TOWARDS ZERO

A STUDY OF SUPERYACHT ALTERNATIVE FUEL INFRASTRUCTURE

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SUMMARY

The paper examines the possible options for developing specific liquid green hydrogen infrastructure to support a 100% hydrogen powered yacht. The consideration of liquid hydrogen as an alternative fuel is driven by explorative design studies exploring the feasibility of liquid hydrogen as an option for zero-carbon superyachts. The current availability of hydrogen is discussed and the challenges of providing green liquid hydrogen to a superyacht within the current industry are explored. The study investigates the proposition of superyacht industry stakeholder developing dedicated hydrogen production and bunkering facilities independent to developments in the wider marine industry. The practical and economic impact of this approach is analysed and the importance of coordination between onboard and shore-based requirements is highlighted. The paper outlines a solution with a CAPEX of between 60 and 82 million USD with OPEX values of between 4-8 million USD per year. The paper concludes that the best way to minimise these values is by a coordinated approach with other parties to increase plant utilisation and scale.

1. INTRODUCTION

The sustainability and environmental impact of the superyacht industry has become a key consideration for superyacht builders, operators, and owners. To meet these sustainability ambitions the use of alternatively fuelled yachts is being widely explored. In many cases naval architects, engineers and equipment suppliers can envisage suitable ship designs utilising several alternative fuels, however, the success of these projects will be dependent upon the availability of suitable fuels infrastructure to manufacture, supply and bunker these fuels. This paper seeks to explore options of how sustainable superyacht liquified hydrogen infrastructure could be developed using investment from within the superyacht industry.

2. FUTURE FUELS

Currently all the large yacht fleet operates using diesel engines. The evolution in the design of yachts has been such that there are a selection of yachts which are designed for high efficiency and reduced environmental impact. In order to significantly further reduce emissions, the use of alternative fuels are required.

In considering the options for sustainable fuels to replace diesel there are a wide range of options suitable for use in marine applications. It would be outside of the scope of this paper to present a detailed analysis of the benefits and disadvantages of each alternative fuel. This issue is addressed in the paper "Bridging the energy transition – a practical study on the use of alternative fuels on large superyachts" by Lateral [1].

The solution adopted will be dependent upon the yacht size, design constraints, operational profile and sustainability goals for each future yacht project when weighed against technical and commercial risks.

The use of liquid hydrogen is considered as one of the most demanding technical solutions requiring an immediate swap to a carbon free fuel, with significant associated new infrastructure requirements. In addition, the production of green hydrogen is a key component for many other alternative fuels, and was therefore considered to form the basis of our study into supporting infrastructure.

3. HYDROGEN YACHTING

The design of a future yacht using liquid hydrogen as a fuel was explored in the 2019 concept design motor yacht project Aqua. In this concept Lateral, in conjunction with Sinot Yacht Architecture & Design, developed a large yacht 100% powered by low temperature Proton exchange Membrane (PEM) hydrogen fuel cells [2].

The prime reasons for exploring the use of liquid hydrogen were:

- The use of green hydrogen is a zero carbon fuel and as such is the most compelling option for a true zero future.
- Liquid hydrogen represents a feasible if challenging onboard volumetric energy density.
- The storage tank and fuel cell technology is at a reasonably mature Technology Readiness Level (TRL) with some class type approval available.
- Whilst there are no specific prescriptive regulations for the storage of hydrogen a clear pathway to regulatory approval is available and has been undertaken by other passenger vessels.

Figure 1 Project Aqua - 110m 100% Hydrogen Powered Yacht Concept
Styling by Sinot Yacht Architecture & Design

Project Aqua was developed to an early technology feasibility level which included developing a propulsion and energy system architecture, equipment sizing, equipment arrangement, performance predictions, general arrangement, and basic naval architecture design.

The conclusions of the concept study were that the technology existed to deliver the onboard ship systems and whilst the volumetric challenges of incorporating cryogenic fuel tanks were severe it was determined that the concept of liquid hydrogen remains feasible provided the yacht can achieve very high efficiency. A key element for the success of a liquid hydrogen yacht as per the design of Aqua would be the availability and supply of green liquid hydrogen.

4. CURRENT AVAILABILITY OF HYDROGEN

The current use of hydrogen as a marine fuel is primarily confined to pilot and demonstration activities and has not yet been adopted at any significant scale. As such there is no established network of bunkering or port production facilities.

Existing uses of hydrogen (almost all of which currently use hydrogen derived from fossil fuels) include refining, industrial and chemicals sectors.

Total hydrogen production in the UK is estimated between 10-27 TWh [3] and is overwhelmingly produced from fossil sources in processes such as steam reformation of natural gas. Hydrogen produced in this way is typically described as grey hydrogen and its use for energy creation can result in higher CO2e per MJ emission than Diesel fuel when considered in a wake-to-well emissions analysis. It would be extremely counterproductive to rely on the use of grey hydrogen for any future yacht project.

Hydrogen production from fossil sources where the resulting carbon emissions are captured for use in other processes or long-term storage are termed as blue hydrogen. Whilst many industries may derive reduced emissions through the use of blue hydrogen the use of blue hydrogen for a superyacht is not considered desirable when the WTW emission criteria are compared to other marine fuels that rely on carbon capture

In order to meet the highest sustainability goals targeted it is imperative to establish a supply of green hydrogen. Liquid green hydrogen is considered as hydrogen entirely derived from renewable power sources and created by electrolysis and subsequent liquefaction.

It is estimated that there are around 460 electrolyser projects currently under development globally, with capacities ranging from hundreds of kW to hundreds of MW. The current project pipeline suggests this could lead to an installed capacity of 134 – 240 GW by 2030, although many of these projects have not yet reached a final investment decision or are at very early stages of development, so the actual figure is likely to be much lower. When compared to both the current UK production capacity it can be seen that a significant volume of this green hydrogen would be required to replace our production of grey hydrogen for industrial and other purposes. Even considering the EU joint declaration in May 2022, in which industry commitments were made to increase electrolyser manufacturing capacity tenfold by 2025[4], the scale of replacing our current hydrogen production is substantial.

Although many of these projects are based around ports with the aims of developing hydrogen 'valleys' or 'hubs' [5] it is notable that there are very few projects dedicated to the production of hydrogen for marine fuel as a particular specified purpose.

Whilst the development and production of increased amounts of green hydrogen is extremely encouraging, using any of this planned production capacity in the near-term to fuel a liquid hydrogen superyacht would be challenging. Some early green hydrogen production projects may be reliant upon government grants and funding, this may be a barrier for superyacht use. Other barriers to adopting the use of liquid green hydrogen for yachting will be:

- Most proposed schemes do not consider liquefaction.
- The amount of liquid hydrogen required by a superyacht is comparatively high.
- The location of proposed projects does not align with areas of the world that the yachts require refuelling.

It could therefore be concluded that in order to develop a green hydrogen network suitably sized and designed to support large yacht operations the stakeholders within the superyacht industry may need to invest into the development of a specific solution to enable yachting "green corridors" which would allow future sustainable operations.

5. HYDROGEN REQUIREMENTS

Determining the likely future hydrogen demand for a future fleet of yachts or other ships would require a separate study and would be likely to be highly speculative in nature. In order to bound the exercise and provide context the study shall initially consider options for the infrastructure required to support a single liquid hydrogen powered yacht. The study will further discuss the effects of scaling these results to a larger fleet. The yacht considered shall be based on the project Aqua concept design.

Length (LOA)	112.3	m
Beam	15.4	m
Gross tonnage	3500	
Range	3700	nm
Range speed	10	kts
Max Speed	17	kts
Installed Hydrogen fuel cell power	4000	kW
Hydrogen tank capacity	27.7	tonnes

Table 1 Project Aqua Key Technical Characteristics

Much of the superyacht fleet operate on a 'milk-run', for most of the time within the Mediterranean and Caribbean operating areas. The operating locations are generally seasonal with a transatlantic crossing expected. Whilst there are several yachts which either operate worldwide in some of the most remote areas of the world or are geographically located elsewhere the initial concept for *Project Aqua* was to base the yacht purely on the most common Mediterranean and Caribbean operating circuit.

For Project Aqua a representative operational usage profile has been developed:

Mode of Operation	% of Year in Operation
Crew harbour mode (no shore power)	62.5
Crew sea transit	10
Crew anchor	5
Guest Anchor	20
Guest Transit	1
Guest top speed	0.5
Guest slow cruise	0.5
Manovering and DP	0.5

Table 2 Assumed Operating Profile for Hydrogen Powered Yacht

As demonstrated in the operational profile in Table 2, superyachts typically spend a considerable amount of time alongside in marinas or harbours. Most large yachts will be provided with the capability to use shore power during this period. For this study it was assumed that the yacht will not use shore power. This assumption is based on uncertainty regarding the availability of shore power for a large yacht in all marinas. Where shore power is available it may not be 100% renewably generated and as such using the onboard green hydrogen systems would result in a reduced environmental impact. This method of operation also allows easy management of hydrogen boil off and tank temperatures.

Hotel load power requirements and propulsion power requirements were determined for each mode of operation. The required propulsion power was calculated by use of basic first principles of naval architecture and empirical methods together with parameterised data from Lateral's extensive statistical data base of large yachts and physical model tests. The hotel load is based on a parametric estimate from the developed General Arrangement (GA). Using these power requirements, a hydrogen consumption and overall total usage was determined based on preliminary system efficiencies.

By combining the power requirements and operational profile, an approximate fuel demand schedule was calculated that indicated estimated monthly fuel demand and the required bunker frequency.

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Monthly H2 consumption [tonnes]	27.2	20.8	37.2	20.0	27.2	21.5	22.8	29.7	21.8	20.1	30.9	29.0
Bunker requirement	0.98	0.75	1.34	0.72	0.98	0.77	0.82	1.07	0.79	0.72	1.11	1.05

Table 3 Estimated Per Month Hydrogen Demand

This data highlights that when operating a yacht with an ultra-efficient propulsion system designed for a low speed range the yacht will need to frequently bunker. This will require infrastructure in both operating areas to support this.

It will be important that the infrastructure is centrally located in the required operating area. This is somewhat different from a diesel yacht which would have fewer bunkers and could remain on station for longer periods. The process of sailing to the bunker station was considered within the standard operational profile. Following this assumption it could be determined that one bunker station in the Mediterranean and one in the Caribbean could support the typical operational profile as per the examples shown in Figure 2.

This determined that each production and bunker facility will need to a maximum capacity of 41 tonnes of hydrogen per month factoring in seasonal use and maintenance requirements.

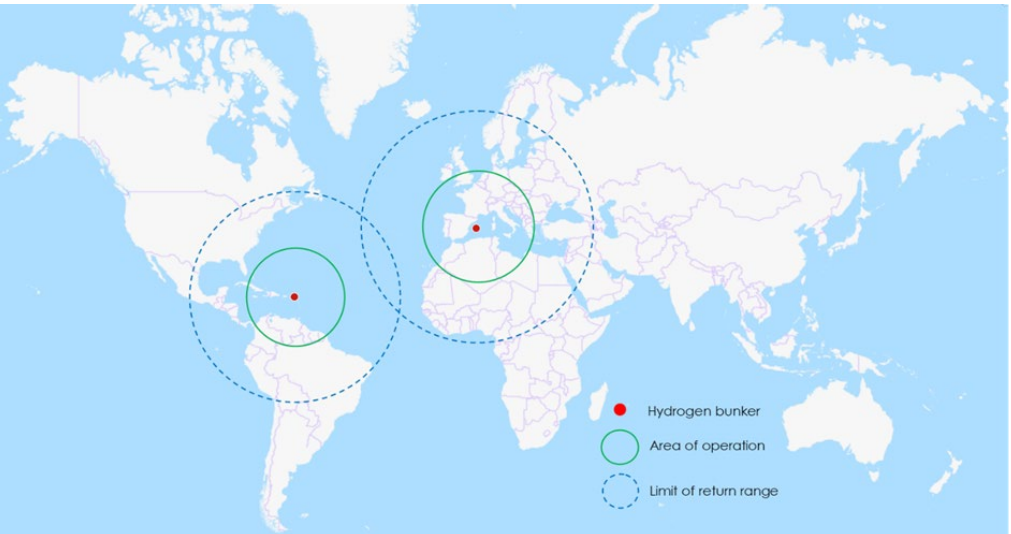

Figure 2 Indicative Layout of a Two Bunker Station Infrastructure Scheme Covering Typical Yacht Operating Areas

6. POSSIBLE INFRASTRUCTURE SOLUTIONS

Two scenarios were considered for exploring potential infrastructure solutions:

Scenario	Description
Scenario 1 – offsite production	• Hydrogen supply procured and delivered to site in gaseous form. • Liquefaction carried out on site, stored cryogenically as liquid.
Scenario 2 – onsite production	• Hydrogen produced on-site using an electrolyser and desalination plant. • Liquefaction carried out on site, stored cryogenically as liquid.

Each of these options comprises a different share of the end-to-end supply process, using different combinations of key equipment and plant items. Scenario 1 assumes that hydrogen is produced and supplied by a third party, with only liquefaction and storage taking place shoreside. Scenario 2 assumes that the full end-to-end hydrogen production takes place shoreside, excluding electricity generation.

In each case a technoeconomic model has been used to develop high-level equipment sizing, which has been used to calculate indicative cost and space requirements.

7. SCENARIO 1 – OFFSITE HYDROGEN PRODUCTION

In this first scenario, it is assumed green hydrogen is available from a third-party supplier and delivered in gaseous form to be liquified and stored shoreside. This would assume the presence of a clean hydrogen supply chain in the area, or perhaps the development of an adjacent hydrogen green 'valley', with the bunkering facility acting as an integrated offtaker.

The liquid hydrogen would then be pumped to the yacht lying in an adjacent berth. To be as sustainable as possible, the facility would need to be supplied with renewable energy.

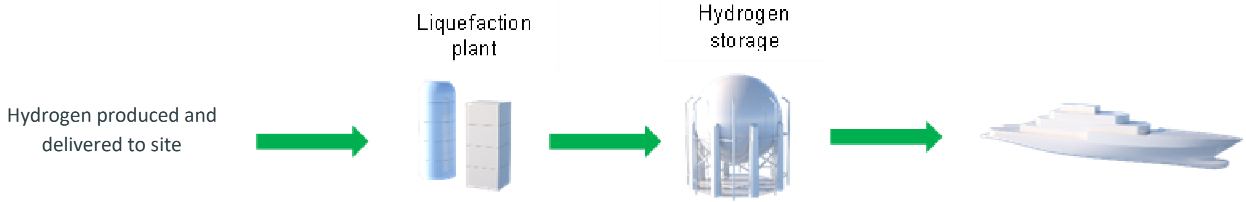

Figure 3 Process Diagram Indicating Scenario 1 Offsite Hydrogen Production

For the purposes of this scenario it is assumed that hydrogen is supplied and transported to the site at a price of 6 USD/kg, and is delivered in gaseous form ready for subsequent liquefaction at the bunkering facility. Transportation of liquid hydrogen is also possible, for example by cryogenic trucks or by specialised liquid hydrogen tankers.

Gaseous transportation is commonly provided via tube trailers or pipeline, depending on the demand parameters and use case economics. Pipelines are generally used to serve large constant demands rather than smaller offtake volumes to maximise pipeline utilisation, and are more likely to be available near centres of high demand such as transport hubs (e.g., airports and ports) and industrial clusters.

In some geographies, the feasibility of converting existing natural gas grids to a 100% hydrogen grids is being explored. A large national hydrogen grid would significantly reduce hydrogen's transport costs and increase its availability. However, there are significant uncertainties around viability and timelines, arising especially from questions around the suitability of hydrogen for domestic heat.

Delivery via tube trailers can supply smaller, more dispersed offtakers, which are not possible or economical to serve via pipeline. Costs per kg of hydrogen for tube-trailer transport are higher than for pipeline transport, and minimising the distance between hydrogen production and offtake is key to reducing costs.

Liquefaction converts incoming gaseous hydrogen to liquid form by cooling it to below -253°C. This process is highly energy intensive with large power demands of approximately 10kWh/kgH_2[6].

While it is subject to ongoing improvements and development, liquefaction can be considered a mature technology. Typical plants vary in size and employ different technologies but share basic operational principles. It is possible to purchase modular liquefaction facilities and the commercial and technical risk of this process is generally well understood and mature.

As mentioned in Section 5, the assumed operational profile and vessel parameters require a volume of 27 tonnes of liquid hydrogen bunkered over a period of approximately eight hours. Meeting this transfer requirement with only minimal storage would require a very large liquefaction facility that would see poor utilisation, leading to high costs. Therefore, to optimise the cost of the facility, the liquefaction plant considered for this scenario is sized to process approximately 1.4 tonnes of hydrogen per day, and feed into liquid hydrogen storage for later use.

In general, the volume of storage required is driven by the need to align supply and demand requirements, or to provide buffering between two parts of a transfer system. For example, where hydrogen is procured via a series of batch deliveries, storage can help to accumulate sufficient volumes onsite until bunkering takes place. Storage is also common at terminals of pipeline connections to provide a buffer between the infrastructure and bunkering equipment.

Handling and storage of hydrogen has similarities to Liquid Natural Gas (LNG), which has been adopted as a fuel for some parts of the commercial shipping sector. However, there are also key differences. For example, hydrogen is a much smaller molecule than LNG and therefore at higher risk of leakage. It is also known to embrittle some types of metal. In addition, hydrogen is cooled to -253°C, while LNG is cooled to around -163°C.

To maintain the very low temperatures required, storage of hydrogen in liquid form requires a vacuum-insulated tank, of which there are various configurations depending on storage volume and application requirements. While various types of storage tanks are available, for the purposes of this scenario a 470m^3 spherical tank has been assumed to store 33 tonnes of hydrogen. This volume allows bunkering of the full tank capacity of the vessel, plus volume contingency for 'boil off' and other system losses and requirements.

Bunkering of liquid hydrogen requires a closed vacuum-insulated system to mitigate the risk of leak or explosion.

8. SCENARIO 2 – ONSITE PRODUCTION

In the case that green hydrogen supply is not available, in addition to the previous facility, it would be necessary to produce the hydrogen locally. Green hydrogen production via electrolysis is considered the best approach, as this requires access to a renewable power supply only.

In this scenario hydrogen is produced locally on site, and therefore the use of storage can reduce the size of electrolyser plant required.

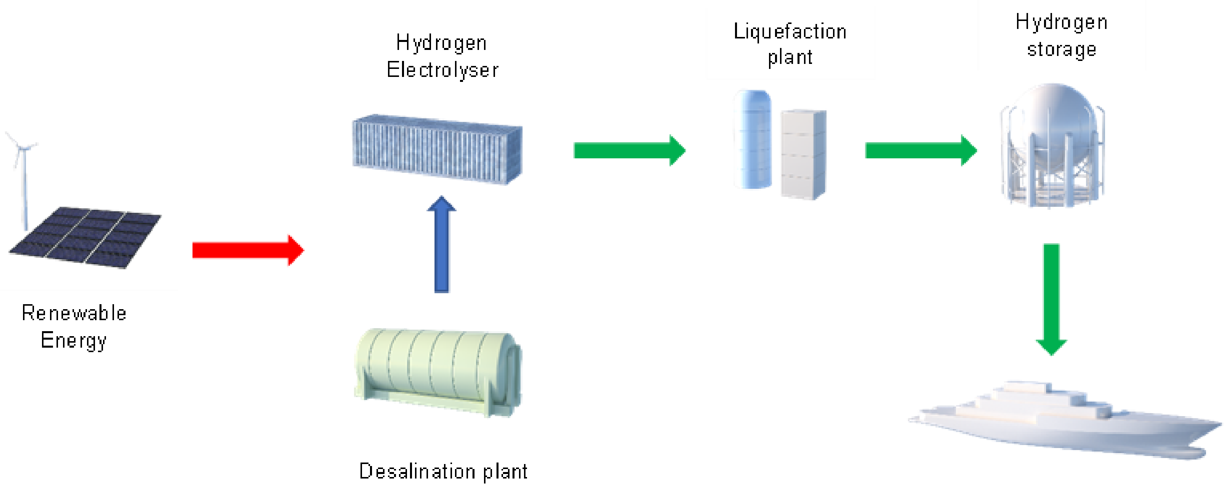

Figure 4 Process Diagram of Onsite Hydrogen Production

Electrolysers are an established technology and produce hydrogen by using electricity to split water into oxygen and hydrogen. The two most common technology types are PEM and Alkaline. PEM has been selected for the modelling based on its favourable operational characteristics including its fast response ramp-up and ramp-down time, smaller size compared to alkaline technologies and lower maintenance cost.

For the purposes of this scenario an 4MW electrolyser has been modelled as this will produce the required amount of hydrogen for refuelling within the necessary timeframes. Hydrogen produced by the electrolyser is in a gaseous form, and therefore requires liquefaction before being stored for future use.

The overall process efficiency of producing liquid hydrogen is low. To operate continuously, the production facility would require 4 MW of renewable energy from either solar or wind. For a sense of scale, a typical 4MW solar facility could be expected to require approximately 12 – 20 acres of land, although this would be highly sensitive to design conditions.

It could be possible to develop a private renewable power generation facility to provide a dedicated power supply. The power generation technologies could be used onsite with the optimum choice dependent on site-specific factors and other design constraints.

The use of on-site renewable generation would provide guaranteed green credentials for the facility. However, load factors are likely to be low without the benefit of integrated energy storage. Overcoming this issue would either require significant deployment of storage combined with oversizing of generation equipment or a 'volume firming' approach, where the annual output and demand balances over a year but not necessarily instantaneously (i.e. not matching the hourly demand profile).

Another option would be to use grid supplied energy. While transmission and distribution systems are decarbonising in many geographies, grid electricity is unlikely to be fully renewable in the short term. Standards dictating the validity of green hydrogen are in development, and some include provisions for the use of market arrangements (such as contracting renewable power via power purchase agreements) to qualify electricity used for hydrogen production as green.

For the purposes of this study, it is assumed that renewable power to serve the facility is purchased from a third-party supplier (for example via a PPA) at typical market rates for the given bunkering regions. As a key feedstock, the cost of input electricity has a significant bearing on the overall levelized cost of hydrogen.

9. OPERATIONAL FACTORS

Given the safety and risk management requirements of storing hydrogen, especially in large volumes, it is likely that many locations will be subject to constraints. The regulatory environment for a given location is also likely to impact operational procedures and design compliance.

Based on high-level equipment sizing and space requirements, a footprint for the facility of approximately 5 acres has been assumed, adjacent to a fuelling berth. This is shown below in the indicative render.

Figure 5 Impression of a Potential Scenario 2 Production and Bunkering Facility

10. EVALUATION OF CAPITAL EXPENDITURE (CAPEX) AND OPERATIONAL EXPENDITURE (OPEX)

Considering the above solutions, the following CAPEX values were estimated for the build and commissioning of one of the facilities described previously.

Equipment	Offsite hydrogen production CAPEX estimate ($m)	Onsite hydrogen production CAPEX estimate ($m)
Electrolyser	-	6.0
Liquefaction Plant	12.0	12.0
Storage	9.0	9.0
Desalination plant	-	4.0
Utilities Installation (Power supply and distribution)	2.0	4.0
Cryogenic loading arm and loading pump	1.0	1.0
Construction costs (e.g. civils, sitewide engineering)	6.0	6
TOTAL	**30.0**	**42.0**

Table 4 Estimated Average CAPEX Costs for a Single Production and Bunkering Facility

The operational profile of the vessel requires the development of at least two facilities, one close to the Caribbean region and another close to the Mediterranean region. Thus, the average CAPEX estimates would need to be doubled to arrive at an estimated overall figure.

The OPEX for the facilities has been considered across three key categories: Electricity, Maintenance and Staff. Whilst the electricity and maintenance costs were directly linked to the power demand generated by the equipment within the facility, the staffing costs were loosely linked and based on our understanding of staffing requirements of similar facilities. The OPEX across both facilities can be found below:

Cost Item	Scenario 1 Estimate ($m)	Scenario 2 Estimate ($m)
Renewable hydrogen supply (Scenario 1 only)	2.2	-
Electricity (green electrons)	0.7	4.1
Maintenance	0.6	0.7
Staffing	0.5	0.5
TOTAL	**4.0**	**5.7**

Table 5 Estimated OPEX Costs

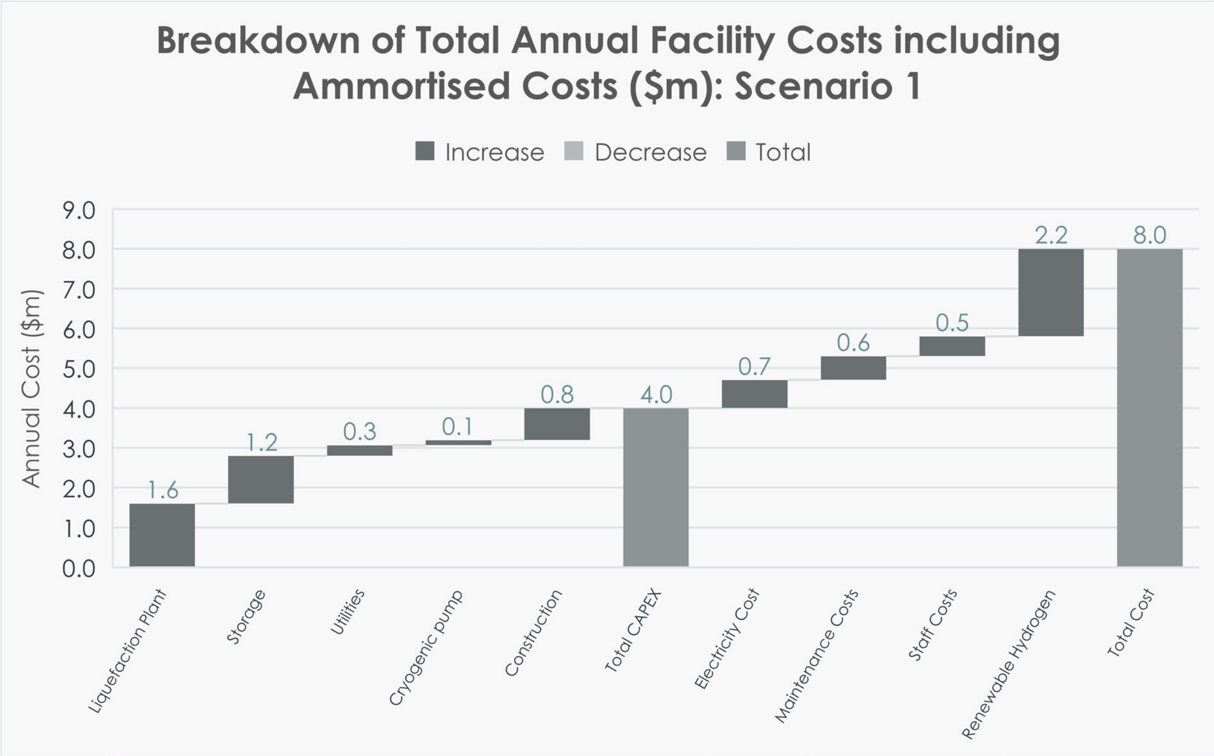

Figure 6 Breakdown of Annual Costs for Offsite Production Facility

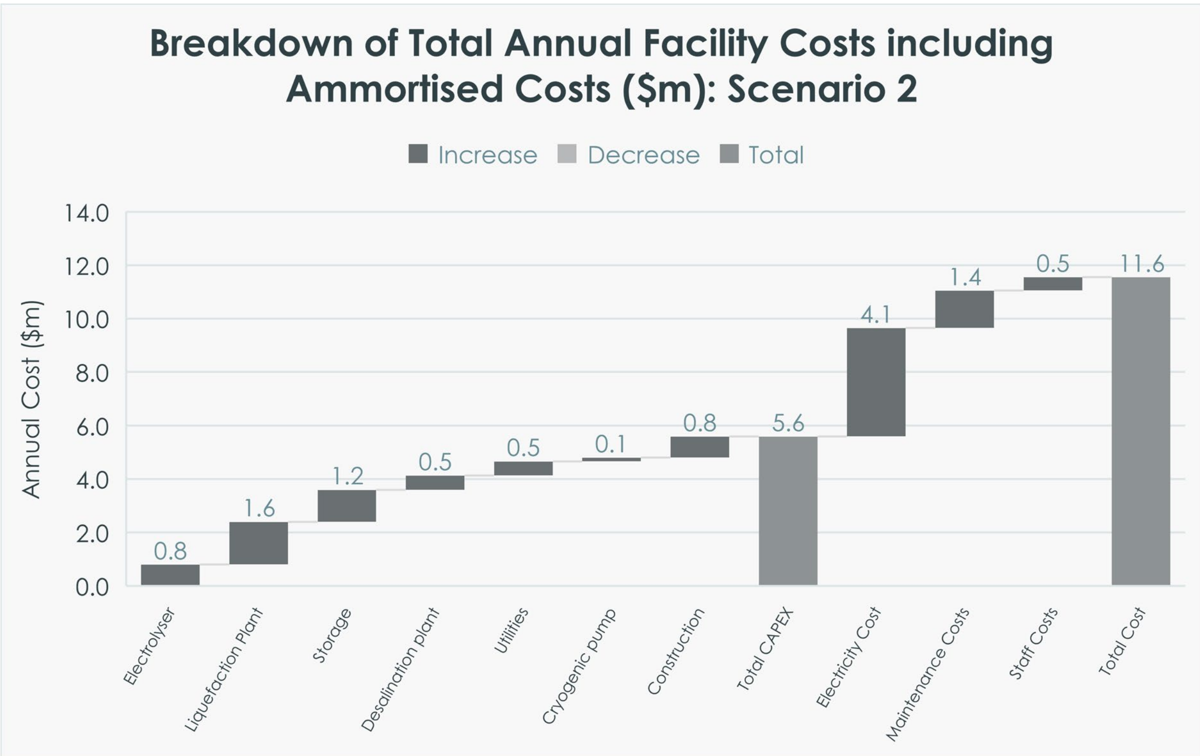

Figure 7 Annual Cost Breakdown for Onsite Production and Bunkering facility

11. EQUIVALENT COST OF DIESEL FUEL

Due to the unusual design and layout of *Project Aqua* it is difficult to directly compare the size, functionality and energy demands of the yacht compared to an equivalent diesel yacht. However, assuming that the hydrogen power system was replaced with a DC grid diesel electric system yacht using modern variable speed diesel generators, then the predicted annual diesel consumption required would be approximately 930 tonnes.

The diesel grade used by modern yachts is DMA marine gas oil (MGO). In the last six months, the average bunker cost for MGO in Europe, middle east and Africa (EMEA)has fluctuated between approximately $1000/tonne to $1450/tonne [7]. It would therefore be expected that the estimated annual fuel expense would be between $930,000 and $1.35 million. The wide range in this number reflects the world events of 2022.

At the 12th session of the IMO's Intersessional Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG 12) it was proposed to adopt carbon pricing in an attempt to accelerate carbon reduction in shipping [8]. The level of carbon pricing/tax was proposed in the range of $75 /tonne to $200 $/tonnes). Approximating the carbon release by a tonne of diesel as 2.86 tonnes of CO_2, this would result in a $215 - $575/tonne price increase in the cost of diesel. Hence, the annual cost of diesel would increase to between $1.11 million and $1.88 million. Whilst the likelihood of large-scale carbon tax of this proposal being adopted and ratified is unclear, this is a factor to be considered in future economic studies.

12. COST IMPACT OF OPERATING AN INDEPENDENT HYDROGEN INFRASTRUCTURE

Table 6 Summarises the estimated CAPEX, OPEX and levelized cost of hydrogen required for the entire infrastructure including both production and bunker facilities.

Criteria	Units	Scenario 1	Scenario 2
Total CAPEX per site	$m	30.0	42.0
Total Amortised CAPEX per year	$m/year	4.0	5.9
OPEX per year	$m/year	4.0	5.7
Total cost per year	$m/year	8.0	11.6
Total Hydrogen Capacity	tonnes	366.0	366.0
Total levelised cost	$/kg H2	21.9	31.7
Total diesel price	$m/year	0.9 – 1.9	
Total delta from diesel price	$m/year	6.1 – 7.1	9.7 – 10.7

Table 6 Summary of Cost Impact for Hydrogen Infrastructure

This would suggest that the cost of adopting an independent hydrogen infrastructure would be between $8.0 to $11.6 million per year. The economics of this analysis would be very dependent upon factors such as future diesel prices, carbon taxes, interest rates, price of renewable energy and the future green liquified hydrogen market opportunities.

13. EFFECT OF PLANT UTILISATION

Due to the seasonality of the yacht's use, the plant utilisation for bunkering is very low (6 months per site per year). We estimate that, within the current utilisation for Scenario 2, the total levelized cost of production for the facility would be $31.7/kg of liquid hydrogen (as per Table 6 above). As the plant utilisation for bunkering is improved, the levelized cost of production will decrease as per Figure 8 below. If the seasonal bunkering profile were to be extended across the full year, the levelized cost will decrease to around $20/kg of liquid hydrogen.

The ability to sell or otherwise productively use excess hydrogen will be a vital requirement for any project in reducing costs.

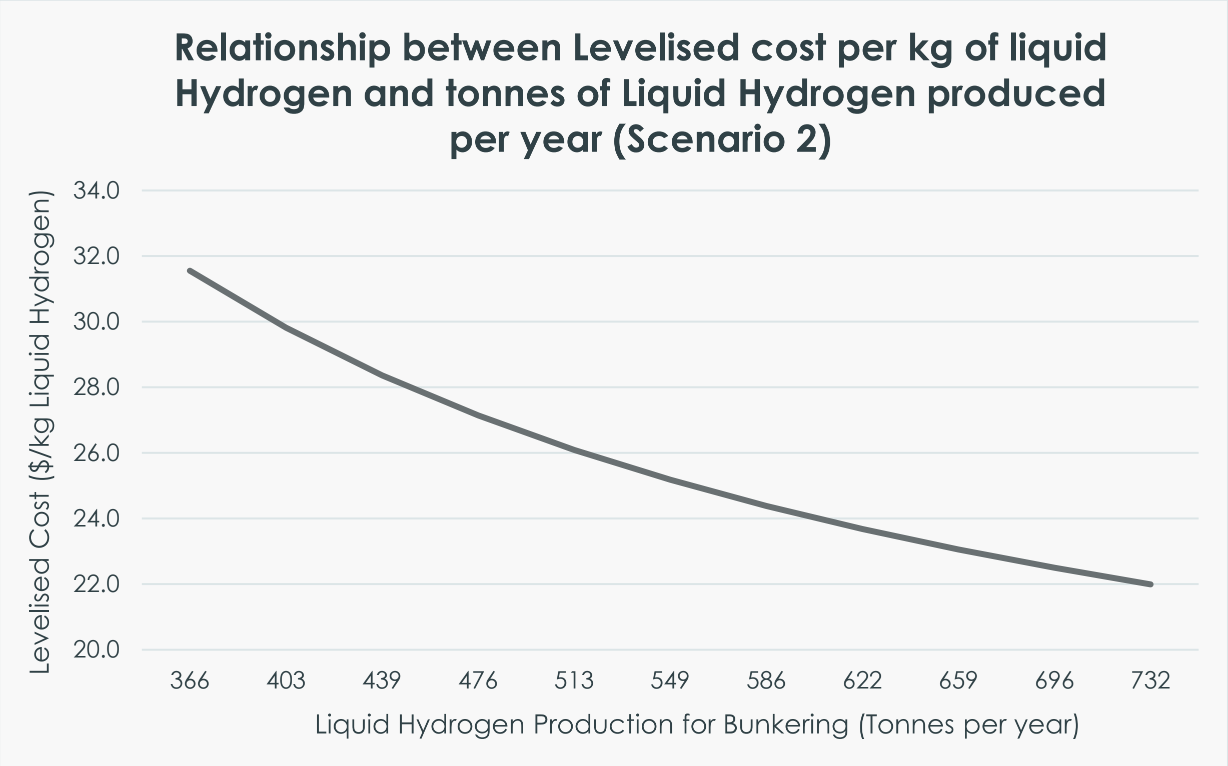

Figure 8 Relationship Between Total Cost vs Tonnes of Hydrogen Produced

14. EFFECTS OF SCALING

The concept discussed in this paper considers a demand profile from a single vessel only. Should demand increase, for example if multiple vessels are to be served from a single facility within the same season, this would require a larger facility, and bring about the following considerations:

- Larger hydrogen demands would require a larger onsite production facility or increased hydrogen supply volumes, impacting infrastructure complexity (e.g., increased incoming power connections, high-capacity pipeline delivery).
- Some elements of the system would scale differently than others, for example some will scale in a modular or near-modular fashion (electrolyser, liquefaction plant, storage), while some of the supporting infrastructure would likely scale non-linearly.

There are several examples globally of larger installations of the equipment considered, which suggests scaling the facility to match an increased demand is likely to be feasible. It is also likely that scaling would provide opportunities to benefit from economies of scale for some parts of the system.

15. BUNKER STATION OPTIMISATION

In order to reduce the high CAPEX cost of each refuelling station and increase the utilisation of the facilities the study has worked on the assumption that only two facilities would be required. This approach restricts the operation and endurance of the yacht working within the Mediterranean and Caribbean cruising area.

A possible solution to attempt to reduce these operational restrictions would be the examination of cost and operational benefits of a liquid hydrogen bunker vessel. This would be a suitable subject for future analysis.

16. OPTIMISING VESSEL PARAMETERS AND OPERATIONAL PRACTICE

By increasing the yacht's range or reducing hydrogen consumption, the frequency of bunkering could be reduced which could mean that the capacity of the electrolyser and liquefaction plant could be reduced. However, onshore hydrogen storage would need to be increased. This would yield a reduction in CAPEX for the plant.

Significantly increasing the yacht's range would not be viable as the effect on usable tank space will potentially make the yacht concept unfeasible. Conversely, significantly reducing the range below the transatlantic distance would drastically lower the annual hydrogen consumption. This would reduce the size of the production plant and increase utilisation, resulting in lower costs.

Using shore power for 50% of the time the yacht is in harbour would reduce the annual hydrogen requirement by approximately 10-20%. This would substantially reduce the size of electrolyser and liquefaction plant required thereby reducing infrastructure costs. In order to operate more frequently on shore power hydrogen boil off and tank pressure/capacity would need to be both considered in the ship design process and also carefully operationally managed.

17. CONCLUSION

This study has considered the details of a possible hydrogen infrastructure at a concept study level. The authors are aware that there are practical considerations that would need to be made in supporting the production, commercialisation and operation of a liquid hydrogen fuelled yacht. These considerations would need to be addressed by further specific and detailed studies.

To develop a dedicated liquid green hydrogen infrastructure of sufficient capacity to cover typical Mediterranean and Caribbean operations for a single large 110m liquid hydrogen powered superyacht, a CAPEX amount of between $60 - $82million would be required for two facilities.

The process of creating green hydrogen also has a low end-to-end process efficiency. As indicated in Section 8, this process requires a substantial amount of renewable energy. The investment to independently produce renewable energy has not been factored in this study. We have also not considered the embedded carbon and supply chain carbon as part of this study. These would need consideration in any further study.

The equipment required to electrolyse, liquefy and deliver the liquefied hydrogen is at a high TRL and is available in “off-the-shelf” modular components. Overall, the technical risk is therefore considered as low. There is potential in the electrolysis and liquefaction process to improve efficiency in the future by use of advanced or optimised future technology. Regulatory aspects of building a hydrogen production and storage facility are likely to be complex depending on the jurisdiction. Additional financial and unforeseen regulatory risks would also exist in developing facilities. Some contingency is allowed in the budget model for these aspects.

The location of any hydrogen production and bunkering facility should be carefully chosen based on the yacht’s operational areas. Two facilities with locations on both sides of the Atlantic would be feasible with some operational limitations within the Mediterranean. Three facilities would allow more operational flexibility but increase CAPEX costs. The design requirements of the yacht have a high impact on the onshore plant. For a hydrogen powered yacht, it is highly important to consider the yacht and land based infrastructure as one holistic engineering challenge.

It is clear that to minimise the annual cost impact, it is critical to achieve a high utilisation of the hydrogen plant. Given the semi-seasonal nature of yachting, there would need to be a ready market for surplus green hydrogen in the surrounding area. This suggests that any scheme would have a wider impact outside of yachting, probably requiring close co-operation with the local economy and government in surrounding areas.

The overall acceptability and feasibility of this concept is hard to define. The benefits of investing in infrastructure for yachting will be dependent upon the clients' perceived benefits of zero carbon yachting and/or any connected business opportunity. The overall CAPEX is, however, sizeable. The cost of a 110m liquified hydrogen yacht project could be as high as $350 million. In this case, the required infrastructure represents at least 25% of the overall project cost. It is therefore not considered to be a suitable approach for the majority of the yacht market. However, for clients demanding a fully sustainable and reliable zero carbon solution with a wider vision of enabling a regional green economy and leaving a legacy to the advancement of science and technology, it remains an option.

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