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BRIDGING THE ENERGY TRANSITION

A PRACTICAL STUDY ON THE USE OF ALTERNATIVE FUELS ON LARGE SUPERYACHTS

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SUMMARY

The paper examines the requirements for superyacht design to adapt during the energy transition period. The driving factors for the use of alternative fuel and the need to exceed regulatory requirements and target zero emissions are discussed. The key factors for the selection of alternative fuels are considered as energy density, well-to-wake (WTW) emissions and safety. A comprehensive range of fuels are assessed for feasibility and desirability against these factors.

Three groups of fuel are identified as feasible, diesel drop-in fuels, methanol, and liquid hydrogen. The detailed ship design considerations for these fuels are discussed with examples from Lateral ship design projects.

The diesel drop-in yacht does not require any design changes, it is however most susceptible to unexpected developments or the effects of bio-mass sustainability. The methanol-fuelled yacht offers a high level of flexibility, and the option to adopt a gradual, reduced-risk approach. It requires some additional ship volume but doesn't challenge the current yacht design convention. The liquid hydrogen yacht requires an uncompromising approach to the technical design of a superyacht and the highest risk. It is not constricted by concerns for fuel sustainability or carbon neutral accounting.

1. INTRODUCTION

The 2015 Paris Agreement set in motion a renewed global effort to minimise the effects of climate change. To meet this agreement, countries and industries across the world have pledged to achieve net zero carbon solutions. This requires the world to transition sources of energy to newer lower carbon solutions.

In 2018 the International Maritime Organisation (IMO) agreed to implement measures to reduce the emission of greenhouse gases (GHG) by shipping. In 2020 strategies were announced with the aim of reducing CO_2 emissions per transport work by 40% compared to 2008 and by 2050 pursuing efforts to achieve a 70 % reduction. This strategy will be driven by the IMO's energy efficiency design index (EEDI), energy efficiency existing ship index (EEXI) and carbon intensity indicator (CII) regulations. These regulations exist within The International Convention for the Prevention of Pollution from Ships (MARPOL). Therefore, from now until 2050 the marine industry with be in an energy transition period.

Superyachts are not currently required to comply with any regulation that enforces reduced GHG emissions or mandates energy efficiency. The energy consumption and emissions of superyachts are however becoming increasingly visible to the world (1). The social responsibility of yacht owners and yacht builders is driving an increased demand for technical solutions to lower the environmental impact of superyachting and ensure the relevance of superyachts during this period of energy transition. This strong client-led demand requires new designs of yachts, which use lower carbon fuels.

There is a wide proliferation of fuel and energy options available to naval architects and marine engineers and this paper will aim to explore what practical options are suitable for use in large superyachts.

2. EMISSION REDUCTION TARGET

Superyachts are unique vessels by the manner in which they operate. Operating globally in some of the most pristine marine environments, the appreciation of that marine environment is key to the superyacht experience. As a result, superyachts traditionally have frequently been designed to operate often above and beyond the strictest MARPOL regulations with regard to the emission of local pollutants.

Within the current large yacht fleet, there are examples of diesel fuelled yachts which are optimised for efficiency, such as Bravo Eugenia (2). Whilst these yachts achieve an impressive reduction in overall carbon emissions, in order to significantly reduce carbon emissions further, and certainly within the context of the aforementioned IMO targets, the use of alternative lower carbon fuels is required.

Yachts are non-essential leisure items which do not undertake useful “transport work”. Therefore, to follow the highest levels of social responsibility and abide by the intent of the IMO agreements the ultimate future target for all yachting has to be zero emissions. This does represent a particular challenge for superyachts as the high capital cost of a superyacht means that to develop new technologies on such a high value platform is a particularly high risk proposition.

In addition, a superyacht life cycle is very long. The oldest superyachts in operation today are over one hundred years old. Given the high intrinsic value of superyachts, high construction quality, rigorous maintenance, and benign operating conditions, it is likely that many modern yachts built today will still be operating in 2122.

Therefore, it is desirable that any future yacht design should either have a degree of adaptability or be designed in such a way as to be as “future-proof” as possible. The adaptability in the design will need to be assessed against the additional cost or design constraint that this imposes on the design during build.

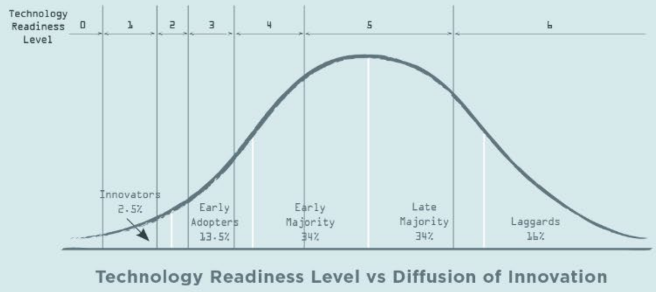
3. BOUNDARIES OF THE STUDY

Within this study, no assessment of the relative cost, likely uptake by other marine industries or competition from other industries shall be considered. To make an accurate assessment including these factors requires robust assumptions to be made regarding potentially volatile global geo-political and economic events which the authors consider impractical.

All the fuels within this paper will be assessed only on their technical suitability for use onboard large superyachts and their emissions reduction potential. These factors will include energy density, well-to-wake (WTW) emissions and safety. The sustainability of fuel production and supply shall be qualitatively considered

For the purposes of this study, a large yacht is defined as a yacht in excess of 80 m length overall (LOA) with transatlantic range and a minimum of 2 weeks endurance in guest use. The study is based on motor yachts however the major conclusions will also be valid for sailing yachts and wind assisted motor yachts.

In order to consider the energy transition period, the fuel storage and energy conversion technology shall be considered at a Lateral Technology Readiness Level (TRL) of 2 or higher (Figure 1). i.e. Nuclear propulsion is excluded as an option.



TECHNOLOGY READINESS LEVEL

TRL 0 – Blue Sky Idea
Anecdotal concept with no analytical proof of feasibility.

TRL 1 – Paper Concept
Exists only in paper proposals or academic research, analytically proven.

TRL 2 – Industrial Development
Product is not being developed for a marine industry application however a test rig or prototype product exists to develop the technology to a real world application.

TRL 3 – Marine Product Development
Product is not offered for sale, however a test rig or prototype product/installation exists.

TRL 4 – First User
At least 1 reference yacht, concept fully certified by authorities for marine use.

TRL 5 – Common Practice
Multiple reference yachts and vendors available.

TRL 6 – Obsolete
Obsolete by increased regulation or alternative technology.

Figure 1 Lateral Technology Readiness Level/Diffusion of Innovation

4. ANALYSIS OF ENERGY DENSITY

A key performance indicator in superyacht design is the ratio of luxury space to Gross tonnage (GT) with the highest possible ratio giving a strong commercial advantage. For a vessel that has no useful "transport work", this ratio effectively defines how much benefit is delivered per unit volume of yacht, in effect it is a measure of density. Therefore, the energy density of any alternative fuel is an important design criteria.

Figure 2 indicates the relative energy density for all alternative fuels considered within this study. The table considers the energy density of fuel only. The actual space required on board will be dependent upon the storage methodology and energy conversion efficiency. Attempts to generate standard "packaging factors" for comparison have concluded that these factors are highly variable and dependent upon the specific yacht design and specification.

Energy density is considered as space required per generated energy, so the efficiency of onboard power generation is a factor. The study has considered where possible standardized efficiencies for combustion engines and fuel cells. Optimising onboard power generation for higher efficiency does offer the ability to improve these numbers but all improvements are likely to be marginal.

Qualitative factors relating to storage or technical requirements have been combined with the results of previous yacht design studies and technical papers (3) to establish feasible limits for energy density.

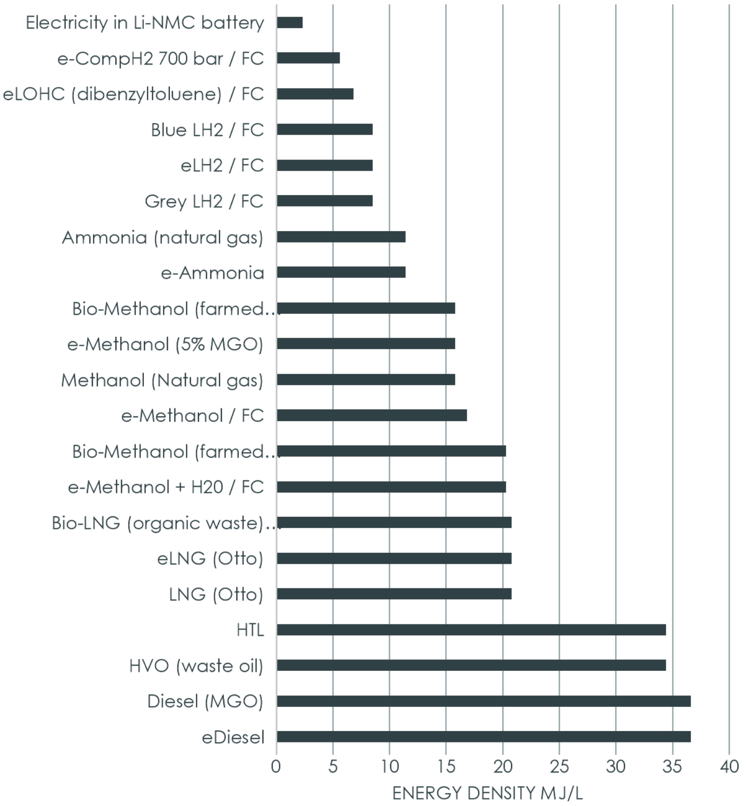


Figure 2 Fuel Energy Density [4][5][6][7][8][9]

5. ANALYSIS OF EMISSIONS

Emissions are considered by the method of well-to-wake (WTW) analysis. WTW analysis studies the full lifecycle of the fuel from primary energy and feedstock production to the delivery of energy onboard the yacht. WTW analysis considers all emissions in the fuel's lifecycle and their relative greenhouse gas effects to establish an equivalent amount of CO_2 released per onboard energy. This study considers the effects over a 100-year timespan.

Standards exist for measuring well-to-wake emissions. The Renewable Energy Directive (RED II) amongst others, define values and frameworks for calculating values. Other frameworks have been suggested such as a framework presented by the EU at Marine Environment Protection Committee (MEPC) [16], which is due to be discussed at MEPC 79. Some sources use their own methods of calculating well to wake also. This results in many methods of calculating values which may be unhelpful to direct comparison and lead to confusion. Suggested values are given within RED II and other similar calculation directives, but these are not absolute values. As mentioned, other sources utilise alternative methods of calculating well-to-wake values. These alternative methods can in some cases be backed by better datasets and can consider more inputs than RED II.

While some factors of well-to-wake analysis seem reasonably well-defined. matters become a little less clear with less widely used and available fuels, where the real-world data is limited. For example, some reports suggest that the use of liquid hydrogen results in zero emissions, while others assume transportation and energy have a carbon cost. This demonstrates how difficult it is to fully evaluate different fuels and any industry stakeholder wishing to make decisions based on WTW values should undertake a more detailed analysis for their specific usage case.

One example of the above is when comparing calculated values from the EU suggestion at MEPC 77 [10]. When utilising their values, e-diesel comes to a value of 28.6 gCO_2e/MJ. This finding is contrary to a report by Lindstad et.al [6] which suggests that the WTW value of e-diesel is 1.3 gCO_2e/MJ and a whitepaper from the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping [7] which suggests that the WTW emissions for e-diesel could be around 5.76 gCO_2e/MJ. Generally, each source is consistent in its approach but comparing between different sources indicates a wide variety of assumptions.

It is also key to acknowledge that almost none of the fuels considered have a zero WTW emission number. This is somewhat at odds with the common terms of zero emissions or net zero. Generally, these terms are more strictly identified as zero tank-to-wake emissions or net zero operational emissions. For the purpose of this study fuels with very low WTW, emissions or variance that leads to zero are considered as fuels with suitable levels of emission reduction.

Accepted industry tank-to-wake (TTW) emission values (i.e., considering emission generated onboard the yacht) may not fully align with the latest high-efficiency technology. We consider that some of these values could be further improved with a detailed lifecycle assessment of the specific yacht. However, given the variation in yacht design, this is not included in the study.

Considering the above factors Figure 3 indicates the WTW emissions along with maximum and minimum values for the range of fuels studied, complete with an indicative method of energy conversion (fuel cells are marked with the notation FC).

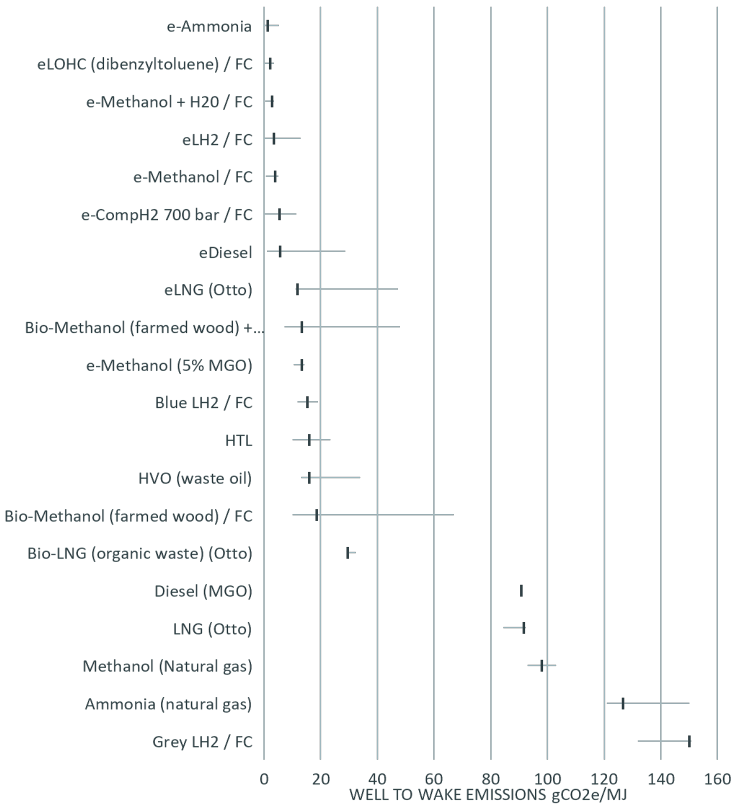


Figure 3 WTW Emission Comparison
References: [6][7][10][11][12][13][14][15][16][17][18][19][20][21][22]

6. SAFETY MITIGATION AND RISK

Many of the fuels considered are inherently more dangerous than diesel, either by means of flammability, storage methodology or toxicity. To ensure safety, any alternative fuel would have to follow specific prescriptive safety requirements i.e., in the case of LNG, compliance with the IGF code. In the case where prescriptive rules do not exist a specific alternative design assessment (ADA) would need to be made by both class and flag authorities. Based on examples of this process it is assumed that an equivalent level of safety can be achieved using further engineering safeguards for all the fuels considered.

The exception to this assumption are ammonia-related fuels. The potential for personnel and environment damage (4) in the event of a fuel leak poses an unacceptably severe impact on a yacht or yacht owner. The risk of these severe events are so great that they cannot be mitigated within the normal risk mitigation efforts for a superyacht. As such the use of ammonia is not considered viable on a large superyacht.

7. PRACTICAL FUEL OPTIONS

Considering the criteria of energy density, emissions, and safety, 3 groups of fuel were selected as feasible for further specific investigation and design integration studies.

7.1 DIESEL DROP-IN FUELS

Diesel drop-in fuels are defined as either bio-derived fuels meeting the requirements of EN15940 & ASTM D975 for paraffinic diesel fuels or synthetic diesel created from green hydrogen and captured carbon. These fuels have similar properties to MGO diesel that yachts are currently designed for.

Paraffinic diesel fuel has a reduced density of the fuel (775 kg/m3 compared to 835 kg/m3 for MGO). Therefore, when directly swapped into a yacht designed for diesel there can be up to a 5% drop in range compared to diesel. In all other ways, the characteristics and properties are essentially the same as diesel and many diesel engines delivered today are warranted by their manufacturers for use with these fuels. Emissions standards for Nox and Sox will be comparable to DMA

The definition of the bio-derived fuel type will relate to both the feedstock and its method of manufacture however they will include fuels commonly referred to as Hydrotreated vegetable oil (HVO), Biomass to liquid (BTL) and Hydrothermal Liquefaction (HTL) (see Figure 4). HVO is widely in production and available from multiple sources, other sources of bioderived fuels are under development. WTW analysis as per section 5 indicates emissions of 16 gCO_2e/MJ for common bio-derived fuels. This would represent an 82% reduction in emissions when compared to diesel. As discussed in section 5 there is some variance in WTW values which depend largely on the assumptions with regard to feedstock and process energy. In the case of synthetic diesel, further WTW emissions reductions would be predicted to be 5.8 gCO_2e/MJ realizing a 94% reduction in emissions

The sustainability of the bio-derived fuel source is critical to achieving these emissions in a sustainable and ethical manner. In order to achieve this, the feedstock must be based on waste only with no direct competition to food sources, it must also not result in deforestation or biodiversity loss. The ability to demonstrate the authenticity of the biomass feedstock will be critical to maintain clear social responsibility and avoid accusations of greenwashing.

Predictions on the availability of bio feedstock are varied. The availability of specific feedstocks may become a limiting factor, assessments on the continued availability of drop-in fuels for marine use are heavily dependent on the growth and uptake of these fuels by other industries. It is therefore considered that there is uncertainty in the supply of biomass and there is a risk that in the future these fuels may not be reliably available to superyachts. The availability of synthetic diesel is dependent on the development of large-scale direct carbon capture, the sustainability of this approach is also uncertain.

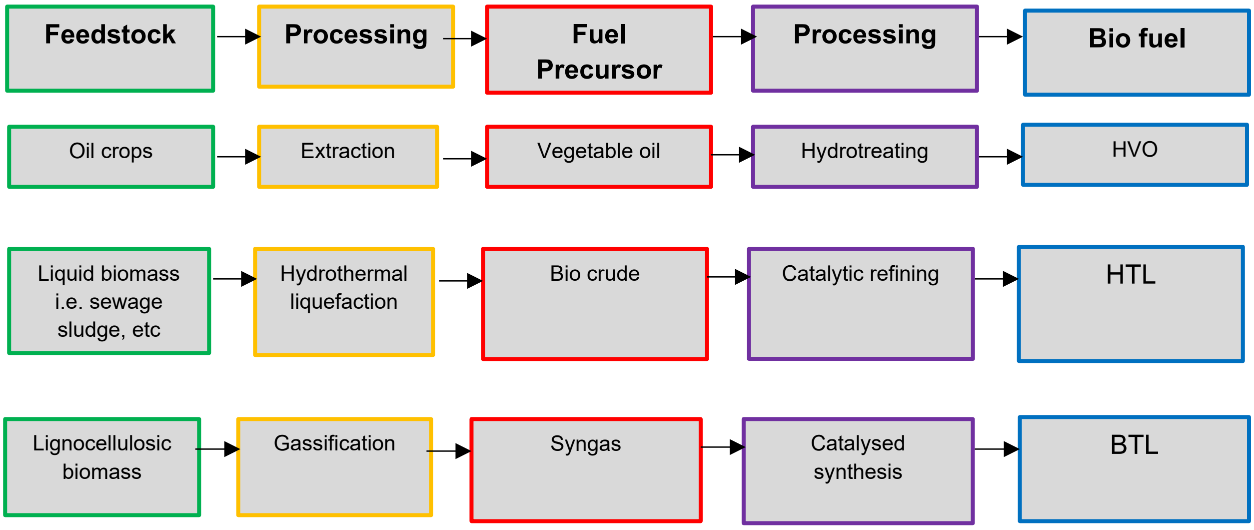


Figure 4 Illustrating Feedstock and Manufacturing Method for Bio Derived Drop-in Fuels

When used onboard these fuels will still emit carbon and other local pollutants. In the future, there is the possibility of local and national authorities imposing strict environmental limits for access to special pristine areas. An example of this is the UNESCO world heritage Fjord network which by 2026 will only be available to zero-carbon ships. It is a possibility that in the future other pristine areas including cities and ports may adopt similar strict measures. In this case, a yacht operating on bio-derived drop-in fuels would be unable to enter the area, even if it was considered net zero.

In this case, the yacht could be futureproofed to some extent by providing a significant stored energy capacity to allow extended periods of battery-only cruising and operation. Lateral would refer to this as operating in a local zero mode. There will be no local emissions and the batteries could be charged by onboard means or via shore power.

At this time, it may be challenging to include sufficient stored energy to accomplish significant range or local zero endurance. The energy density of batteries is significantly improving and as such, in the future, as batteries improve a yacht could be refitted for additional capability. This would then potentially allow a yacht to access and loiter in these areas. By considering future battery technology progress no significant penalty in lost volume is not incurred at build.

The integration of large-scale energy storage into existing yacht designs allows the battery to become the primary source of power which allows optimisation of machinery operation and size. It also allows silent periods (running with no generators) which are a frequently requested feature.

An example of this can be seen in project Kairos (see Figure 5) which features an optimised propulsion configuration with 3 diesel generators versus a more normal 4 genset configuration. This is achieved by using the battery as a primary source of energy. Efforts can be concentrated on the energy density and performance of the generators without needing to match engine output to specific operating conditions.

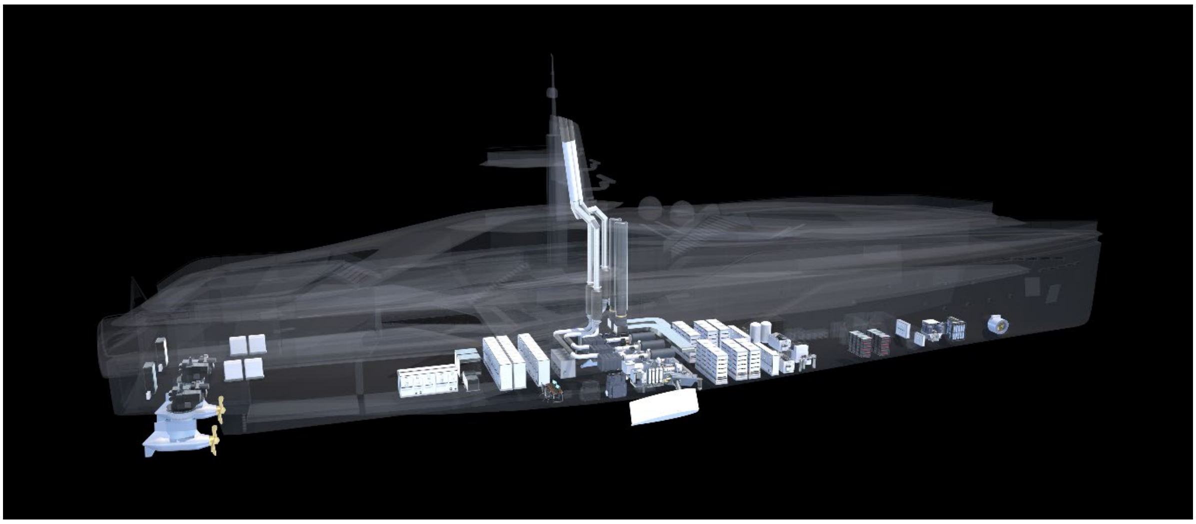


Figure 5 Project Kairos Integrating Large-scale Batteries for a Local Zero Capability

7.2 METHANOL

Methanol is a liquid fuel that can be stored at ambient temperature and pressure. The fuel is of moderate toxicity, it is, however, highly flammable with a flashpoint of 37°C. The volumetric energy density of methanol requires approx. 2.2 more volume of methanol when compared to diesel. Interim safety guidance is available via IMO MSC1/circ.1621. As per section 5, the use of methanol has the maximum possibility of achieving emissions of 2.9 gCO_2e/MJ which would result in a 97% reduction in emissions.

Methanol has a chemical composition of CH_3OH, as such any yacht fuelled by methanol will emit carbon. To achieve low WTW emissions it is critical that the carbon source used to manufacture the methanol comes from a neutral source. There are many methods of methanol production. The methanol institute proposes a classification scheme as shown in figure 6

Renewable methanol as classified by the methanol institute must be developed from either a sustainable bio-derived source (bio Methanol) or be synthesised using green hydrogen and carbon extracted from the environment i.e. by Direct Air Capture (DAC) to create e- methanol. In order to achieve WTW reductions aligned with the ultimate target of zero emission all methanol used must be renewable. The use of fossil-derived methanol will result in increased WTW emissions when compared to a diesel yacht. Between Fossil derived methanol and renewable methanol there are many possibilities to create and use low-carbon blue methanol.

Within the International renewable energy agency (IRENA) study of renewable methanol (23), it is concluded that bio-derived methanol will be "unlikely to able to cover all needs" and that ultimately that "methanol and its derived products should also be increasingly produced from CO_2 captured from the air". The timescales and process for this process is not clear and any assumptions in this regard are open to many assumptions and uncertainty. The process of direct air capture (DAC) whilst technically developed, has yet to be proven at any large industrial scale. DAC is currently an energy-intensive process requiring significant renewable energy. Timescales for the widespread adoption of DAC are open to many assumptions and may require fundamental shifts in technology or energy outlook.

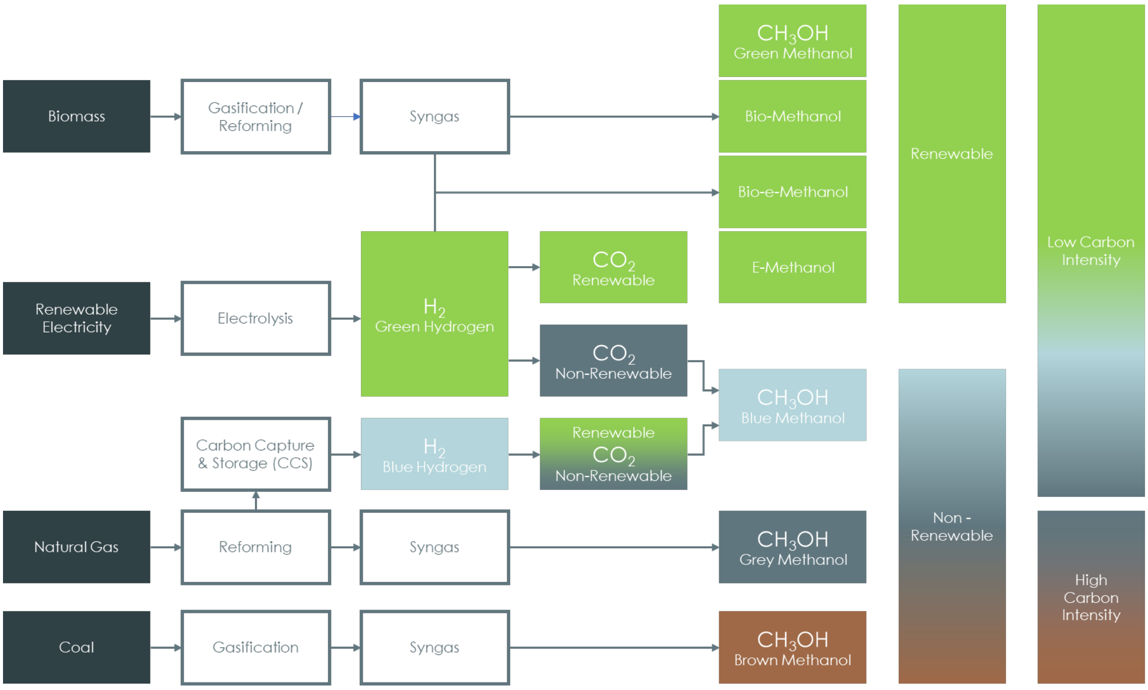


Figure 6 Methanol Institute Classification of Methanol Types Based on Production and Feedstock

In the event of DAC or bio-derived sources not being viable the most likely source of carbon will be via the emissions of large-scale carbon emitters in hard-to-decarbonise industries i.e. power stations, steel and cement factories etc. in this instance the IRENA report acknowledges "the *CO_2 would most likely come from the burning of fossil fuels. Even though recycled, it would still amount to fossil-based CO_2, which is non-renewable and makes the overall process net CO_2 positive. However, given that the CO_2 from these sources would otherwise be released into the atmosphere, using it one more time for the production of methanol with green hydrogen would result in a low-carbon methanol*".

As per section 5 noting the inconsistency in WTW analysis methodology, agreeing on the categorisation of these fuels will be critical in determining actual WTW emissions. As per the use of bio-derived fuels, for high-profile yacht owners maintaining the authenticity and accountability of this process will be critical to avoid achieving stated emissions and avoiding accusations of hypocrisy and greenwashing.

The most significant challenge for the ship integration of methanol is the lower energy density when combined with the requirements for cofferdams around tanks. Compared to diesel, this requires significantly larger tank volumes. The ships double bottom must be optimised to maximise storage potential. To ensure an equivalent range to that of a typical modern yacht it is likely that there will be an impact to ship design, dependent on the ship size and specification it's likely that this will require additional volume to be added to the methanol yacht or internal space be reduced.

Lateral has developed parametric techniques for the modelling of tank capacity versus hull design and other vessel parameters. This allows designs to be rapidly iterated so that the effects of optimising the hull for efficiency is compared to solutions for maximising double-bottom storage. Results from initial studies suggest that the amount of extra volume required is very dependent on yacht size and layouts with impacts ranging from zero to 7% additional GT required.

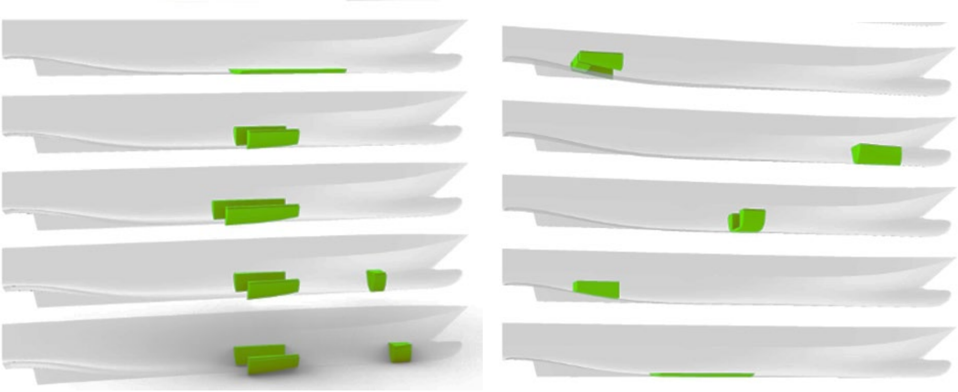


Figure 7 Comparison of Hullform and Tank Options

Depending on future unexpected technological developments the provision of large liquid fuel tanks could also partially support the use of other low density liquid fuels i.e., LOHC.

The equipment required to produce power for a methanol yacht can be varied. Methanol can be reformed into hydrogen and used with fuel cells. The benefit of this approach is that the fuel cells can be designed with good efficiency, they have good inherent N&V properties, and the reforming process only emits CO and CO_2 with no other GHG gases. The disadvantage to using fuel cells is that they have a much lower power density than conventional diesel generators. In the case of completely replacing a multi-MW diesel installation, the required technical space required by fuel cells will be much larger.

It is possible to use methanol in conventional diesel engines, this approach has been proven successful in many large 2-stroke engines. The development of methanol fuelled 4-stroke diesel engines of a capacity compatible with yacht design is under development. These solutions are predicted to have similar power density compared to existing diesel engines with similar efficiencies. This does mean that a methanol internal combustion engine (ICE) will use more methanol for the same range when compared to fuel cells. The engines would be predicted to meet the strictest emission levels for Nox but when compared to fuel cells there will be an increase in the CO_2 eq/MJ as Nox is a potent GHG.

Within these design challenges, however, a yacht could be imagined in which on delivery it is provided entirely with diesel machinery but is pre-designed with sufficient tankage, fuel systems and ventilation to allow a gradual conversion to a 100% methanol yacht over its lifetime. In order to maximise the advantage of both power options, this yacht could be designed to accommodate fuel cells to cover low speed and anchor power requirements and methanol ICE to cover higher power conditions.

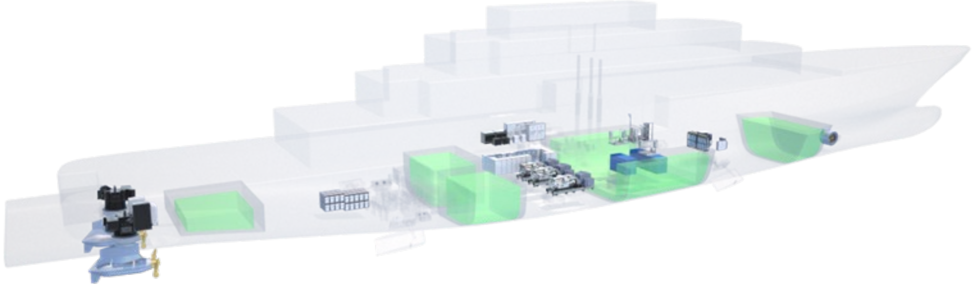


Figure 8 Indicative Possible Arrangement of a Methanol Fuelled Yacht

It is possible that in an intermediate state, the yacht could operate for a period as a limited dual fuel yacht with methanol fuel cells and diesel engines. In the event of the unavailability of methanol or any other technical issue, the yacht can operate as a diesel yacht, but significant methanol storage is allocated to enable low power operations.

In this way, a yacht can be created which allows for a gradual and controlled transition to methanol removing many of the risk factors by considering the requirements of conversion during the initial build process.

The emissions benefits of a gradual transition to methanol could be dependent on a range of different factors however indicatively for a typical large yacht WTW CO_2eq. values could be reduced by approximately 40-50% when partially converted to methanol.

7.3 LIQUID GREEN HYDROGEN

Green hydrogen is created by using renewable energy to electrolyse water creating hydrogen and oxygen gas. To improve the energy density of the hydrogen it is necessary to liquefy the hydrogen by cooling the gas to below minus 253℃. In operation, the yacht will not emit any carbon or other pollutants as per a local zero yacht. As per section 5, the WTW emissions would be 3.6 gCO_2/MJ resulting in a 96% reduction in carbon emissions. Dependent upon detailed a detailed life cycle assessment this WTW has the potential to be further reduced.

Blue Hydrogen is hydrogen derived from fossil sources but where the carbon produced in the process is captured either for storage or other uses. WTW assessment of this process is particularly variable with varying assumptions with regard to the amount of carbon that could be economically captured and how to account for this process. As per methanol using carbon capture from fossil sources, it's possible that this may be considered low carbon fuel not on a pathway to zero emissions. The use of hydrogen that is dependent upon carbon capture also invalidates a key advantage when considering hydrogen. Therefore, the use of blue hydrogen is not considered desirable.

The process of creating green liquid hydrogen is energy intensive requiring a large amount of reliable renewable power as a prerequisite. However, hydrogen does not rely on any non-sustainable feedstock.

There are no specific safety regulations for the storage of hydrogen as a fuel but there is a well-established route to approval via the ADA process exists. This process addresses the risks caused by hydrogen's high flammability, the effects of hydrogen embrittlement of metals, the difficulties of preventing hydrogen leaks and hazards associated with a cryogenic fuel.

Storing the fuel in a cryogenic liquid state requires the use of vacuum-insulated tanks. It is not possible to integrate these tanks within the ships double bottom. The heat transferred through the insulated tank will cause the hydrogen to evaporate or boil off. This is a continuous process that requires the gaseous hydrogen to be continuously used at a rate equal to or greater than the boil-off. The management of this process both operationally and in the design of the tank system is a key ship integration issue. Liquefaction equipment would not be considered part of the onboard hydrogen system for a yacht.

The integration of the vacuum-insulated tanks is very difficult, due to the liquid hydrogen's very low energy density the tank will need to be very large. The tank position will be constrained in its location by safety and practical concerns.

The initial concept design work on project Aqua - a 110m liquefied hydrogen design undertaken in 2019 - indicated that it could be possible to integrate a transatlantic range fuel tank within a yacht design but that this would result in a much lower ratio of luxury space to GT than is expected within the current large yacht market.

Since 2019 Lateral has been reviewing options for the design of liquid hydrogen yachts with the aim of increasing this ratio. The methods of achieving this are

- Ultra-efficiency
- Operationally optimised range and speed specification
- Optimisation of tank geometry and position
- Optimisation of the general arrangement

Ultra-efficiency is important to minimise the volume of hydrogen needed. Efficiency at range conditions is critical. By adopting an ultra-efficient hull form utilising a very high length displacement ratio, with enhanced efficiency propulsion components and reduced appendage drag the cruising propulsive power can be significantly reduced. This approach is then combined with the specification of a waste heat recovery system, energy-efficient machinery, energy-optimised stabilisation system and an optimised HVAC spec to reduce hotel load.

The range and speed of modern yachts is significantly higher than older vintage yachts, this is in part due to the ease with which modern diesel machinery has enabled additional performance. Significant reductions in the volume of hydrogen carried can be achieved if a strictly functional approach is taken to lowering the speed and range specification of the yacht. Lateral term this operationally optimized in that it is fit for purpose in how yachts are used in the real world.

The position, number and shape and size of the cryogenic hydrogen tank or tanks is critical to achieving an optimised design with maximum volume utilisation. Given the safety-led constraints with the position of tanks and other safety integration requirements, this is not flexible and can result in unconventional General Arrangement (GA). Working around the tank position the GA needs to be optimised to find efficient positions for service and technical spaces working around the constraints of the hydrogen tanks.

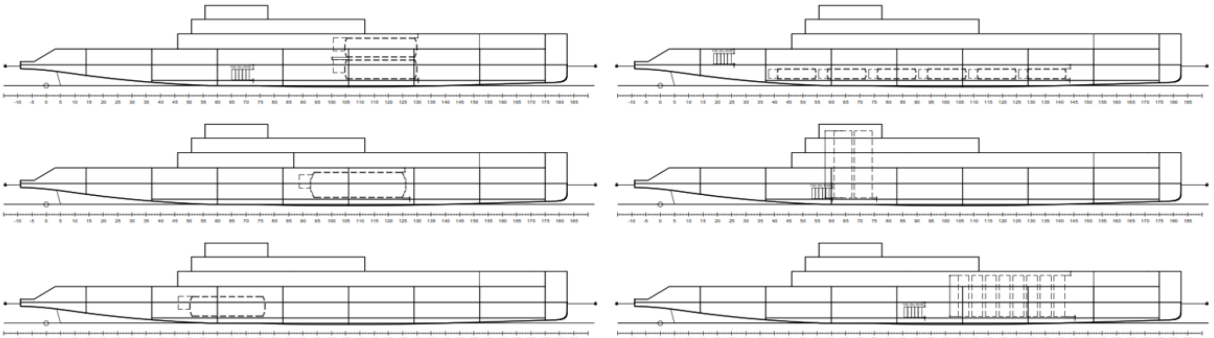


Figure 9 Example of Optimisation Study for Liquid Hydrogen Tanks

By undertaking all of these options it is possible to consider a yacht design with an approximate 10-12 % reduction in luxury area to GT ratio when compared to a diesel yacht. This would be unfavourable in the current market however noting that other alternative fuel options may also have a negative impact it is considered a feasible solution. Any Liquid hydrogen yacht designs could potentially also be developed to suit bio LNG or e LNG.

The need to undertake all of the above measures does mean that the solution space available for clients and yacht designers to work in is restrictive when compared to normal yacht designs and other alternative fuels. It is also clear that there is no refit or gradual adoption case for liquid hydrogen it requires an immediate change and needs to be designed from the yacht's inception. The requirement to immediately change fuels suggests that a prospective owner may need to invest in dedicated infrastructure to ensure fuel security.

8. HYBRID FUEL DESIGNS

Any of these fuels may be combined with conventional fuels to derive yachts with limited alternative fuel options i.e., a diesel yacht with a limited methanol power and fuel storage. These yachts may offer some reduced emissions combined with a reduced risk, therefore their emergence on the market may be a factor during the energy transition period. The ability of these yachts to approach zero emissions will be limited and in some cases, it’s possible that the impact on the design is the same or greater than attempting to include more comprehensive fuel storage.

9. CONCLUSIONS

All three fuel options presented are considered viable options to navigate the energy transition depending on client priorities and details of a particular yacht's requirements. All options represent feasible methods of drastically reducing WTW emissions for superyachts.

The diesel drop-in yacht represents a typical modern yacht in build today, it is most susceptible to unexpected developments or the effects of biomass sustainability. It may come close to achieving net zero but is still a carbon emitter in its operation.

The methanol-fuelled yacht offers a high level of flexibility, a gradual, reduced-risk approach to reduced emission and does not require a significant change in yacht design or layout methodology. It is likely to meet the requirements of most yacht clients during the energy transition period and offers the highest level of future-proofing. It may achieve net zero but is still a carbon emitter in its operation.

The liquid hydrogen yacht offers an audacious view of zero-carbon yachting. It requires a radical and uncompromising approach to the design of a superyacht. It is not constricted by concerns for fuel sustainability or carbon-neutral accounting. It does come with a high level of project risk and the immediate change to alternative fuel suggests that some infrastructure development will be required. It is likely that this represents the needs of a smaller niche of clients.

There is wide variation in the methodology and published results for well-to-wake emissions for different fuels, there is also considerable variation in the accounting methods for carbon neutrality. If the objective is to demonstrably operate superyachts with reduced carbon emissions it will be critically important to ensure that the specific emissions are well understood and correctly accounted for with specific WTW analyses.

Many future fuels may be bio-derived fuels it will be important to ensure that these bio-sources are authentic and ethical. Sources of biomass must be based on waste only with no direct competition to food sources and not result in deforestation or biodiversity loss.

As the main driver for reduced superyacht carbon emissions is social responsibility it is important that the transparency and accountability of how emissions are calculated, and the source of the fuel do not fail to be responsible.

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