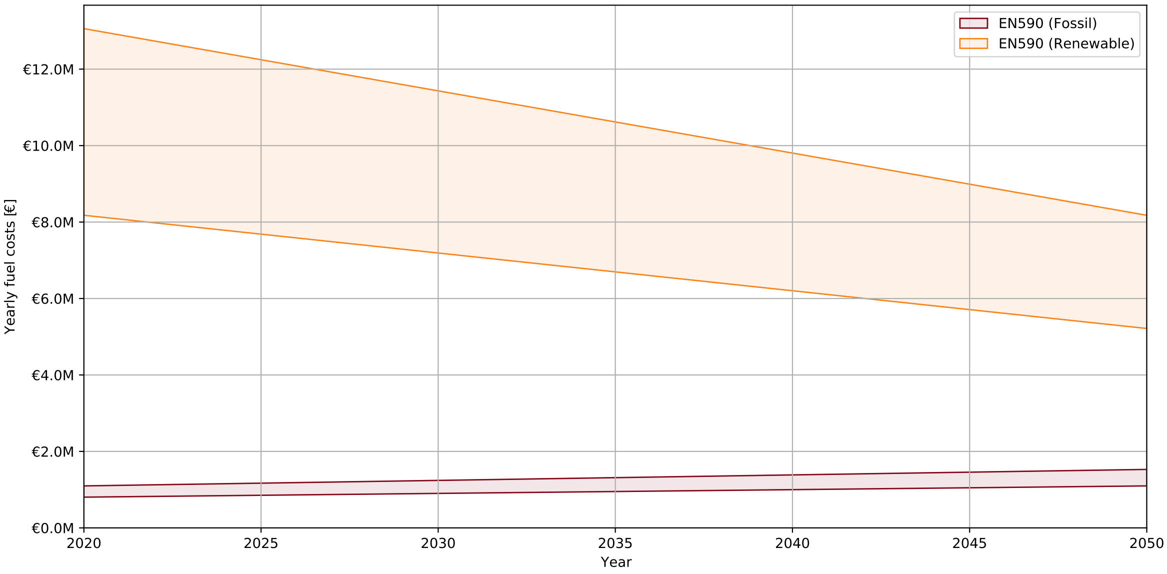


(a) Yearly emissions of yacht A.

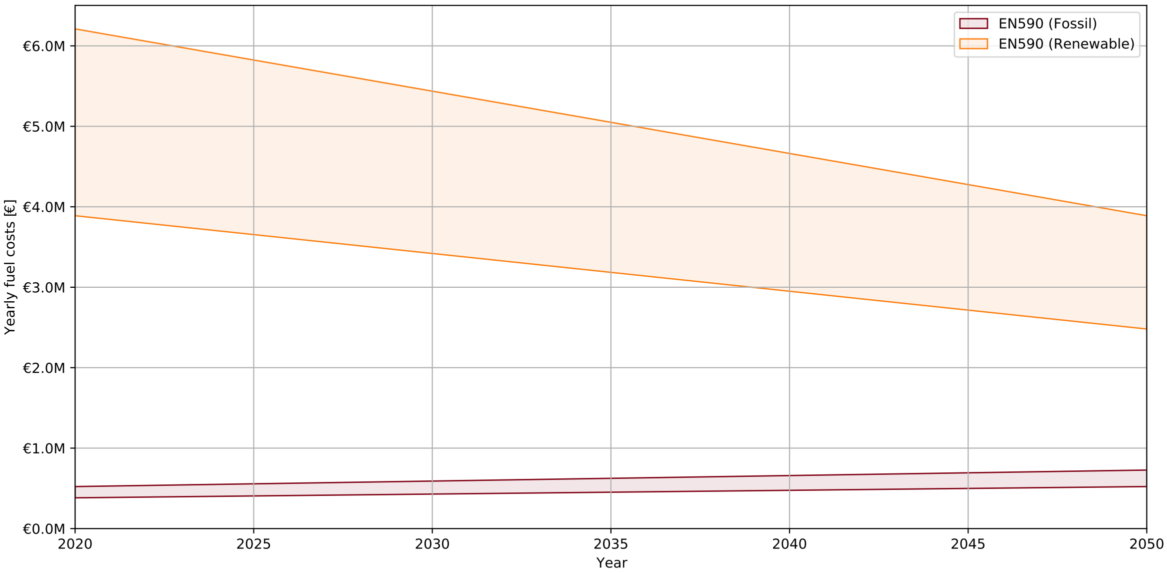


(b) Yearly emissions of yacht B.

Figure 8.13: Yearly emissions of CO_2, NO_x, SO_x and PM for the diesel baseline pathway 0 (2020 to 2050). The emissions are shown in tonnes per year for both fossil and renewable diesel (EN590) and are split up into well-to-tank and tank-to-wake emissions.



(a) Yearly fuel costs of yacht A.



(b) Yearly fuel costs of yacht B.

Figure 8.14: Yearly fuel costs (with upper and lower limits) for pathway 0 which uses diesel ICEs for propulsion and auxiliary power from 2020 to 2050. Both fossil and renewable yearly fuel costs are shown.

8.4. Pathway 1 - Methanol ICE

The first methanol pathway uses methanol as fuel with internal combustion engines to generate the required propulsion and auxiliary power. The general details of the pathways are described in 7 Pathways. The details this pathway are given in 7.3.2 Pathway 1 - Methanol ICE. The schematic configurations and tank layouts of methanol pathway 1 for the two yachts are shown in Figure 8.4 and Figure 8.10. These configurations and tank layouts have a central and aft tank and are used in the design tool. With the design tool, the emissions for this pathway of a yacht in a year and the costs are determined. Below is an overview of constant and variable parameters.

Constants:

- Tank layout (two tanks)
- Converter type (ICE)
- Converter efficiency (see 7.2.2)
- Converter price (see 7.2.3)

Variables:

- Yacht length (see 5.2.5)
- Converter configuration (depends on length iteration)
- Fuel price (see 7.2.1)
- Operational profile (yacht specific)

8.4.1. Emissions

The CO_2, NO_x, SO_x and PM emissions are determined from the fuel consumption which depends on the operational profiles of the yachts. These yearly emissions are shown in Figure 8.15. To put the emissions of the first methanol pathway into perspective, the CO_2 and NO_x are related to forest area and truck emissions respectively in Table 8.14.

When comparing the emissions of the first methanol pathway to the diesel baseline pathway, one can see a significant decrease in yearly emissions of SO_x and PM (see Figure 8.15). Only the CO_2 emissions have increased for fossil methanol compared to fossil diesel, while the NO_x emissions have decreased slightly. The methanol ICE configuration of yacht A emits around 10% more CO_2 than the diesel baseline configuration. The benefit of using methanol is clearly seen in the SO_x and PM emissions. The SO_x emissions are reduced to zero and the PM emissions have more than halved compared to the diesel baseline. When renewable methanol is used, the well to wake CO_2 emissions can also be reduced to zero.

That the CO_2 emissions have slightly increased can also be seen in the forest area required to sequester the CO_2 emissions of the yachts (see Table 8.14). This required forest area has increased by the same percentage as the CO_2 emissions have. Both yachts therefore require a slightly larger forest area in order to sequester the amount of emitted CO_2.

Table 8.14: CO_2 and NO_x emissions in perspective. The net CO_2 emissions are related to the forest area required to sequester the yearly CO_2 emitted by the yacht (data from Toochi (2018)). The NO_x emissions are related to the amount of diesel cars and heavy-duty diesel trucks (>20t), driving 80 km/h continuously, that emit an equal amount of NO_x (data from ICCT (2014); Velders (2013)).

Yacht	Fuel feedstock	CO_2 emissions		NO_x emissions		
		CO_2-WTW [t]	A_{forest} [km^2]	NO_x [t]	Cars	Heavy-duty trucks
A	Fossil	7045	16.08	20.2	48	9
	Renewable	0	0	20.2	48	9
B	Fossil	3350	7.65	9.6	23	4
	Renewable	0	0	9.6	23	4

8.4.2. Costs

The fuel costs over the entire period of pathway 1 are shown in Figure 8.16. The fuel costs are compared to the fuel costs of the baseline pathway that uses diesel ICEs. Since there is no change in efficiency of the converters between configuration 1 and configuration 2 (see 7.2.2 Converter efficiency), the decreasing trend in fuel costs is purely caused by a decrease in fuel price. If the efficiency would change there would be a small decreasing jump in 2035 in fuel costs as at that year the configuration is refitted and a newer, more efficient engine may be installed. The gradual change in fuel costs is the result of a change in fuel price (see 7.2.1 Fuel price). Figure 8.16 shows that the yearly fuel costs for fossil methanol are higher than that of the diesel baseline. Therefore, a decrease in SO_x and PM resulting from using fossil methanol comes at a slightly higher yearly fuel cost. The fuel costs of renewable methanol on the other hand are significantly less than that of renewable diesel in the baseline pathway. This indicates that when zero CO_2 emissions are required (or desired), the yearly fuel costs are less expensive when renewable methanol is used than when renewable diesel is used. Additionally, the SO_x and PM emissions are also reduced by using renewable methanol compared to renewable diesel, which is assumed to have equal NO_x, SO_x and PM emissions as fossil diesel.

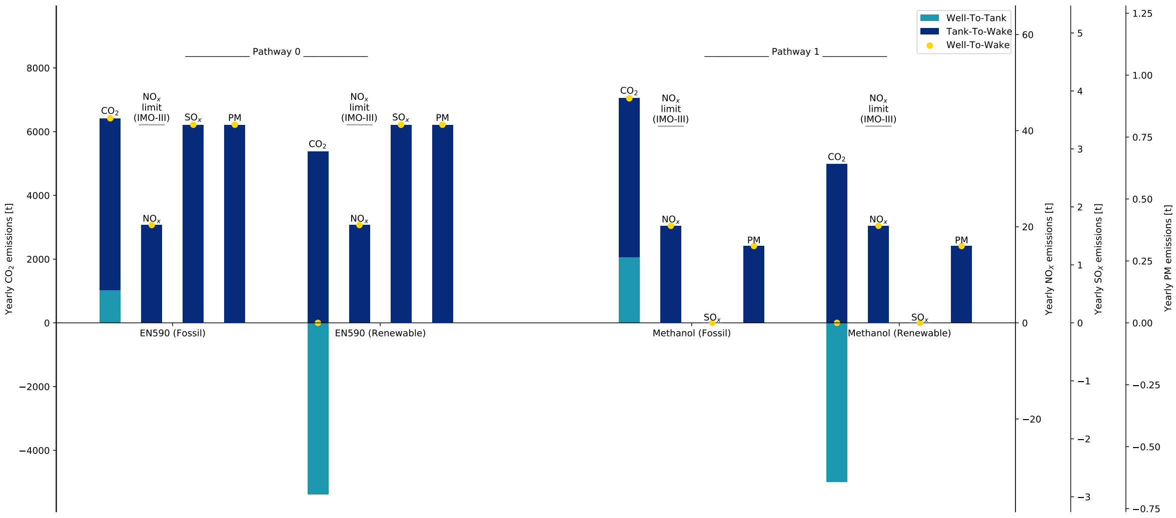
The costs of the converters for both propulsion and auxiliary power are shown in Table 8.15. The costs of converters are also shown relative to the value of the yacht in Table 8.16 together with the relative costs of storage which is stated between brackets. The total relative costs range from around 1.8% to 3.1%, while the relative costs of the storage itself ranges from 0.12% to 0.20%. The storage costs are therefore likely to only make up a very small part of the total costs of the yacht. It can also be seen that the relative converter costs increase with decreasing yacht size. The relative storage costs are mostly related to the required energy capacity as a result of the required range. When comparing yacht A and B which have a comparable range, it can be concluded that the relative storage costs also increase with decreasing yacht size.

Table 8.15: Costs of converters for propulsion and auxiliary power generation and storage costs of pathway 1.

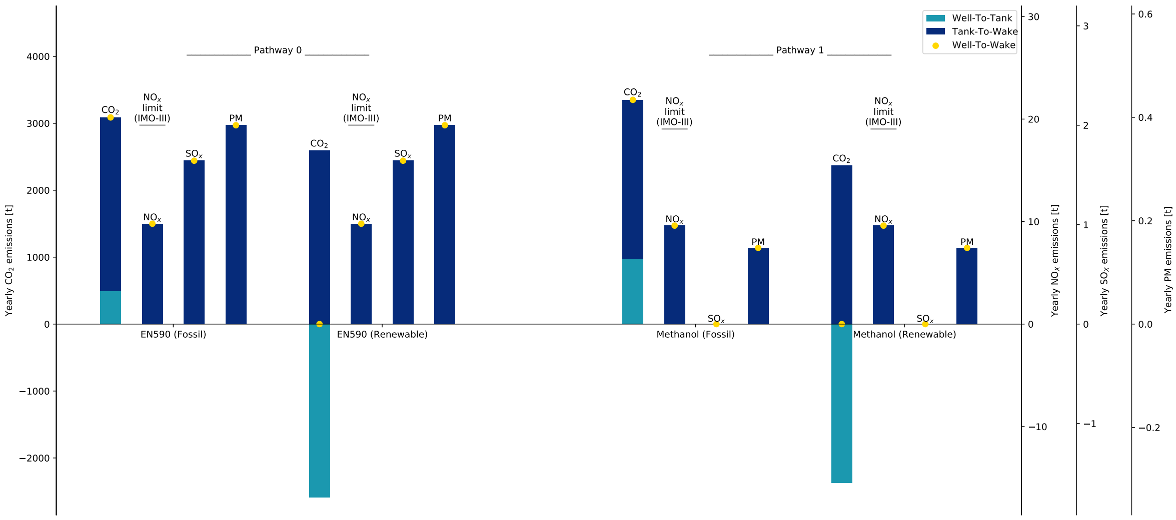
Yacht	Configuration 1					Configuration 2				
	Propulsion		Auxiliary		Storage	Propulsion		Auxiliary		Storage
	Type	Price [M€]	Type	Price [M€]	Price [€]	Type	Price [M€]	Type	Price [M€]	Price [€]
A	ICE	2.780	ICE	1.528	293,603	ICE	2.780	ICE	1.528	293,603
B	ICE	0.896	ICE	0.570	98,799	ICE	0.896	ICE	0.570	98,799

Table 8.16: Total converter costs and storage costs of pathway 1. The total costs (converters and storage) are expressed as a percentage of the yacht's value. The relative storage costs are given between brackets.

Yacht	Configuration	Converter costs [M€]	Storage costs [M€]	Yacht value [M€]	Relative costs [%]
A	ICE - Methanol	4.308	0.294	250	1.84 (0.12)
	ICE - Methanol	4.308	0.294	250	1.84 (0.12)
B	ICE - Methanol	1.466	0.099	50	3.13 (0.20)
	ICE - Methanol	1.466	0.099	50	3.13 (0.20)

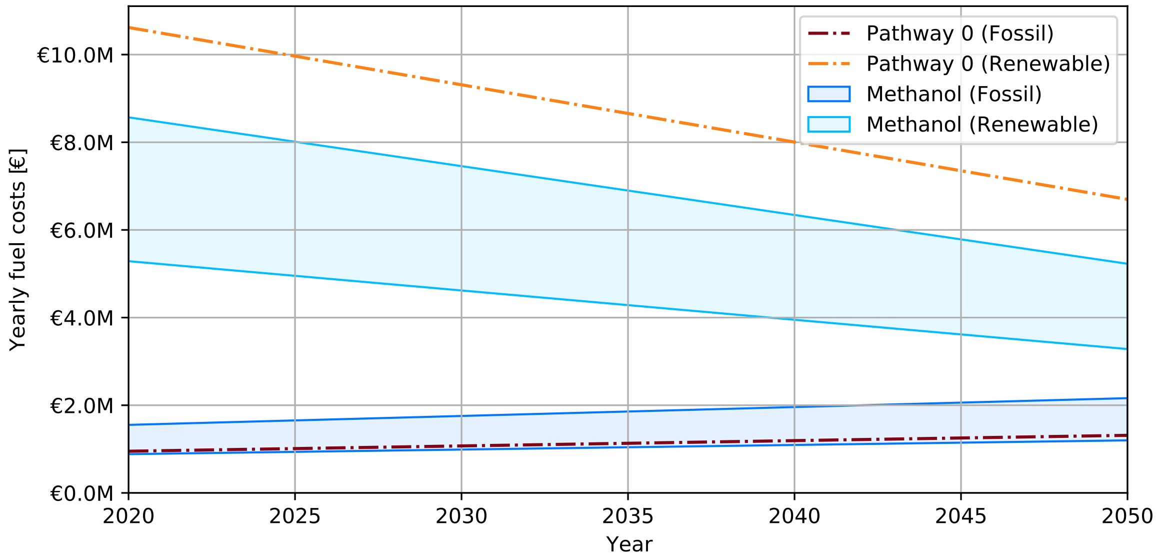


(a) Yearly emissions of yacht A.

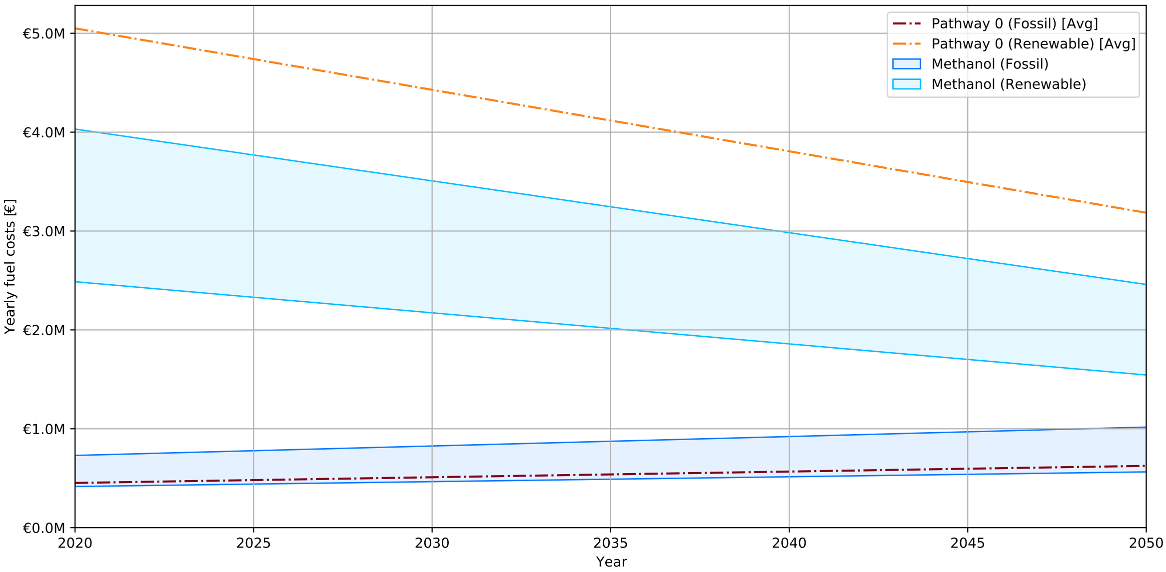


(b) Yearly emissions of yacht B.

Figure 8.15: Yearly emissions of CO_2, NO_x, SO_x and PM for pathway 1 (2020 to 2050), compared to the diesel baseline (pathway 0). The emissions are shown in tonnes per year for both fossil and renewable methanol and are split up into well-to-tank and tank-to-wake emissions.



(a) Yearly fuel costs of yacht A.



(b) Yearly fuel costs of yacht B.

Figure 8.16: Yearly fuel costs (with upper and lower limits) for pathway 1 which uses methanol ICEs for propulsion and auxiliary power from 2020 to 2050. The average fuel costs of the baseline pathway 0 are also shown as a comparison. Both fossil and renewable yearly fuel costs are shown.

8.5. Pathway 2 - Methanol ICE+FC

The second methanol pathway uses methanol as fuel with internal combustion engines to generate the required propulsion power and HT-PEMFC to generate the auxiliary power. The general details of the pathways are described in 7 Pathways. The details this pathway are given in 7.3.3 Pathway 2 - Methanol ICE+FC. A schematic configuration and tank layout of methanol pathway 2 for the two yachts is shown in Figure 8.6 and Figure 8.12. These configurations and tank layouts, with a central and aft tank, are used in the design tool. With the design tool, the emissions of a yacht in a year and the costs can be determined. Below is an overview of constant and variable parameters.

Constants:

- Tank layout (two tanks)
- Converter type (ICE+FC)
- Converter efficiency (see 7.2.2)
- Converter price (see 7.2.3)

Variables:

- Yacht length (see 5.2.5)
- Converter configuration (depends on length iteration)
- Fuel price (see 7.2.1)
- Operational profile (yacht specific)

8.5.1. Emissions

The emissions are determined from the fuel consumption which depends on the operational profile of the yacht. These emissions include CO_2, NO_x, SO_x and PM. These yearly emissions are shown in Figure 8.17 and are compared to the diesel baseline of pathway 0. To put the emissions of the first methanol pathway into perspective, the CO_2 and NO_x are related to forest area and truck emissions respectively in Table 8.17.

Figure 8.17 shows that the NO_x, SO_x and PM emissions of methanol pathway 2 are all significantly lower than the emissions of the diesel baseline pathway. This is mainly the result of using fuel cells for the generation of auxiliary power. The only NO_x and PM emissions that these methanol fuelled yachts emit come from the internal combustion engines that are used for the propulsion of the yacht. As is the case with the first methanol pathway, the CO_2 emissions have increased compared to the diesel baseline, although this time not by 10% for yacht A but by 4%. The CO_2 emissions have increased by a smaller percentage because the efficiency of the fuel cells used is slightly higher than that of the ICEs.

That the CO_2 emissions have slightly increased compared to the diesel baseline can also be seen in the forest area required to sequester the CO_2 emissions of the yachts (see Table 8.17). This required forest area has increased by the same percentage as the CO_2 emissions have. The NO_x emissions of methanol pathway 2 however, have decreased significantly and therefore the NO_x emissions of the yachts equal less trucks and less cars than the diesel baseline and also the first methanol pathway.

Table 8.17: CO_2 and NO_x emissions in perspective. The net CO_2 emissions are related to the forest area required to sequester the yearly CO_2 emitted by the yacht (data from Toochi (2018)). The NO_x emissions are related to the amount of diesel cars and heavy-duty diesel trucks (>20t), driving 80 km/h continuously, that emit an equal amount of NO_x (data from ICCT (2014); Velders (2013)).

Yacht	Fuel feedstock	CO_2 emissions		NO_x emissions		
		CO_2-WTW [t]	A_{forest} [km^2]	NO_x [t]	Cars	Heavy-duty trucks
A	Fossil	6681	15.25	6.9	16	3
	Renewable	0	0	6.9	16	3
B	Fossil	2968	6.78	2.9	7	1
	Renewable	0	0	2.9	7	1

8.5.2. Costs

The fuel costs over the entire period of pathway 2 are shown in Figure 8.18. The fuel costs are compared to the fuel costs of the baseline pathway that uses diesel ICEs. Since there is no change in efficiency of the converters between configuration 1 and configuration 2 (see 7.2.2 Converter efficiency), the decreasing trend in fuel costs is purely caused by a decrease in fuel price. If the efficiency would change there would be a small decreasing jump in 2035 in fuel costs as at that year the configuration is refitted and a newer, more efficient engine may be installed. The gradual change in fuel costs is the result of a change in fuel price (see 7.2.1 Fuel price). The yearly fuel costs have decreased very slightly compared to methanol pathway 1 because the fuel cells are slightly more efficient and therefore less methanol fuel is consumed. Therefore, the yearly fuel costs of pathway 2 compare similarly to the diesel baseline pathway as pathway 1.

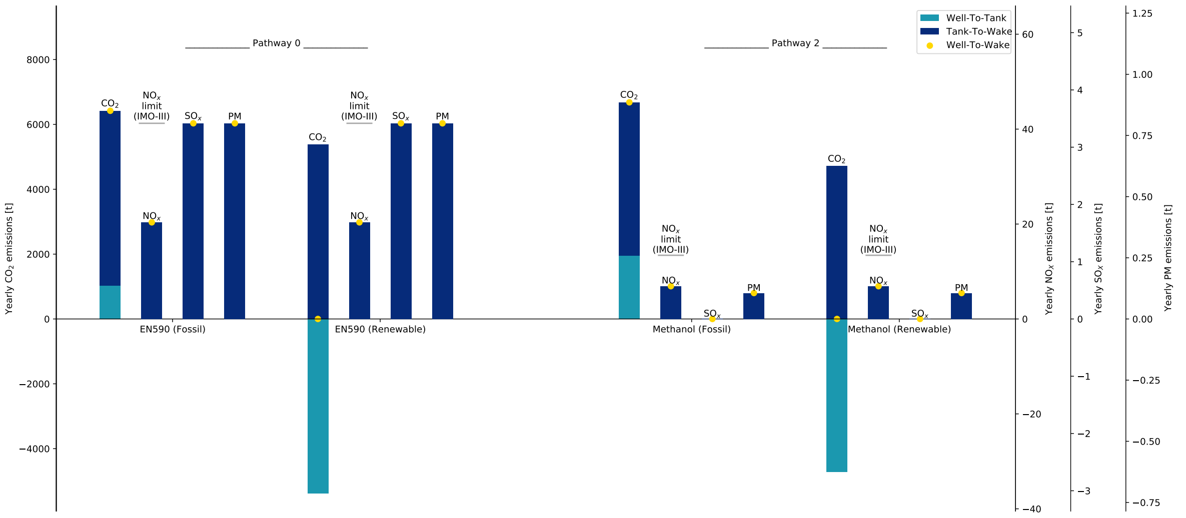
The costs of the converters for both propulsion and auxiliary power are shown in Table 8.18. The costs of converters are also shown relative to the value of the yacht in Table 8.19 together with the relative costs of storage which is stated between brackets. The total relative costs range from around 4.2% to 6%, while the relative costs of the storage itself ranges from 0.12% to 0.19%. The increase in relative costs is caused by the expensive fuel cells. The storage costs are therefore likely to only make up a very small part of the total costs of the yacht. It can also be seen that the relative converter costs increase with decreasing yacht size. The relative storage costs are mostly related to the required energy capacity as a result of the required range. When looking at yacht A and B which have a comparable range, it can be concluded that the relative storage costs also increase with decreasing yacht size. The converter costs of this pathway are significantly higher compared to pathway 1: 2.4 times as high for yacht A and 2 times as high for yacht B. This is purely caused by the much more expensive fuel cells.

Table 8.18: Costs of converters for propulsion and auxiliary power generation and storage costs of pathway 2. HT-PEMFCs are used for the generation of auxiliary power.

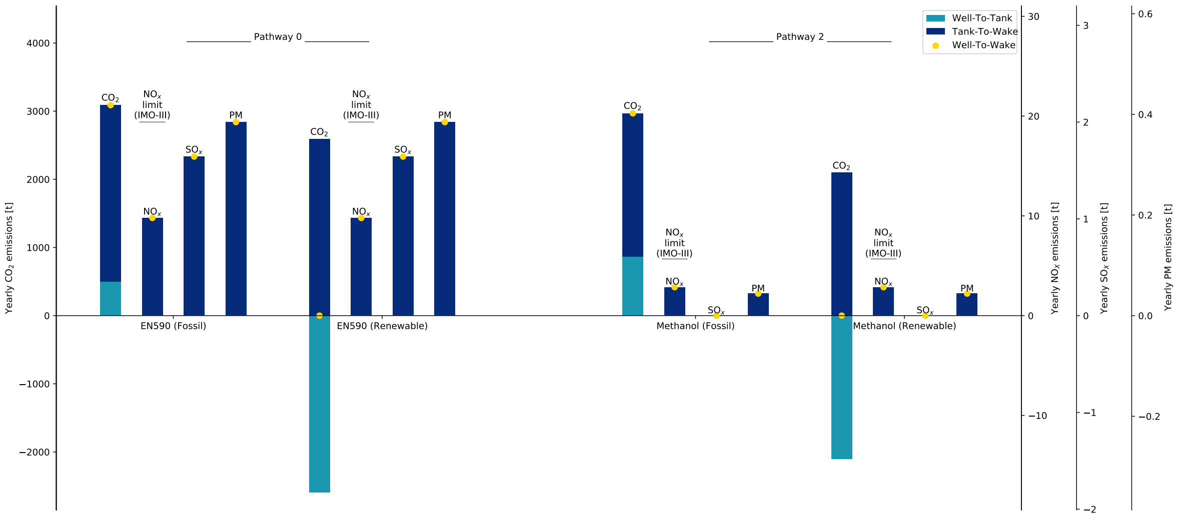
Yacht	Configuration 1					Configuration 2				
	Propulsion		Auxiliary		Storage	Propulsion		Auxiliary		Storage
	Type	Price [M€]	Type	Price [M€]	Price [€]	Type	Price [M€]	Type	Price [M€]	Price [€]
A	ICE	2.780	FC	7.560	293,603	ICE	2.780	FC	7.560	293,603
B	ICE	0.737	FC	2.160	96,332	ICE	0.737	FC	2.160	96,332

Table 8.19: Total converter costs and storage costs of pathway 2. The total costs (converters and storage) are expressed as a percentage of the yacht's value. The relative storage costs are given between brackets.

Yacht	Configuration	Converter costs [M€]	Storage costs [M€]	Yacht value [M€]	Relative costs [%]
A	ICE+HT-PEMFC - Methanol	10.340	0.294	250	4.25 (0.12)
	ICE+HT-PEMFC - Methanol	10.340	0.294	250	4.25 (0.12)
B	ICE+HT-PEMFC - Methanol	2.897	0.096	50	5.99 (0.19)
	ICE+HT-PEMFC - Methanol	2.897	0.096	50	5.99 (0.19)

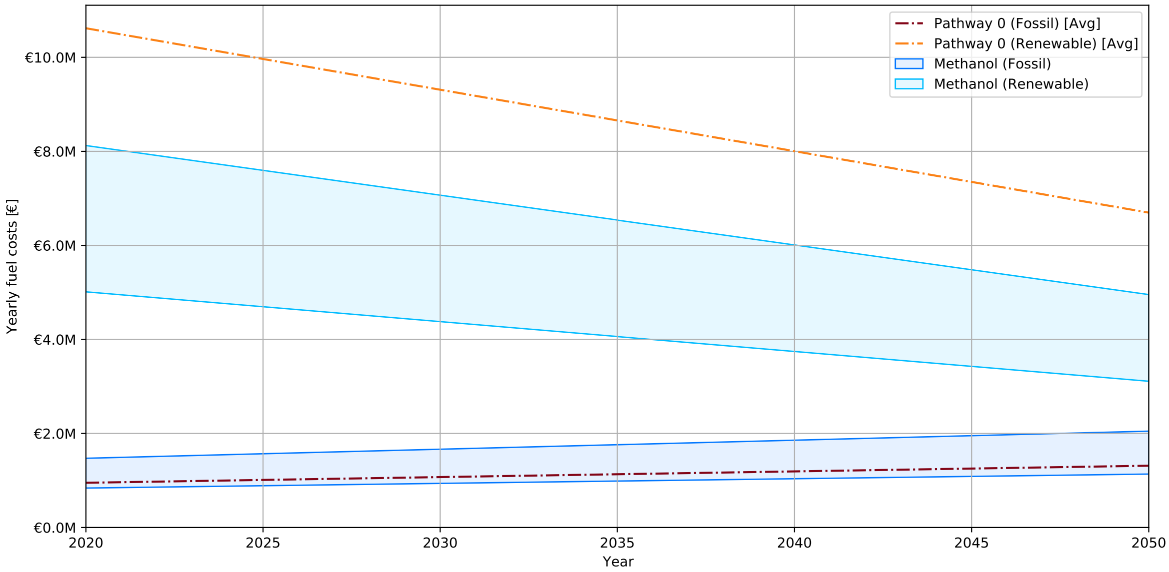


(a) Yearly emissions of yacht A.

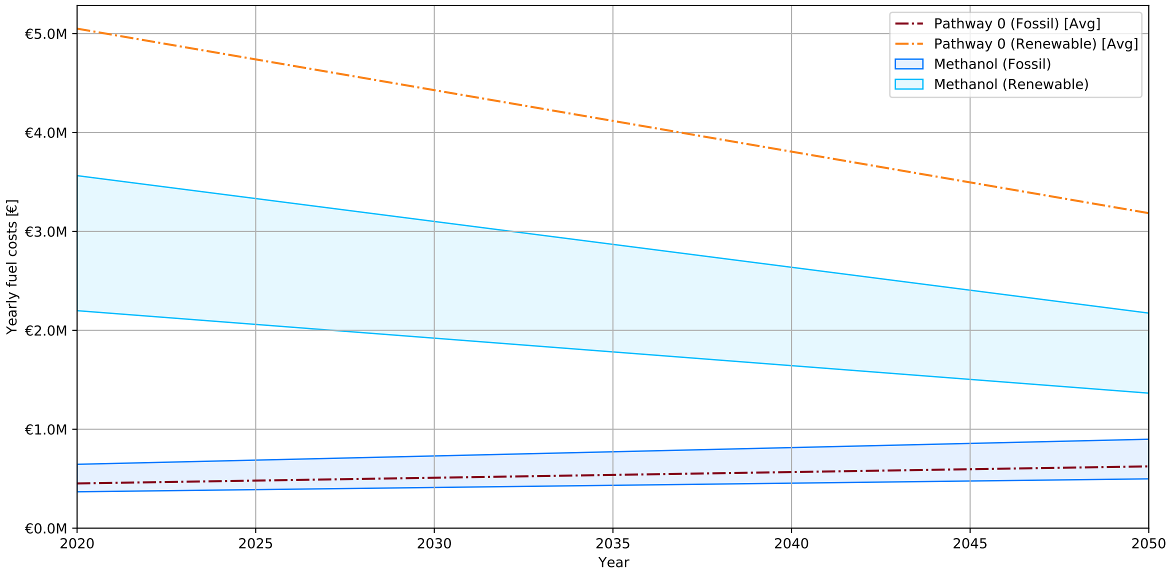


(b) Yearly emissions of yacht B.

Figure 8.17: Yearly emissions of CO_2, NO_x, SO_x and PM for pathway 2 (2020 to 2050), compared to the diesel baseline (pathway 0). The emissions are shown in tonnes per year for both fossil and renewable methanol and are split up into well-to-tank and tank-to-wake emissions.



(a) Yearly fuel costs of yacht A.



(b) Yearly fuel costs of yacht B.

Figure 8.18: Yearly fuel costs (with upper and lower limits) for pathway 2 which uses methanol ICEs for propulsion power and HT-PEMFCs for auxiliary power from 2020 to 2050. The average fuel costs of the baseline pathway 0 are also shown as a comparison. Both fossil and renewable yearly fuel costs are shown.

8.6. Pathway 3 - Diesel ICE to methanol ICE

The third methanol pathway uses diesel as fuel with internal combustion engines to generate the required propulsion power and auxiliary power from 2020 to 2035 and methanol fuelled ICEs to generate the propeller and auxiliary power from 2035 to 2050. The details of the pathways are described in 7 Pathways. The details this pathway are given in 7.3.4 Pathway 3 - Diesel ICE to methanol ICE. The diesel configurations and tank layouts of pathway 3 for the two yachts are shown in Figure 8.2 and Figure 8.8. The methanol configurations and tank layouts of pathway 3 for the two yachts are shown in Figure 8.4 and Figure 8.10. These configurations and tank layouts are used in the design tool. With the design tool, the emissions of a yacht in a year and the costs can be determined. Below is an overview of constant and variable parameters.

Constants:

- Yacht length (see 5.2.5, only for 2020-2035)
- Tank layout (2020-2035: one tank, 2035-2050: two tanks)
- Converter type (ICE)
- Converter configuration (only for 2020-2035)
- Converter efficiency (see 7.2.2)
- Converter price (see 7.2.3)

Variables:

- Yacht length (see 5.2.5, only for 2035-2050)
- Converter configuration (depends on length iteration, only for 2035-2050)
- Fuel price (see 7.2.1)
- Operational profile (yacht specific)

8.6.1. Emissions

The emissions are determined from the fuel consumption which depends on the operational profile of the yacht. These emissions include CO_2, NO_x, SO_x and PM. These yearly emissions for the first time span (2020-2035) are equal to the diesel baseline of pathway 0 and for the second time span (2035-2050) they are equal to that of the first methanol pathway. The average yearly emissions throughout the entire time span (2020-2050) are compared to the baseline pathway and shown in Figure 8.19. To put the average emissions of the third pathway into perspective, the average CO_2 and NO_x are related to forest area and truck emissions respectively in Table 8.20.

Since pathway 3 is a combination of a diesel (2020-2035) and a methanol (2035-2050) configuration, the average yearly emissions are in between the yearly emissions of each configuration individually (see Figure 8.19). The individual yearly emissions are equal to pathway 0 and pathway 1 for the diesel and methanol configuration respectively. The average yearly emissions, compared to the baseline pathway, of CO_2 have increased slightly, the average yearly NO_x emissions are equal and the SO_x and PM emissions have decreased significantly. The CO_2 emissions of yacht A have increased by 4.9% compared to the baseline pathway.

Both the CO_2 and NO_x emissions are very similar to that of the baseline pathway and the first methanol

Table 8.20: Average CO_2 and NO_x emissions in perspective. The net CO_2 emissions are related to the forest area required to sequester the yearly CO_2 emitted by the yacht (data from Toochi (2018)). The NO_x emissions are related to the amount of diesel cars and heavy-duty diesel trucks (>20t), driving 80 km/h continuously, that emit an equal amount of NO_x (data from ICCT (2014); Velders (2013)).

Yacht	Fuel feedstock	CO_2 emissions		NO_x emissions		
		CO_2-WTW [t]	A_{forest} [km^2]	NO_x [t]	Cars	Heavy-duty trucks
A	Fossil	6732	15.37	20.3	48	9
	Renewable	0	0	20.3	48	9
B	Fossil	3219	7.35	9.7	23	5
	Renewable	0	0	9.7	23	5

pathway. This results in a small increase in forest area required to sequester the CO_2 emissions of the yachts and approximately an equal amount of cars and heavy-duty trucks to equal the NO_x emissions (see Table 8.20).

8.6.2. Costs

The fuel costs over the entire period of pathway 3 are shown in Figure 8.20. The fuel costs are compared to the fuel costs of the baseline pathway that uses diesel ICEs. Since there is no change in efficiency of the converters between configuration 1 and configuration 2 (see 7.2.2 Converter efficiency), the decreasing trend in fuel costs is purely caused by a decrease in fuel price and by the switch from diesel to methanol. If the efficiency would change there would be an additional small decreasing jump in 2035 in fuel costs as at that year the configuration is refitted and a newer, more efficient engine may be installed. The gradual change in fuel costs is the result of a change in fuel price (see 7.2.1 Fuel price). This pathway, that is a combination of the baseline diesel pathway and methanol pathway 1, is more interesting in terms of yearly fuel costs. Since the switch from diesel to methanol is made in 2035, there is a corresponding jump in yearly fuel costs in this year. The fossil methanol costs increase, compared to the fossil diesel costs, while the renewable methanol costs decrease significantly compared to the renewable diesel costs. This pathway is particularly interesting when fossil diesel is used during the first 15 years and a switch to renewable methanol is made in 2035. This option represents the case that renewable diesel is considered too expensive during the first 15 years and (renewable) methanol's availability is not sufficient to be a feasible option. Then in 2035, the price of renewable methanol has decreased significantly (compared to the 2020 price) and renewable methanol may be a feasible option then.

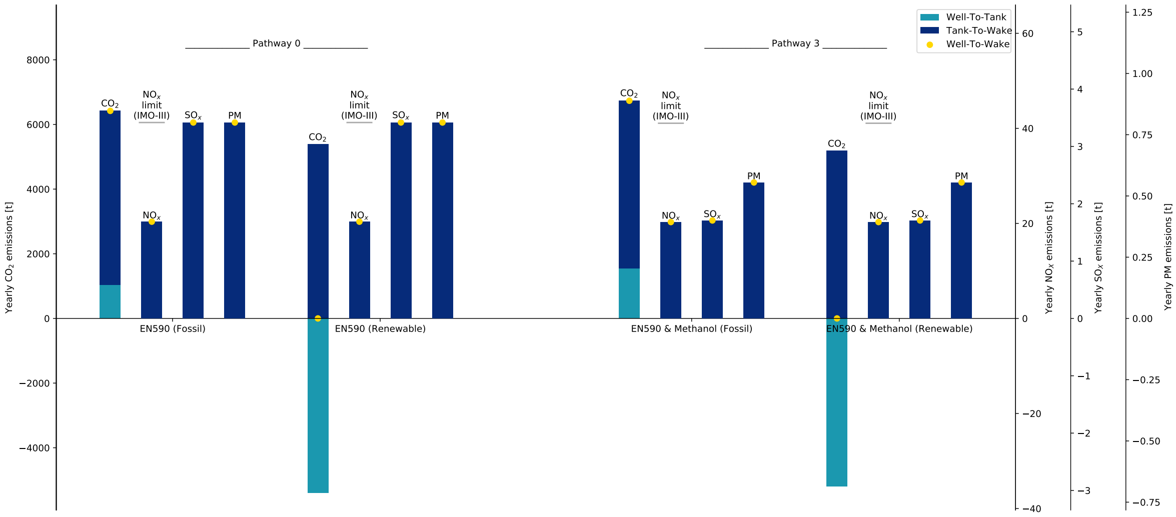
The costs of the converters for both propulsion and auxiliary power are shown in Table 8.21. The storage costs of diesel tanks in the double bottom are assumed to be equal to zero, as discussed in 5.5.3 Fuel storage. The costs of converters are also shown relative to the value of the yacht in Table 8.22 together with the relative costs of storage which is stated between brackets. The total relative costs range from around 1.7% to 3.1%, while the relative costs of the storage itself ranges from 0.12% to 0.20% for the methanol configurations. The storage costs are therefore likely to only make up a very small part of the total costs of the yacht. It can also be seen that the relative converter costs increase with decreasing yacht size. The relative storage costs are mostly related to the required energy capacity as a result of the required range. When looking at yacht A and B which have a comparable range, it can be concluded that the relative storage costs also increase with decreasing yacht size.

Table 8.21: Costs of converters for propulsion and auxiliary power generation and storage costs of pathway 3.

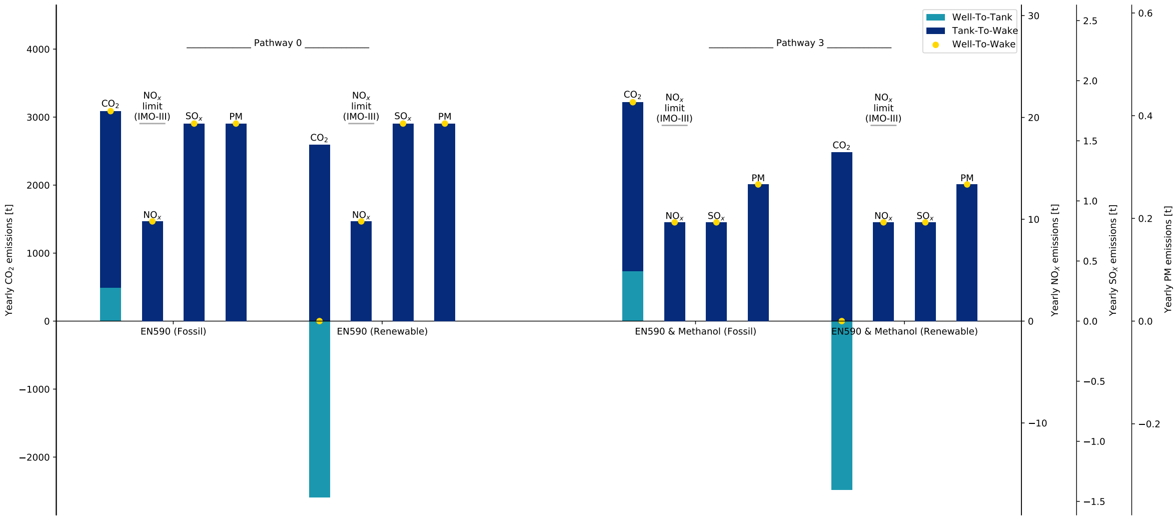
Yacht	Configuration 1					Configuration 2				
	Propulsion		Auxiliary		Storage	Propulsion		Auxiliary		Storage
	Type	Price [M€]	Type	Price [M€]	Price [€]	Type	Price [M€]	Type	Price [M€]	Price [€]
A	ICE	2.780	ICE	1.528	0.0	ICE	2.780	ICE	1.528	293,603
B	ICE	0.896	ICE	0.570	0.0	ICE	0.896	ICE	0.570	98,799

Table 8.22: Total converter costs and storage costs of pathway 3. The total costs (converters and storage) are expressed as a percentage of the yacht's value. The relative storage costs are given between brackets.

Yacht	Configuration	Converter costs [M€]	Storage costs [M€]	Yacht value [M€]	Relative costs [%]
A	ICE - Diesel	4.308	0.000	250	1.72 (0.00)
	ICE - Methanol	4.308	0.294	250	1.84 (0.12)
B	ICE - Diesel	1.466	0.000	50	2.93 (0.00)
	ICE - Methanol	1.466	0.099	50	3.13 (0.20)

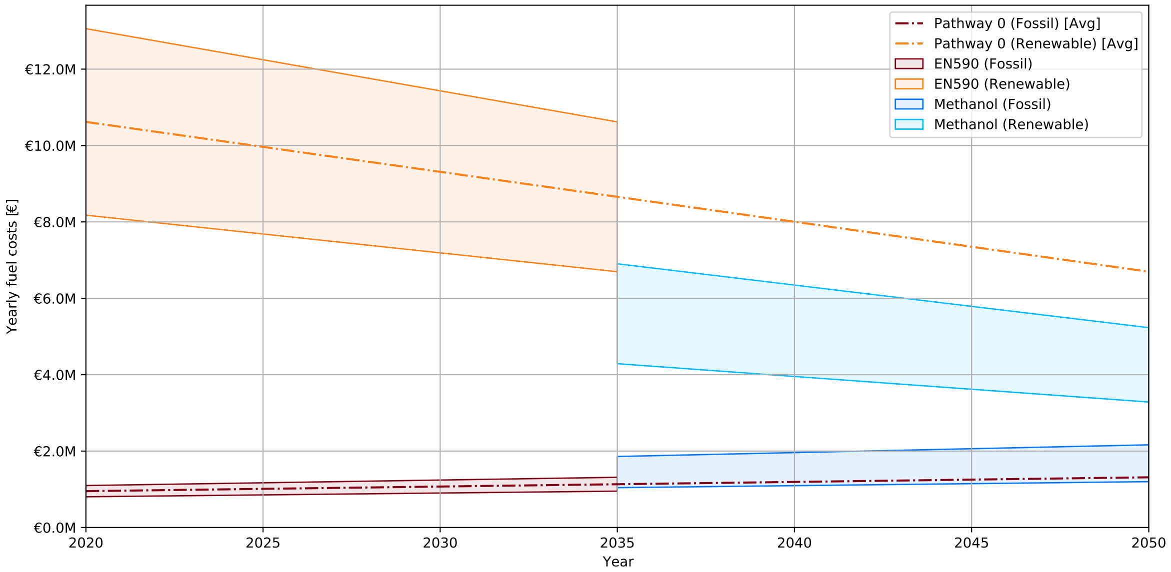


(a) Average yearly emissions of yacht A.

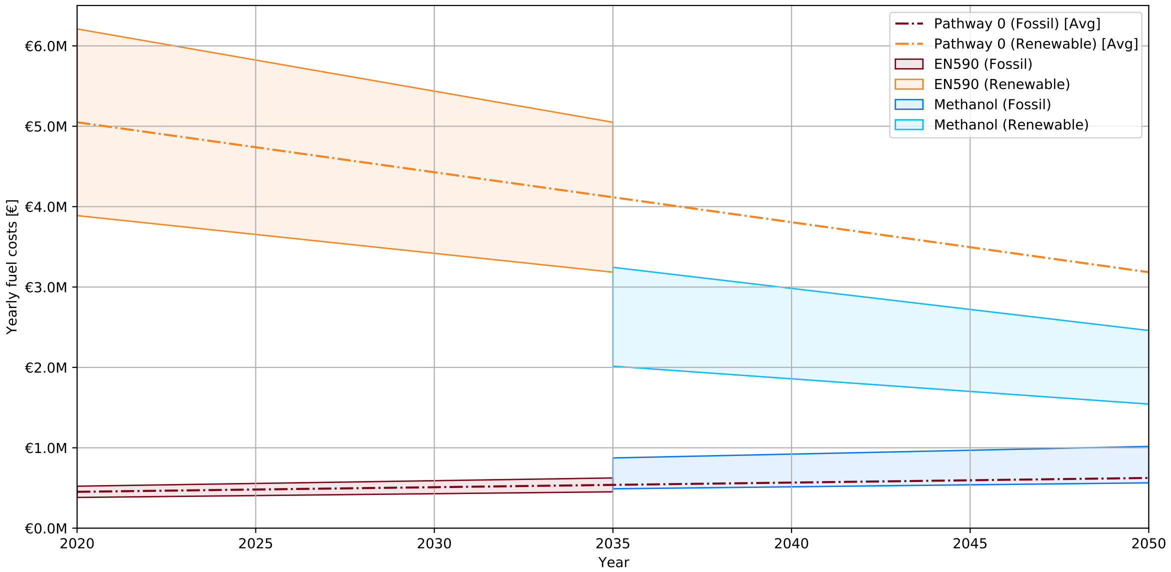


(b) Average yearly emissions of yacht B.

Figure 8.19: Average yearly emissions of CO_2, NO_x, SO_x and PM for pathway 3 (2020 to 2050), compared to the diesel baseline (pathway 0). The emissions are shown in tonnes per year for both fossil and renewable diesel and methanol and are split up into well-to-tank and tank-to-wake emissions.



(a) Yearly fuel costs of yacht A.



(b) Yearly fuel costs of yacht B

Figure 8.20: Yearly fuel costs (with upper and lower limits) for pathway 3 which uses diesel ICEs for propulsion and auxiliary power from 2020 to 2035 and methanol ICEs from 2035 to 2050. The average fuel costs of the baseline pathway 0 are also shown as a comparison. Both fossil and renewable yearly fuel costs are shown.

8.7. Pathway 4 - Methanol ICE to methanol ICE+FC

The fourth and final methanol pathway uses methanol as fuel with internal combustion engines to generate the required propulsion power and auxiliary power from 2020 to 2035 and methanol fuelled ICEs to generate the propeller and auxiliary power from 2035 to 2050. The details of the pathways are described in 7 Pathways. The details this pathway are given in 7.3.5 Pathway 4 - Methanol ICE to methanol ICE+FC. The ICE configurations and tank layouts of pathway 4 for the two yachts are shown in Figure 8.4 and Figure 8.10. The ICE+FC configurations and tank layouts of pathway 4 for the two yachts are shown in Figure 8.6 and Figure 8.12. These configurations and tank layouts are used in the design tool. With the design tool, the emissions of a yacht in a year and the costs can be determined. Below is an overview of constant and variable parameters.

Constants:

- Tank layout (two tanks)
- Converter type (2020-2035: ICE, 2035-2050: ICE)
- Converter efficiency (see 7.2.2)
- Converter price (see 7.2.3)

Variables:

- Yacht length (see 5.2.5)
- Converter configuration (depends on length iteration)
- Fuel price (see 7.2.1)
- Operational profile (yacht specific)

8.7.1. Emissions

The emissions are determined from the fuel consumption which depends on the operational profile of the yacht. These emissions include CO_2, NO_x, SO_x and PM. These yearly emissions for the first time span (2020-2035) are equal to the first methanol pathway and for the second time span (2035-2050) they are equal to that of the second methanol pathway. The average yearly emissions throughout the entire time span (2020-2050) are compared to the baseline pathway and shown in Figure 8.21. To put the average emissions of the fourth pathway into perspective, the average CO_2 and NO_x are related to forest area and truck emissions respectively in Table 8.23.

The fourth methanol pathway is a combination using methanol fuelled ICEs and then switching to fuel cells for the generation of auxiliary power. Therefore, the average yearly emissions (see Figure 8.21) are a combination between the emissions of pathway 1 and pathway 2. Compared to the baseline, the CO_2 emission of yacht A have increased by 6.9% while the NO_x, SO_x and PM emissions have decreased. Compared to the ICE only methanol pathway 1, all average emissions are lower (except for SO_x which is equal to zero for both), because fuel cells are used in the second time span (after 2035) which significantly lowers these emissions.

This decrease in emissions is also seen in the forest area required to sequester the emitted CO_2 and the number of cars and heavy-duty trucks to emit an equal amount of NO_x (see Table 8.23). A significant decrease of 33% in NO_x emissions is seen for yacht A, compared to both the diesel baseline and methanol pathway 1.

Table 8.23: Average CO_2 and NO_x emissions in perspective. The net CO_2 emissions are related to the forest area required to sequester the yearly CO_2 emitted by the yacht (data from Toochi (2018)). The NO_x emissions are related to the amount of diesel cars and heavy-duty diesel trucks (>20t), driving 80 km/h continuously, that emit an equal amount of NO_x (data from ICCT (2014); Velders (2013)).

Yacht	Fuel feedstock	CO_2 emissions		NO_x emissions		
		CO_2-WTW [t]	A_{forest} [km^2]	NO_x [t]	Cars	Heavy-duty trucks
A	Fossil	6863	15.67	13.6	32	6
	Renewable	0	0	13.6	32	6
B	Fossil	3159	7.22	6.2	15	3
	Renewable	0	0	6.2	15	3

8.7.2. Costs

The fuel costs over the entire period of pathway 4 are shown in Figure 8.18. The fuel costs are compared to the fuel costs of the baseline pathway that uses diesel ICEs. Since there is no change in efficiency of the converters between configuration 1 and configuration 2 (see 7.2.2 Converter efficiency), the decreasing trend in fuel costs is purely caused by a decrease in fuel price and by the switch from methanol ICEs to methanol FCs for the generation of auxiliary power. If the efficiency would change there would be an additional small decreasing jump in 2035 in fuel costs as at that year the configuration is refitted and a newer, more efficient engine may be installed. The gradual change in fuel costs is the result of a change in fuel price (see 7.2.1 Fuel price). The jump in yearly fuel costs of this fourth pathway is less than for the switch from diesel to methanol in pathway 3, but still noticeable. The fossil methanol fuel costs are a little closer to the average diesel costs of pathway 0 after the switch to fuel cells in 2035. This pathway can show the scenario that fuel cells are initially (2020-2035) considered too expensive, to not have a high enough efficiency or to have a lifetime that is too short. However in 2035, fuel cells may have become less expensive, more efficient or have a better lifetime. By this time, the fuel price of renewable methanol has also decreased, allowing the low emission combination of fuel cells and renewable methanol to be more feasible in terms of yearly fuel costs (and capital costs).

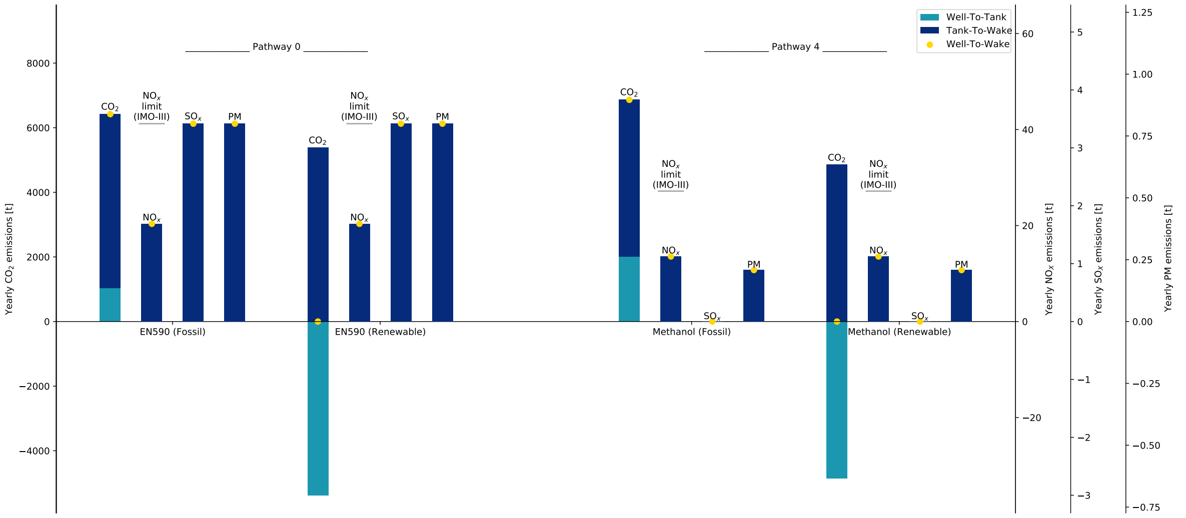
The costs of the converters for both propulsion and auxiliary power are shown in Table 8.24. The costs of converters are also shown relative to the value of the yacht in Table 8.25 together with the relative costs of storage which is stated between brackets. The total relative costs range from around 1.8% to 6%, while the relative costs of the storage itself ranges from 0.12% to 0.20%. The storage costs are therefore likely to only make up a very small part of the total costs of the yacht. The increase in relative costs is caused by the expensive fuel cells.

Table 8.24: Costs of converters for propulsion and auxiliary power generation and storage costs of pathway 4.

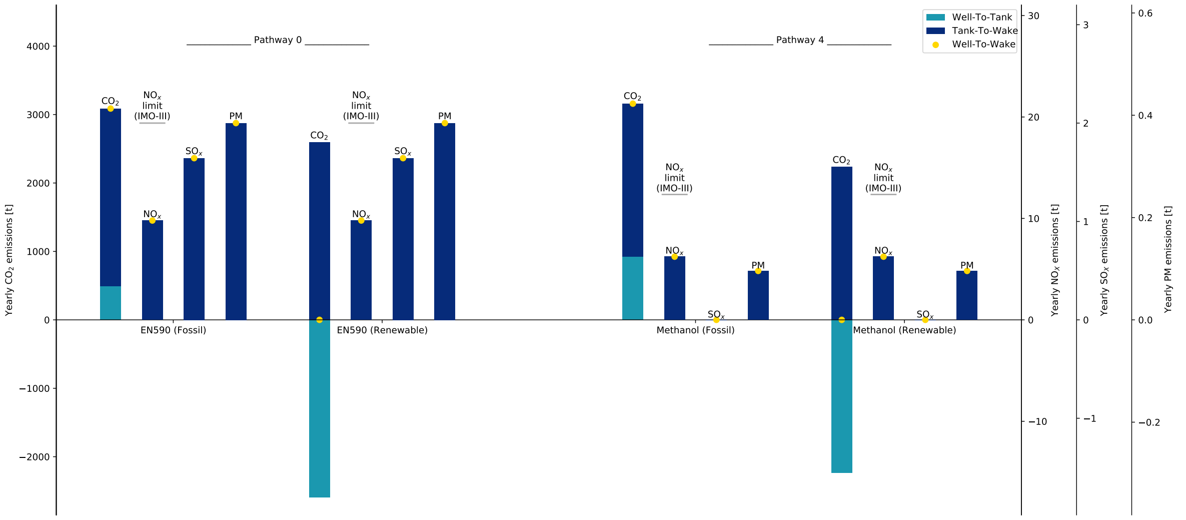
Yacht	Configuration 1					Configuration 2				
	Propulsion		Auxiliary		Storage	Propulsion		Auxiliary		Storage
	Type	Price [M€]	Type	Price [M€]	Price [€]	Type	Price [M€]	Type	Price [M€]	Price [€]
A	ICE	2.780	ICE	1.528	293,603	ICE	2.780	FC	7.560	293,603
B	ICE	0.896	ICE	0.570	98,799	ICE	0.737	FC	2.160	96,332

Table 8.25: Total converter costs and storage costs of pathway 4. The total costs (converters and storage) are expressed as a percentage of the yacht's value. The relative storage costs are given between brackets.

Yacht	Configuration	Converter costs [M€]	Storage costs [M€]	Yacht value [M€]	Relative costs [%]
A	ICE - Methanol	4.308	0.294	250	1.84 (0.12)
	ICE+HT-PEMFC - Methanol	10.340	0.294	250	4.25 (0.12)
B	ICE - Methanol	1.466	0.099	50	3.13 (0.20)
	ICE+HT-PEMFC - Methanol	2.897	0.096	50	5.99 (0.19)

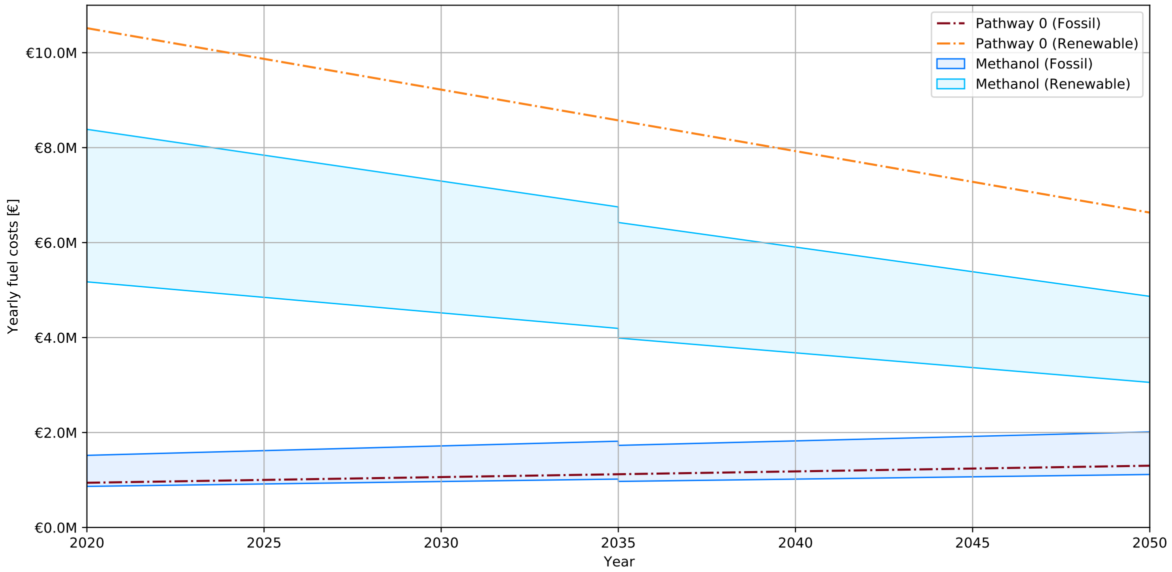


(a) Average yearly emissions of yacht A.

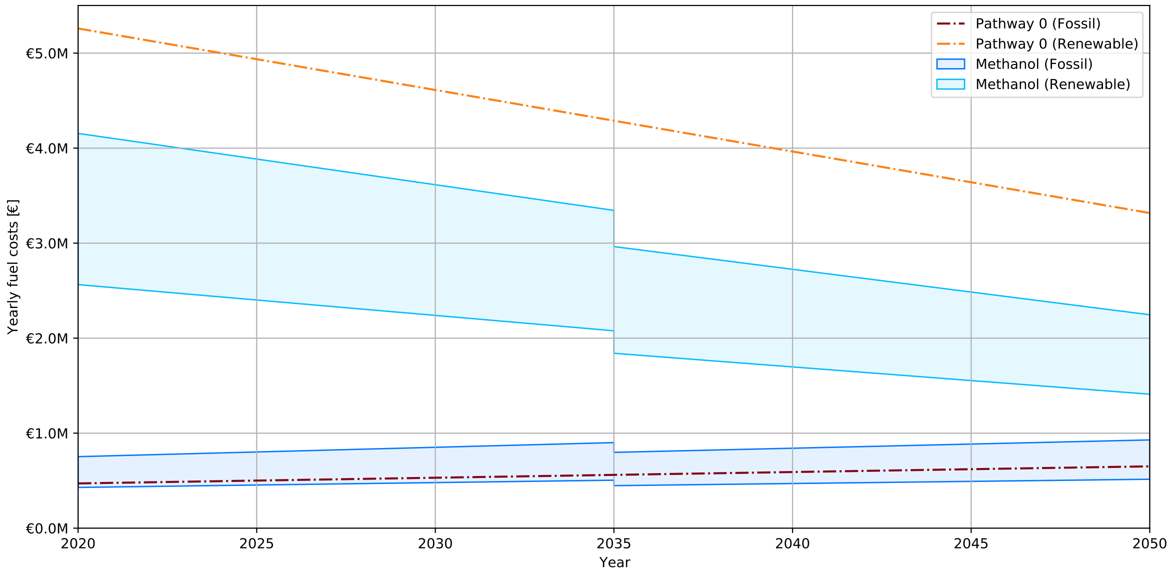


(b) Average yearly emissions of yacht B.

Figure 8.21: Average yearly emissions of CO_2, NO_x, SO_x and PM for pathway 4 (2020 to 2050), compared to the diesel baseline (pathway 0). The emissions are shown in tonnes per year for both fossil and renewable diesel and methanol and are split up into well-to-tank and tank-to-wake emissions.



(a) Yearly fuel costs of yacht A.



(b) Yearly fuel costs of yacht B.

Figure 8.22: Yearly fuel costs (with upper and lower limits) for pathway 4 which uses methanol ICEs for propulsion and auxiliary power from 2020 to 2035 and methanol ICEs and fuel cells from 2035 to 2050. The average fuel costs of the baseline pathway 0 are also shown as a comparison. Both fossil and renewable yearly fuel costs are shown.

8.8. Case study conclusion

8.8.1. Design impact conclusions

Two yachts were investigated in terms of design impact: a large low speed yacht and a small low speed yacht. A case study was also performed for a small high speed yacht (see Appendix D) but the results were less reliable as the properties of this yacht are outside the range of the design tool. The design tool is used to determine the power and fuel storage requirements as well as the space available with several tank layouts and converters options. Overall, it can be stated that both the methanol tank layouts implemented in the design tool result in feasible layouts in terms of arrangement that satisfy the requirements. However, the impact of the large volume of methanol compared to diesel which is largely outside the double bottom and the cofferdams is rather large on the interior of the yacht. The relative impact of the cofferdam does decrease with decreasing yacht size.

Yacht A

For the large low speed yacht, the cofferdams were small compared to the volume of the methanol tank, especially for the single tank layout. Both the single methanol tank layout and double methanol tank layouts were determined by the design tool with all internal combustion engines and with fuel cells for the generation of auxiliary power. The effect of the alternative cofferdam was also shown, resulting in less length increase required to keep the interior area equal. All configurations led to feasible designs which fit in the yacht and are considered to be constructible. The effect on trim was also assessed for this yacht. The single methanol tank resulted in a larger change in trim than the double methanol tank, but this is not considered a problem. However, the double methanol tank is more desirable in terms of trim options. Therefore, the double tank layout is used in the pathway analysis.

Yacht B

The small low speed yacht showed that the cofferdams use a significant amount of volume and interior area on a smaller yacht. Even with a single methanol tank, which is the most volume efficient option, the cofferdams are relatively large compared to the methanol tank itself. Both the internal combustion engine and fuel cell configurations are considered feasible, if the fuel cells are rearranged in the engine room. For this smaller yacht, the effect of the alternative cofferdam becomes really visible. With a double methanol tank layout, the aft tank can be less than half the size of the aft tank with normal cofferdams. The effect on trim was also assessed for this yacht but led to similar conclusions as for the larger yacht. The single methanol tank resulted in a larger change in trim than the double methanol tank, but this is not considered a problem. However, the double methanol tank is more desirable in terms of trim options. Therefore, the double tank layout is used in the pathway analysis.

8.8.2. Pathway conclusions

The 4 methanol pathways and the diesel baseline pathway were researched in terms of costs and emissions for two different yachts that each represent a different type of yacht. The yachts consisted of a large yacht with a lower maximum speed and a small yacht with a low maximum speed. The four methanol pathways were compared to the diesel baseline pathway in order to determine the difference in performance. Overall, it can be stated that using methanol results in no SO_x emissions and fewer PM emissions. The amount of NO_x emissions depends primarily on the energy converter that is used, with fuel cells resulting in significantly less NO_x emissions, as well as further reducing the PM emissions. CO_2 emissions increase slightly when fossil methanol is used compared to fossil diesel. However, renewable methanol can bring the net CO_2 emissions to zero at a lower fuel cost than renewable diesel.

Pathway 1

The first pathway, that uses methanol ICEs, showed an increase of CO_2 emissions, comparable NO_x emissions, no SO_x emissions and much lower PM emissions compared to the diesel baseline. These differences were similar for both yachts. The CO_2 emissions are reduced to zero when renewable methanol is used. The fuel costs for this pathway were slightly higher for fossil methanol than for fossil diesel, but the average diesel fuel costs was within the upper and lower limit of the methanol fuel costs. Renewable methanol fuel costs were significantly (5x) higher than fossil methanol costs but not as high as renewable diesel fuel costs. The converter costs for this pathway were in the order of 2% of the yacht's total costs for the large yacht to 3% for the small yacht. Since methanol converters are similar in costs as diesel converters, this percentage would be similar for diesel yachts. The relative storage costs of the methanol tanks was estimated at 0.1 to 0.2 percent of the yacht's total costs and can therefore be considered of small impact in terms of costs.

Pathway 2

The second pathway, which uses methanol ICEs and PEMFCs, showed comparable CO_2 emissions, a significant reduction of NO_x, no SO_x emissions and also a significant reduction of PM emissions compared to the diesel baseline. The CO_2, NO_x and PM emissions were also lower for this pathway than for the first pathway, which can be expected because fuel cells reduce these emissions. The increased efficiency of the FCs resulted in a reduction of fuel costs, which brought the average fossil methanol fuel costs on a level that is equal to fossil diesel. The renewable methanol fuel costs are now only half of that of renewable diesel in the baseline pathway. Because fuel cells are more expensive, the converter costs increased to 4 to 6% of the yachts total costs. The storage costs remained similar to pathway 1.

Pathway 3

The third pathway, which is a combination of the baseline pathway for the first half of the time span and the first methanol pathway for the second half, showed slightly increased CO_2 emissions, similar NO_x emissions, halved SO_x emissions and a reduction of one third of PM emissions compared to the diesel baseline. This is also expected as this pathway is a combination of the baseline pathway and the first methanol pathway. The fuel costs therefore also showed a combination of the two pathways, which results in a jump in fuel costs at the halfway point. The fossil fuel costs increased slightly, while the renewable fuel costs reduced significantly. Both the converter and storage costs are also a combination of the two pathways.

Pathway 4

The fourth and final pathway, a combination of pathway 1 and pathway two, switches to fuel cells for auxiliary power at the halfway point. This results in emissions that are the average of pathway 1 and pathway 2 and therefore slightly better than the first pathway. As with the third pathway, again a jump in fuel costs was seen halfway the time span. The switch to fuel cells halfway resulted in a decrease in both renewable and fossil methanol, from the level of pathway 1 to the level of pathway 2. As no trends in converter efficiency or price were used, the converter and fuel costs are simply the average of pathway 1 and pathway 2. If these trends would be used, this pathway may be beneficial if fuel cells reduced in price and increased in efficiency over time. This would allow the yacht owner to postpone the large investment in fuel cells until they've become more efficient and less expensive.

9

Methanol in perspective

In this chapter methanol as alternative fuel is put into perspective. The possibilities and opportunities of methanol but also the difficulties, potential problems and unanswered questions are discussed.

9.1. Potential of methanol

From this research it can be concluded that methanol has much potential as an alternative fuel. Most important is the possibility to reduce emissions. Since methanol contains no sulphur, the emissions of SO_x are zero and the emissions of PM are about a third of that of diesel. Next to that the NO_x emissions in ICEs of methanol are approximately equal to that of diesel for IMO Tier III but no after treatment is required for methanol. This can save a lot of space inside the engine room as the after treatment unit of diesel can be quite large. CO_2 emissions are slightly higher for fossil methanol than fossil diesel, but when renewable methanol is used, the net CO_2 emissions are zero. Methanol therefore has the potential to become a net zero greenhouse gas emission fuel with also much lower other emissions than conventional diesel. This reduction in emissions allows yacht owners to reduce their environmental footprint and allows them to travel to destinations that will enforce stricter emission regulations in the future.

Next to the possibility to reduce emissions methanol is also relatively easy to implement. Methanol can be used in internal combustion engines with relatively few modifications and also in fuel cells. Both converters are being developed and can be ordered. Methanol can also be stored relatively easy compared to other alternative fuels. For most alternative fuels such as hydrogen, LNG and ammonia, cryogenic or pressurised storage is required. Methanol can be stored in conventional diesel tanks and does not have to be cooled or pressurised to keep the methanol liquid. The methanol tanks do however require to be surrounded by cofferdams (except where adjacent to the shell plating below the lowest possible waterline).

9.2. Difficulties of methanol

As with all alternative fuels there are some difficulties and potential problems with methanol. The first difficulty is with the large volume of methanol required and where in the yacht the methanol can be stored. Since the energy content of methanol is significantly lower than that of diesel about 2.3 times more fuel volume is required to achieve the same range. This wouldn't be a large problem if the methanol could be stored in the double bottom, as the double bottom often consists of quite a lot of void spaces. However, the methanol has to be surrounded by cofferdams which have minimum dimensions as they have to be inspected from the inside. This results in that the double bottom is not a feasible location, especially in terms of construction, to use as methanol tanks.

The most feasible tank layout is to have one larger tank close to the centre of gravity of the yacht with a height up to the waterline. This way the volume of the cofferdams is minimised and the impact on trim is small. One larger tank is however less desired as it gives very limited options to change the trim of the yacht. Therefore a tank layout with two separate tanks offers sufficient trim options while also keeping the cofferdam volume relatively low. However, even with only two separate tanks, the cofferdams make up 30% of the tank volume for a large yacht and over 50% for a small yacht. The additional fuel volume required, the large cofferdam volume and the feasible locations of the tanks combined result in a significant reduction of interior space. This can be compensated by increasing the dimensions (e.g. length) of the yacht in case of a new design but this is not feasible for an existing yacht (retrofitting). If an alternative to the large cofferdams could be found with much smaller dimensions, this would reduce the used interior area by approximately 10% if the same tank layouts are used. If this alternative would allow the double bottom to be used effectively for the storage of methanol, this would greatly reduce the interior are that is used, perhaps even to the point that no interior area is required and all methanol can be stored in the double bottom. This would also enable retrofitting yachts with methanol.

Next to the inconvenient storage of methanol, the price of renewable methanol as found in the literature is quite high, approximately 5 times as high as fossil methanol. While this allows for a net zero GHG emission yacht, the fuel costs will increase significantly compared to both fossil diesel and fossil methanol. Compared to renewable diesel, renewable methanol currently is about a third less expensive (as found in the literature). Further development in the production processes of methanol, and other renewable fuels, may reduce the fuel costs of renewable fuels making them a more attractive options. Government measures (e.g. carbon taxes, etc.) can also help to decrease the price gap between fossil and renewable fuels.

Another difficulty of methanol is the global availability. As determined in the literature review, methanol is globally well available, better than other alternative fuels. However, this availability is limited to the larger ports, which are not always close to the areas where superyachts sail. The locations that attract yacht owners are often dense tourist destinations or more remote natural heritage sites. Especially the latter is often not close to a large port where methanol is available. A reduction in range, as would be very beneficial from a design impact point of view, is therefore not recommended with the current global availability. Whether methanol will also become available in smaller ports located more closely to these yacht destinations mostly depends on which alternative fuel will be favoured by all of the shipping industry, of which the yachting industry is only a very small fraction. An equal range, if not a larger range to account for availability, to that of a diesel yacht is therefore preferred.

This research assesses methanol as fuel for yachts on a low level of detail to determine the impact methanol can have on a yacht. In order to actually develop a detailed design and build that design, all aspects of methanol have to be investigated with much greater detail. More questions will arise when designing the tanks and engine room, especially when looking at the safety requirements from the rules and regulations. The current rules and regulations require double walled piping as well as interting and/or venting capabilities of all spaces where methanol can be present. These details were outside the scope of this research, but very important to a methanol yacht design.

9.3. Lessons learned

In this section, a short overview of lessons learned for a future methanol design and methanol as a fuel in general are listed. These lessons learned are derived from the literature study and design tool results as presented in this research.

Design lessons:

- The volume of methanol required is much larger than diesel. Therefore the tanks and the required cofferdams use a large amount of interior space. If an equal interior area is desired, the dimensions of the yacht could be increased to generate extra interior area. As is done in this research, increasing the length could be an option for new designs.
- With the current rules & regulations (i.e. cofferdams) it is desirable to store methanol in as few separate tanks as possible, where the tanks have a height up to the lowest possible waterline and span the entire width of the yacht. This reduces the volume of the cofferdams for an equal fuel volume.
- When a single methanol tank is used, it should be located as close to the centre of gravity of the yacht as possible to keep the impact on trim as small. With a two tank layout, trim should not be

an issue when there is some freedom in the placement of each tank.

- A large draught (i.e. a high waterline) is beneficial for methanol tanks as it increases height of the methanol tanks where no cofferdams are required between the shell plating and the tank. This reduces the interior area which is occupied by the tanks.
- Methanol can be considered easier to implement on a large yacht than on a smaller yacht, as a large yacht has a larger draught (generally) which allows for more methanol volume per metre tank length (and therefore less interior area). This also increases the constructional feasibility as there is more height to weld the tank and cofferdam construction. A large draught usually also indicates a higher double bottom, which may even allow the methanol tanks including cofferdams to be placed in the double bottom entirely. This would greatly reduce the impact on the design of the yacht.
- Frame spacing is an important aspect to consider with the current minimum cofferdam dimensions in the rules & regulations. If the frame spacing is less than the minimum required cofferdam width, an additional frame has to be used by the cofferdam in terms of constructional feasibility. This results in a large increase in cofferdam volume relative to the methanol tank volume, which is undesirable.

Methanol lessons in general:

- CO_2 emissions of methanol can only be reduced, compared to fossil diesel, if renewable methanol is used. Then a zero GHG emission yacht is possible (depending on the well to tank emissions).
- NO_x emissions are similar for methanol and diesel in internal combustion engines but no after treatment is required for methanol engines whereas diesel engines do require this. This reduces the space required for the engines and after treatment in the engine room.
- SO_x and PM emissions are zero and much lower than diesel respectively.
- Availability is better than most other alternative fuels. However, not so widely available that it can justify a range reduction for yachts, as they often sail to more remote areas and tourist dense locations where methanol is not closely available.
- The costs of energy converters using methanol as fuel is similar to diesel. The cost of methanol tanks is estimated to be low, in the order of 0.1 to 0.2 percent of the total costs of the yacht.
- The fuel costs when using fossil methanol are slightly higher than when using fossil diesel. However, when using methanol fuel cells this difference becomes negligible. The fuel costs for renewable methanol are lower than renewable diesel in the literature sources found in this research, but about 5 times higher than fossil methanol. Fuel costs should be treated with caution as the price of renewable fuels varies between literature sources and will change over time.
- Retrofitting existing yachts to operate on methanol is currently not considered feasible, which is due to the large design impact but also the costs which are expected to be extremely high. Therefore, other fuel storage solutions have to be found that have a much smaller impact on existing yachts. Without a large decrease in design impact, methanol is not the right solution for retrofitting.

9.4. Possible implementations

Actually designing a yacht that sails on methanol will be a large challenge. Especially doing this in the near future may be difficult, both in terms of designing according to the rules and regulations and in terms of operating and using the yacht with respect to the current availability. The difficulty will become slightly less once alternative solutions are accepted in the rules and regulations, such as a smaller cofferdam design.

Methanol would be easier to implement on a large yacht than on a small yacht. On a large yacht there is generally more space available for technical areas and more void spaces in the hull. Especially if alternative solutions to the cofferdam become accepted in the future the double bottom, which is generally large in a large yacht, and the voids in it can offer a lot of space for methanol tanks. This would greatly reduce the impact on the interior that is has with the current cofferdams and tank layouts used in this research. However, even with the current cofferdam requirements and dimensions, a larger yacht generally offers much more space and height in the double bottom and in the hull. This makes the construction of especially the tanks and cofferdams more feasible.

The implementation of methanol on a smaller yacht is considered to be more difficult. The double bottom is much smaller and lower than the double bottom of a large yacht. This rules out any possibility of using the double bottom for methanol tanks almost completely as long as a cofferdam (regular or smaller alternative) is required, since the construction of the double bottom on these smaller yachts in itself is already a difficult task due to the limited height in combination with the curved and stiffened hull leaving little space to weld. The methanol tank and cofferdams, with the tank layouts used in this research, require a relatively large amount of interior space compared to a large yacht. Therefore, the impact of methanol on the design of a small yacht is relatively large.

The target of a successful implementation of methanol on a yacht would be to maximise the space and volume available for methanol storage while at the same time minimising the volume required. The space and volume available could be maximised by increasing the dimensions of the yacht or by the owner accepting a loss of interior space. The methanol volume required could be minimised by reducing the required range but this is not a good solution as the global availability is insufficient for that.

The required volume could also be reduced by increasing the converter efficiency, which can be done by using the more efficient fuel cells for the generation of auxiliary power. Propulsion power generation requires a large amount of fuel cells which is very expensive and requires a lot of space in the engine room. Next to that, most fuel cells have slower start up and response times which makes them less suitable for the variable propulsion power, especially the more efficient SOFC. The auxiliary power on the other hand is more constant. Unlike most ship types, a yacht only sails a small percentage of the time. Therefore, auxiliary power consumes a large amount of the total energy stored on-board. An increase in efficiency, relative to the internal combustion engines, will result in a decrease in required fuel volume. This effect can be significant, especially for a large increase in efficiency as would be the case for SOFC which have an efficiency of up to 85%, over twice that of an ICE.

Another possibility to reduce the required fuel capacity is to reduce the range and/or maximum speed. The required fuel capacity is determined by a range calculation with two main engines running. When the maximum speed is reduced, smaller engines may be chosen that run closer to their optimum load and rpm at range speed than two more powerful engines. The range speed itself also determines the fuel consumption for a large part. Reducing this speed can also reduce the required fuel capacity. However, it is up to the yacht owner whether such a reduction is acceptable.

10

Conclusions and recommendations

This research investigated the net impact of using methanol as an alternative fuel on yachts with the help of a design impact tool and pathway analysis method that was developed. This final chapter states the conclusions that can be drawn from this research and presents recommendations for future research and development.

10.1. Conclusions

In this section the sub questions, as stated in 1.2 Research questions, will be answered.

What are the power and energy requirements of yachts throughout their operational profile?

In order to develop the design impact tool, a method to determine the power and energy storage requirements had to be chosen. The propulsion power is determined by the empirical Holtrop & Mennen method. The required auxiliary power is determined through a regression formula based on existing Feadships. Both powers are determined throughout the operational profile. With the required powers, the energy converters are chosen. Their properties are then used in a range calculation to determine the required energy capacity to reach the required range.

What are feasible fuel storage options for a methanol fuelled yacht, considering safety and rules and regulations?

Feasible tank layouts were investigated to determine this by analysing the available space in existing yachts. It is concluded that the double bottom is not a feasible location for methanol tanks, especially on smaller yachts. The required cofferdams, which are relatively large compared to the tank, have a large impact on what principle tank layouts are feasible. Therefore, it is desirable to keep the amount of separate tanks to one or two. Additionally, an analysis was done on the effects of a smaller alternative cofferdam. However, the impact of methanol tanks on the design remained large as the fuel cannot be stored in the double bottom only. Therefore, the tanks use considerable interior space.

Which energy converters are feasible options for a methanol fuelled yacht and how do they perform in terms of costs and emissions?

Because the design impact tool uses a database of energy converters these converters had to be investigated, which is done in the literature review. Both internal combustion engines (ICEs) and high-temperature PEM fuel cells were found to be feasible energy converters. Both energy converters are available, are being build and have efficiencies comparable to diesel ICEs. Methanol ICEs were found to be on par with diesel ICEs in terms of costs and efficiency. The difference in emissions comes primarily from the properties of the fuel itself, which results in slightly higher CO_2 emissions, no SO_x emissions and lower PM emissions for methanol. The NO_x emissions of ICEs are comparable for both fuels but methanol ICEs do not require after treatment to meet the IMO Tier-III requirements. Only with fuel cells is a further reduction in NO_x and PM emissions possible.

What are possible pathways of existing and new yachts towards a zero (GHG) emission future of a methanol fuelled system?

With the design impact tool, the impact of using methanol over a longer time span is investigated. Several pathways were determined. In order to represent realistic future scenarios, 4 pathways that use methanol as fuel were created as well as a diesel baseline pathway to compare them with. The methanol pathways consist of one using methanol ICEs throughout the entire pathway, one using methanol ICEs for propulsion power and FCs for auxiliary power throughout the entire pathway, one delaying the switch to methanol by using diesel ICEs for the first half and methanol ICEs for the second half and one that uses methanol ICEs for the first half and switches to FCs for auxiliary power the second half. All pathways lead to zero GHG emissions when renewable methanol is used.

How do these pathways perform in terms of costs and emissions for different cases based on existing Feadships?

The 4 methanol pathways and the baseline pathway were researched in terms of costs and emissions for three yachts: a large low speed yacht, a small low speed yacht and a small high speed yacht. The four methanol pathways were compared to the diesel baseline pathway. Overall, it can be stated that using methanol results in no SO_x emissions and fewer PM emissions. The NO_x emissions depend primarily on the energy converter that is used with fuel cells resulting in significantly less NO_x emissions, as well as further reducing the PM emissions. CO_2 emissions increase slightly when fossil methanol is used compared to fossil diesel. However, renewable methanol can bring the net CO_2 emissions to zero at a lower fuel cost than renewable diesel.

10.1.1. Main research question

With the sub questions answered, the main research question can be answered.

What is the net impact of methanol as a fuel for existing and new yachts on costs, emissions and design for several pathways?

From this research it is concluded that using methanol as fuel for yachts has an impact on costs, emissions and a large impact on the design. Methanol offers SO_x free emissions, a reduction of PM emissions and NO_x emissions equal to that of diesel without the necessity of after treatment. CO_2 emissions slightly increase with fossil methanol but can be net zero if renewable methanol is used.

The impact of methanol on costs is considered negligible in terms of converters and storage compared to a diesel yacht. If the yacht's length is increased to keep the interior area equal this does not result in a decrease in value of the yacht. Fossil methanol fuel costs are slightly higher than fossil diesel, while renewable methanol fuel costs are lower than renewable diesel. The costs of retrofitting a yacht with methanol is considered to be very high.

The design impact of methanol is relatively large. 2.3 times the amount of fuel is required for an equal range. As the double bottom is not a feasible location for methanol tanks, the tanks result in a large impact on the design and arrangement. A significant amount of interior area is occupied by the tanks and the surrounding cofferdams. The yacht's length may be increased to compensate for this loss in interior area. However, this is not a feasible option for existing yachts.

In conclusion, using methanol as alternative fuel positively impacts the emissions while the impact on converter and storage costs is small. The fuel costs are slightly increased for fossil methanol and for a fully net zero GHG emission yacht, which requires renewable methanol, the fuel costs are 5 times higher than fossil methanol but lower than renewable diesel. Finally the impact on design is relatively large and may form a challenge for the naval architect.

10.2. Recommendations

In this section recommendations are given for further research into the implementation of methanol on yachts and to improve the design impact tool.

- In order to improve the accuracy of the design impact tool, several aspects of the modules in the tool can be improved. The resistance prediction model that is used is the relatively old Holtrop & Mennen method. In order to improve the accuracy of the resistance prediction method, a more recent empirical method can be used which has coefficients that are tuned to yachts specifically or a 3D hull may be used as input in combination with a CFD calculation. The power prediction method now assumes a diesel direct propulsion and a single propeller open water efficiency to determine the power from the resistance. To make this power prediction applicable to a wider range of propulsion systems, these systems and their properties have to be added and a model to more accurately estimate the propeller open water efficiency could also be added.
- The auxiliary power is estimated by regression of existing Feadships. The auxiliary power required is also often overestimated. To improve the accuracy of the required auxiliary power estimation, more detail can be added to this calculation.
- Next to the resistance and power prediction, a more accurate and detailed tank layout model can also be developed. A 3D hull may be used as input, not only for the resistance prediction, but also to determine more accurately the space available in the hull and the properties of the methanol tanks and cofferdams.
- The cost estimation model is now very simplified and consists only of fuel costs, converter costs and storage costs. The change in fuel price over time is difficult to determine and has a large uncertainty.
  The price of converters is modelled as a price per kW as found in literature sources. More detailed price information of these converters would improve the accuracy.
  The storage costs are also simplified and based on the steel weight of the tanks. As this is a simplified steel weight calculation, combined with a simplified costs estimation based on this steel weight, the uncertainty of these costs is large. Next to that, steel weight may not be the best indicator of storage costs as these costs are also largely determined by the instruments and gauges installed in these tanks.
  Finally, in terms of costs, there are much more safety measures that also influence costs. Double walled piping and ventilation and inerting also add to the total costs of methanol, and could be added to the tool to give a more accurate cost estimation.
- For further research into alternative fuels in general, more fuels could be added to the design impact tool. The properties of these alternative fuels can already be implemented in the design tool. The storage methods and safety measures of these alternative fuels however are not implemented. To compare methanol and other alternative fuels to each other and to a diesel yacht, implementing this could give valuable insights.
- Of the safety measures required by the rules and regulations, only the cofferdam was added to the design impact tool, as this was considered to have the most impact on the design. However, other safety measures should also be implemented to correctly present the implementation of methanol and to show the actual impact on the design.
- The impact of methanol is only determined for three yachts. Analysing the impact for larger, smaller yachts or yachts in between the ones used in the case study could give other insights and conclusions.
- Both the tank layout and engine room layout is not optimised in any way. The design impact tool may be combined with a packing tool in order to find optimal solutions for both layouts, resulting in a smaller impact on the design.
- In order to improve the usability of the design impact tool a graphical user interface (GUI) can be developed. This could improve and stimulate interactive use of the design impact tool.

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A

Yacht data - Confidential

This appendix contains confidential data of Feadship yachts. In Figure A.1 the relation between installed generator power and gross tonnage (GT) is shown for 66 Feadship yachts. The data points are also fitted with a regression power curve of which the coefficients are shown in Equation A.1.

[redacted]

Figure A.1: Installed generator power of 66 Feadship yachts plotted against the GT of the yacht.

$$P_{generator} = \text{[redacted]} \cdot GT^{\text{[redacted]}} \tag{A.1}$$

The load factor (estimated auxiliary power demand divided by the installed generator power) of the auxiliary load is plotted against the installed generator power in Figure A.2 for five scenarios in the operational profile: sailing with guests, sailing with crew only, manoeuvring, in harbour and for anchor. This is done for 13 Feadship yachts by analysing their auxiliary load lists.

[redacted]

Figure A.2: Load factor of the auxiliary load plotted against the installed generator power for 13 Feadship yachts. The load factor is determined by dividing the estimated auxiliary power demand (for different operations in the operational profile from Feadship load lists) by the installed generator power.

B

Literature review - Alternative fuels

In the literature review, alternative fuels other than methanol were also investigated. For completeness, the research done with regards to these other fuels is shown in this appendix.

B.1. Physical properties

In Table B.1 below, a number of relevant properties of methanol and other fossil and alternative fuels are presented.

Table B.1: Properties of Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), Liquefied Natural Gas (LNG), hydrogen, methanol and ammonia.

Property	Unit	HFO	MGO	LNG	Hydrogen	Methanol	Ammonia
Chemical formula			$C_{12}H_{26}$-$C_{14}H_{30}$	CH_4	H_2	CH_3OH	NH_3
Physical state at SATP		Liquid	Liquid	Gas	Gas	Liquid	Gas
Boiling temperature (1 bar)	°C		175-650[2]	-161.48[2]	-253.15[1]	65[2]	-33.15[1]
Density (SATP)	kg/m^3			0.65[3]	0.0899[1]	682[1]	0.792[1]
Density (15°C)	kg/m^3	989[2]	855.6-890[2,4]	0.67[3]	0.0841[3]	795.5[2]	0.72[3]
Dynamic Viscosity (40°C)	cSt		2.72-3.5[2]			0.58[2]	
LHV	MJ/kg	40[2]	42.7[2]	48.5-50.1[2]	120.21[1]	19.9[2]	18.6[1]
Lubricity WSD	µm		280-400[2]			1100[2]	
Vapour density (air=1)			>5[2]	0.55[2]		1.01-1.1[2]	
Flash point	°C	>60[2]	>60[2]	-175[2]		9-12[2]	132[1]
Auto-ignition temperature	°C		250-500[2]	540[2]	560[1]	440-470[2]	630[1]
Explosive limits	%		0.3-10[2]	5-15[2]	4-77[1]	6.0-36.0[2]	15.4-28.0[1]

References:
1) Alternative fuels on board of carbon-neutral cruise vessels (Volger, 2019)
2) Study on the use of ethyl and methyl alcohol as alternative fuels in shipping (Ellis and Tanneberger, 2015)
3) Engineeringtoolbox.com
4) ISO 8217-2017 (World Fuel Services, 2017)

Description of properties in Table B.1 from Ellis and Tanneberger (2015):

- Physical state: Fuels can be present in various physical states (gaseous, liquid, solid). The phase of a fuel depends on the temperature and pressure. Therefore, the physical state is determined at Standard Ambient Temperature and Pressure (SATP), which is at 25°C (298K) and 1.0 bar (100 000 kPa). The physical state is important for the type (and size) of storage of the fuel, as liquid fuels are generally easier to store than gaseous fuels and contain more energy per volume.
- Boiling temperature: The temperature at which the liquid fuel evaporates to a gaseous phase (at ambient pressure). Mixtures of molecules, such as diesels, usually have a boiling range instead of a single temperature.
- Density: The density of a fuel is also dependent on temperature and pressure. The densities of marine fuels are often presented at 15°C (and at atmospheric pressure). The density is important

for the required storage volume.

- Dynamic viscosity: A measure for the fluid's resistance to flow and is temperature dependent. This property is of importance to the fuel injection and the transportation of fuel from the tank to the engine.
- Lower Heating Value (LHV): A measure of the energy density of the fuel. It can be expressed both volumetric (MJ/m^3) or by mass (MJ/kg). It is of main importance to the required amount (mass or volume) of fuel to achieve a given range. The LHV also gives an indication for the amount of heat released by the fuel in case of a fire.
- Lubricity: Lubricity is a measure of the reduction in friction or wear by a material, and may have an effect on the life of machinery. A usual test to measure the lubricity is the HFRR test and results in a micrometre wear scar diameter (WSD), where a greater WSD indicates more wear and therefore less ability to lubricate.
- Vapour density: The vapour density is given with respect to the density of air. It determines whether vaporised fuel will sink, float or rise in air.
- Flash point: This is the lowest temperature at which a liquid gives off enough vapour at the surface to form an ignitable mixture in air. This value is dependent on the test method.
- Auto-ignition temperature: The temperature at which the fuel self-ignites without any source of ignition, such as a spark or flame.
- Explosive limits: This is the range between the lowest and highest concentration of fuel vapour in air that will burn or explode.

B.2. Storage

In Table B.2 below, the storage properties of the selected fuels are presented. HFO, MGO and methanol can all be stored in conventional fuel tanks and require no special insulation or cooling and can optimally use the space available. LNG, liquid hydrogen and liquid ammonia all require specialised fuel tanks with double walls (DW) aimed at isolation in order to keep the fuel at low temperatures to ensure it remains liquid, which are explained further below. A schematic cross section of the storage tanks of different fuels, taking the volumetric energy content (MJ/m^3) of the fuels into account, is shown in Figure B.1. From this figure it is clear that, although the required volume of methanol is over two times as large as that of MGO to contain the same amount of energy, it still outperforms other alternative fuels since there is no need for isolation, as is the case with hydrogen, LNG and ammonia.

B.2.1. LNG storage

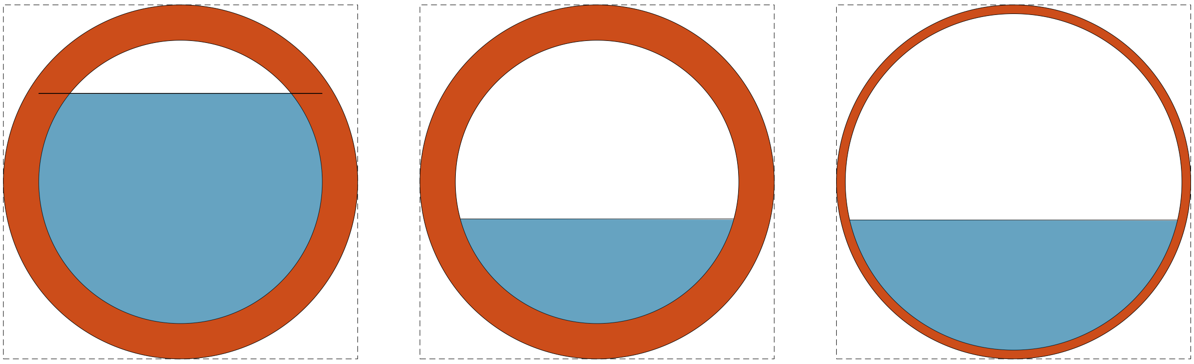
LNG can be stored in multiple types of tanks. The tanks can be integral tanks which are part of the ships' hull and independent tanks which are self-supporting. The integral tanks can be membrane tanks or semi-membrane tanks. Membrane tanks consist of a thin membrane layer supported through insulation by the hull structure. Semi-membrane tanks are only partly supported through insulation by the hull structure. Next there are three independent tank types: type A, B and C. Type A tanks are designed using recognised standards of classical ship structural analysis and constructed with plane surfaces. The design pressure should not exceed 0.7 bar. Type B tanks are designed using model tests and analytical tools. An example is the spherical Moss tank. The pressure in this type of tank usually does not exceed 0.55 bar but can reach 1 bar in emergency cases. Type C tanks are pressurised vessels. These tanks have a cylindrical shape and a design pressure between 2.7 and 4.0 bar. Type C tanks are considered the most suitable option for dual fuel (LNG) propulsion (Bolbot, 2014).

Although LNG tanks are heavily insulated, some thermal current exists between the interior and exterior of the tanks. As the LNG is stored just below/at its boiling temperature the small thermal current causes the LNG to boil. The formed vapour is called boil-off and amounts to 0.1-0.25% of the cargo each day. Boil-off is less of a problem for the pressurised type C tanks. In order to keep the LNG cooled, the boil-off vapour has to be extracted from the tanks. The vapour can be cooled/re-liquefied and returned to the tanks at the required temperature or used as fuel (Bolbot, 2014).

Table B.2: Storage properties of Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), Liquefied Natural Gas (LNG), hydrogen, methanol and ammonia.

Property	Unit	HFO	MGO	LNG	Hydrogen	Methanol	Ammonia
Physical state at storage conditions		Liquid	Liquid	Cryogenic liquid	Cryogenic liquid	Liquid	Liquid
Storage temperature	°C	15^{2}	15^{2}	-162^{2}	-253^{1}	15^{2}	-33^{1} or 20^{3}
Storage pressure	bar	1.0^{2}	1.0^{2}	0.55^{4}-1.0^{2,4}	1.0^{1}-3.0^{1}	1.0^{2}	1.0^{1} or 10^{3}
Density at storage temperature	kg/m^{3}	989^{2}	855.6-890^{2}	448.39^{2}	70.9^{1}	795.5^{2}	792.0^{1}
Volumetric LHV	MJ/l	39.56	36.5-38.0	21.7-22.5	8.5	15.8	14.7
Volumetric LHV_{fuel}/LHV_{MGO} ratio		0.92	1.0	1.69	4.37	2.35	2.53
Dynamic Viscosity	cSt		3.5^{2}			0.58^{2}	
Boil-off		No	No	Yes^{4}	Yes^{1}	No^{1}	Yes^{1}
Insulation				D-W	D-W vacuum		D-W insulated
Insulation thickness estimate					20% of radius^{1}		5% of radius^{1}

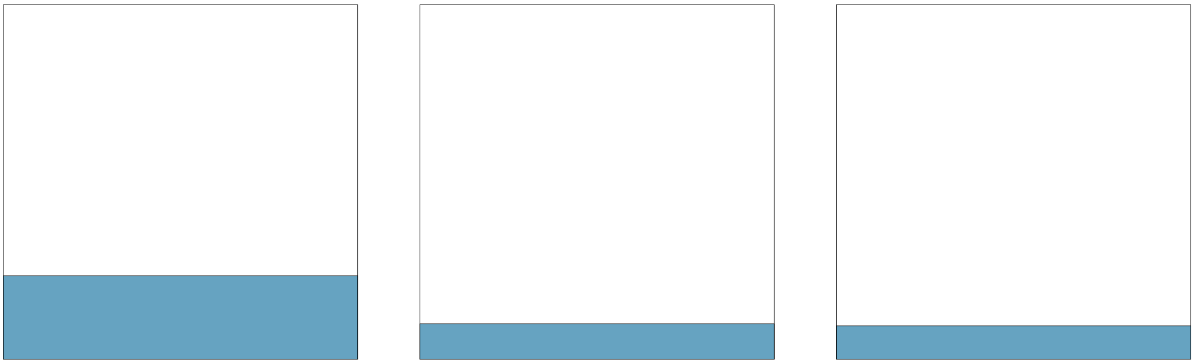
References:
1) Alternative fuels on board of carbon-neutral cruise vessels (Volger, 2019)
2) Study on the use of ethyl and methyl alcohol as alternative fuels in shipping (Ellis and Tanneberger, 2015)
3) Safe and effective application of ammonia as a marine fuel (de Vries, 2019)
4) Storage, Handling and Boil-off of LNG on ships (Bolbot, 2014)



(a) Liquefied hydrogen (87.0% filled).

(b) Liquefied natural gas (33.5% filled).

(c) Liquefied ammonia (35.7% filled).



(d) Methanol (23.5% filled).

(e) MGO (10.0% filled).

(f) HFO (9.4% filled).

Figure B.1: Schematic cross section of storage tanks for different fuel types. The LH_2/LNG and ammonia tanks are assumed cylindrical with regards to the available volume, with double wall thicknesses from Table B.2. The double wall thickness of LNG is assumed to be equal to that of hydrogen. All tanks are filled (blue part) to contain equal energy content as a 10% filled MGO tank. Both LHV (MJ/kg) and density (kg/m^{3}) are used in this calculation.

B.2.2. Liquid hydrogen storage

Liquid hydrogen can be stored in tanks which can keep the temperature below the boiling temperature with agreeable boil-off. These tanks are insulated by a double wall with multiple layers of insulation material and a vacuum space between both walls. This double walled insulation is approximately 20% of the radius of the tank. Due to the vacuum, low temperature and pressure inside the tank, tank geometries are limited to spherical, cylindrical and ellipsoid shapes (or a combination of these shapes). In order to maintain the interior temperature to minimise deformations of the tank, a minimum amount of hydrogen is required to remain in the tank. This minimum ranges from 10% to 30% of the tank volume (Volger, 2019).

B.2.3. Liquid ammonia storage

Ammonia is already transported on a large scale in tanks for use in the chemical industry. Ammonia has a considerably higher boiling point than LNG or LH_2. To keep ammonia in its liquid state, it only needs to be cooled to -33°C. The tank does however needs good isolation to minimise boil-off (boil-off can be used as fuel flow). Alternatively, the tank can be pressurised to 10 bar (at 20°C) to keep the ammonia in its liquid state or a combination of cooling and pressurisation (de Vries, 2019). It is possible to completely empty the tank with much smaller deformations than that of a LH_2 tank. A cylindrical tank is considered the most suitable storage method for large volumes of ammonia due to the insulation, temperature, pressure and double wall requirements (Volger, 2019). Ammonia has similar storage conditions to LPG (which is also often stored in cylindrical tanks), regarding temperature and pressure. Therefore, LPG tankers can also transport ammonia.

B.2.4. Methanol storage

Methanol can be stored in conventional tanks but in accordance with the current regulations, methanol tanks are required to be inerted with nitrogen. The maximum filling percentage is 98% of the total tank volume (Lloyd's Register, 2019).

Apart from the storage tank itself, the methanol tank is to be surrounded by a secondary gas tight and liquid tight barrier. The simplest solution is a cofferdam, an empty space with methanol (vapour and liquid) detection and containment measures. According to current regulations, a cofferdam can also be water filled and therefore act as a water or ballast tank (Lloyd's Register, 2019). There are exceptions to this demand as stated by IMO (CCC 6): “Integral fuel tanks should be surrounded by protective cofferdams, except on those surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methyl/ethyl alcohol, or fuel preparation space.” (IMO CCC6, 2019). The current Lloyd's Register rules only allow the exclusion of a cofferdam where the tank is bounded by bottom shell plating or fuel pump rooms and do not allow the fuel tanks to be placed within 800 mm from the ship's shell plating. However, the CCC 6 report was published later than the LR rules for methanol fuelled ships, so these less strict requirements may be implemented in a later version of the rules.

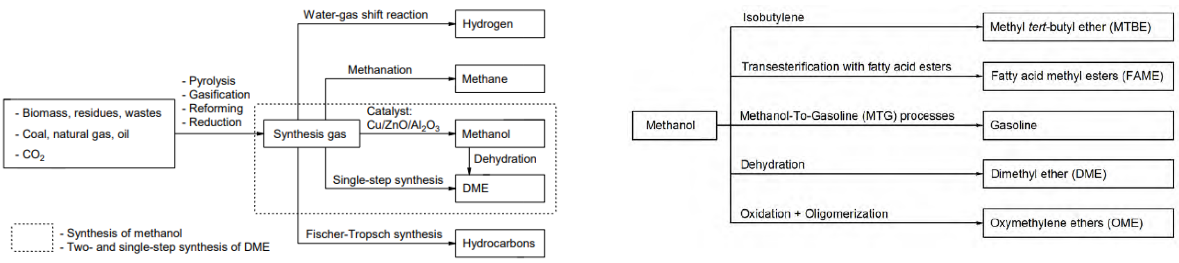
B.3. Production processes of methanol derivatives

In the two figures (Figure B.2a, Figure B.2b) below a schematic overview is shown of feedstocks, processes and the resulting products related to methanol. The production of DME, MTBE, FAME, MTG and MTH is further described in the following sections.

B.3.1. Dimethyl Ether (DME)

DME is the first and simplest derivative of methanol, which requires two methanol molecules to form DME and water (Equation B.1). Dimethyl ether can also be produced from directly from syngas (Equation B.2). Both reactions are shown below. DME has a higher cetane number than diesel (Matzen and Demirel, 2016), an octane number and ignition temperature of close to that of diesel fuel, making it an interesting diesel alternative. However, it is not liquid at STP (boiling point of -24°C) which makes it harder to store and to distribute. It can also be used as a supplement to LPG (liquefied petroleum gas). Using DME in diesel engines leads to lower NO_X emissions, no SO_X emissions, less smoke and less engine noise than conventional diesel and can be easily transported. DME can also be used as a feedstock for the production of gasoline and hydrogen (Dalena et al., 2018).

Methanol to DME through dehydration reaction:



(a) Synthesis of various fuels from syngas. **(b)** Synthesis of fuels from methanol.

Figure B.2: Schematic overview of production processes and products in methanol related production. Figures from: Sauer et al. (2016).

$$2\,CH_3OH \rightleftharpoons CH_3OCH_3 + H_2O \tag{B.1}$$

Overall reaction of syngas to DME:

$$2\,CH_3OH \rightleftharpoons CH_3OCH_3 + H_2O \tag{B.2}$$

Methanol, ethanol and DME achieve similar reductions in CO_2 emissions, however, if the amount of heat used in their production is taken into account, methanol and DME result in higher CO_2 reductions than ethanol (Shamsul et al., 2014).

B.3.2. Methyl Tert-Butyl Ether (MTBE)

MTBE was already used as a fuel in the methanol trials in California in the 1980s and 1990s. MTBE gained a bad name because of ground water contamination due to tank leaks in the old infrastructure, which consequently gave methanol, from which the MTBE was produced, also a bad reputation there. MTBE is used as an octane-enhancing gasoline additive (replacing TEL, which is poisonous) in Europe without any issues (Verhelst et al., 2019). MTBE is produced through a chemical reaction between methanol and isobutylene, which is produced from crude oil.

B.3.3. Fatty Acid Methyl Ester (FAME)

FAME can be utilised as bio-diesel after purification. It is a renewable fuel that is produced mainly from vegetable oils and animal fats. It results in a biodiesel that has less overall emissions and is less dangerous for the environment than conventional diesel. The viscosity of vegetable oils are about 10-20 times greater than diesel, which is problematic in diesel engines. One process to reduce this viscosity is the transesterification. This process requires fatty acids and alcohols (also called alcoholysis) and is assisted by a catalyser. Methanol is often used in this process and over 90% is converted to bio-diesel (Vyas et al., 2010).

B.3.4. Methanol-to-gasoline (MTG)

Methanol can be upgraded to molecules with more carbon atoms such as alkanes, olefins and aromatic hydrocarbons. There are two general ways of converting carbon sources (coal, natural gas, biomass, etc.) into liquid fuels: the Fischer-Tropsch (FT) route and the methanol-to-gasoline (MTG) route. The FT process includes syngas production, the FT step and the product refining process. The MTG process requires methanol, generally produced from syngas, and the MTG step is the actual production of hydrocarbons in the gasoline range (C5-C11). The FT process results in a wider range of hydrocarbons generated and refinery of the FT products is generally for the production of diesel or lubricants (He et al., 2009). The MTG process has a modified reaction selectivity towards alkanes in the gasoline range. Methanol first dehydrates to DME (see subsection B.3.1) which is then further dehydrated to light olefins. A further reaction step leads to higher olefins, paraffins, aromatics and naphthenes in the range of gasoline (Keil, 1999). The yield of gasoline range hydrocarbons from methanol depends heavily on the chosen catalyst. Zeolite catalysts on a fixed bed are mainly employed for MTG processes. Obtaining optimal methanol conversion is rather easy but obtaining a high yield of gasoline range hydrocarbons is more difficult. Gasoline range hydrocarbon yield ranges from 40% to 88% with close to 100% methanol conversion at temperatures around 350°C-415°C (Galadima and Muraza, 2015; Keil, 1999). Next to fixed bed catalytic reactors, there are fluid bed MTG processes. A demonstration plant operated from 1982 until 1984 and gasoline yields reached 92% (He et al., 2009). A schematic block diagram of the MTG process is shown in Figure B.3.

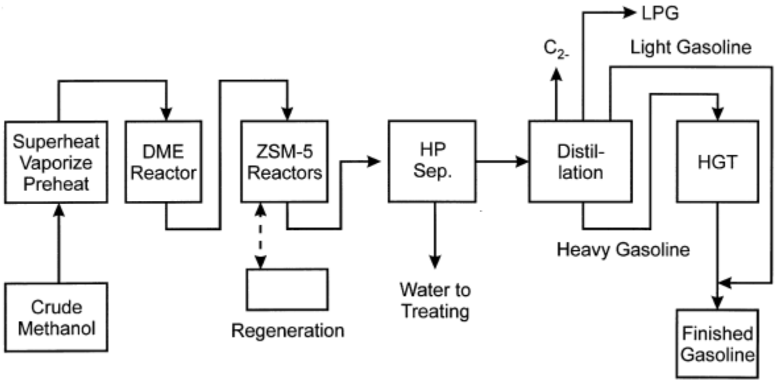


Figure B.3: Schematic block diagram of a (fixed bed) methanol to gasoline (MTG) process. Image from: Keil (1999)

B.3.5. Methanol-to-hydrocarbons (MTH)

The Fischer-Tropsch (FT) process is a well-known process to upgrade carbon sources to larger hydrocarbon molecules in the gasoline range as well as larger hydrocarbons in the diesel range and above. The FT process starts with the syngas production and methanol is one of the intermediate products. There are two major FT processes: high temperature (HTFT) and low temperature (LTFT). HTFT results in mostly alkenes (olefins) while LTFT results in mostly alkanes (paraffins) which are also a main component of crude oil and diesel. The carbon efficiency, an efficiency measure of how much carbon from the feedstock is left in the final product, of a FT facility generally lies between 28%-34%. The thermal efficiency ranges from 50%-60% (de Klerk, 2011). The FT process produces syncrude, which contains various alkanes, alkenes, alcohols and other hydrocarbons. This syncrude is then refined to the final products, such as diesel fuel (de Klerk, 2008).

An example of the Fischer-Tropsch process to produce larger hydrocarbons is the Audi E-diesel plant in Laufenburg, Switzerland. Here hydrogen, produced by the electrolysis of water with renewable electricity, and CO_2 are converted to e-diesel through the FT process. The plant was planned for construction in 2018/2019 and will have a production capacity of around 400000 litres per year. A schematic overview of the e-diesel plant and its in- and outputs is shown in Figure B.4.

B.4. Production processes of other fuels

A short description is given of the production processes of the other fuels.

B.4.1. HFO/MGO

HFO and MGO are produced by the fractional distillation of crude oil. The crude oil is heated and enters the distillation column. Here the different components of the crude oil are separated based on their boiling point. HFO is a residual fuel resulting from the distillation of crude oil while MGO is a more refined distillate and is similar to the diesel used in trucks.

B.4.2. LNG

LNG stands for liquefied natural gas. Natural gas is extracted from gas fields and is then cooled to the boiling point of natural gas to liquefy the gas. The composition is more or less the same as that

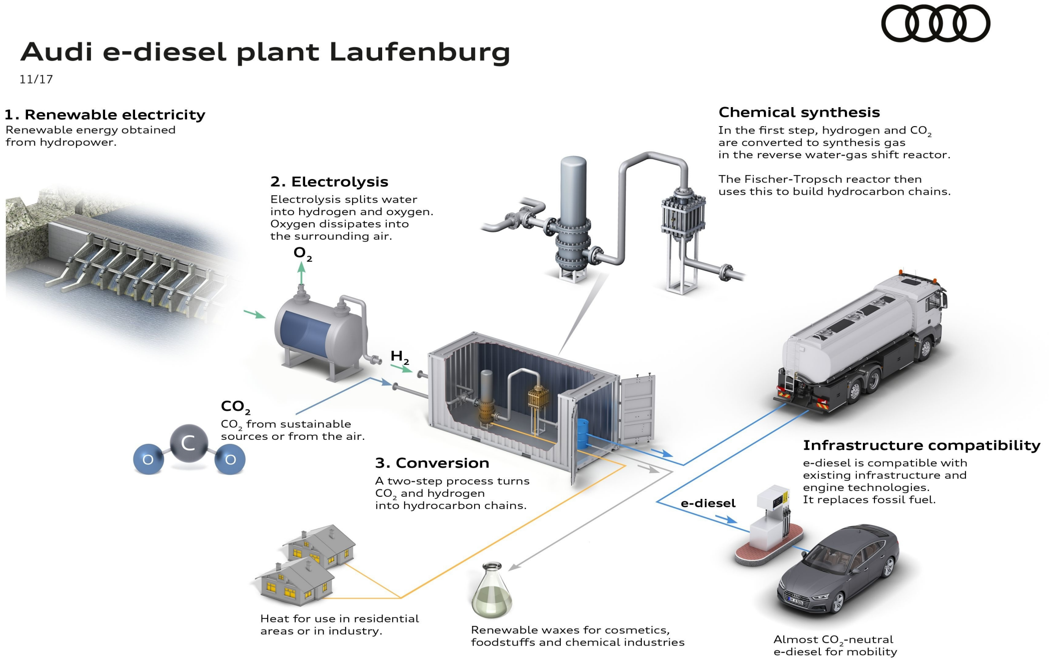


Figure B.4: Schematic overview of inputs, outputs and processes regarding a potential Audi e-diesel production plant in Laufenburg (Switzerland). Image from: Audi (2017).

of natural gas. The production process of LNG ensures that the LNG is almost sulphur free (DNV GL, 2018).

B.4.3. Hydrogen

Methanol is mostly produced from the reforming of natural gas to syngas, of which hydrogen is a main component. This is the same process as in the production of methanol from natural gas. Hydrogen can also be produced by electrolysing water, which can be done with renewable energy to make the process emission free (no GHG) (DNV GL, 2018).

B.4.4. Ammonia

Most ammonia is currently produced from natural gas using the Haber-Bosch process. It can also be produced from naphtha, HFO or coal, but this generates larger CO_2 emissions. Ammonia can be produced by the electrolysis of water, resulting in hydrogen, and combining the hydrogen with nitrogen which is abundantly available in the atmosphere. The electrolysis can be done with renewable energy to reduce (or eliminate) emissions. In contrast with most other fuels (except for hydrogen), renewable ammonia can completely eliminate carbon (well to wake), both in the production as in the energy conversion (DNV GL, 2018).

B.5. Well to wake GHG emissions

The greenhouse gas (GHG) emission can be separated into two emission phases: well to tank emissions and tank to wake emissions. The well to tank emissions include all GHG emissions occurring during the extraction of the feedstock of the fuel, the production of the fuel, the transport from the production facility to eventually the ship and all other steps in between the well and tank. The tank to wake emissions are the emissions related with the energy conversion of the fuel, i.e. from storage inside the ship to the energy delivered to the propeller and thrust generated (Ellis and Tanneberger, 2015).

Both the well to tank and tank to wake emissions are important to the climate and to achieve the climate goals. While greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) both contribute to global warming and climate change on a global scale and are related to the choice of fuel, emissions such as SO_X, NO_X and particulate matter (PM) have a more local/regional impact and are more related to the energy conversion. SO_2 for example, contributes to acid deposition which affects water and soil quality. NO_X reacts with ammonia to form nitric acid vapour and related particles that can penetrate deeply into sensitive lung tissue and damage it, causing premature death in extreme cases (European Maritime Safety Agency, 2016).

In the 2015 paper by Ellis and Tanneberger, the well to tank and tank to wake emissions were reported for different fuels in a combustion engine. The fuels considered in that paper are MDO, LNG, methanol and ethanol. As can be seen in Figure B.5, the GHG emissions of methanol produced from natural gas are slightly higher than MDO and LNG (with no methane slip). However, since methanol produced from biomass (wood in this case) only emits the CO_2 during combustion that is absorbed from the atmosphere by the biomass, no additional CO_2 is emitted (i.e. no tank to wake GHG emissions). Therefore, GHG emissions are much lower for bio methanol than for the fossil alternatives. This is also true for methanol produced from renewable electricity and CO_2. If all energy required in the production and transportation of the fuel is supplied by renewable sources, both the well to tank and tank to wake can be GHG emission free.

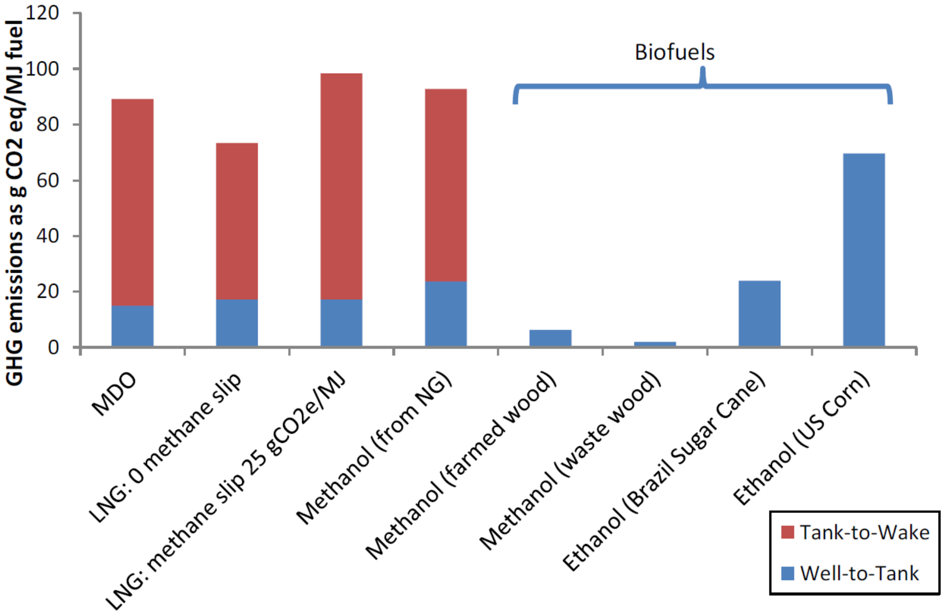


Figure B.5: Well to tank and tank to wake greenhouse gas emissions of MDO, LNG, methanol (fossil and biomass feedstocks) and ethanol. GHG emission values are in CO_2 equivalent grams per MJ of combusted fuel. Figure from: Ellis and Tanneberger (2015).

The well to wake emissions are also shown in Table B.3 based on Harmsen et al. (2020). Compared to the conventional fuels HFO and MGO, the alternative fuels have higher CO_2 equivalent emissions looking at the whole cylce (well to wake). The fossil methanol well to wake emissions have a wide range around that of the conventional fuels. Although the alternative fuels have (much) lower tank to wake emissions, this is compensated by the higher emissions associated with the production and distribution (well to tank). Biofuels and electrofuels all perform much better than the fossil diesel options in terms of CO_2 equivalent emissions. This is due to the uptake of CO_2 during production (except for ammonia which containt no carbon) instead of emission. Of the fuels that can be produced from renewable electricity (electrofuels), methanol has the lowest CO_2 equivalent emissions.

Table B.3: Well to tank (WTT), tank to wake (TTW) and combined well to wake (WTW) greenhouse gas emissions ($CO_{2,eq}$ g/MJ) for HFO, MGO, methanol, LNG (including methane slip), ammonia and hydrogen. Data from: Harmsen et al. (2020).

Feedstock	Emission phase	HFO	MGO	Methanol	LNG	Ammonia	Hydrogen
Fossil							
	WTT	11.1	14.2	24.9 to 32.2	19.4	n.a.	115.2
	TTW	77.4	74.1	69.1	75	0	0
	WTW	88.5	88.3	84.2 to 94.3	94.4	n.a.	115.2
Biofuels							
	WTT	-62.8 to -13.7		-66.9 to -62.5	-52.3		15 to 20
	TTW	70.8		69.1	75		0.0
	WTW	8.1 to 57.1		2.2 to 6.6	22.7		15 to 20
Electrofuels							
	WTT	n.a.		-67.5	n.a.	1.8	4 to 13
	TTW	n.a.		69.1	75	0	0.0
	WTW	n.a.		1.6	n.a.	1.8	4 to 13

C

Design tool - Details

This appendix contains more detailed information of the design tool. The parameters of the design tool, which can be changed, are presented in several tables. A more detailed schematic representation of the design tool is also shown.

The fuel parameters from the database are shown in Table C.1, the yacht specific parameters are shown in Table C.2, the converter parameters from the database are shown in Table C.3 and the design tool parameters and options are shown in Table C.4.

Table C.1: Overview of the parameters of the different fuels in the database. The parameters are divided into general fuel properties, price levels of the fuels and CO_2 emission factors.

Parameter	Default	Unit	Description
Fuel properties			
$Fuel$	-	-	Name/identifier of the fuel
$Feedstock$	-	-	Feedstock of the fuel (Fossil, Renewable)
ρ_{store}	-	kg/m^3	Density of fuel at storage temperature and pressure
LHV_m	-	MJ/kg	Gravimetric lower heating value of the fuel
LHV_v	-	GJ/m^3	Volumetric lower heating value of the fuel (optional)
Costs			
$Price2020low$	-	€/MWh	Lower bound of the fuel price in 2020
$Price2020high$	-	€/MWh	Upper bound of the fuel price in 2020
$Price2050low$	-	€/MWh	Lower bound of the fuel price in 2050
$Price2050high$	-	€/MWh	Upper bound of the fuel price in 2020
Emissions			
$CO2_{WTT}$	-	$CO_{2,eq}$ g/MJ	CO_2 well to tank emissions
$CO2_{TTW}$	-	$CO_{2,eq}$ g/MJ	CO_2 tank to wake emissions

Table C.2: Overview of the parameters of the yacht. The 42 parameters are grouped by their primary purpose, although some parameters have multiple purposes.

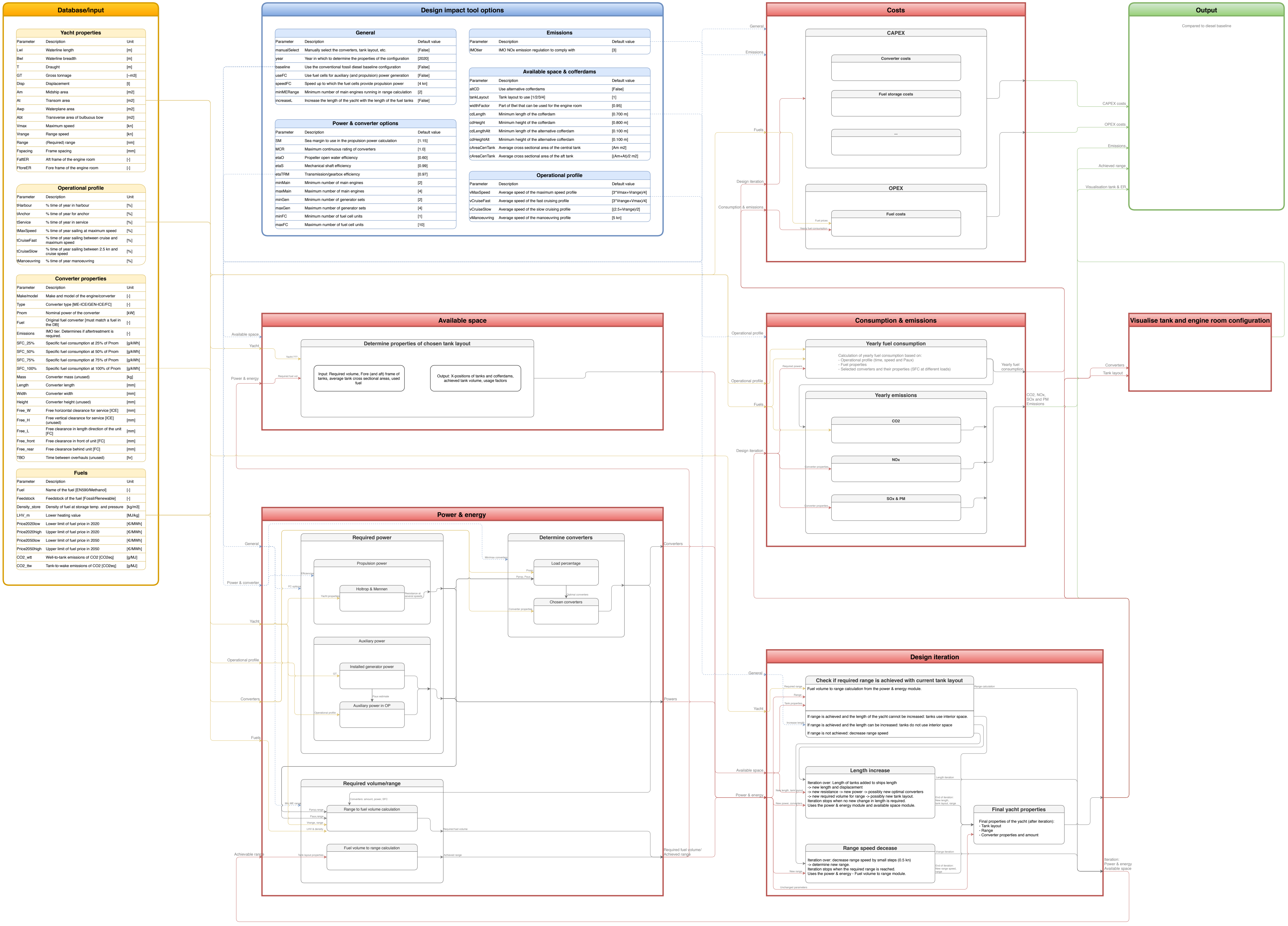
Parameter	Default	Unit	Description
General yacht parameters (also for power & energy)			
BN	-	-	Build number
$Name$	-	-	Yacht/design name
L_{WL}	-	m	Waterline length
B_{WL}	-	m	Waterline breadth
T	-	m	Design draught
Δ	-	t	Displacement
GT	-	-	Gross tonnage
v_{max}	-	kn	Maximum speed
v_{range}	-	kn	Range speed
$range$	-	nm	Required range
Power & energy - Resistance			
A_M	-	m^2	Midship area
A_T	-	m^2	Transom area
A_{WP}	-	m^2	Waterplane area
$A_{B,T}$	-	m^2	Transverse bulb area (if present)
S_{hull}	-	m^2	Wetted area of the hull (optional)
S_{app}	-	m^2	Wetted area of the appendages (optional)
lcb	-	%	Longitudinal centre of buoyancy
$Aftbody$	-	-	Afterbody shape (Normal, Ushaped, Vshaped, Pram)
$Arrangement$	-	-	Propeller arrangement (single-screw, twin-screw)
D_p	-	m	Propeller diameter
Z_p	-	-	Number of propeller blades
P/D	-	-	Pitch/diameter ratio
n_{bt}	-	-	Number of bow thrusters
D_{bt}	-	m	Bow thruster tunnel diameter
Available space			
T_{low}	-	m	Lowest possible waterline
A_{cen}	-	m^2	Cross sectional area of central tank
A_{aft}	-	m^2	Cross sectional area of aft tank
$f_{ER,aft}$	-	-	Aft frame number of the engine room
$f_{ER,fore}$	-	-	Fore frame number of the engine room
$f_{cen,aft}$	$f_{ER,fore}$	-	Aft frame number of the central tank
$f_{cen,fore}$	-	-	Fore frame number of the central tank (optional)
$f_{aft,aft}$	-	-	Aft frame number of the aft tank (optional)
$f_{aft,fore}$	-	-	Fore frame number of the aft tank (optional)
$f_{spacing}$	-	mm	Frame spacing of the yacht
h_{ER}	-	mm	Height of the engine room
h_{DB}	-	mm	Height of the double bottom
n_{decks}	-	-	Number of decks of the yacht (incl. superstructure)
Costs			
$Value$	-	€	Estimated total value of the yacht
Operational profile			
t_{Max}	-	%	Percentage of time at maximum speed
$t_{CruiseFast}$	-	%	Percentage of time at fast cruising speed
$t_{CruiseSlow}$	-	%	Percentage of time at slow cruising speed
t_{Anchor}	-	%	Percentage of time for anchor
$t_{Harbour}$	-	%	Percentage of time in harbour
$t_{Manoeuvring}$	-	%	Percentage of time manoeuvring
$t_{Service}$	-	%	Percentage of time in service

Table C.3: Overview of the parameters of the different converters in the database. The parameters are divided into general parameters used for all converters and converter specific parameters.

Parameter	Default	Unit	Description
General			
$Make$	-	-	Make of the converter
$Model$	-	-	Model of the converter
$Type$	-	-	Converter type: ME-ICE, GEN-ICE, FC
P_{rated}	-	kW	Rated power of the converter
$Fuel$	-	-	Standard fuel of the converter (EN590, Methanol)
m	-	kg	Converter mass (not used)
l	-	mm	Converter length
w	-	mm	Converter width
h	-	mm	Converter height
TBO	-	hr	Time Between Overhauls or lifetime of converter (not used)
use	1	-	Use the converter in the tool (1: yes, 0: no)
Main engine specific			
rpm	-	rev/min	Converter rpm (not used)
$SFC_{25\%}$	-	g/kWh	Specific fuel consumption at 25% load
$SFC_{50\%}$	-	g/kWh	Specific fuel consumption at 50% load
$SFC_{75\%}$	-	g/kWh	Specific fuel consumption at 75% load
$SFC_{100\%}$	-	g/kWh	Specific fuel consumption at 100% load
$Free_w$	800	mm	Service space around converter
$Free_h$	600	mm	Service space above converter
Generator set specific			
$freq$	-	Hz	Frequency of generator set (not used)
$SFC_{25\%}$	-	g/kWh	Specific fuel consumption at 25% load
$SFC_{50\%}$	-	g/kWh	Specific fuel consumption at 50% load
$SFC_{75\%}$	-	g/kWh	Specific fuel consumption at 75% load
$SFC_{100\%}$	-	g/kWh	Specific fuel consumption at 100% load
$Free_w$	800	mm	Service space around converter
$Free_h$	600	mm	Service space above converter
Fuel cell specific			
$Eff_{25\%}$	-	%	Efficiency at 25% load
$Eff_{50\%}$	-	%	Efficiency at 50% load
$Eff_{75\%}$	-	%	Efficiency at 75% load
$Eff_{100\%}$	-	%	Efficiency at 100% load
$Free_l$	0	mm	Service space around converter in length direction
$Free_h$	0	mm	Service space above converter
$Free_{front}$	800	mm	Service space in front of converter
$Free_{rear}$	0	mm	Service space behind converter

Table C.4: Overview of the parameters and options of the design impact tool. The parameters are divided into several categories based on their function. Next to the parameters in this table, some parameters from Table C.2 can also be changed from within the design tool.

Parameter	Default	Unit	Description
Tool and pathway options			
$manualSelect$	False	-	Manually select the converters or select the ones with the highest load percentage
$printOutput$	False	-	Print design tool output
$safeFig$	False	-	Save plot figures to output folder
$startyear1$	2020	-	Start year of the first configuration
$endyear1$	2035	-	End year of the first configuration
$startyear2$	2035	-	Start year of the second configuration
$endyear2$	2050	-	End year of the second configuration
General			
$year$	2020	-	Year of the build or refit (for prices and efficiencies of converters)
$IMOtier$	3	-	IMO NO_x emissions regulation to comply with
$baseline$	False	-	Use the diesel baseline
$refit$	False	-	Refit: no length increase possible
$increaseL$	True	-	Increase length of the yacht to compensate for lost interior space
Power & resistance constants			
SM	1.15	-	Sea margin
SM_c	1.00	-	Sea margin calm water - to determine the required converters
SM_r	1.10	-	Sea maring range calculation
MCR	1.00	-	Maximum continuous rating of converters (<1)
η_O	0.61	-	Propeller open water efficiency
η_S	0.99	-	Mechanical shaft efficiency
η_{TRM}	0.98	-	Transmission efficiency
Power & energy - Converter options			
$minMain$	2	-	Minimum number of main engines
$maxMain$	2	-	Maximum number of main engines
$minGen$	2	-	Minimum number of generator sets
$maxGen$	4	-	Maximum number of generator sets
$minFC$	1	-	Minimum number of fuel cell units
$maxFC$	10	-	Maximum number of fuel cell units
$minME_{range}$	2	-	Minimum number of main engines running during range calculations
$useFC$	False	-	Use fuel cells for auxiliary load (optional: part of propulsion)
$speedFC$	0	kn	Speed up to which the fuel cells are required to deliver propulsion power (in addition to auxiliary power)
Available space			
$altCD$	False	-	Use alternative cofferdams
$tankLayout$	1	-	Which tank layout should be used
$widthFactor$	0.95	-	Part of the waterline breadth that can be used by ER equipment
$cdLength$	0.700	m	Minimum length of the cofferdams
$cdHeight$	0.800	m	Minimum height of the cofferdams
$cdLengthAlt$	0.100	m	Minimum length of the alternative cofferdams
$cdHeightAlt$	0.100	m	Minimum height of the alternative cofferdams
$decksTanks$	1	-	Number of decks that the methanol tanks span



Database/input

Yacht properties

Parameter	Description	Unit
Lwl	Waterline length	[m]
Bwl	Waterline breadth	[m]
T	Draught	[m]
GT	Gross tonnage	[~m3]
Disp	Displacement	[t]
Am	Midship area	[m2]
At	Transom area	[m2]
Awp	Waterplane area	[m2]
Abt	Transverse area of bulbuous bow	[m2]
Vmax	Maximum speed	[kn]
Vrange	Range speed	[kn]
Range	(Required) range	[nm]
Fspacing	Frame spacing	[mm]
FaftER	Aft frame of the engine room	[-]
FforeER	Fore frame of the engine room	[-]

Operational profile

Parameter	Description	Unit
tHarbour	% time of year in harbour	[%]
tAnchor	% time of year for anchor	[%]
tService	% time of year in service	[%]
tMaxSpeed	% time of year sailing at maximum speed	[%]
tCruiseFast	% time of year sailing between cruise and maximum speed	[%]
tCruiseSlow	% time of year sailing between 2.5 kn and cruise speed	[%]
tManoeuvring	% time of year manoeuvring	[%]

Converter properties

Parameter	Description	Unit
Make/model	Make and model of the engine/converter	[-]
Type	Converter type [ME-ICE/GEN-ICE/FC]	[-]
Pnom	Nominal power of the converter	[kW]
Fuel	Original fuel converter [must match a fuel in the DB]	[-]
Emissions	IMO tier. Determines if aftertreatment is required.	[-]
SFC_25%	Specific fuel consumption at 25% of Pnom	[g/kWh]
SFC_50%	Specific fuel consumption at 50% of Pnom	[g/kWh]
SFC_75%	Specific fuel consumption at 75% of Pnom	[g/kWh]
SFC_100%	Specific fuel consumption at 100% of Pnom	[g/kWh]
Mass	Converter mass (unused)	[kg]
Length	Converter length	[mm]
Width	Converter width	[mm]
Height	Converter height (unused)	[mm]
Free_W	Free horizontal clearance for service [ICE]	[mm]
Free_H	Free vertical clearance for service [ICE] (unused)	[mm]
Free_L	Free clearance in length direction of the unit [FC]	[mm]
Free_front	Free clearance in front of unit [FC]	[mm]
Free_rear	Free clearance behind unit [FC]	[mm]
TBO	Time between overhauls (unused)	[hr]

Fuels

Parameter	Description	Unit
Fuel	Name of the fuel [EN590/Methanol]	[-]
Feedstock	Feedstock of the fuel [Fossil/Renewable]	[-]
Density_store	Density of fuel at storage temp. and pressure	[kg/m3]
LHV_m	Lower heating value	[MJ/kg]
Price2020low	Lower limit of fuel price in 2020	[€/MWh]
Price2020high	Upper limit of fuel price in 2020	[€/MWh]
Price2050low	Lower limit of fuel price in 2050	[€/MWh]
Price2050high	Upper limit of fuel price in 2050	[€/MWh]
CO2_wtt	Well-to-tank emissions of CO2 [CO2eq]	[g/MJ]
CO2_ttw	Tank-to-wake emissions of CO2 [CO2eq]	[g/MJ]

Design impact tool options

General

Parameter	Description	Default value
manualSelect	Manually select the converters, tank layout, etc.	[False]
year	Year in which to determine the properties of the configuration	[2020]
baseline	Use the conventional fossil diesel baseline configuration	[False]
useFC	Use fuel cells for auxiliary (and propulsion) power generation	[False]
speedFC	Speed up to which the fuel cells provide propulsion power	[4 kn]
minMERange	Minimum number of main engines running in range calculation	[2]
increaseL	Increase the length of the yacht with the length of the fuel tanks	[False]

Power & converter options

Parameter	Description	Default value
SM	Sea margin to use in the propulsion power calculation	[1.15]
MCR	Maximum continuous rating of converters	[1.0]
etaO	Propeller open water efficiency	[0.60]
etaS	Mechanical shaft efficiency	[0.99]
etaTRM	Transmission/gearbox efficiency	[0.97]
minMain	Minimum number of main engines	[2]
maxMain	Maximum number of main engines	[4]
minGen	Minimum number of generator sets	[2]
maxGen	Maximum number of generator sets	[4]
minFC	Minimum number of fuel cell units	[1]
maxFC	Maximum number of fuel cell units	[10]

Emissions

Parameter	Description	Default value
IMOtier	IMO NOx emission regulation to comply with	[3]

Available space & cofferdams

Parameter	Description	Default value
altCD	Use alternative cofferdams	[False]
tankLayout	Tank layout to use [1/2/3/4]	[1]
widthFactor	Part of Bwl that can be used for the engine room	[0.95]
cdLength	Minimum length of the cofferdam	[0.700 m]
cdHeight	Minimum height of the cofferdam	[0.800 m]
cdLengthAlt	Minimum length of the alternative cofferdam	[0.100 m]
cdHeightAlt	Minimum height of the alternative cofferdam	[0.100 m]
cAreaCenTank	Average cross sectional area of the central tank	[Am m2]
cAreaCenTank	Average cross sectional area of the aft tank	[(Am+At)/2 m2]

Operational profile

Parameter	Description	Default value
vMaxSpeed	Average speed of the maximum speed profile	[3*Vmax+Vrange)/4]
vCruiseFast	Average speed of the fast cruising profile	[3*Vrange+Vmax)/4]
vCruiseSlow	Average speed of the slow cruising profile	[(2.5+Vrange)/2]
vManoeuvring	Average speed of the manoeuvring profile	[5 kn]

Costs

CAPEX

Converter costs

Fuel storage costs

...

OPEX

Fuel costs

Output

Compared to diesel baseline

Available space

Determine properties of chosen tank layout

Input: Required volume, Fore (and aft) frame of tanks, average tank cross sectional areas, used fuel

Output: X-positions of tanks and cofferdams, achieved tank volume, usage factors

Consumption & emissions

Yearly fuel consumption

Calculation of yearly fuel consumption based on:
- Operational profile (time, speed and Paux)
- Fuel properties
- Selected converters and their properties (SFC at different loads)

Yearly emissions

CO2

NOx

SOx & PM

Visualise tank and engine room configuration

Power & energy

Required power

Propulsion power

Holtrop & Mennen

Auxiliary power

Installed generator power

Auxiliary power in OP

Determine converters

Load percentage

Chosen converters

Required volume/range

Range to fuel volume calculation

Fuel volume to range calculation

Design iteration

Check if required range is achieved with current tank layout

Fuel volume to range calculation from the power & energy module.

If range is achieved and the length of the yacht cannot be increased: tanks use interior space.

If range is achieved and the length can be increased: tanks do not use interior space

If range is not achieved: decrease range speed

Length increase

Iteration over: Length of tanks added to ships length
-> new length and displacement
-> new resistance -> new power -> possibly new optimal converters
-> new required volume for range -> possibly new tank layout.
Iteration stops when no new change in length is required.
Uses the power & energy module and available space module.

Range speed decease

Iteration over: decrease range speed by small steps (0.5 kn)
-> determine new range.
Iteration stops when the required range is reached.
Uses the power & energy - Fuel volume to range module.

Final yacht properties

Final properties of the yacht (after iteration):
- Tank layout
- Range
- Converter properties and amount

C.1. Converter costs - Confidential

Table C.5 shows the converter costs, conversion costs and after treatment costs for different converter types. The converter cost is expressed as a price per kW of the converter itself. The conversion cost is a fixed number that is approximately equal to the cost of after treatment for diesel engines. The after treatment also has a fixed price.

Table C.5: Price per kW of main engines, generator sets and fuel cells and the price of conversion from diesel to methanol and after treatment (SCR). All prices are given in Euro's (a €0.90 per $1.00 rate is used to determine the price in euro's). References: 1 - Brynolf (2014), 2 - Lloyd's Register and UMAS (2020), 3 - Feadship, 4 - Serenergy.

[redacted]

D

Case study - Yacht C

This chapter contains the case study of the third yacht, which is a small high speed yacht. This yacht is not included in the case study of chapter 8 as the properties of this yacht are outside the range of the design tool where the results are reliable (see 6.3 Holtrop & Mennen resistance and power prediction). This is partly caused by the waterjet propulsion system of this yacht, resulting in a significant underestimation of the required power at range speed. The Holtrop & Mennen resistance prediction method also resulted in an underestimated resistance at range speed, increasing the inaccuracy of the required power at range speed. The resistance and required power at maximum speed are very close to the actual values. Nevertheless, one may still be interested in the impact of using methanol on a small high speed yacht. Therefore, this case study is included as an appendix in this chapter.

D.1. Yacht C - Small high speed yacht

The third and final case study is done for a small yacht that has a high Froude number at maximum sailing speed. The particulars of this yacht C, such as the main dimensions, speeds and required range, are shown in Table D.1. The operational profile of the this yacht is shown in Figure D.1. There was no AIS data available for the reference yacht, therefore the AIS data of a similar high speed yacht with waterjets is used to determine the operational profile. The operational profile is used to determine the yearly fuel consumption of the different pathways. The operational profile of this yacht is different than the operational profiles of yacht A and B. Yacht C has a very small sailing time percentage and a very large percentage for anchor. Of the time spend sailing also a very small percentage of time is spend sailing close to the maximum speed of the yacht, as the maximum speed of this yacht is relatively high.

Table D.1: Main particulars of yacht C.

Property	Value	Unit
L_{WL}	47.00	m
B_{WL}	7.89	m
T_{design}	1.85	m
Δ	321	t
v_{max}	28.0	kn
v_{range}	10.0	kn
$Fn_{v_{max}}$	0.671	-
$range_{req}$	1600	nm

With the properties of the yacht, the design tool determines the power requirements for the converters and the energy storage requirements of the fuel (see 5.1 Power and fuel capacity requirements). The power required for propulsion and auxiliary power in different scenarios in the operational profile are shown in Table D.2.

Table D.2: Required propulsion and auxiliary power (in kW) determined from the properties of yacht C (before the length increase iteration).

Power	Propulsion		Auxiliary					
Scenario	v_{max}	v_{range}	Installed	Sailing guests	Sailing crew	Manoeuvring	Harbour	Anchor
P_{req}	6010	293	268	192	172	271	167	168

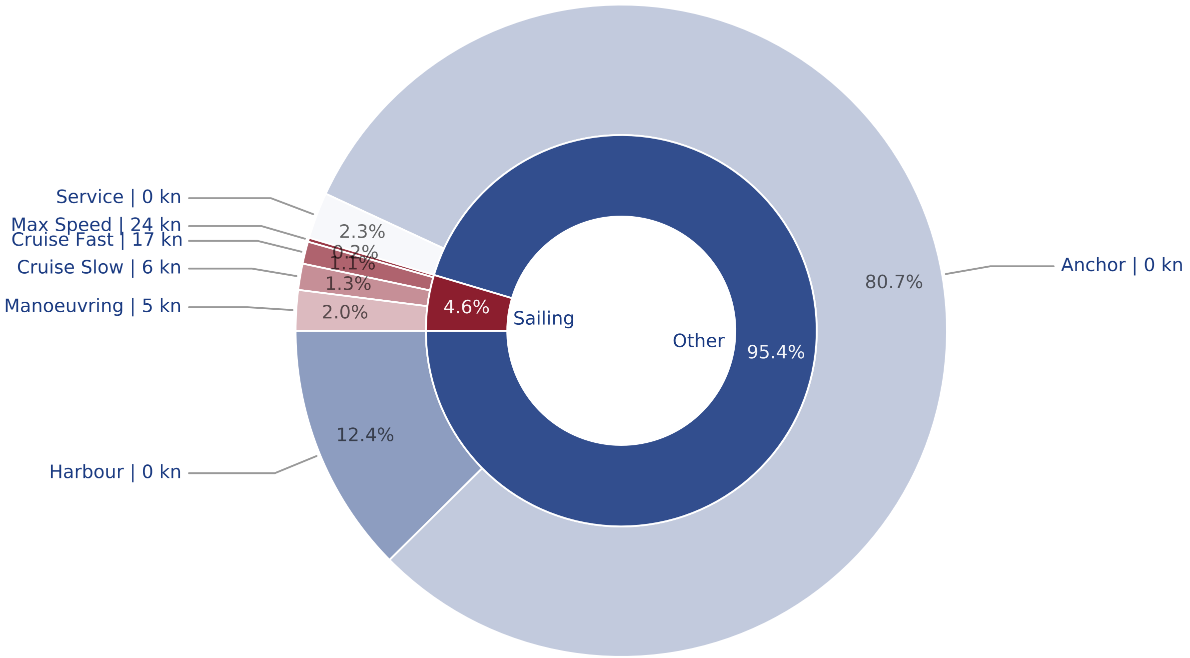


Figure D.1: Operational profile of yacht C. The average speeds used in the fuel consumption calculation are shown next to the operation. The percentages show the amount of time in a year that is spend in this operation.

D.1.1. Design - options & impact

In order to determine the design impact of methanol for this yacht, the two tank layouts (1 tank and 2 tanks) are both reviewed, as well as the converters and their impact on the design. In Table D.3 the required fuel volume, the achieved fuel volume and the usage factor of the tank(s) are shown. The required fuel volume given in this table is determined through the range calculation (see 5.1.5) after the length increase iteration (see 5.2.5) to keep the interior area equal to the diesel baseline. The achieved fuel volume is determined through the available space calculation (see 5.2) also including the length increase iteration as is done for the required fuel volume. The usage factor of the tank is determined through Equation 4.1 and represents the storage efficiency of the tank. A high usage factor represents a high methanol volume over total tank volume (including cofferdams) ratio which means that the cofferdam volume is relatively small compared to the tank volume usable for fuel.

The impact of using methanol in combination with ICEs or fuel cells on the required fuel volume is again, like yacht A and B, clearly seen in Table D.3. The required methanol volume is around 2.3 times the required diesel volume, which is in line with the LHV difference between both fuels. Using fuel cells for

Table D.3: Required tank volume ($V_{fuel,req}$) following from the range calculation and the achieved fuel volume (V_{fuel}), after the length increase iteration (Δ_l). For the usage factor (Equation 4.1) the first value is with normal cofferdams and the second with alternative cofferdams.

Configuration	1 tank				2 tanks			
	$V_{fuel,req}$ [m^3]	V_{fuel} [m^3]	f_{usage} [-]	Δ_l [m]	$V_{fuel,req}$ [m^3]	V_{fuel} [m^3]	f_{usage} [-]	Δ_l [m]
MGO - ICE	21^a	25^a	1.000^a	0	-	-	-	0
MeOH - ICE	48/48	49/54	0.467/0.891	2.80/2.80	48/48	52/51	0.393/0.864	3.50/2.80
MeOH - ICE+FC	45/45	49/48	0.467/0.888	2.80/2.10	45/45	47/45	0.381/0.860	2.80/2.10

[a] Diesel tanks are in the double bottom and no length iteration is done.

the auxiliary power slightly decreases the required volume, as the efficiency of the used HT-PEMFCs is only slightly higher (42 - 45% compared to approximately 40%).

The usage factors for both the one tank and two tanks layout are significantly lower for yacht C than for yacht A and B (see Table 8.3 and Table 8.8). Yacht C has a single methanol tank usage factor of 0.467 compared to a usage factor of 0.743 and 0.601 for yacht A and B respectively with the same tank layout, a decrease of 37% and 22%. An even larger decrease in usage factor between yacht C and the others is seen for the two tank layout which has a usage factor of only 0.393. These very low usage factors for yacht C can be explained by the low waterline and therefore low tank height (see Figure D.3). Although the frame spacing of this yacht is just large enough for the cofferdams to span a single frame (instead of 2 for yacht B), the low draught of this yacht results in methanol tanks that are not very high. This severely limits the cross sectional area of the tank and thereby the methanol volume that can be stored per unit length of the tank. The result is a very low usage factor for all tank layouts. It may be possible to increase the tank height to span the entire tanktop deck, but cofferdams would then be necessary on the sides of the tank as well, increasing the structural complexity and reducing the fuel storage efficiency.

Table D.3 also shows a significant reduction in usage factor when two tanks are used instead of one. A usage factor of 0.467 for one tank and 0.393 for two tanks which is a decrease of 16%. For the same fuel volume that is stored, 16% more total volume (including cofferdams) is used by the 2 tank layout compared to the single tank layout. The usage factor would be even lower if more separate tanks were used. The effect of using two separate tanks is also seen on the length increase that is required to keep the interior area equal (or at least equal since the length increase is rounded up to whole frame lengths). With one tank the length increase is 2.8 m which is a 6% increase in waterline length, while with two tanks this length increase becomes 3.5 m which is a 7.5% increase in waterline length for approximately the same fuel volume. For yacht C in general, the cofferdams use a very large part of the total volume with over 50% for the single tank and over 60% for the two tank layout being used by the cofferdams. Alternative cofferdams offer a solution for this storage inefficiency, requiring less than 15% of the total volume for cofferdams. In general the use of alternative cofferdams results in a decrease in length increase required, especially for the two tank layout. However, since the length increase is rounded up to an entire frame length, the use of alternative cofferdams does not always lead to a reducing in length increase, as is the case for the methanol ICE 1 tank layout in Table D.3 (although the tank itself actually spans less frames).

The diesel baseline and methanol configurations and tank layouts options are shown in Figure D.2, Figure D.3, Figure D.4, Figure D.5 and Figure D.6 on the next pages. The engines and fuel cell configurations are determined with the number of main engines set to 2, the number of generator sets between 2 and 4 (determined based on required power and optimal load percentage) and the number of fuel cells between 1 and 10 (determined as the generator sets). The top views for the alternative cofferdam configurations are very similar to the normal cofferdam configurations and are therefore not shown.

When comparing Figure D.3 to Figure D.2 it is clear that the methanol tank volumes are significant and occupy a large amount of interior space. Especially since diesel is stored in the double bottom and therefore doesn’t occupy any interior space. With methanol however, this option is not considered feasible in terms of construction of the tanks and cofferdams. For this smaller yacht with a smaller draught one can see that the cofferdams use a significant amount of space relative to the fuel volume, for a single tank configuration. This is the result of the minimum dimensions of the normal cofferdam which are quite large compared to the dimensions of the tank as well as the relatively low waterline up to which the tanks go. For the two tank layout of Figure D.4 the share of cofferdams in the total tank volume becomes even larger, which was also shown in Table D.3 by the lower usage factor. In general the tanks become less efficient in storing methanol when the tank dimensions become smaller relative to the cofferdam dimensions. This can be seen in the aft tank of Figure D.4. That the tanks become smaller relative to the cofferdam dimensions is also a direct consequence of an increase in amount of (separate) tanks. Reducing the dimensions of the cofferdam partly remedies this effect, which is done in the alternative cofferdam layouts.

Since the hull of most yachts shapes upwards towards the aft, to make room for the propeller and improve the propeller inflow, the tank located to the aft of the yacht has a smaller height than the tank

Table D.4: Interior area usage (A_{int}) for the diesel reference layout, the one tank methanol layout and the two tank methanol layout all using ICEs only and the required length increase (Δ_l) to keep the interior area equal. The diesel reference layout has tanks in the double bottom which do not require interior area.

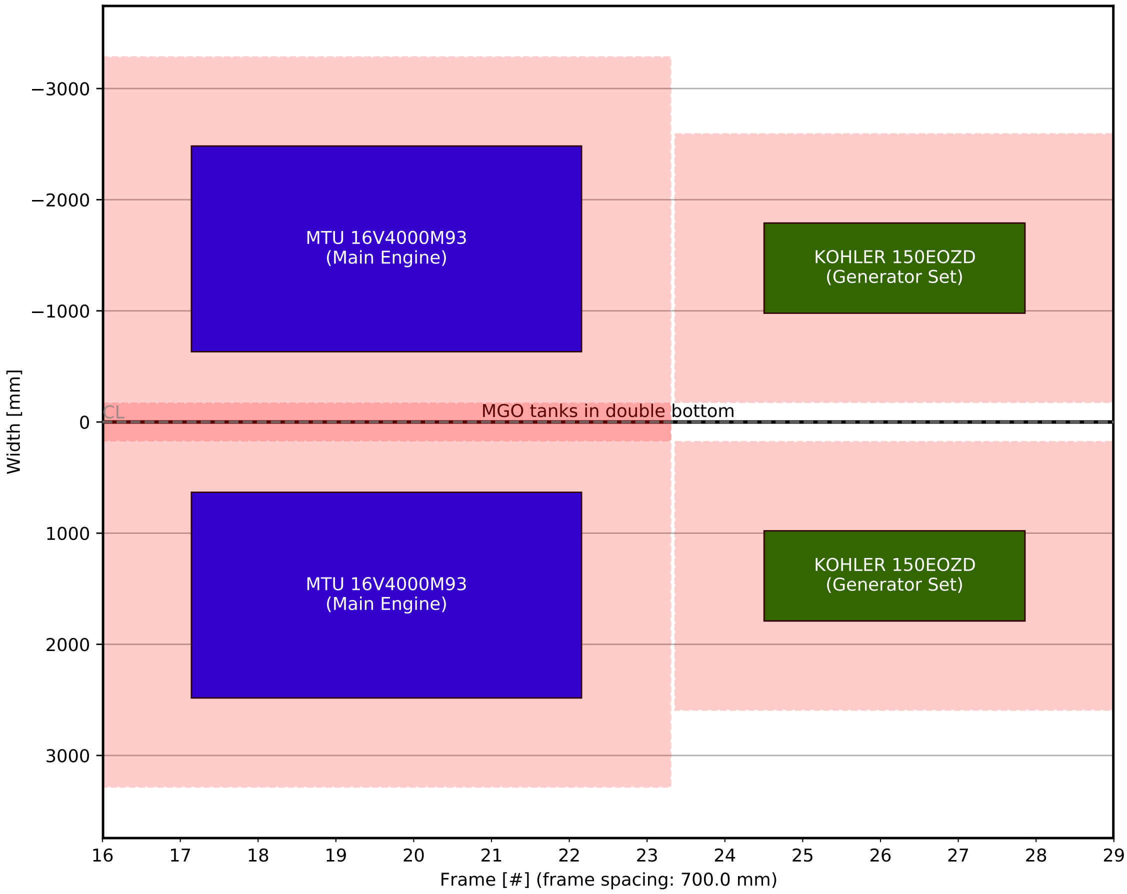
Tank layout	Total				Central tank			Aft tank		
	V_{fuel} [m^3]	f_{usage} [-]	A_{int} [m^2]	Δ_l [m]	V_{fuel} [m^3]	f_{usage} [-]	A_{int} [m^2]	V_{fuel} [m^3]	f_{usage} [-]	A_{int} [m^2]
MGO - DB	25	1.000	0	0	-	-	-	-	-	-
MeOH - 1 tank	49	0.467	55	2.80	49	0.467	55	-	-	-
MeOH - 1 tank - Alt cofferdams	54	0.891	50	2.80	54	0.891	50	-	-	-
MeOH - 2 tanks	52	0.393	72	3.50	31	0.417	39	21	0.364	33
MeOH - 2 tanks - Alt cofferdams	51	0.864	50	2.80	42	0.883	39	9	0.787	11

around the midship. This is visualised in the layout figures as a rectangular tank with a height from the lowest possible waterline down to halfway between this waterline and the keel but in reality this tank follows the bottom shell plating (the tool only uses an average cross sectional area). Because the (average) height of this aft tank is smaller than the central tank, this aft tank is even less efficient in storing methanol than the central tank. This aft tank therefore occupies relatively more interior area than the central tank does per unit fuel volume. This can also be seen in Table D.4. A significant increase in interior area occurs when switching from a one tank layout to a two tank layout with normal cofferdams: +31%. For alternative cofferdams there the interior area occupied by the tanks is equal for the single tank layout and the two tank layout.

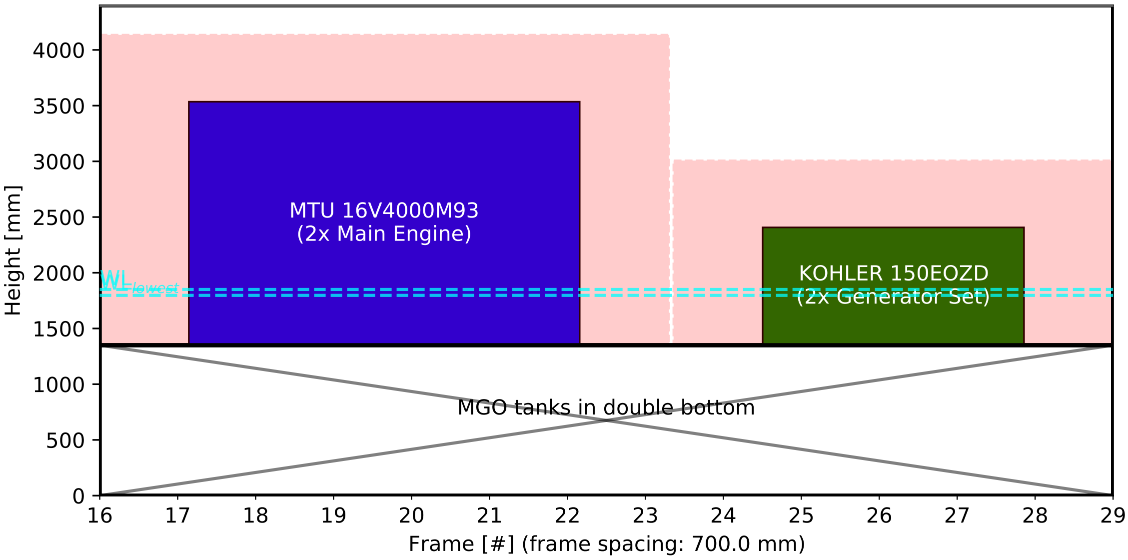
The HT-PEM fuel cell unit in Figure D.5 and Figure D.6 does not fit in the engine room when longitudinally oriented as it overlaps with the main engine. These FCs are long units delivering 300 kW per unit. However, these units consist of 10 racks next to each other with each rack containing 6 modules of 5 kW. The units do not necessarily have to consist of 10 racks next to each other. If instead a few 3 or 4 rack wide units are chosen, these units will fit inside the engine room in length direction. The 300 kW fuel cell unit does not fit in the engine room when rotated by 90° and placed in transverse direction as the width of the engine room is smaller than the length of one 300 kW unit. The rotation of these units is not part of the design impact tool as this has no influence on the outcome and is only for visualisation purposes. However, for this yacht it is determined that one fuel cell unit of 300 kW would fit in the engine room next to the main engines, if the unit is split into two units of 5 racks wide. With the fuel cell unit in Figure D.5 and Figure D.6, there is spare power by the fuel cells to also provide propulsion power (next to the required auxiliary power) for speeds up to 4 knots. When the fuel cells are distributed differently throughout the engine room than in these figures, a second 300 kW fuel cell unit (e.g. split in halve) may fit in the engine room. With two fuel cell units, a speed of 10 knots can be reached by fuel cell power alone, which is equal to the range speed.

Trim

The trim impact for yacht C was not determined due to time limitations and the trim impact was already determined for two other yachts. As methanol on the two other yachts has a small trim impact for a single tank layout and almost no trim impact for a two tank layout, it is expected that the effect on trim is similar for this third yacht. The general conclusion from the trim impact assessment of the two other yachts was that it was desirable to have two separate tanks as this gives enough trim options.

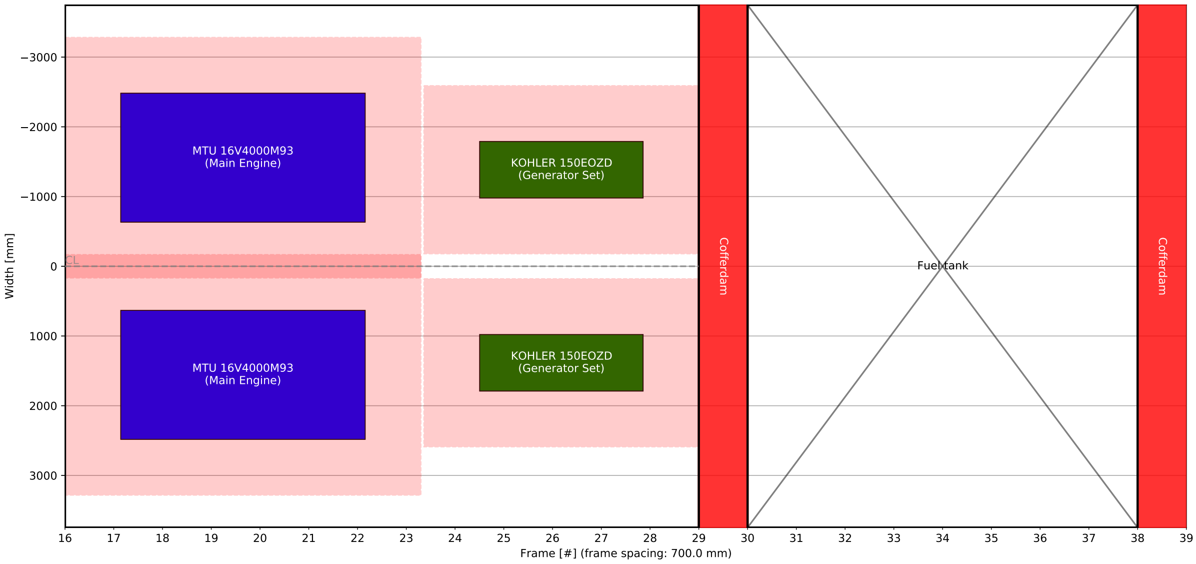


(a) Top view of the diesel baseline layout with ICEs for propulsion and auxiliary power.

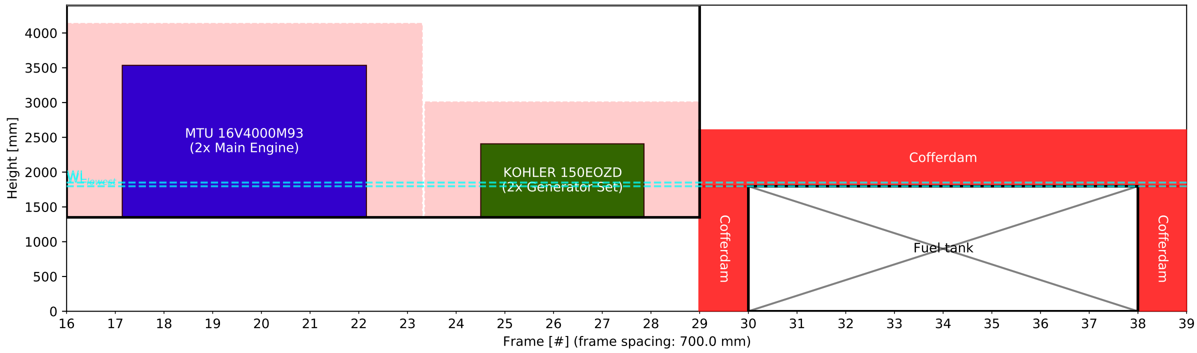


(b) Side view of the diesel baseline layout with ICEs for propulsion and auxiliary power.

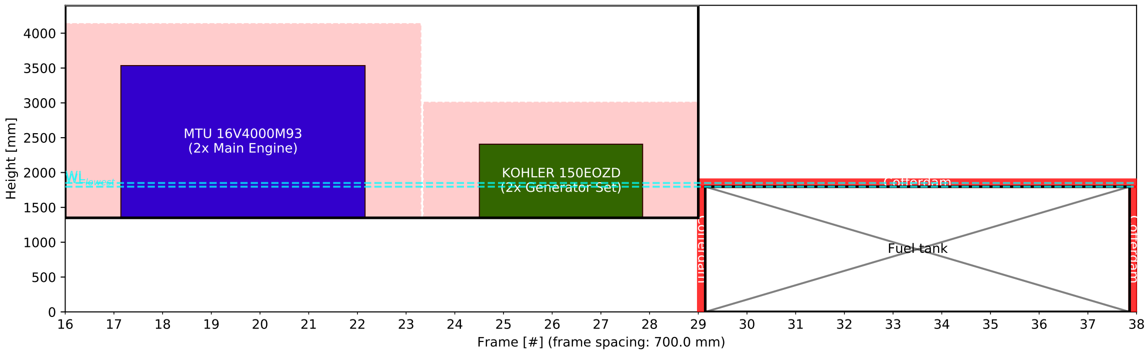
Figure D.2: Schematic layout of the diesel baseline with MGO tanks in the double bottom.



(a) Top view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

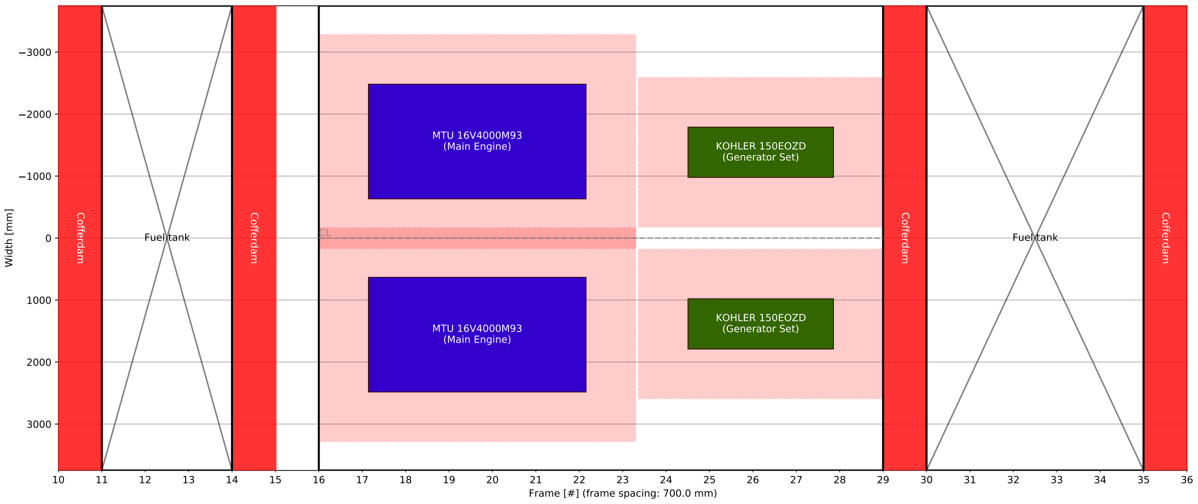


(b) Side view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

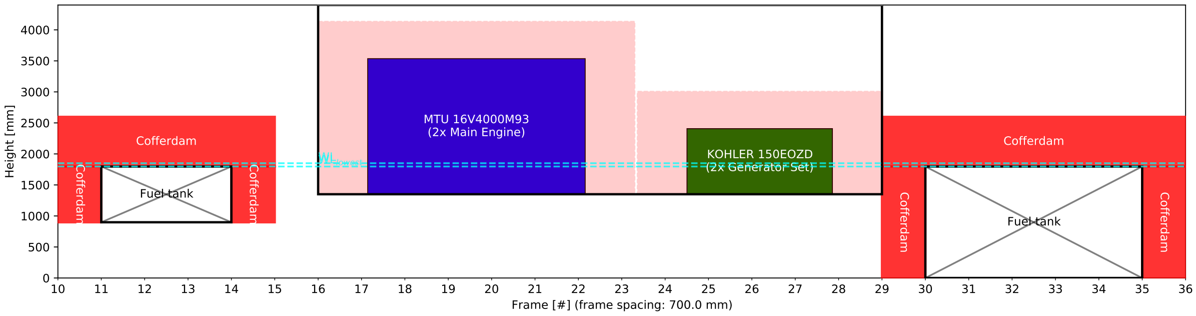


(c) Side view of the methanol layout with ICEs for propulsion and auxiliary power and alternative cofferdams. Top view is very similar to Figure D.3a but with smaller cofferdams.

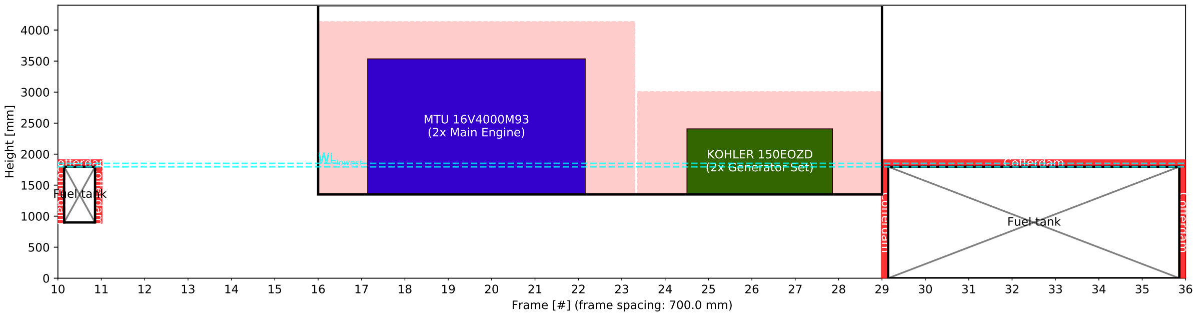
Figure D.3: Schematic layouts of the ICE methanol configuration with one tank.



(a) Top view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

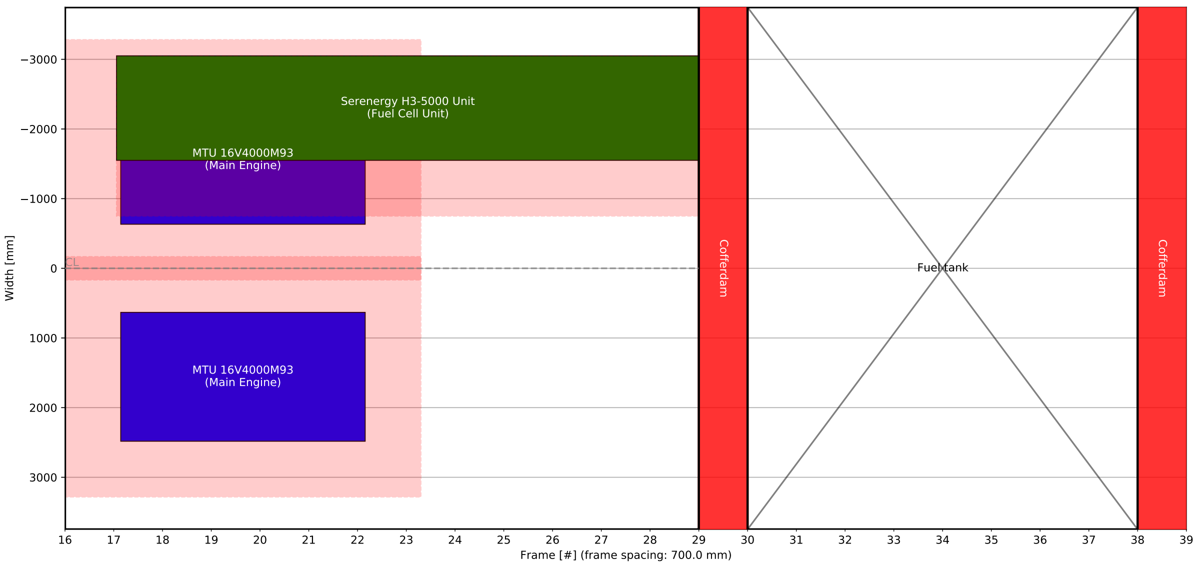


(b) Side view of the methanol layout with ICEs for propulsion and auxiliary power and normal cofferdams.

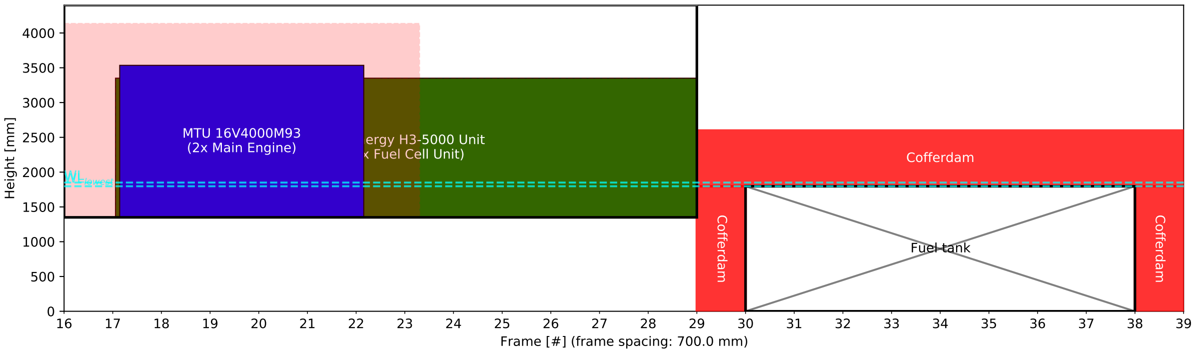


(c) Side view of the methanol layout with ICEs for propulsion and auxiliary power and alternative cofferdams. Top view is very similar to Figure D.4a but with smaller cofferdams.

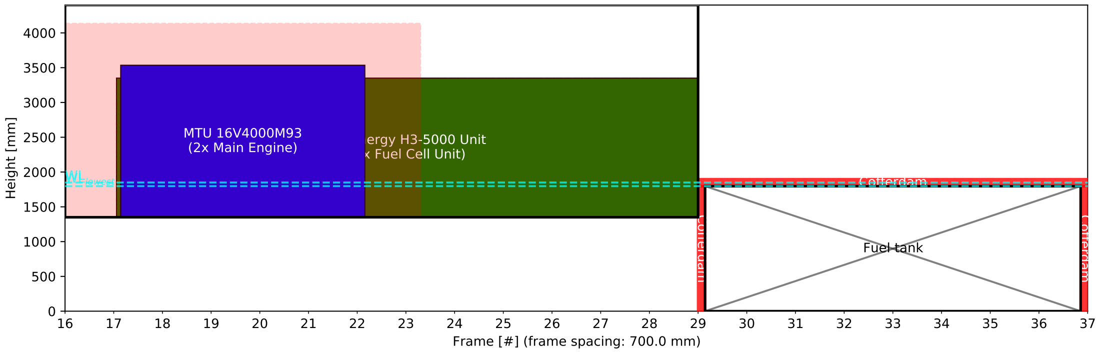
Figure D.4: Schematic layouts of the ICE methanol configuration with one tank around midship and a second tank in the aft of the yacht.



(a) Top view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.

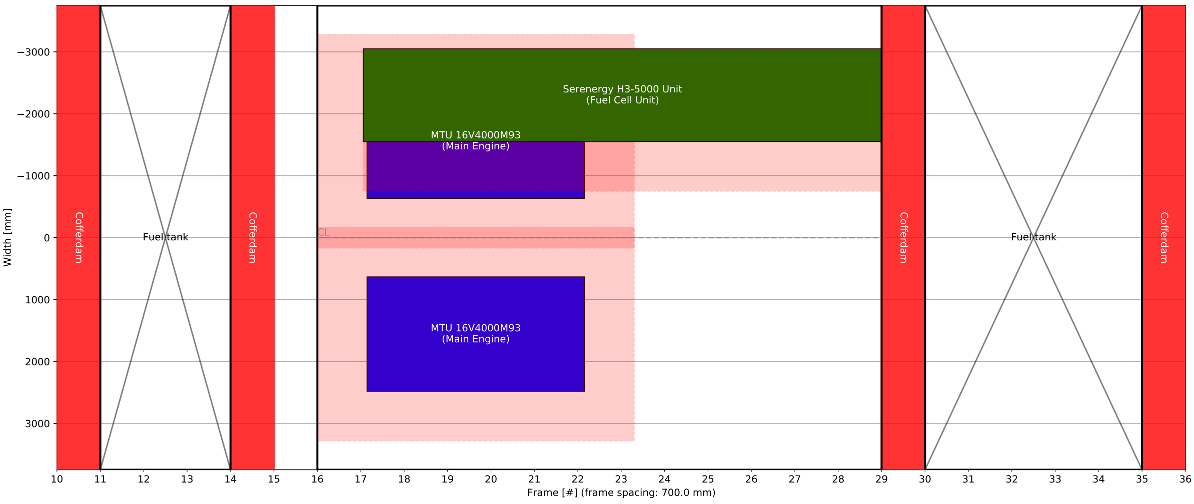


(b) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.

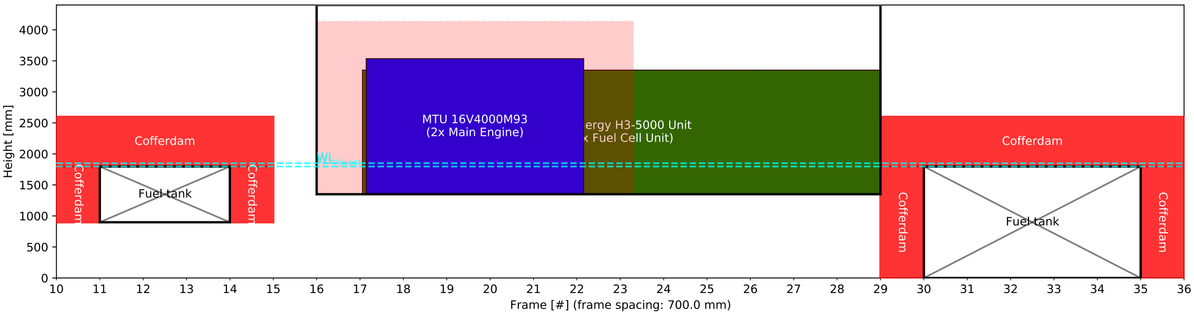


(c) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and alternative cofferdams. Top view is very similar to Figure D.5a but with smaller cofferdams.

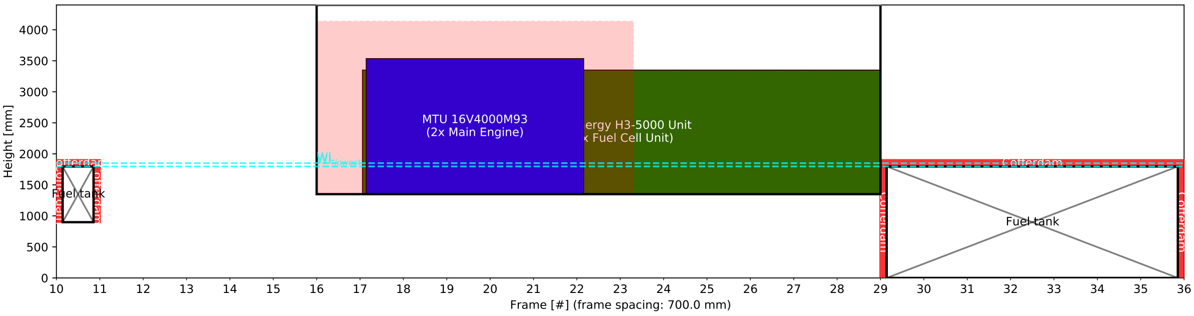
Figure D.5: Schematic layouts of the ICE+FC methanol configuration with one tank.



(a) Top view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.



(b) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and normal cofferdams.



(c) Side view of the methanol layout with ICEs for propulsion, HT-PEMFCs for auxiliary power and alternative cofferdams. Top view is very similar to Figure D.6a but with smaller cofferdams and a shorter aft tank.

Figure D.6: Schematic layouts of the ICE+FC methanol configuration with one tank around midship and a second tank in the aft of the yacht.

D.2. Pathway 0 - Baseline diesel ICE

Pathway 0 is the baseline to which the other pathways will be compared. It uses diesel as fuel with internal combustion engines to generate the required propulsion and auxiliary power. The general details of the pathways are described in 7 Pathways. The details of the baseline diesel pathway are given in 7.3.1 Pathway 0 - Baseline diesel ICE. The schematic representation of the configuration and tank layout of the diesel baseline for yacht C is shown in Figure D.2. This configuration and tank layout is used in the design tool. With the design tool, the emissions of a yacht in a year and the costs are determined.

D.2.1. Emissions

The CO_2, NO_x, SO_x and PM emissions are determined from the fuel consumption which depends on the operational profile of this yacht and are shown in Figure D.7. To put the emissions of the pathways into perspective, the CO_2 and NO_x are related to forest area and truck emissions respectively in Table D.5.

As can be seen in Figure D.7, the net CO_2 emissions of renewable diesel are zero while the other emissions are equal to the emissions of fossil diesel. The tank to wake emissions of renewable diesel are equal to that of fossil diesel but because the upstream (well to tank) emissions are negative, the net emissions of renewable diesel are much lower than the net emissions of fossil diesel.

The CO_2 and NO_x emissions of pathway 0 are related to forest area and the emissions of cars and trucks in Table D.5. For fossil diesel, yacht C requires a forest area of over 3.5 km^2 for the sequestration of CO_2 from the atmosphere in order to equal the CO_2 emitted by this yacht. When looking at the NO_x emissions and comparing the emissions to the NO_x emissions of cars and trucks, the scale of NO_x

Table D.5: CO_2 and NO_x emissions in perspective. The net CO_2 emissions are related to the forest area required to sequester the yearly CO_2 emitted by the yacht (data from Toochi (2018)). The NO_x emissions are related to the amount of diesel cars and heavy-duty diesel trucks (>20t), driving 80 km/h continuously, that emit an equal amount of NO_x (data from ICCT (2014); Velders (2013)).

Yacht	Fuel feedstock	CO_2 emissions		NO_x emissions		
		CO_2-WTW [t]	A_{forest} [km^2]	NO_x [t]	Cars	Heavy-duty trucks
C	Fossil	1570	3.58	5.0	12	2
	Renewable	0	0	5.0	12	2

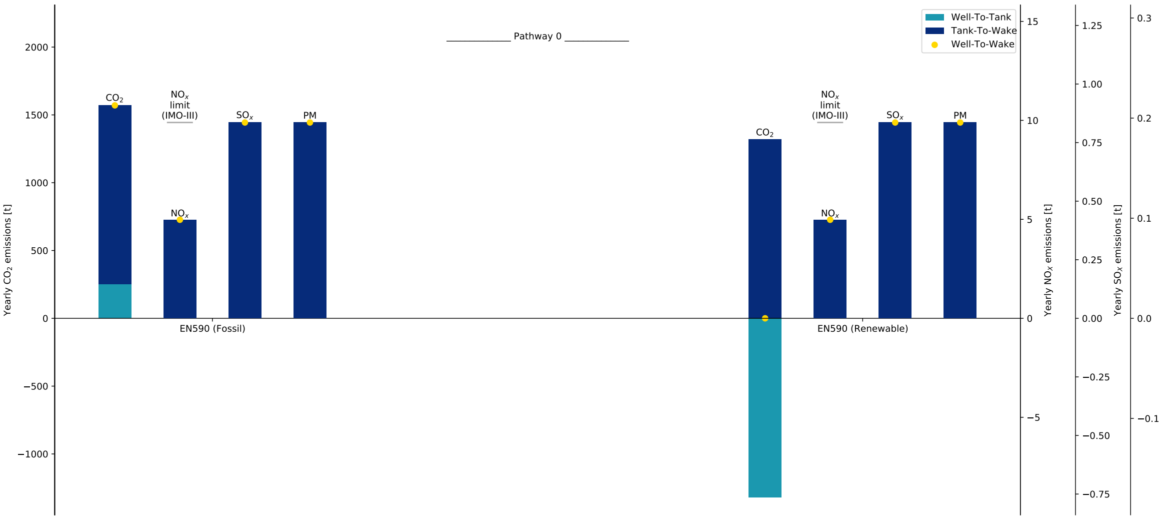


Figure D.7: Yearly emissions of CO_2, NO_x, SO_x and PM for the diesel baseline pathway 0 (2020 to 2050). The emissions are shown in tonnes per year for both fossil and renewable diesel (EN590) and are split up into well-to-tank and tank-to-wake emissions.

emissions of this yacht become clear. 12 diesel cars, driving continuously all year at 80 km/h, emit the same amount of NO_x as yacht C. Compared to heavy-duty trucks (of over 20 tonnes), this yacht emits the same amount of NO_x as 2 of these heavy-duty diesel trucks, again driving continuously at 80 km/h all year long. Although the NO_x emissions of a yacht using renewable diesel are equal to the NO_x emissions of fossil diesel (as assumed in Table 5.4), the environmental impact with respect to CO_2 emissions can be greatly reduced when using the renewable variant of the fuel at the cost of a higher fuel price (and reduced availability).

D.2.2. Costs

The fuel costs over the entire period of pathway 0 are shown in Figure D.8. Since there is no change in efficiency of the converters between configuration 1 and configuration 2 (see 7.2.2 Converter efficiency), the changing trend in fuel costs is purely caused by a decrease in fuel price. If the efficiency would change there would be a small decreasing jump in 2035 in fuel costs as at that year the configuration is refitted and a newer, more efficient engine may be installed. The gradual change in fuel costs is the result of a change in fuel price (see 7.2.1 Fuel price). The yearly fuel costs of renewable diesel are many times higher than for fossil diesel, especially in 2020 where renewable diesel is approximately 10 times as expensive. When looking at the yearly fuel costs in 2050, this difference becomes smaller. However, renewable diesel offers significantly less CO_2 emissions and likely also less other emissions.

The costs of the converters for both propulsion and auxiliary power are shown in Table D.6. The storage costs of diesel tanks in the double bottom are assumed to be equal to zero, as discussed in 5.5.3 Fuel storage. The costs of converters are also shown relative to the value of the yacht in Table D.7 together with the relative costs of storage which is stated between brackets. The total relative costs are around 5% of the yacht's value, which are relatively high compared to yacht A and B (see Table 8.13). It can

Table D.6: Costs of converters for propulsion and auxiliary power generation in million Euros and storage costs in Euros of pathway 0.

Yacht	Configuration 1					Configuration 2				
	Propulsion		Auxiliary		Storage	Propulsion		Auxiliary		Storage
	Type	Price [M€]	Type	Price [M€]	Price [€]	Type	Price [M€]	Type	Price [M€]	Price [€]
C	ICE	2.072	ICE	0.380	0.0	ICE	2.072	ICE	0.380	0.0

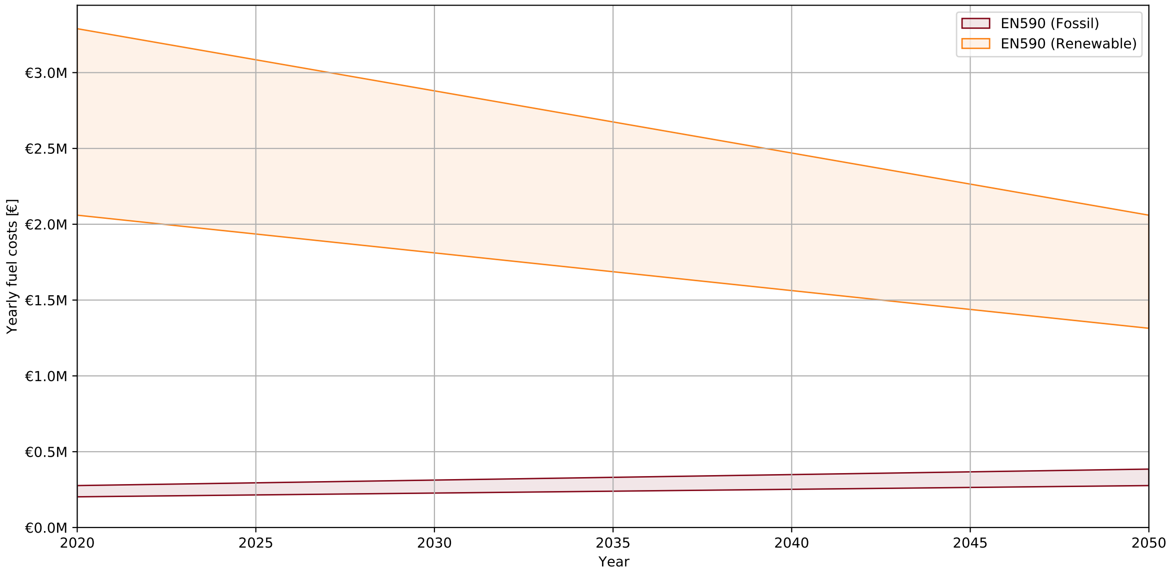


Figure D.8: Yearly fuel costs (with upper and lower limits) for pathway 0 which uses diesel ICEs for propulsion and auxiliary power from 2020 to 2050. Both fossil and renewable yearly fuel costs are shown.

Table D.7: Total converter costs and storage costs of pathway 0. The total costs (converters and storage) are expressed as a percentage of the yacht's value. The relative storage costs are given between brackets.

Yacht	Configuration	Converter costs [M€]	Storage costs [M€]	Yacht value [M€]	Relative costs [%]
C	ICE - Diesel	2.452	0.000	50	4.90 (0.00)
	ICE - Diesel	2.452	0.000	50	4.90 (0.00)

also be seen that the relative converter costs increase with decreasing yacht size, but the speed of the yacht is also of great influence. This is particularly true for yacht C as this yacht requires a high amount of installed power due to its maximum speed of 28 knots.

D.3. Pathway 1 - Methanol ICE

The first methanol pathway uses methanol as fuel with internal combustion engines to generate the required propulsion and auxiliary power. The general details of the pathways are described in 7 Pathways. The details this pathway are given in 7.3.2 Pathway 1 - Methanol ICE. The schematic configuration and tank layout of methanol pathway 1 for yacht C are shown in Figure D.4. This configuration and tank layout has a central and aft tank and is used in the design tool. With the design tool, the emissions for this pathway of a yacht in a year and the costs are determined.

D.3.1. Emissions

The CO_2, NO_x, SO_x and PM emissions are determined from the fuel consumption which depends on the operational profile. These emissions are shown in Figure D.9. To put the emissions of the first methanol pathway into perspective, the CO_2 and NO_x are related to forest area and truck emissions respectively in Table D.8.

When comparing the emissions of the first methanol pathway to the diesel baseline, one can see a significant decrease in yearly emissions of SO_x and PM (see Figure D.9). Only the CO_2 emissions have increased for fossil methanol compared to fossil diesel, while the NO_x emissions have remained the same. The methanol ICE configuration of yacht C emits around 10% more CO_2 than the diesel baseline. The benefit of using methanol is clearly seen in the SO_x and PM emissions. The SO_x emissions are reduced to zero and the PM emissions have more than halved compared to the diesel baseline. When renewable methanol is used, the well to wake CO_2 emissions can also be reduced to zero.

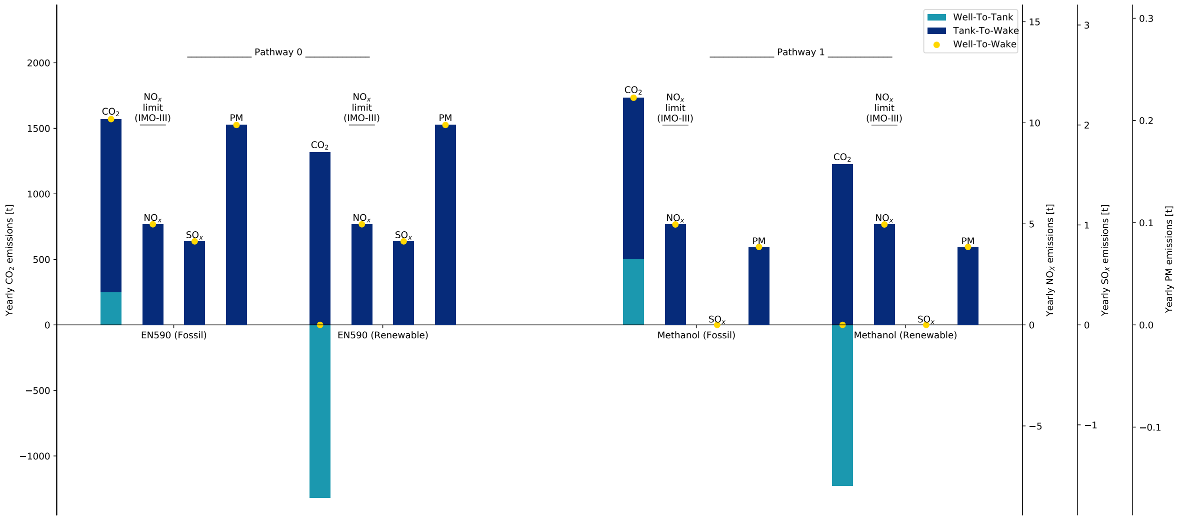


Figure D.9: Yearly emissions of CO_2, NO_x, SO_x and PM for pathway 1 (2020 to 2050), compared to the diesel baseline (pathway 0). The emissions are shown in tonnes per year for both fossil and renewable methanol and are split up into well-to-tank and tank-to-wake emissions.

Table D.8: CO_2 and NO_x emissions in perspective. The net CO_2 emissions are related to the forest area required to sequester the yearly CO_2 emitted by the yacht (data from Toochi (2018)). The NO_x emissions are related to the amount of diesel cars and heavy-duty diesel trucks (>20t), driving 80 km/h continuously, that emit an equal amount of NO_x (data from ICCT (2014); Velders (2013)).

Yacht	Fuel feedstock	CO_2 emissions		NO_x emissions		
		CO_2-WTW [t]	A_{forest} [km^2]	NO_x [t]	Cars	Heavy-duty trucks
C	Fossil	1733	3.96	5.0	12	2
	Renewable	0	0	5.0	12	2

That the CO_2 emissions have slightly increased can also be seen in the forest area required to sequester the CO_2 emissions (see Table D.8). This required forest area has increased by the same percentage as the CO_2 emissions have. The NO_x emissions of methanol pathway 1 remain equal to that of the baseline pathway.

D.3.2. Costs

The fuel costs over the entire period of pathway 1 are shown in Figure D.10. The fuel costs are compared to the fuel costs of the baseline pathway that uses diesel ICEs. Since there is no change in efficiency of the converters between configuration 1 and configuration 2 (see 7.2.2 Converter efficiency), the decreasing trend in fuel costs is purely caused by a decrease in fuel price. If the efficiency would change there would be a small decreasing jump in 2035 in fuel costs as at that year the configuration is refitted and a newer, more efficient engine may be installed. The gradual change in fuel costs is the result of a change in fuel price (see 7.2.1 Fuel price). Figure D.10 shows that the yearly fuel costs for fossil methanol are higher than that of the diesel baseline. Therefore, a decrease in SO_x and PM resulting from using fossil methanol comes at a slightly higher yearly fuel cost. The fuel costs of renewable methanol on the other hand are significantly less than that of renewable diesel in the baseline pathway. This indicates that when zero CO_2 emissions are required (or desired), the yearly fuel costs are less expensive when renewable methanol is used than when renewable diesel is used. Additionally, the SO_x and PM emissions are also reduced by using renewable methanol compared to renewable diesel, which is assumed to have equal NO_x, SO_x and PM emissions as fossil diesel.

The costs of the converters for both propulsion and auxiliary power are shown in Table D.9. The costs of converters are also shown relative to the value of the yacht in Table D.10 together with the relative costs of storage which is stated between brackets. The total relative costs are around 5% of the yacht's value, while the relative costs of the storage itself are only 0.09%. The storage costs are therefore likely to only make up a very small part of the total costs of the yacht. The relative storage costs are also related to the required energy capacity as a result of the required range (for the other yachts, see

Table D.9: Costs of converters for propulsion and auxiliary power generation and storage costs of pathway 1.

Yacht	Configuration 1					Configuration 2				
	Propulsion		Auxiliary		Storage	Propulsion		Auxiliary		Storage
	Type	Price [M€]	Type	Price [M€]	Price [€]	Type	Price [M€]	Type	Price [M€]	Price [€]
C	ICE	2.072	ICE	0.380	45,408	ICE	2.072	ICE	0.380	45,408

Table D.10: Total converter costs and storage costs of pathway 1. The total costs (converters and storage) are expressed as a percentage of the yacht's value. The relative storage costs are given between brackets.

Yacht	Configuration	Converter costs [M€]	Storage costs [M€]	Yacht value [M€]	Relative costs [%]
C	ICE - Methanol	2.452	0.045	50	4.99 (0.09)
	ICE - Methanol	2.452	0.045	50	4.99 (0.09)

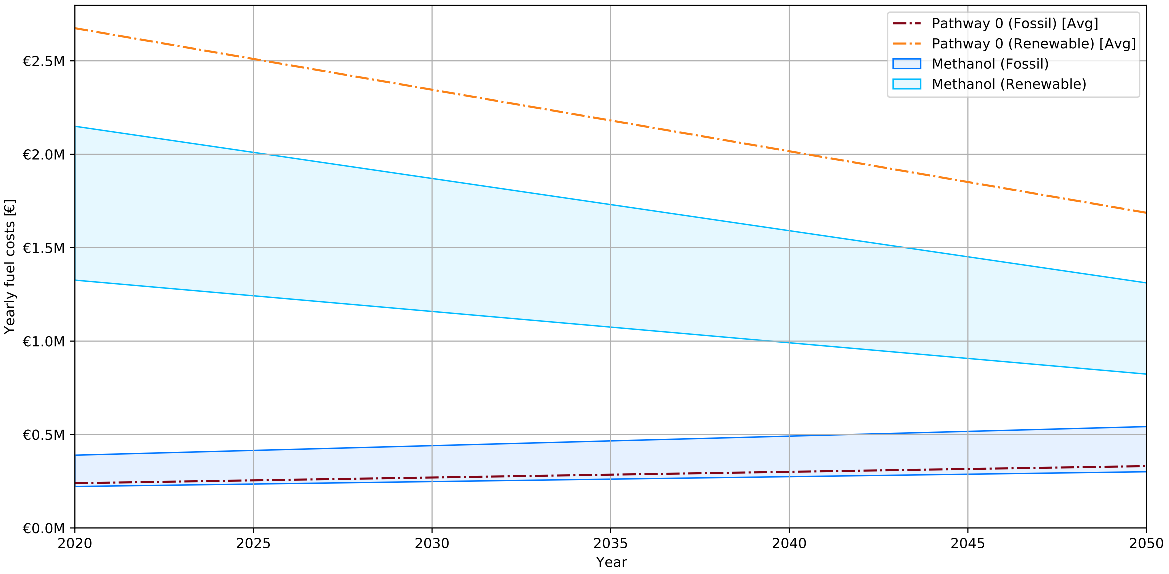


Figure D.10: Yearly fuel costs (with upper and lower limits) for pathway 1 which uses methanol ICEs for propulsion and auxiliary power from 2020 to 2050. The average fuel costs of the baseline pathway 0 are also shown as a comparison. Both fossil and renewable yearly fuel costs are shown.

Table 8.16). When looking at yacht A and B which have a more comparable range (yacht C has a range that is approximately a third of the other two yachts), it can be concluded that the relative storage costs also increase with decreasing yacht size.

D.4. Pathway 2 - Methanol ICE+FC

The second methanol pathway uses methanol as fuel with internal combustion engines to generate the required propulsion power and HT-PEMFC to generate the auxiliary power. The general details of the pathways are described in 7 Pathways. The details this pathway are given in 7.3.3 Pathway 2 - Methanol ICE+FC. A schematic configuration and tank layout of methanol pathway 2 for yacht C is shown in Figure D.6. This configuration and tank layout, with a central and aft tank, is used in the design tool. With the design tool, the emissions of a yacht in a year and the costs can be determined.

D.4.1. Emissions

The emissions are determined from the fuel consumption which depends on the operational profile of the yacht. These emissions include CO_2, NO_x, SO_x and PM. These yearly emissions are shown in Figure D.11 and are compared to the diesel baseline of pathway 0. To put the emissions of the first methanol pathway into perspective, the CO_2 and NO_x are related to forest area and truck emissions respectively in Table D.11.

Table D.11: CO_2 and NO_x emissions in perspective. The net CO_2 emissions are related to the forest area required to sequester the yearly CO_2 emitted by the yacht (data from Toochi (2018)). The NO_x emissions are related to the amount of diesel cars and heavy-duty diesel trucks (>20t), driving 80 km/h continuously, that emit an equal amount of NO_x (data from ICCT (2014); Velders (2013)).

Yacht	Fuel feedstock	CO_2 emissions		NO_x emissions		
		CO_2-WTW [t]	A_{forest} [km^2]	NO_x [t]	Cars	Heavy-duty trucks
C	Fossil	1389	3.17	0.7	2	0
	Renewable	0	0	0.7	2	0

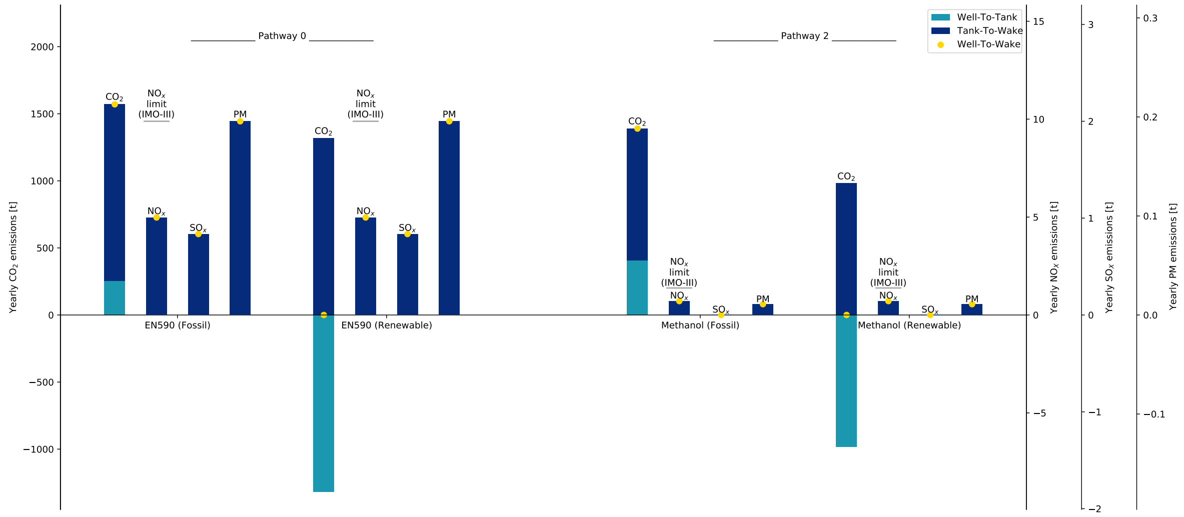


Figure D.11: Yearly emissions of CO_2, NO_x, SO_x and PM for pathway 2 (2020 to 2050), compared to the diesel baseline (pathway 0). The emissions are shown in tonnes per year for both fossil and renewable methanol and are split up into well-to-tank and tank-to-wake emissions.

Figure D.11 shows that the NO_x, SO_x and PM emissions of methanol pathway 2 are all significantly lower than the emissions of the diesel baseline pathway. This is mainly the result of using fuel cells for the generation of auxiliary power. The only NO_x and PM emission that this methanol fuelled yacht emits comes from the internal combustion engines that are used for the propulsion of the yacht. The CO_2 emissions have decreased compared to the diesel baseline by 12%, because the efficiency of the fuel cells used is slightly higher than that of the ICEs.

That the CO_2 emissions have decreased compared to the diesel baseline can also be seen in the forest area required to sequester the CO_2 emissions of this yacht (see Table D.11). This required forest area has decreased by the same percentage as the CO_2 emissions have. The NO_x emissions of methanol pathway 2 have decreased significantly and therefore the NO_x emissions of yacht C equal zero trucks and less cars than the diesel baseline and also the first methanol pathway.

D.4.2. Costs

The fuel costs over the entire period of pathway 2 are shown in Figure D.12. The fuel costs are compared to the fuel costs of the baseline pathway that uses diesel ICEs. Since there is no change in efficiency of the converters between configuration 1 and configuration 2 (see 7.2.2 Converter efficiency), the decreasing trend in fuel costs is purely caused by a decrease in fuel price. If the efficiency would change there would be a small decreasing jump in 2035 in fuel costs as at that year the configuration is refitted and a newer, more efficient engine may be installed. The gradual change in fuel costs is the result of a change in fuel price (see 7.2.1 Fuel price). The yearly fuel costs have decreased compared to methanol pathway 1 because the fuel cells are slightly more efficient and therefore less methanol fuel is consumed. Therefore, the yearly fuel costs of pathway 2 are similar to the diesel baseline pathway.

The costs of the converters for both propulsion and auxiliary power are shown in Table D.12. The costs of converters are also shown relative to the value of the yacht in Table D.13 together with the relative

Table D.12: Costs of converters for propulsion and auxiliary power generation and storage costs of pathway 2. HT-PEMFCs are used for the generation of auxiliary power.

Yacht	Configuration 1					Configuration 2				
	Propulsion		Auxiliary		Storage	Propulsion		Auxiliary		Storage
	Type	Price [M€]	Type	Price [M€]	Price [€]	Type	Price [M€]	Type	Price [M€]	Price [€]
C	ICE	2.072	FC	1.080	42,766	ICE	2.072	FC	1.080	42,766

Table D.13: Total converter costs and storage costs of pathway 2. The total costs (converters and storage) are expressed as a percentage of the yacht's value. The relative storage costs are given between brackets.

Yacht	Configuration	Converter costs [M€]	Storage costs [M€]	Yacht value [M€]	Relative costs [%]
C	ICE+HT-PEMFC - Methanol	3.152	0.043	50	6.39 (0.09)
	ICE+HT-PEMFC - Methanol	3.152	0.043	50	6.39 (0.09)

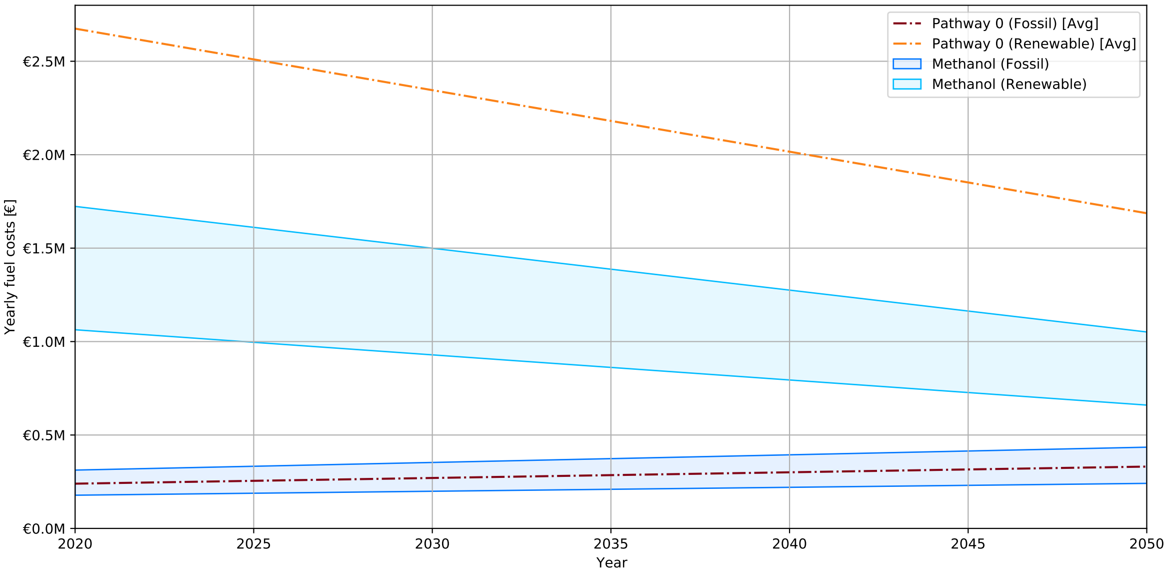


Figure D.12: Yearly fuel costs (with upper and lower limits) for pathway 2 which uses methanol ICEs for propulsion power and HT-PEMFCs for auxiliary power from 2020 to 2050. The average fuel costs of the baseline pathway 0 are also shown as a comparison. Both fossil and renewable yearly fuel costs are shown.

costs of storage which is stated between brackets. The total relative costs is over 6%, while the relative costs of the storage itself is, like pathway 1, 0.09%. The increase in total relative costs is caused by the more expensive fuel cells. The storage costs, which are relatively small, are therefore likely to only make up a very small part of the total costs of the yacht.

D.5. Pathway 3 - Diesel ICE to methanol ICE

The third methanol pathway uses diesel as fuel with internal combustion engines to generate the required propulsion power and auxiliary power from 2020 to 2035 and methanol fuelled ICEs to generate the propeller and auxiliary power from 2035 to 2050. The details of the pathways are described in 7 Pathways. The details this pathway are given in 7.3.4 Pathway 3 - Diesel ICE to methanol ICE. The diesel configuration and tank layout of pathway 3 is shown in Figure D.2. The methanol configuration and tank layout of pathway 3 is shown in Figure D.4. These configurations and tank layouts are used in the design tool. With the design tool, the emissions of a yacht in a year and the costs can be determined.

D.5.1. Emissions

The CO_2, NO_x, SO_x and PM emissions are determined from the fuel consumption which depends on the operational profile. These yearly emissions for the first time span (2020-2035) are equal to the diesel baseline (pathway 0) and are equal to that of the first methanol pathway for the second time span (2035-2050). The average yearly emissions throughout the entire time span (2020-2050) are compared to the baseline pathway and shown in Figure D.13. The average CO_2 and NO_x are related to forest area and truck emissions respectively in Table D.14.

Table D.14: Average CO_2 and NO_x emissions in perspective. The net CO_2 emissions are related to the forest area required to sequester the yearly CO_2 emitted by the yacht (data from Toochi (2018)). The NO_x emissions are related to the amount of diesel cars and heavy-duty diesel trucks (>20t), driving 80 km/h continuously, that emit an equal amount of NO_x (data from ICCT (2014); Velders (2013)).

Yacht	Fuel feedstock	CO_2 emissions		NO_x emissions		
		CO_2-WTW [t]	A_{forest} [km^2]	NO_x [t]	Cars	Heavy-duty trucks
C	Fossil	1,652	3.77	5.0	12	2
	Renewable	0	0	5.0	12	2

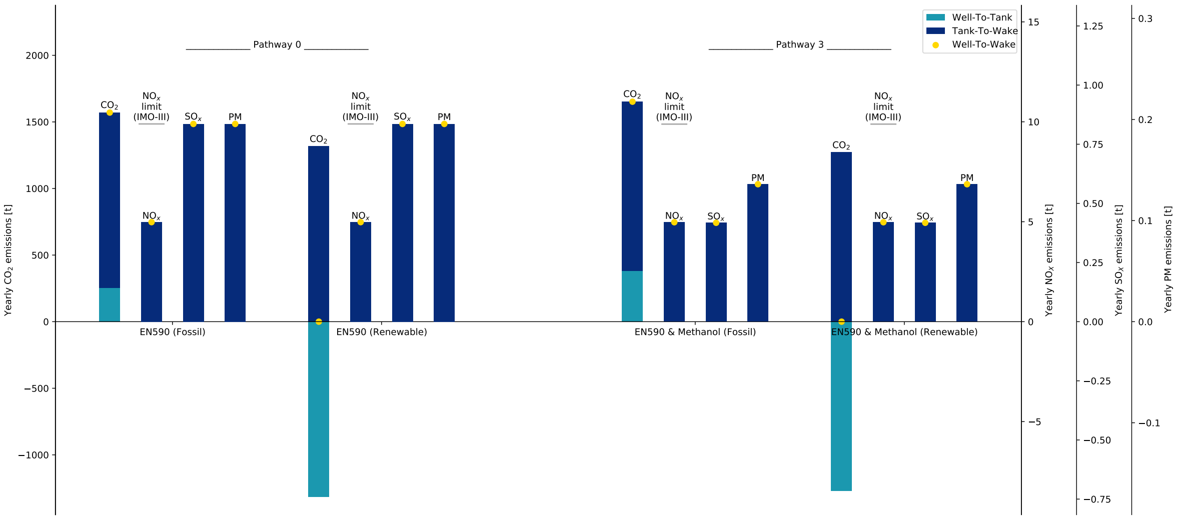


Figure D.13: Average yearly emissions of CO_2, NO_x, SO_x and PM for pathway 3 (2020 to 2050), compared to the diesel baseline (pathway 0). The emissions are shown in tonnes per year for both fossil and renewable diesel and methanol and are split up into well-to-tank and tank-to-wake emissions.

Since pathway 3 is a combination of a diesel (2020-2035) and a methanol (2035-2050) configuration, the average yearly emissions are in between the yearly emissions of each configuration (see Figure D.13). The individual yearly emissions are equal to pathway 0 and pathway 1 for the diesel and methanol configuration respectively. The average yearly emissions, compared to the baseline pathway, of CO_2 have increased slightly, the average yearly NO_x emissions are approximately equal and the SO_x and PM emissions have decreased significantly. The CO_2 emissions of yacht A have increased by 5% compared to the baseline pathway.

Both the CO_2 and NO_x emissions are very similar to that of the baseline pathway and the first methanol pathway. This results in a small increase in forest area required to sequester the CO_2 emissions of the yacht and equal amount of cars and heavy-duty trucks to equal the NO_x emissions (see Table D.14).

D.5.2. Costs

The fuel costs over the entire period of pathway 3 are shown in Figure D.14. The fuel costs are compared to the fuel costs of the baseline pathway that uses diesel ICEs. Since there is no change in efficiency of the converters between configuration 1 and configuration 2 (see 7.2.2 Converter efficiency), the decreasing trend in fuel costs is purely caused by a decrease in fuel price and by the switch from diesel to methanol. If the efficiency would change there would be an additional small decreasing jump in 2035 in fuel costs as at that year the configuration is refitted and a newer, more efficient engine may be installed. The gradual change in fuel costs is the result of a change in fuel price (see 7.2.1 Fuel price). This pathway, which is a combination of the baseline diesel pathway and methanol pathway 1,

Table D.15: Costs of converters for propulsion and auxiliary power generation and storage costs of pathway 3.

Yacht	Configuration 1					Configuration 2				
	Propulsion		Auxiliary		Storage	Propulsion		Auxiliary		Storage
	Type	Price [M€]	Type	Price [M€]	Price [€]	Type	Price [M€]	Type	Price [M€]	Price [€]
C	ICE	2.072	ICE	0.380	0.0	ICE	2.072	ICE	0.380	45,408

Table D.16: Total converter costs and storage costs of pathway 3. The total costs (converters and storage) are expressed as a percentage of the yacht's value. The relative storage costs are given between brackets.

Yacht	Configuration	Converter costs [M€]	Storage costs [M€]	Yacht value [M€]	Relative costs [%]
C	ICE - Diesel	2.452	0.000	50	4.90 (0.00)
	ICE - Methanol	2.452	0.045	50	4.99 (0.09)

is more interesting in terms of yearly fuel costs. Since the switch from diesel to methanol is made in 2035, there is a corresponding jump in yearly fuel costs in this year. The fossil methanol costs increase, compared to the fossil diesel costs, while the renewable methanol costs decrease significantly compared to the renewable diesel costs. This pathway is particularly interesting when fossil diesel is used during the first 15 years and a switch to renewable methanol is made in 2035. This option represents the case that renewable diesel is considered too expensive during the first 15 years and (renewable) methanol's availability is not sufficient to be a feasible option. When in 2035, the price of renewable methanol has decreased significantly (compared to the 2020 price) and renewable methanol may be a feasible option.

The costs of the converters for both propulsion and auxiliary power are shown in Table D.15. The storage costs of diesel tanks in the double bottom are assumed to be equal to zero, as discussed in 5.5.3 Fuel storage. The costs of converters are also shown relative to the value of the yacht in Table D.16 together with the relative costs of storage which is stated between brackets. The total

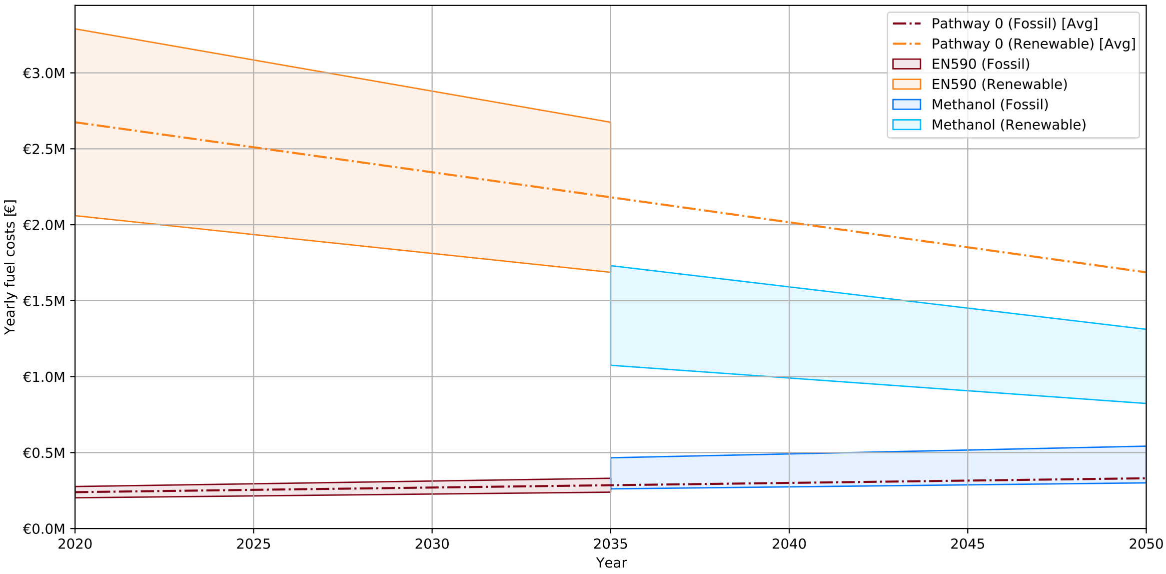


Figure D.14: Yearly fuel costs (with upper and lower limits) for pathway 3 which uses diesel ICEs for propulsion and auxiliary power from 2020 to 2035 and methanol ICEs from 2035 to 2050. The average fuel costs of the baseline pathway 0 are also shown as a comparison. Both fossil and renewable yearly fuel costs are shown.

relative costs are around 5% for both configurations, while the relative costs of the storage itself ranges from 0% to 0.09%. The storage costs are therefore likely to only make up a very small part of the total costs of the yacht.

D.6. Pathway 4 - Methanol ICE to methanol ICE+FC

The fourth and final methanol pathway uses methanol as fuel with internal combustion engines to generate the required propulsion power and auxiliary power from 2020 to 2035 and methanol fuelled ICEs to generate the propeller and auxiliary power from 2035 to 2050. The details of the pathways are described in 7 Pathways. The details this pathway are given in 7.3.5 Pathway 4 - Methanol ICE to methanol ICE+FC. The ICE configuration and tank layout of pathway 4 is shown in Figure D.4. The ICE+FC configuration and tank layout of pathway 4 is shown in Figure D.6. These configurations and tank layouts are used in the design tool. With the design tool, the emissions of a yacht in a year and the costs can be determined.

D.6.1. Emissions

The CO_2, NO_x, SO_x and PM emissions are determined from the fuel consumption which depends on the operational profile. These yearly emissions for the first time span (2020-2035) are equal to the first methanol pathway and for the second time span (2035-2050) they are equal to that of the second methanol pathway. The average yearly emissions throughout the entire time span (2020-2050) are compared to the baseline pathway and shown in Figure D.15. To put the average emissions of the fourth pathway into perspective, the average CO_2 and NO_x are related to forest area and truck emissions respectively in Table D.17.

The fourth methanol pathway is a combination using methanol fuelled ICEs and then switching to fuel cells for the generation of auxiliary power. Therefore, the average yearly emissions (see Figure D.15) are a combination between the emissions of pathway 1 and pathway 2. Compared to the baseline, the CO_2 emission of yacht C are approximately equal, while the NO_x, SO_x and PM emissions have decreased. Compared to the ICE only methanol pathway 1, all average emissions are lower (except for SO_x which is equal to zero for both), because fuel cells are used in the second time span (after 2035).

This decrease in emissions is also seen in the number of cars and heavy-duty trucks to emit an equal amount of NO_x (see Table D.17). A significant decrease of 44% in NO_x emissions is seen for yacht C,

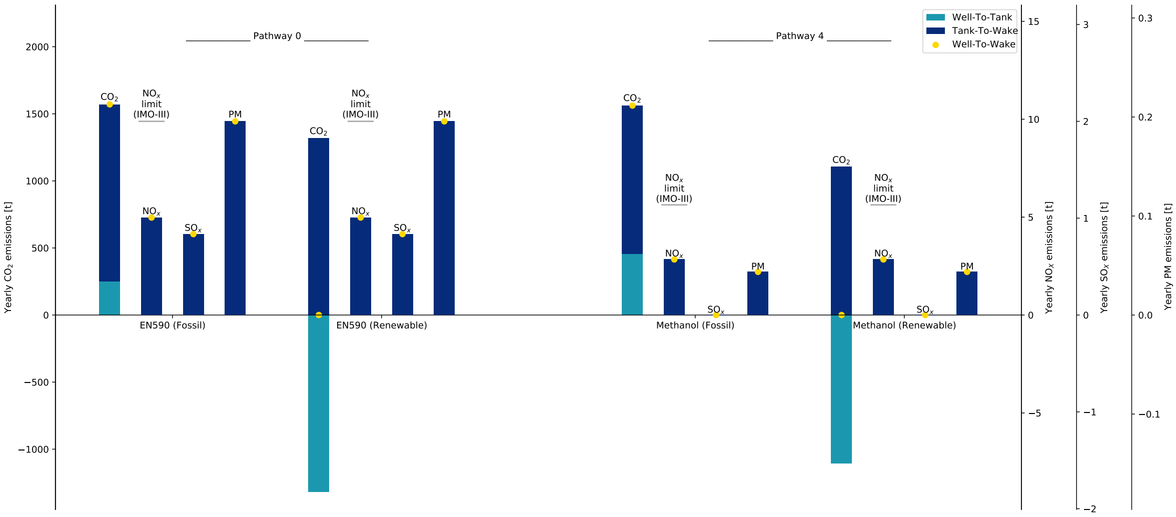


Figure D.15: Average yearly emissions of CO_2, NO_x, SO_x and PM for pathway 4 (2020 to 2050), compared to the diesel baseline (pathway 0). The emissions are shown in tonnes per year for both fossil and renewable diesel and methanol and are split up into well-to-tank and tank-to-wake emissions.

Table D.17: Average CO_2 and NO_x emissions in perspective. The net CO_2 emissions are related to the forest area required to sequester the yearly CO_2 emitted by the yacht (data from Toochi (2018)). The NO_x emissions are related to the amount of diesel cars and heavy-duty diesel trucks (>20t), driving 80 km/h continuously, that emit an equal amount of NO_x (data from ICCT (2014); Velders (2013)).

Yacht	Fuel feedstock	CO_2 emissions		NO_x emissions		
		CO_2-WTW [t]	A_{forest} [km^2]	NO_x [t]	Cars	Heavy-duty trucks
C	Fossil	1561	3.57	2.8	7	1
	Renewable	0	0	2.8	7	1

compared to both the diesel baseline and methanol pathway 1.

D.6.2. Costs

The fuel costs over the entire period of pathway 4 are shown in Figure 8.18. The fuel costs are compared to the fuel costs of the baseline pathway that uses diesel ICEs. Since there is no change in efficiency of the converters between configuration 1 and configuration 2 (see 7.2.2 Converter efficiency), the decreasing trend in fuel costs is purely caused by a decrease in fuel price and by the switch from methanol ICEs to methanol FCs for the generation of auxiliary power. If the efficiency would change there would be an additional small decreasing jump in 2035 in fuel costs as at that year the configuration is refitted and a newer, more efficient engine may be installed. The gradual change in fuel costs is the result of a change in fuel price (see 7.2.1 Fuel price). The jump in yearly fuel costs of this fourth pathway is less than for the switch from diesel to methanol in pathway 3, but still significant. The fossil methanol fuel costs are almost equal to the average diesel costs of pathway 0 after the switch to fuel cells in 2035. This pathway can show the scenario that fuel cells are initially (2020-2035) considered too expensive, to not have a high enough efficiency or to have a lifetime that is too short. However in 2035, fuel cells may have become less expensive, more efficient or have a better lifetime. By this time, the fuel price of renewable methanol has also decreased, allowing the low emission combination of fuel cells and renewable methanol to be more feasible in terms of yearly fuel costs (and possibly capital costs).

The costs of the converters for both propulsion and auxiliary power are shown in Table D.18. The costs of converters are also shown relative to the value of the yacht in Table D.19 together with the relative costs of storage which is stated between brackets. The total relative costs range from around 5% to 6.5%, while the relative costs of the storage itself remains around 0.09%. The increase in relative costs is caused by the more expensive fuel cells.

Table D.18: Costs of converters for propulsion and auxiliary power generation and storage costs of pathway 4.

Yacht	Configuration 1					Configuration 2				
	Propulsion		Auxiliary		Storage	Propulsion		Auxiliary		Storage
	Type	Price [M€]	Type	Price [M€]	Price [€]	Type	Price [M€]	Type	Price [M€]	Price [€]
C	ICE	2.072	ICE	0.380	45,408	ICE	2.072	FC	1.080	42,766

Table D.19: Total converter costs and storage costs of pathway 4. The total costs (converters and storage) are expressed as a percentage of the yacht's value. The relative storage costs are given between brackets.

Yacht	Configuration	Converter costs [M€]	Storage costs [M€]	Yacht value [M€]	Relative costs [%]
C	ICE	2.452	0.045	50	4.99 (0.09)
	ICE+HT-PEMFC	3.152	0.043	50	6.39 (0.09)

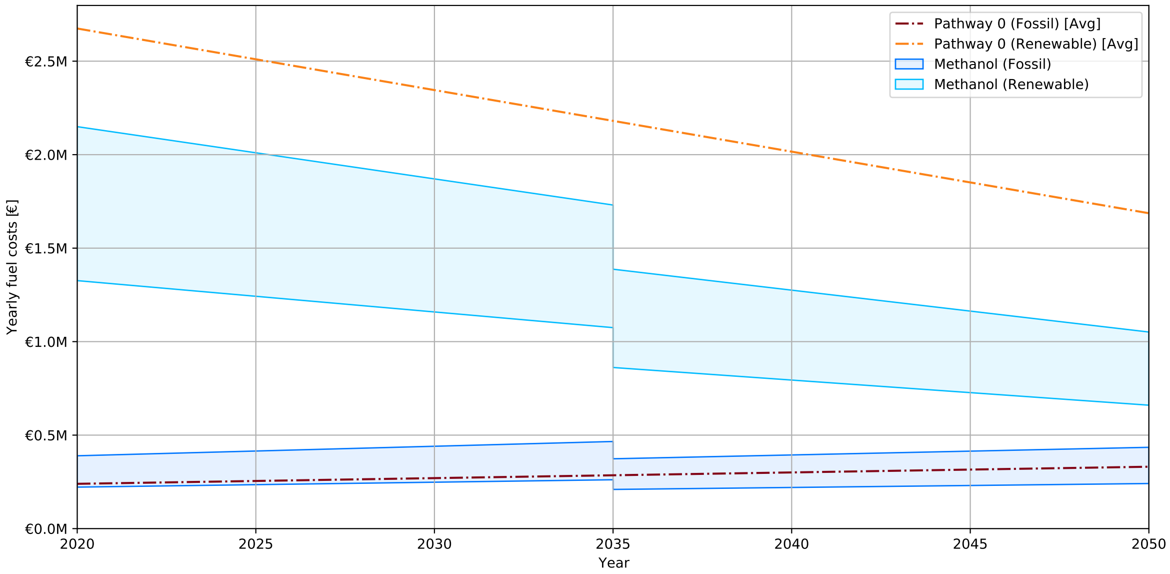


Figure D.16: Yearly fuel costs (with upper and lower limits) for pathway 4 which uses methanol ICEs for propulsion and auxiliary power from 2020 to 2035 and methanol ICEs and fuel cells from 2035 to 2050. The average fuel costs of the baseline pathway 0 are also shown as a comparison. Both fossil and renewable yearly fuel costs are shown.

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