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PROSPECTS OF HYDROGEN UTILIZATION AS A FUELING SOURCE FOR RECREATIONAL VESSELS

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Master´s Degree in Industrial Engineering

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PROSPECTS OF HYDROGEN UTILIZATION AS A FUELING SOURCE FOR RECREATIONAL VESSELS

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ABSTRACT

The modeling of the levelized cost of fuel production and total cost of ownership of recreational vessels at Reial Club Maritim in Barcelona underscores the pivotal role of technological advancements and regulatory incentives in enhancing the techno-economic competitiveness of sustainable alternative fuel sources for decarbonization.

Keywords: RES, Battery-electric, Fuel Cell, Green Hydrogen, HVO, biomethanol, e-fuels, levelized costs of fuel production, TCO, recreational vessels

1. Introduction

The global energy transition is driving efforts across industries to mitigate greenhouse gas emissions, with particular focus on maritime transportation. Alternative fuels such as biofuels, hydrogen, and synthetic fuels, coupled with advancements in electric and hybrid propulsion technologies, are pivotal in achieving decarbonization goals. Hydrogen, increasingly available for transport purposes, holds promise due to its high energy density and potential for producing low-carbon derivatives. However, challenges remain regarding scalability, infrastructure readiness, and the suitability of hydrogen fuel cells for powering recreational boats efficiently [1].

The maritime sector, traditionally reliant on fossil fuels for economic reasons and operational familiarity, is guided by the International Maritime Organization's roadmap towards achieving net-zero emissions by 2050. These goals present a crucial opportunity to transition towards a greener maritime economy, with a focus on hydrogen as a carbon-free propulsion system. While larger shipping vessels are increasingly adopting alternative fuels, the logistical challenges related to establishing efficient refueling infrastructure hinder widespread adoption of electric-powered vessels in ports. Nevertheless, this scenario offers a distinct opportunity for the recreational boating sector to benefit from advancements in maritime operations. Recreational boats, with their shorter travel distances and longer port stays, are well-suited to adopt hydrogen as a net-zero energy source, enhancing sustainability and reducing costs [2].

2. State of the art

The Maritime Forecast to 2050 identifies challenges like a scarcity of carbon-neutral fuels and inadequate infrastructure, requiring substantial investments and innovative financial models to achieve successful decarbonization in the shipping industry. Several companies have already taken steps towards decarbonizing the maritime sector. Initiatives include developing the world's largest real-time ocean weather sensor network to optimize ship routes for reduced fuel consumption, AI-driven fleet management systems to minimize LNG use and emissions, and engineering solutions enhancing vessel efficiency through hull shape improvements and wind propulsion systems. These innovations highlight the industry's potential to meet IMO's decarbonization targets through engineering optimizations and the adoption of alternative fuels [3].

Several studies have evaluated the techno-economic decarbonization of the maritime industry to understand which is the most cost-competitive alternative fuel for reaching net-zero. In their 2021 analysis, Korberg et al. explore various renewable fuels as potential replacements for fossil fuels in large boats. The study underscores the economic costs associated with each fuel source, revealing electricity as the most competitive while highlighting ongoing economic challenges for hydrogen and e-fuels. Their research emphasizes the Total Cost of Ownership (TCO) as pivotal in assessing the competitiveness of these fuels, where fuel costs constitute a significant portion. Overall, sustainable fuels face economic hurdles compared to conventional options, with variability in suitability and cost-effectiveness across different vessel categories [4].

Other authors examine maritime decarbonization across various vessel and fuel categories, highlighting that no single fuel source is universally cost-competitive for all vessel types. This thesis aims to fill the research gap on recreational boats by examining the economic viability of hydrogen fuel cells, leveraging industry economies of scale to compare hydrogen with other alternative fuels.

3. Definition of the models

Under the aim of understanding the prospects of hydrogen as a potential decarbonization technology for recreational vessels, the first part of the thesis provides a comprehensive benchmark analysis considering various alternative fuels, including RES, green hydrogen, biofuels, and synthetic fuels, to evaluate their cost competitiveness and technological viability. Several KPIs such as efficiency, production costs, emissions reduction, and refueling time, along with resource availability, scalability, and technology readiness, were examined to identify the best options for decarbonizing recreational maritime activities.

In this case, the Levelized Cost of Fuel Production per alternative fuel technology was estimated to evaluate their cost competitiveness. The calculation involves summing the capital costs of building production facilities, the operational and maintenance expenses over the facility's lifespan, and then dividing these total costs by the total amount of fuel produced. This calculation is adjusted for the time value of money using a discount rate, providing a measure of the average cost per unit of fuel over the facility's operational life.

To evaluate the economic feasibility of different fueling technologies for recreational vessels, the TCO for vessels powered by green hydrogen, electricity, biofuels, and e-fuels was modeled. This analysis considered initial capital investment, fuel production costs, maintenance expenses, and operational efficiency accounting for time value of money, similarly to the LCFP analysis. By factoring in these elements, the study provided a comprehensive comparison of the long-term financial implications and economic viability of each fuel type, highlighting their respective cost advantages and challenges in sustainable recreational maritime operations.

To apply the TCO and levelized cost of fuel production analyses to a real-world case scenario, the decarbonization of Reial Club Maritim Barcelona was selected. This port is notable for its significant fleet of leisure vessels and its proximity to numerous alternative fuel production plants. This strategic location allows for practical insights into the feasibility and economic impact of implementing green hydrogen, electricity, biofuels, and e-fuels as sustainable energy sources. By focusing on Reial Club Maritim Barcelona, the model considers scenarios centered on decarbonization with each alternative fuel and finding the optimal technology mix. This approach provides a realistic assessment of the decarbonization potential from a port owner's perspective, as well as the infrastructural and financial requirements needed to transition to cleaner fuels within a bustling recreational maritime hub.

4. Results

The results of the comprehensive alternative fuel benchmark outline the attractiveness of each technology for reducing emissions in the recreational maritime industry as summarized in Exhibit 1.

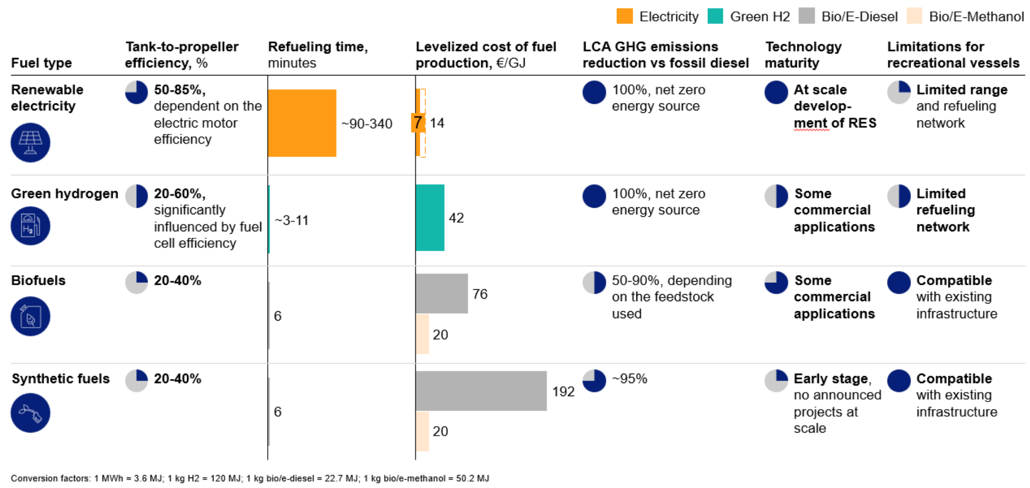

Exhibit 1: Techo-economic benchmark of alternative fuel technologies. Source: Own elaboration

While renewable electricity may appear the most cost-competitive option due to Spain's geographical conditions and offers the highest tank-to-propeller efficiency, potentially reducing fuel consumption, it has significant drawbacks. The extended refueling time results in a limited range for recreational boats, and the refueling network has not yet been developed at scale. These factors hinder its deployment as the primary net-zero technology. Furthermore, green hydrogen emerges to be the second most attractive technology in terms of cost competitiveness and operational efficiency. However, its development has not yet reached scale, resulting in limited access to a supply network, which currently prioritizes other industrial uses. On the contrary, biofuels and e-fuels are notable for their compatibility with existing ICE fleets and refueling infrastructure, which reduces the need for substantial future investments. Nonetheless, their accessibility to cost-effective feedstock is limited, resulting in notably higher fuel costs, particularly in diesel applications.

The financial feasibility study assessed the TCO for hydrogen fuel cell-powered recreational boats in comparison to vessels using biofuels, synthetic fuels, and electricity. Assuming an annual travel distance of 3,600 nautical miles with an energy consumption of 1.4 TJ per year, initial purchase prices ~40-60% higher for battery electric and fuel cell vessels, and no mark-up for fuel procurement by vessel owners, fuel costs were found to represent over 50% of the TCO across all technologies. Therefore, underscoring the need for substantial technological advancements to enhance the appeal of decarbonization solutions. Currently, e-diesel ICE vessels showed the highest TCO due to costly production and limited availability of production plants, hindering widespread adoption without scalability. Similarly, green hydrogen FC vessels incurred higher costs compared to traditional ICE vessels, but improvements in production and adoption could drive economies of scale, potentially bolstering their competitiveness in the future.

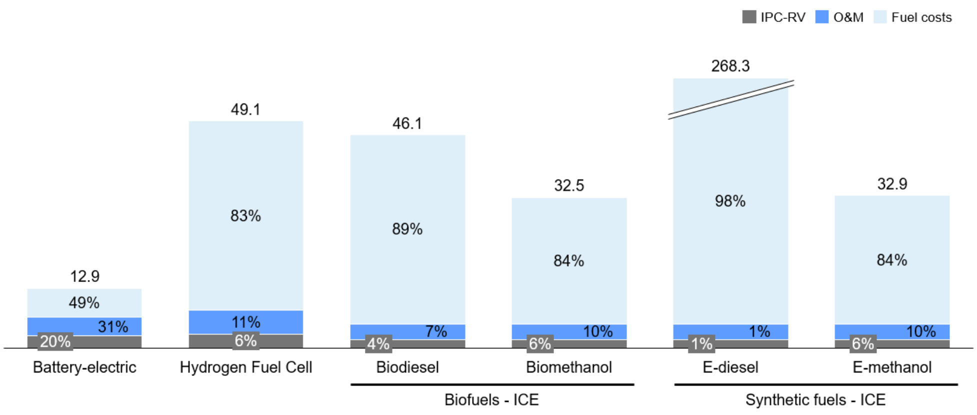

Exhibit 2: TCO analysis per alternative fuel and vessel category. Source: Own elaboration

Furthermore, a sensitivity analysis indicated that for shorter distances, biodiesel and green hydrogen vessels were less competitive due to elevated production costs, whereas differences in TCO diminished for longer distances.

Based on the findings outlined above, the modeling of Reial Club Maritim Barcelona, with 239 recreational boats fleet, was undertaken to assess the implications of its proximity to fuel production facilities, transportation and distribution costs, network charges and tolls, and capital expenditures required for establishing new refueling infrastructure. This approach aimed to provide insights into the feasibility and economic viability of transitioning the port's fleet to sustainable fuels like green hydrogen, biofuels, synthetic fuels, and electricity. Six scenarios have been considered with different technology mix, all yielding to the conclusion that +70% of the port's decarbonization operational costs would be related to fuel consumption which reveals the importance of attractive offtake agreements with fuel providers and efficiency enhancement.

The findings indicate that the technology mix offering the lowest operational costs due to minimal fuel expenses may not necessarily yield the highest financial margins for the port owner or achieve the most efficient logistical operations. Indeed, the best-case scenario combining a mix of technologies, highlights the strategic advantages of integrating renewable electricity and green hydrogen (scenario 6 in Exhibit 3). This combination not only enhances operational cost competitiveness and mitigates GHG emissions as well as marine noise, but also ensures sustainable revenue margins over the long term. Despite a longer payback period relative to biofuel-based scenarios, the strategic investment in renewable electricity and green hydrogen positions the port to capitalize on future advancements in decarbonization technologies. This approach not only mitigates environmental impact but also aligns with evolving regulatory frameworks aimed at reducing maritime emissions.

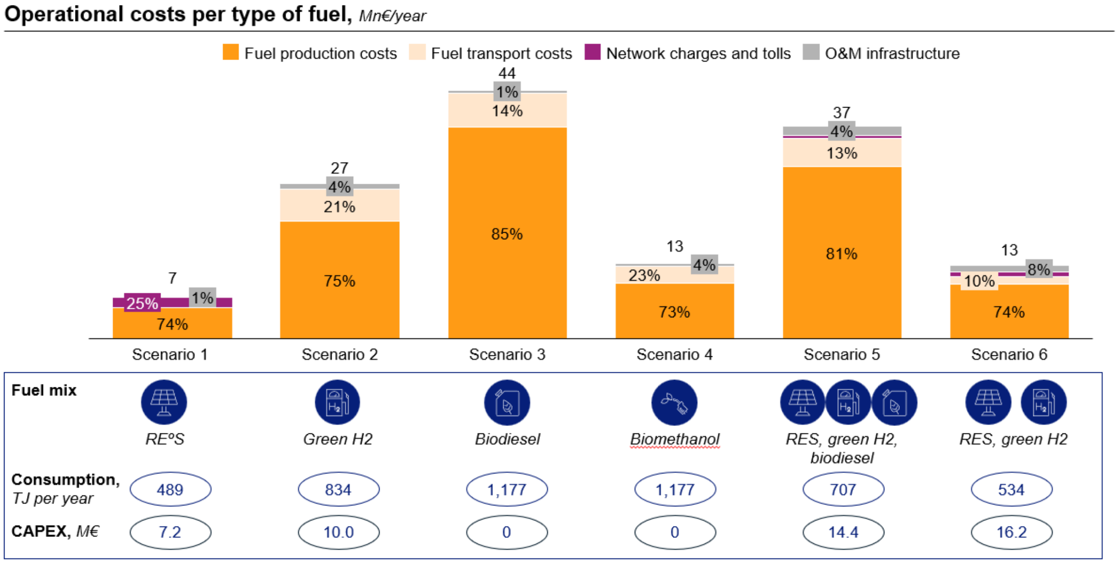

Exhibit 3: Economic analysis from port's owner perspective per decarbonization scenario. Source: Own elaboration

5. Conclusions

Renewable electricity and green hydrogen emerged as the alternative fuel technologies with the lowest levelized costs of fuel production, greatest emissions reduction potential, and higher tank-to-propeller efficiency. Financial feasibility assessments indicated that fuel costs constitute over 50% of TCO across technologies, emphasizing the need for large-scale development to enhance decarbonization solutions for recreational vessels. in hydrogen production technologies, such as more efficient electrolysis processes and innovative storage solutions. These technological advancements are expected to reduce production costs and improve energy density, making hydrogen a more viable and competitive alternative fuel. Additionally, the development of a comprehensive hydrogen distribution network and refueling infrastructure will enhance its accessibility and feasibility for widespread use in recreational boating and other maritime applications.

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PERSPECTIVAS DE UTILIZACIÓN DEL HIDRÓGENO COMO FUENTE DE COMBUSTIBLE PARA EMBARCACIONES DE RECREO

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RESUMEN

El modelo de costes de producción de combustible y costes totales de propiedad de embarcaciones de recreo en el Reial Club Maritim de Barcelona destaca la importancia de avances tecnológicos e incentivos regulatorios en la mejora de la competitividad de los combustibles alternativos para la descarbonización, sobre todo en el caso del hidrógeno verde.

Palabras clave: RES, barías electricas, hidrógeno verde, HVO, biometanol, combustibles sintéticos, embarcaciones de recreo, costes de producción nivelados, TCO

1. Introducción

La transición energética a nivel mundial está impulsando esfuerzos de todas las industrias para mitigar las emisiones de gases de efecto invernadero, con especial atención en el transporte marítimo. Los combustibles alternativos, como los biocombustibles, el hidrógeno verde, las renovables y los combustibles sintéticos, junto con los avances en las tecnologías de propulsión eléctrica e híbrida, son fundamentales para alcanzar los objetivos de descarbonización. El hidrógeno, cada vez más disponible para el transporte, resulta prometedor por su alta densidad energética y su potencial para producir derivados bajos en carbono. Sin embargo, sigue habiendo problemas de escalabilidad, preparación de las infraestructuras e idoneidad de las pilas de combustible de hidrógeno para propulsar embarcaciones de recreo de forma eficiente [1].

El sector marítimo, tradicionalmente dependiente de los combustibles fósiles por razones económicas y de familiaridad operativa, se guía por la hoja de ruta de la Organización Marítima Internacional para lograr emisiones netas en 2050. Estos objetivos presentan una oportunidad crucial para la transición hacia una economía marítima más ecológica, centrada en el hidrógeno como sistema de propulsión libre de carbono. Aunque los buques de mayor tamaño están adoptando cada vez más combustibles alternativos, los problemas logísticos relacionados con el establecimiento de una infraestructura de repostaje eficiente dificultan la adopción generalizada de buques de propulsión eléctrica en los puertos. Sin embargo, este escenario ofrece una clara oportunidad para que el sector de la navegación de recreo se beneficie de los avances en las operaciones marítimas. Las embarcaciones de recreo, con distancias de viaje más cortas y estancias más largas en los puertos, son idóneas para adoptar el hidrógeno como fuente de energía neta cero, mejorando la sostenibilidad y reduciendo los costes [2].

2. Estado del arte

Las previsiones marítimas hasta 2050 señalan retos como la escasez de combustibles neutros en carbono y la inadecuación de las infraestructuras, que exigen inversiones sustanciales y modelos innovadores para lograr una descarbonización satisfactoria del sector del transporte marítimo. Varias empresas ya han tomado medidas para descarbonizar el sector marítimo. Algunas iniciativas existentes incluyen el desarrollo de la mayor red mundial de sensores meteorológicos oceánicos en tiempo real para optimizar las rutas de los buques y reducir el consumo de combustible, sistemas de gestión de flotas basados en IA para minimizar el uso de GNL y las emisiones, y soluciones de ingeniería que mejoran la eficiencia de los buques mediante mejoras en la forma del casco y sistemas de propulsión. Estas innovaciones ponen en relieve el potencial del sector para cumplir los objetivos de descarbonización mediante optimizaciones de ingeniería y la adopción de combustibles alternativos [3].

Varios estudios han evaluado la descarbonización tecno-económica de la industria marítima para comprender cuál es el combustible alternativo más competitivo en términos de costes para alcanzar emisiones neutras. En su análisis de 2021, Korberg et al. exploran varios combustibles renovables como posibles sustitutos de los combustibles fósiles en las grandes embarcaciones. El estudio subraya los costes económicos asociados a cada fuente de combustible, revelando que la electricidad es la más competitiva, al tiempo que pone de relieve los retos económicos actuales para el hidrógeno y los combustibles sintéticos. El estudio destaca que el coste total de propiedad (TCO) es fundamental para evaluar la competitividad de estos combustibles, ya que estos costes constituyen una parte significativa. En general, los combustibles sostenibles se enfrentan a obstáculos económicos en comparación con las opciones convencionales, y su idoneidad y rentabilidad varían según las distintas categorías de buques [4].

Otros autores examinan la descarbonización marítima a través de diversas categorías de embarcaciones y combustibles, destacando que ninguna fuente de combustible es universalmente competitiva en costes en comparación con los combustibles tradicionales y aparente para todos los tipos de embarcaciones. Esta tesis pretende llenar el vacío existente en la investigación sobre embarcaciones de recreo examinando la viabilidad económica de las pilas de combustible de hidrógeno, aprovechando las economías de escala de la industria para comparar el hidrógeno con otros combustibles alternativos.

3. Definición del modelo

Con el objetivo de comprender las perspectivas del hidrógeno como tecnología potencial de descarbonización de las embarcaciones de recreo, la primera parte de la tesis ofrece un análisis comparativo exhaustivo que tiene en cuenta varios combustibles alternativos, como las renovables, el hidrógeno verde, los biocombustibles y los combustibles sintéticos, para evaluar su competitividad en costes y su viabilidad tecnológica. Se examinaron varios KPI, como la eficiencia, los costes de producción, la reducción de emisiones y el tiempo de repostaje, junto con la disponibilidad de recursos, la escalabilidad y la preparación tecnológica, para identificar las mejores opciones para descarbonizar las actividades marítimas recreativas.

En este caso, se calculó el coste nivelado de producción de combustible por tecnología de combustible alternativo para evaluar su competitividad en costes. El cálculo consiste en sumar los costes de capital de construcción de las instalaciones de producción, los gastos operativos de funcionamiento y mantenimiento durante la vida útil de la instalación y dividir estos costes totales por la cantidad total de combustible producido. Este cálculo se ajusta al valor temporal del dinero mediante una tasa de descuento, lo que proporciona una medida del coste medio por unidad de combustible a lo largo de la vida operativa de la instalación.

Para evaluar la viabilidad económica de las diferentes tecnologías de abastecimiento de combustible para embarcaciones de recreo, se modeló el coste total de propiedad de las embarcaciones propulsadas por hidrógeno verde, electricidad, biocombustibles y combustibles sintéticos. Este análisis tuvo en cuenta la inversión inicial de capital, los costes de producción de combustible, los gastos de mantenimiento y la eficiencia operativa teniendo en cuenta el valor temporal del dinero, de forma similar al análisis del coste de producción de combustible. Al tener en cuenta estos elementos, el estudio proporcionó una comparación exhaustiva de las implicaciones financieras a largo plazo y la viabilidad económica de cada tipo de combustible, destacando sus respectivas ventajas y retos en las operaciones marítimas recreativas sostenibles.

Para aplicar los análisis del coste total de propiedad y del coste nivelado de producción de combustible a un caso real, se seleccionó la descarbonización del Reial Club Maritim Barcelona. Este puerto destaca por su importante flota de embarcaciones de recreo y su proximidad a numerosas plantas de producción de combustibles alternativos. Esta ubicación estratégica permite obtener información práctica sobre la viabilidad y el impacto económico de la implantación del hidrógeno verde, la electricidad, los biocombustibles y los e-combustibles como fuentes de energía sostenibles. Al centrarse en el Reial Club Maritim Barcelona, el modelo considera escenarios centrados en la descarbonización con cada combustible alternativo y en encontrar la combinación tecnológica óptima. Este enfoque proporciona una evaluación realista del potencial de descarbonización desde la perspectiva del propietario de un puerto, así como los requisitos infraestructurales y financieros necesarios para la transición a combustibles más limpios dentro de un bullicioso centro marítimo recreativo.

4. Resultados

Los resultados de la evaluación comparativa exhaustiva de los combustibles alternativos ponen de manifiesto el atractivo de cada tecnología para reducir las emisiones en el sector marítimo de recreo, tal y como se resume en la Ilustración 1.

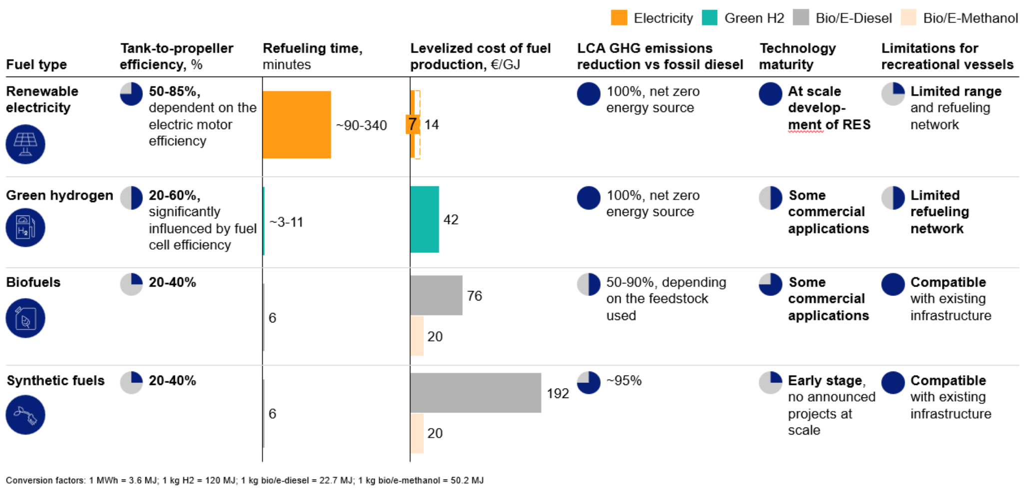

Ilustración 1: Análisis tecno-económico de los combustibles alternativos para el sector marítimo. Fuente: Elaboración propia

Aunque la electricidad renovable puede parecer la opción más competitiva en costes debido a las condiciones geográficas de España y ofrece la mayor eficiencia tanque-hélice, reduciendo potencialmente el consumo de combustible, tiene inconvenientes importantes. El prolongado tiempo de repostaje se traduce en una autonomía limitada para las embarcaciones de recreo, y la red de repostaje aún no se ha desarrollado a escala. Estos factores dificultan su despliegue como tecnología primaria con emisiones nulas. Por otra parte, el hidrógeno verde se perfila como la segunda tecnología más atractiva en términos de competitividad de costes y eficiencia operativa. Sin embargo, su desarrollo aún no ha alcanzado escala, lo que se traduce en un acceso limitado a una red de suministro, que actualmente da prioridad a otros usos industriales. Por el contrario, los biocombustibles y los combustibles sintéticos destacan por su compatibilidad con las flotas de vehículos de combustión interna y las infraestructuras de repostaje existentes, lo que reduce la necesidad de importantes inversiones futuras. No obstante, su accesibilidad a materias primas rentables es limitada, lo que se traduce en unos costes de combustible notablemente más elevados, sobre todo en las aplicaciones diésel.

El estudio de viabilidad financiera evaluó el coste total de propiedad de las embarcaciones de recreo propulsadas por pilas de combustible de hidrógeno en comparación con las embarcaciones que utilizan biocombustibles, combustibles sintéticos y electricidad. Suponiendo una distancia de viaje anual de 3.600 millas náuticas con un consumo de energía de 1,4 TJ al año, unos precios de compra iniciales entre un 40% y un 60% más altos para las embarcaciones eléctricas de batería y de pila de combustible, y sin margen de beneficio para la adquisición de combustible por parte de los propietarios de las embarcaciones, se constató que los costes de combustible representaban más del 50% del coste total de propiedad en todas las tecnologías. Esto subraya la necesidad de avances tecnológicos sustanciales para aumentar el atractivo de las soluciones de descarbonización. En la actualidad, los buques e-diesel ICE presentan el mayor coste total de propiedad debido a su costosa producción y a la limitada disponibilidad de plantas de producción, lo que dificulta su adopción generalizada sin escalabilidad. Del mismo modo, las embarcaciones de pila de hidrógeno incurren en costes más elevados en comparación con las embarcaciones ICE tradicionales, pero las mejoras en la producción y la adopción podrían impulsar las economías de escala, reforzando potencialmente su competitividad en el futuro.

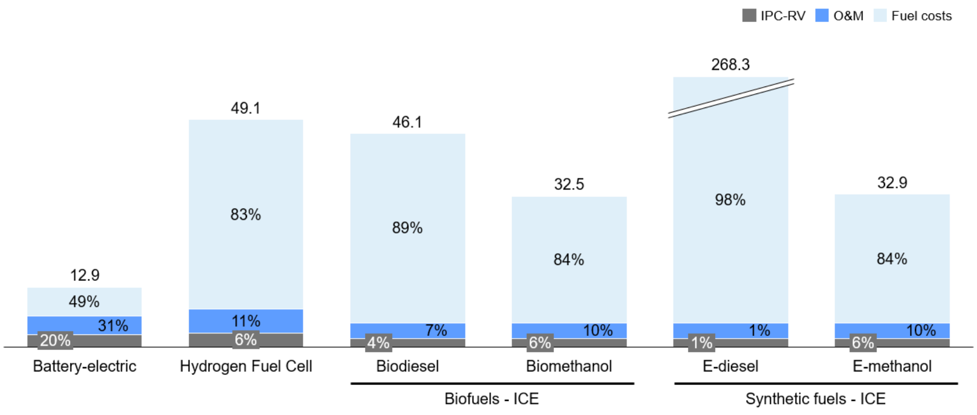

Ilustración 2: Análisis del TCO analysis por combustible alternativo y tipo de embarcación de recreio. Fuente: Elaboración propia

Adicionalmente, se realizó un análisis de sensibilidad que concluye que para distancias más cortas, los buques de biodiésel e hidrógeno verde son menos competitivos debido a los elevados costes de producción, mientras que las diferencias en el TCO disminuían para distancias más largas.

En base a las estimaciones económicas descritas anteriormente, se ha llevado a cabo la modelización de la descarbonización del Reial Club Marítim Barcelona. Con una flota de 239 embarcaciones de recreo, se busca evaluar las implicaciones de su proximidad a las instalaciones de producción de combustible, los costes de transporte y distribución, las tasas y peajes de la red y los gastos de capital necesarios para establecer una nueva infraestructura de repostaje. El objetivo de este enfoque es proporcionar información sobre la viabilidad económica de la transición de la flota del puerto desde combustibles fósiles a combustibles sostenibles. Se han considerado seis escenarios con diferentes combinaciones tecnológicas, y todos ellos concluyen que +70% de los costes operativos de descarbonización del puerto estarían relacionados con el consumo de combustible, lo que revela la importancia de los acuerdos atractivos de suministro con los proveedores de combustible y la mejora de la eficiencia.

Los resultados indican que la combinación de tecnologías que ofrece los costes operativos más bajos debido a los gastos mínimos de combustible no necesariamente produce los márgenes financieros más altos para el propietario del puerto ni logra las operaciones logísticas más eficientes. De hecho, en el mejor de los casos con un mix de tecnologías, se ponen de manifiesto las ventajas estratégicas de integrar electricidad renovable e hidrógeno verde (escenario 6 de la ilustración 3). Esta combinación no sólo mejora la competitividad de los costes operativos y mitiga las emisiones de GEI, así como el ruido marino, sino que también garantiza márgenes de ingresos sostenibles a largo plazo. A pesar de un periodo de amortización más largo en relación con los escenarios basados en biocombustibles, la inversión estratégica en electricidad renovable e hidrógeno verde posiciona al puerto para capitalizar futuros avances en tecnologías de descarbonización. Este enfoque no sólo mitiga el impacto ambiental, sino que también se ajusta a los marcos normativos en evolución destinados a reducir las emisiones marítimas.

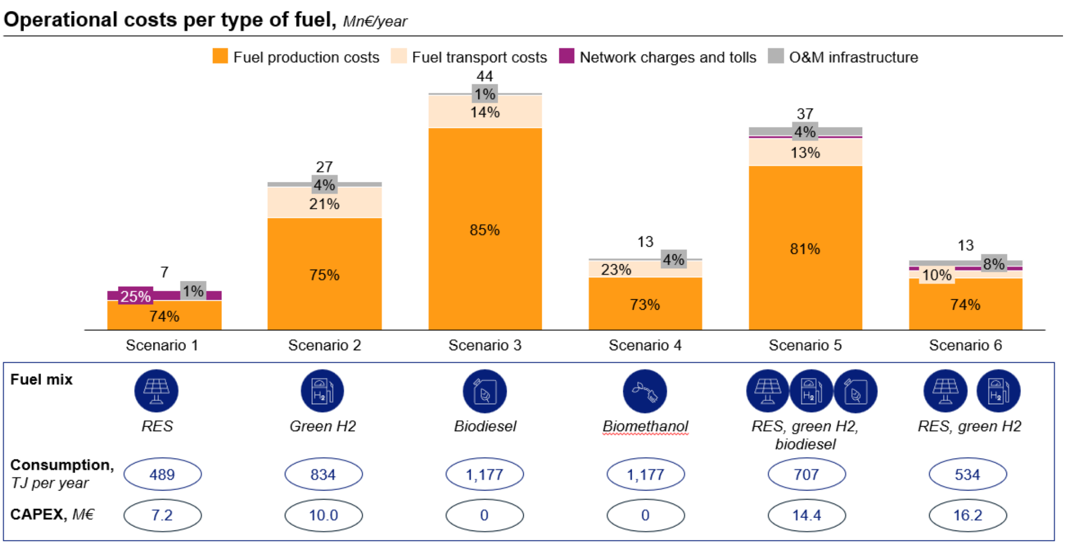

Ilustración 3: Análisis económico desde el punto de vista del dueño del puerto en base a los distintos escenarios de descarbonización. Fuente: elaboración propia

5. Conclusiones

La electricidad renovable y el hidrógeno verde destacan por ser las tecnologías de combustible alternativo con los menores costes de producción, el mayor potencial de reducción de emisiones y la mayor eficiencia del tanque a la hélice. El análisis financiero del coste total de propiedad de un barco de recreo revela que los costes de combustible representan +50% en todas las tecnologías, destacando la necesidad del desarrollo a gran escala para mejorar la competitividad de la descarbonización marítima. Los avances en las tecnologías de producción de hidrógeno, como procesos de electrólisis más eficientes y soluciones innovadoras de almacenamiento, se espera que reduzcan los costes de producción y mejoren la densidad energética, convirtiendo al hidrógeno en un combustible alternativo más viable y competitivo. Además, el desarrollo de una red de distribución de hidrógeno integral y de infraestructura de repostaje mejorará la accesibilidad para su uso generalizado en la navegación recreativa.

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Chapter 1. INTRODUCTION

The energy transition is already present in today´s world and the energy sector plays a significant role in reshaping the future by mitigating greenhouse gas emissions. The maritime industry in one of the sectors facing significant pressure to reduce their carbon footprint. Hence, many efforts are being taken towards decarbonization such as the use of alternative fuels (biofuels, hydrogen, ammonia) and the adoption of new propulsion technologies (electric and hybrid).

Nowadays, hydrogen supply is becoming more readily available for the maritime industry thanks to the entry of new players, especially for the recreational vessels niche market. However, questions arise around whether hydrogen production will be big enough at scale, infrastructure developments will be sufficient for this technology to take off and whether hydrogen fuel cells (FC) could power recreational vessels. Hence, the scope of this thesis is to analyze the competitiveness of hydrogen as a fueling alternative for recreational boats while evaluating its potential for improving these vessels´ cost efficiency.

There are many advantages and opportunities for hydrogen in this market. Thanks to its high mass energy density and the possibility to produce low-carbon hydrogen derivatives (green ammonia, green methanol, e-fuels), it has become the most suitable energy source for boats where space and weight are the main constraints. Indeed, hydrogen is already being used as feedstock for ammonia production, which will potentially be used for fueling shipping vessels. In the case of recreational boats, hydrogen is used to power fuel cells which produce power for electric propulsion systems. These electric motors are lighter and smaller than the equivalent marine conventional fuel engine for recreational boats. Therefore, green hydrogen is already playing a leading role in attaining long-term sustainability [1].

Despite its potential to address environmental challenges, hydrogen comes together with some space for future improvements in order to transition from a niche market into an energy resource that could be exploited internationally. The biggest challenge is the lack of infrastructure for hydrogen production, storage, and transportation. In fact, the lower volumetric energy density introduced several difficulties to the hydrogen storage where capacity depends on the pressure of compressors. Hence, several innovative approaches are being explored under the purpose of optimizing the value chain. For example, by doubling the pressure, storage can be doubled, which increases the range of the boat [2].

It is true that hydrogen can accelerate the path to reducing environmental concerns in the maritime industry. However, this industry is still highly reliant on fossil fuels due to their economic advantages and significantly experienced operations with marine diesel engines. Therefore, the International Maritime Organization (IMO) established a strategic roadmap to achieve net-zero by 2050 in international shipping based on a decline in carbon intensity by improving ship´s energy efficiency. Hull shape optimization, engine derating, routing algorithms and rigid sails are considered the most promising innovation tools under this goal as they are highly cost-effective. To complement the ship´s efficiency optimization, low-carbon energy fueling sources should be used to achieve a 20% GHG emissions reduction by 2030 and 70% by 2040. Considering the maritime industry's pivotal role, enabling over 80% of global commerce, these initiatives are critical for sustainable and environmentally responsible shipping practices. [3].

The International Maritime Organization's (IMO) strategic objectives provide a pivotal opportunity for transitioning to a more environmentally friendly maritime economy, emphasizing hydrogen as a carbon-free propulsion engine. While large shipping vessels are adopting alternative fuels, the challenges of limited port activity for electric-powered vessels make establishing efficient refueling infrastructure difficult for them. However, this situation creates a unique opportunity for the recreational boating industry to leverage the economies of scale within the broader maritime sector. By embracing the efficiency gains and technological advancements of maritime operations, recreational boating can enhance sustainability and reduce costs. Notably, the use of hydrogen as a viable net-zero energy source for recreational boats is a promising avenue, given their shorter travel distances and extended periods spent in ports, making them an ideal candidate for implementing hydrogen-powered technologies. Indeed, some ports or local governments may include GHG emissions limits where hydrogen and battery-electric vessels would be the most attractive alternative for reaching net-zero as biofuels and e-fuels do not result in 100% CO2e mitigation. Nevertheless, this proposed solution is not without downsides, including fuel cell degradation, a lack of reliable hydrogen sources in ports, and significant reliance on larger storage tanks that may reduce valuable space [4].

Thus, in this thesis several sustainable energy fueling sources would be compared to understand the future potential of hydrogen fuel cells for recreational boats that usually sail shorter distances and may have refueling stations more handy. Hydrogen refueling infrastructure is already being built in some ports and may become a viable option for reducing the carbon footprint in the near future. The goal is to understand which is the most cost-effective fueling source that can drive the decarbonization of leisure vessels. Technology constraints in the boat and refueling infrastructures will also be included in the analysis to identify the most feasible alternative.

1.1. State of the Art

The Maritime Forecast to 2050 highlights significant challenges impeding the shipping industry's shift to decarbonization. These include a shortage of carbon-neutral fuels, requiring a substantial increase in supply by 2030 to meet global greenhouse gas targets. The insufficient infrastructure for fuel production, storage, and distribution demands significant investments. Introducing new fuels and technologies raises safety concerns, and the industry may lack the expertise for implementation. Some low-emission technologies are still in early stages, hindering widespread commercial availability. The high costs of decarbonization call for new contractual arrangements to distribute expenses across the value chain. Overcoming these challenges is crucial for the industry to achieve successful decarbonization [5].

Some companies have already taken action towards the decarbonization of the maritime industry. *So far* is in the process of developing the largest real-time ocean weather sensor network globally, offering the most precise marine weather information and forecasts to support industry-specific solutions. The company’s main goal is to optimize ship routes to reduce fuel consumption. *Nautilus Lab* has the same scope, through AI and machine learning it is already optimizing routes to reduce LNG consumption and improved emissions reduction via advanced fleet management and charter party clauses. Other examples include BAR Technologies, whose tailored engineering solutions enable hull shape enhancement to make vessels more efficient; Wisamo, who are accelerating maritime decarbonization through an innovative wind propulsion system; and Bound 4 Blue who is also focusing on wind propulsion systems to reduce the industry's environmental footprint.

The maritime industry has a promising opportunity to meet IMO decarbonization targets through a combination of engineering optimization solutions and alternative fuels. Engineering solutions, such as tunnel hulls and foils, offer drag reduction and increased speed, especially beneficial for recreational boats. However, the challenge of accessing refueling infrastructure along long-distance routes emphasizes the importance of evaluating the economic feasibility of alternative fuels. The section explores existing literature on sustainable marine fuels to assess their applicability in maritime transportation.

In their 2021 analysis, Korberg et al. investigate the prospects of diverse renewable fuels as potential replacements for fossil fuels in various propulsion systems for large boats. The study begins by scrutinizing the economic costs associated with each fuel source, highlighting diesel fuels as the most expensive and methane fuels as the most cost-effective across all categories. Importantly, electricity emerges as the most economically competitive fuel source, while hydrogen and e-fuels present persistent economic challenges requiring resolution in the near future. Furthermore, a sensitivity analysis is conducted to explore the outcomes of different market conditions. Under a scenario where electrolysis efficiency is enhanced and costs associated are low, e-fuels and green hydrogen become a more cost competitive alternative [6].

The research extends its analysis to the Total Cost of Ownership (TCO), emphasizing the crucial role of TCO in assessing the competitiveness of alternative fuels for recreational boats. TCO provides an overview of the financial impact over the entire lifespan of the vessels, providing a holistic perspective on the economic, operational, and environmental implications of selecting any fueling resource. Korberg's et. al. findings underscore that fuel costs constitute approximately 50% of the TCO, with a noteworthy exception for fully battery-electric systems where batteries represent the largest share of the TCO. After analyzing different vessel types and scenarios, the author concludes that TCO is highly affected by fuel costs, utilization and efficiency. A greater efficiency and lower fuel costs lead to a cost parity between fuel cells and internal combustion engines no matter the fuel type. Moreover, by including a battery cost-reduction, electric propulsion systems become more competitive than other fuel option except for bio-methanol. Only large vessels are contemplated in this analysis such as ferries, general cargo, bulk carrier and container ships. Nonetheless, it should be noted that the potential replacement of four-stroke marine engines with fuel cells becomes feasible if the latter can achieve efficiencies 15–20% higher, which could also be applicable to recreational boats [6].

Additionally, other studies have been explored under the aim of understanding the outcomes in changing market and vessels conditions as shown in Table 1.

Fuel type	Vessel type	Assumptions	Conclusions	Applicable to recreational boats	Source
Hydrogen	Fuel cell + battery in a 5,6 m long boat	Acceleration rate=Deceleration rate 50% overall efficiency – 20-80% state of charge • FC operating point (500 W, ~57% efficiency) • 1/2000 battery degradation rate per cycle	Fuel cells exhibit significant promise in extending the range of marine vessels, which also increases electricity costs If green H2 electricity production costs are lowered to~$2/kg, it will become competitive vs. grey H2	✓	[4]
Biofuels	Ferries, general cargo, bulk carrier and container ships	Three propulsion systems are considered for this analysis (ICE, FC and BE) Three different utilization rates for sensitivity analysis (short-medium-long)	Bio-methanol followed by bio-ammonia are the most cost-competitive biofuels Utilization rates, fuel costs and efficiency are the main drivers of the fuel choice for large vessels	Depending on the fuel type	[6]
E-fuels	Large ferries & container ships	Large ferries operate 1260 h/year and have 6 h between bunkering Container ships operate 5280 h/year and have 480 h between bunkering Several propulsion systems are considered (ICE, BE)	Need from regulatory action since traditional fuels are still more cost competitive than e-fuels Cheapest alternative for both types of vessels under review are bio-e-fuels, mainly bio-e-methanol	Depending on the fuel type	[7]
Battery electric	Solar-aided tourist boats (14m long, 4.9m wide)	Most common design for tourist boats with 45 px capacity 15 PV panels installed in the rooftop ~25 m^2 with an annual yield of 200 kWh/m^2 Travel time would be ~40 min, x5 times per day	Solar-aided boats reduce diesel fuel consumption by 15% and annual CO2 emissions by 4.26 tons while producing 5540 kWh Main limitation is that the rooftop area is insufficient to convert a diesel-powered boat into fully electric	✗ Significant weight from the battery	[8]

Table 1: Literature review regarding different vessels and fuel types. Source: Own elaboration [4], [6], [7], [8].

In conclusion, it is evident that sustainable fuels currently incur higher costs compared to conventional fuels within the present macroeconomic landscape. Moreover, the suitability and cost-effectiveness of each fuel type exhibit variability across different vessel categories, as delineated in Table 1. For bio-methane and e-methane, their incompatibility with the existing engines of recreational boats poses a challenge. The required conversion would entail elevated investment costs, rendering them less attractive alternatives when juxtaposed with HVO or e-diesel. Conversely, the primary constraints for electric recreational boats lie in charging time and battery weight, making hydrogen fuel cells an appealing solution for recreation boats.

Nonetheless, greater government efforts are required to make greener approaches more profitable and turn them into the main preference in the maritime industry. Co-production of sustainable fuels with other sectors or mandatory fuel blends could revert current trends in this market.

The aim is to address the gap in existing research which is currently focused on larger marine vessels since these boats represent a larger share of marine carbon emissions. However, recreational boats can leverage the economies of scale of the industry that will make alternative fuels a more viable option. By examining the economic viability of hydrogen fuel cells for recreational boats, this thesis will assess the economic prospects of hydrogen and compare it to other alternative fuels.

1.2. Motivation

The use of fossil fuels should be mitigated to meet the Paris Agreement goals and reduce the carbon footprint of vessels. Governments have already started to take action with subsidies and incentives to low-emission technologies. The transportation sector is responsible for a large share of GHG emissions which is why they must fall by 25% by 2030 to meet green objectives. According to the International Energy Agency (IEA), the maritime and aviation sub-sectors would create the greatest impact by switching into less carbon-intensive industries thanks to sustainable fuels and government policies as road transport could potentially be decarbonized with EVs in the long-term [9]. Hence, the amelioration of energy efficiency in shipping and sailing vessels to reduce GHG emissions and attain the IMO´s net-zero strategic objectives is seen as a promising opportunity for hydrogen fuel cells.

Hydrogen could become the leading net-zero fueling source in the maritime industry for recreational vessels, but storage and transportation pose a threat on the international expansion of this energy source. Nevertheless, technological advances are in the initial stages of the innovation chain, meaning hydrogen could become a highly cost-efficient alternative in the near future.

E-fuels and biofuels have already started to emerge in the maritime sector by using methanol since it is the most cost-effective fueling source. However, methanol production includes many technological barriers that need to be overcome such as the efficiency reduction caused by the additional transformation of feedstock. Larger ships would potentially be fueled by e-ammonia or bio-ammonia and smaller vessels consider e-diesel or Hydrotreated Vegetable Oil (HVO). Nonetheless, these alternative fuels do not meet a net-zero production. Consequently, the potential positive environmental impact of adopting green hydrogen technology in recreational sailing must be considered. As hydrogen refueling infrastructure is already under development, hydrogen fuel cell vessels will become economically and technically feasible for short distance travels.

Many studies have explored the competitiveness of fuel cells and batteries for hybrid low-power boats. The main downside of this approach is the significant cost of electricity required to produce green hydrogen. Therefore, additional in-depth economic assessments, considering the levelized energy costs and the time required for fuel cells to recoup their investment, are required.

Hydrogen leisure boats have not been commercialized yet in the market as the technology is not able to take advantage of economies of scale for cost reduction yet. There are some pilot prototypes trying to demonstrate the competitiveness of hydrogen boats, but there is still room for improvement. For this reason, the focus of this thesis is to understand the potential prospects of green hydrogen for sailing vessels including a fuel cell of 40kW and an electric motor with a nominal speed of 4800rpm. Alternative fueling sources would also be explored such as biofuels, synthetic fuels, and electricity to highlight the potential benefits of fuel cell recreational maritime applications.

1.3. Project's Objectives

The main purpose of this thesis is to prove the future potential of hydrogen as a propulsion technology for recreational vessels and as the leading resource to decarbonize the recreational practice around the globe. This includes analyzing the different conclusions obtained from comparing it to other sustainable fueling alternatives. Looking forward to attaining the above-mentioned target, the following partial objectives have been set:

1. Comparison of the various sustainable fueling technologies that could be used in recreational sailing boats such as biofuels, synthetic fuels, hydrogen, and electricity. A comprehensive analysis of the economic feasibility, environmental impact and operational considerations will be used as key performance indicators to compare each fuel type.
2. Comparison of the refueling infrastructure required for each fuel type, including a cost-analysis to understand the dynamics of the supply market for each fueling technology.
3. Study of the financial feasibility of transitioning to hydrogen-powered boats in the context of sustainable and cost-effective maritime practices, including a market analysis of the fuel cells, hydrogen tanks, electric batteries and any other element required for the boat infrastructure. Financial feasibility includes the estimation of the total cost of ownership (TCO) of a hydrogen powered recreational boat, as well as benchmarking with the same recreational vessel fueled with biofuels, synthetic fuels and electricity in terms of TCO.
4. Identify the unique long-term advantages and challenges of hydrogen as a sustainable fuel source for recreational sailing vessels to understand whether hydrogen has a competitive advantage over other alternatives in terms of technology, financial feasibility, environmental impact, and others.
5. Study of the application of hydrogen technology to real-world case scenarios. This objective includes an assessment of the outcomes achieved in terms of reduced emissions, cost savings, government incentives and other relevant metrics for a specific maritime port.
6. Comparison and analysis of the results obtained in the thesis with previous techno-economic studies developed in the literature including the decarbonization of other shipping vessels in the transportation sector.

1.4. Alignment with Sustainable Development Goals (SDGs)

Under the objective of developing a more sustainable and environmentally responsible world, this thesis also focuses on attaining several United Nations´ Sustainable Development Goals (SDGs). The alignment of various initiatives and goals has become paramount and can help address some of the challenges the world is facing nowadays. Hence, the relationship between five SDGs and this thesis is described below.

- GOAL 7: AFFORDABLE AND CLEAN ENERGY

Nowadays, the world is facing an energy transition from fossil fuels to renewable resources. Many industries are already taking action towards this challenge by looking for greener investments. Technological advancements enable the transition from emerging to mature renewable markets in which hydrogen, biofuels, synthetic fuels and many other clean solutions have an immense potential. Innovation together with economies of scale and government incentives can guarantee sustainable, cost-effective energy resources worldwide in the long-run.

- GOAL 9: INDUSTRY INNOVATION AND INFRASTRUCTURE

Innovation and investments in infrastructure are some of the main drivers of the energy transition. In order to reach carbon neutrality, it is essential to develop greener approaches fostering a multiplier effect on economic growth and value creation. By setting 2030 strategic goals that accelerate the path to net zero, existing technologies would become more efficient attracting green investments. This thesis focuses on the analysis of green hydrogen as a fuel source and for future infrastructure investments in maritime industry. The cell operating conditions, electrocatalyst materials, diaphragm/membrane, stackability of electrolyzers and photo electrolysis are the most promising areas of innovation for water electrolysis [10]. Hence, many renewable energy improvements are yet to come in the near future to build resilient infrastructure and promote sustainable industrialization.

- GOAL 11: SUSTAINABLE CITIES AND COMMUNITIES

The world is moving nowadays towards building more sustainable communities. The energy transition is part of all nations day to day concerns, which is why governments are making significant efforts to decarbonize all industrial activities including the transportation sector. Regarding the maritime industry, some subsidies and incentives are being given to make the ports and ships less pollutive. Hence, this thesis supports the green transition in the maritime industry by focusing on sustainable sailing boats powered by green hydrogen.

- GOAL 12: RESPONSIBLE PRODUCTION AND CONSUMPTION

Responsible production and consumption is interconnected with an efficient use of resources. In this case, hydrogen fuel cells can provide highly efficient and clean energy for boat propulsion, which reduces the use of fossil fuels and at the same time the carbon footprint of the maritime sector. Moreover, to produce hydrogen efficiently innovation and industry transformation are required. By using renewable resources such as solar and wind energy, green hydrogen will become a responsible and sustainable energy resource.

- GOAL 13: CLIMATE ACTION

As mentioned above, the decrease in CO_2 emissions continues to be our target to mitigate global warming effects and contribute to climate change. For this reason, the transition from traditional maritime fuels, which were extremely carbon intensive, to more sustainable fuels such as hydrogen, supports our target and contributes to technological innovation. By analyzing the different sustainable fuels and comparing them in techno-economic terms, the reader will become more aware about emerging technologies in the market and will be able to make more informed decisions to help our planet.

1.5. Structure and Planning

In this section, the structure of this thesis is explained in detail including the timeline of each part of the analysis. In order to understand the opportunities of hydrogen as a fuel propulsor of sailing boats, it is necessary to conduct an in-depth analysis of the different sustainable fueling technologies as well as the economic feasibility of the hydrogen sailing boat prototype. Once the economic and technical potential has been proven, a case study will be examined.

First, a review of the literature is made in order to understand how other authors have studied the economic and technical feasibility of different fueling technologies. In this thesis, the sustainable fueling resources that are considered are biofuels, synthetic fuels, hydrogen, and electricity. Since there could be many applications in the transportation sector (personal vehicles, trains, ships…), a review of past studies is key to understanding the broad picture and which economic calculations are most applicable for sailing boats.

Then, each fueling resource is analyzed separately under the objective of calculating the cost efficiency of each technology while understanding the market dynamics. The goal is to understand the future potential of each technology as well as the feasibility of the fueling infrastructure in ports.

Once the advantages and disadvantages of hydrogen as the main propulsor of sailing boats have been stated, an economic evaluation of the boat components is made through the TCO. The costs related to fuel cell and safety system, the hydrogen tanks, cooling system, the battery, and other elements are taken into account in this part of the thesis. The TCO for a hydrogen powered recreational boat is compared to the TCO of other sustainable fueling alternatives.

Finally, it is all put into practice by building a realistic case study based on a selected port location to exemplify the practical application of hydrogen in recreational sailing, elucidating the challenges encountered, outcomes achieved, and valuable insights gained.

The culmination of these three parts contributes to a holistic understanding of the prospects and implications of hydrogen utilization in the context of recreational sailing boats.

1.6. Resources

To attain the objectives that have previously been mentioned, many sources of information are needed such as academic journals and articles, government reports and policies, industry reports, real-world case studies, and databases to input reliable information into the analysis. The main tools that are going to be used for the report writing, calculations, and data outputting are Microsoft Office tools: Word, PowerPoint and Excel.

Chapter 2. TECHNO-ECONOMICAL COMPARISON

In this section, a comprehensive benchmarking analysis of various alternative fuels, namely Renewable Energy Sources (RES), green hydrogen (H2), biofuels (e.g., biodiesel and biomethanol), and synthetic fuels (e.g., e-diesel and e-methanol), is provided to discern their cost competitiveness and technological viability. The objective is to evaluate these alternative fuels across several Key Performance Indicators (KPIs) to ascertain their suitability for marine applications. Through an analytical comparison, this section delves into factors such as tank-to-propeller efficiency, as well as a benchmarking of levelized costs of fuel production, greenhouse gas (GHG) emissions reduction potential in the pipe and compared to the corresponding fossil alternative and refueling time. Furthermore, a qualitative analysis is conducted, considering resource availability, scalability, and technology readiness of each alternative fuel. This comprehensive approach provides valuable insights into identifying the most promising alternative fuel options for the decarbonizing the recreational maritime industry, facilitating informed decision-making towards sustainable and efficient marine propulsion systems.

It should be noted that factors such as fuel distribution and transportation, cargo fees, taxes and tolls are not considered in this section under the aim of providing a more generic reference value. These parameters highly depend on the port and production unit location. Therefore, large scale production units are being analyzed to compare cost competitiveness more effectively.

2.1. Renewable Electricity (Solar PV)

Renewable electricity is a key player in the global shift towards cleaner energy sources, among which solar PV has been recognized by European policymakers as a crucial technology already available at scale for citizens to access green and affordable electricity. Solar PV systems convert sunlight directly into electricity thanks to the semiconductors that create a voltage from the flow of electrons in the different solar cells, offering a sustainable and abundant energy solution with minimal environmental impact.

In Spain, the government has revised the energy and climate plan (PNIEC) establishing a target of 160 GW of RES by 2030 including 76.4 GW of solar PV, which proves its ambition to become one of the leading regions in the scale-up of this technology [11]. Indeed, Spain enjoys a geographical advantage with abundant sunlight throughout the year, surpassing many other European countries. The nation began intensifying its focus on solar PV investments prior to 2010, experiencing significant growth with the highest Compound Annual Growth Rate (CAGR) observed between 2018 and 2023, reaching ~40%. As of Q1 2024, Spain has already installed a substantial capacity of 25.8 gigawatts (GW) in solar PV infrastructure which proves its expertise and well-established infrastructure [12].

The abundant solar potential in Spain presents a promising opportunity for the maritime industry to transition from Internal Combustion Engine (ICE) recreational boats to electric boats, thus offering a viable decarbonizing alternative. An analysis of the feasibility and benefits of this transition is conducted below, considering factors such as cost competitiveness, energy efficiency, environmental impact, and technological maturity.

2.1.2 Energy consumption

The energy consumption of electric boats can be calculated by multiplying the traction force required to propel the vessel by the distance traveled and then dividing this product by the tank-to-propeller efficiency. This calculation accounts for the energy needed to overcome resistance and propel the boat forward, taking into consideration the efficiency of the propulsion system in converting stored energy (in the battery) into mechanical propulsion energy at the propeller.

The tank to propeller energy diagram flow for electric boats is shown in Figure 1.

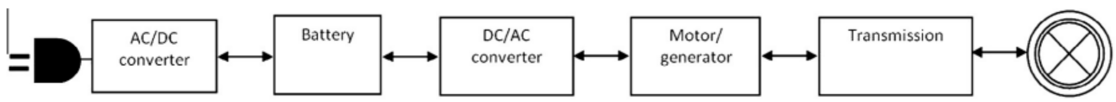

Figure 1: Energy flow diagram for electric boats. Source: Travesset-Baro et. al (2015) [13]

The corresponding efficiency has been calculated assuming the corresponding efficiency ranges presented in Table 2 as follows:

$$\eta_{TTP_{EV}} = \eta_{AC/DCconverter} \cdot \eta_{Battery\ input} \cdot \eta_{Battery\ output} \cdot \eta_{DC/ACconverter} \cdot \eta_{electric\ motor/generator} \cdot \eta_{mechanical\ transmission}$$

Components	**Unit**	**Minimum efficiency**	**Maximum efficiency**
AC/DC converter	%	90%	96%
Battery input	%	90%	99%
Battery output	%	93%	98%
DC/AC converter	%	96%	98%
Electric motor/generator	%	81%	95%
Mechanical transmission	%	89%	98%
Tank to propeller	**%**	**52%**	**85%**

Table 2: Efficiency range of each component of the value chain form tank to propeller of electric boats. Source: Travesset-Baro et. al (2015) [13]

Moreover, the refueling time should also be considered as an important KPI for electric vessels. Ports would need to adapt the infrastructure and install electric chargers if any share of the fleet were electric.

In many electric boats, an AC/DC converter is built into the vessel's system and is typically connected directly to the battery. However, this setup usually requires the boat to be connected to an AC (alternating current) power source for recharging, which can result in longer charging times compared to continuous current chargers. Consequently, electric boats need to be plugged into an AC power supply for recharging, such as those provided by Iberdrola's charging stations. These stations offer charging powers ranging from 11 kW to 22 kW for semi-fast charging and 43 kW for fast charging [14]. The AC of a charging station is calculated using the formula $P = 3 \cdot V \cdot I$, where P represents power, V represents voltage, and I represents current. Refueling time is determined by dividing the battery's energy by the power of the charging station. Assuming that the battery installed in the vessel has a nominal voltage of 365V, and 65kWh of energy, the resulting charging times range from ~2-6 hours as represented in Table 3.

Iberdrola e-chargers	**Unit**	**Semi-fast charging**		**Fast-charging**
Power	*kW*	22	11	43
Refueling time	***h***	**3.0**	**5.9**	**1.5**

Table 3: Electric vessels required refueling time based on the capacity of charging stations. Source: Own elaboration.

2.1.2 Fuel production analysis

This section delves into the realm of renewable electricity generated by solar PV systems in Spain, exploring key factors such as cost competitiveness, process efficiency, technology maturity, and GHG emissions. Solar PV has emerged as a leading contender in the global transition towards sustainable energy sources, and Spain's abundant solar resources render it a pivotal player in this landscape. By assessing the economic viability, operational efficiency, technological advancement, and environmental impact of solar PV installations in Spain, the goal is to determine whether the combination of technology advancements and cost competitiveness enables the scaling up of solar PV for integration into ports to power recreational boats.

2.1.2.1 Cost analysis

The levelized cost of electricity (LCOE) for solar PV in Spain is an important metric for evaluating the economic viability of solar PV systems. LCOE takes into account both the capital expenditure (CAPEX) and operational expenditure (OPEX) required to install and maintain the system over its lifetime. The CAPEX includes the initial investment in the solar panels, inverters, mounting structures, and other equipment required for the installation. On the other hand, OPEX includes ongoing expenses such as maintenance, repairs, cleaning, and monitoring of the system. The split between CAPEX and OPEX can vary depending on the size and complexity of the solar PV system, as well as the location and environmental conditions. Therefore, three different solar PV plants in Spain are used as a reference to estimate the LCOE by unit of energy (TJ) to later compare it with other alternative fuels considered for powering recreational vessels.

CAPEX for solar PV utility-scale projects encompass various upfront costs necessary for the development of the system. These costs typically include the purchase of solar panels, inverters, mounting structures, and other equipment required for energy generation. Additionally, CAPEX covers expenses related to installation labor, infrastructure development, land acquisition or leasing, permitting, engineering studies, and contingency funds. In this case, Table 4 represents CAPEX estimate used for LCOE calculation as derived from the €/MW values of three distinct utility-scale plants in Spain, resulting in an average of ~612 k€/MW.

Solar PV Plant	**Unit**	**Value**
FV Peñarrubia – Iberdrola		
Investment	*k€*	30,000
Capacity	*MW*	50
CAPEX	*k€/MW*	600
Francisco Pizarro – Iberdrola		
Investment	*k€*	300,000
Capacity	*MW*	553
CAPEX	*k€/MW*	543

4 plantas Extremadura y Andalucía - Enel Green Power		
Investment	*k€*	125,000
Capacity	*MW*	180
CAPEX	*k€/MW*	694
Average capex	***k€/MW***	**612**

Table 4: CAPEX estimate based on three utility-scale solar PV projects in Spain. Source: Own elaboration.

In addition, as dynamics of the solar industry evolve there would be a learning curve for upfront costs of solar PV based on optimization of manufacturing, economies of scale, and technological innovation. Therefore, an upfront investment costs for solar modules in Spain are expected to decrease ~20% by 2030 [15].

On the other hand, OPEX encapsulate ongoing expenses associated with the operation, maintenance, and management of the system throughout its operational lifespan. These costs commonly include maintenance activities to ensure optimal system performance, monitoring and management expenses for tracking energy production and optimizing efficiency, insurance premiums to safeguard against risks, land lease or rent payments for project sites, grid connection fees, administrative and regulatory compliance costs, and financing expenses (e.g, interest repayments). Furthermore, OPEX costs are often estimated as a percentage of CAPEX. Simura, et. al 2016 assume OPEX represents between 0.8%-1.2% of CAPEX for estimating production of solar PV plants [16], while NREL estimates are slightly higher revealing a share of 1.7%-2.3% [17]. In this thesis, an average of 1.5% is used including a perpetual increase of ~0.9% in OPEX costs throughout the lifecycle of the solar PV plant assuming more frequent maintenance repairs to maintain sustainable performance levels.

By taking into account the continuous evolution and enhancement of cost competitiveness, LCOE of solar PV has been estimated for 2030 under the purpose of comparing it with less mature alternative fuel technologies.

$$LCOE_{2030} = \frac{CAPEX_{2030} + \sum_{n=1}^{N} OPEX_{annual} \cdot \frac{1 - \frac{1+g}{1+WACC}^{n}}{WACC - g}}{\sum_{n=1}^{N} Energy\ output_{annual} \cdot \frac{1-(1+WACC)^{-n}}{WACC}}$$

$$g = growth\ rate\ of\ OPEX; n = lifecycle\ of\ the\ solar\ PV\ plant$$

As a result, ~24€/MWh LCOE for solar PV is obtained by using a 5% weighted average cost of capital (WACC) [16], [17].

2.1.2.2 Technology maturity

Solar PV in Spain has a positive impact on GDP, increasing by ~30% from 2019 to 2021 thanks to the footprint of the sector. Since the elimination of the sun tax in 2018 the sector has evolved significantly, which eased the development of Spanish competitive advantage for RES. Spain is among the top 10 countries in Europe with the greatest installed solar capacity and many stakeholders are focusing on ensuring there are enough investments for technology scale-up. Decreasing module prices, high GHG emissions reduction potential compared to fossil alternatives, competitive geographical advantage and significant expertise make Spanish solar PV electricity an attractive opportunity for decarbonization of many sectors, including maritime transport. However, the main bottleneck for solar PV may be the scale-up of this technology due to regulatory and grid connection constraints[18].

The extensive regulatory framework and prolonged permitting procedures in Spain present notable hurdles across various sectors, notably impacting solar PV projects. These challenges can impede project development, competitiveness, and energy security. The permitting process in Spain is notorious for its sluggishness, posing a bottleneck for renewable energy deployment. Complicated and time-consuming administrative processes can delay the completion of renewable energy projects. Access and connection permits can incur delays and the entire permit-granting process for large-scale solar PV projects may extend to a staggering +8 years. Red Eléctrica Española, the grid operator, assumes a pivotal role in evaluating access capacity and connection feasibility which remains as one of the main bottlenecks for solar PV scale-up of solar PV installations [19].

Curtailment occurs when the electricity generated by RES exceeds the demand or grid capacity, leading to the temporary shutdown or reduction of renewable energy production. In Spain, this issue is particularly pronounced for solar PV due to its intermittent nature and the mismatch between solar generation patterns and peak electricity demand. Consequently, there is a pressing need to enhance storage capacity to mitigate curtailment and ensure the efficient utilization of solar energy resources. Increasing storage capacity, through the deployment of battery storage systems or other storage technologies, is essential for facilitating the integration of solar PV into the grid and advancing Spain's transition towards a more sustainable and resilient energy system[20].

2.1.2.3 GHG emissions

Renewable energy sources used for powering vessels are a carbon neutral alternative considering the emissions in the pipe, being one of the most promising opportunities for decarbonization of the maritime sector. Several studies have examined the GHG emissions of solar PV under a lifecycle analysis (LCA) yielding to varying results. In this thesis, NREL harmonized results have been used as a reference for estimating LCA GHG emissions and its potential reduction compared to fossil fuels. NREL gathered +100 studies published for solar PV comparing LCA emissions for crystalline silicon modules and thin film modules harmonizing the results based on the parameters shown in Table 5 [21].

Parameter	**Value**
Solar Irradiation (kWh/m^2 /yr)	1,700-2,400
System Lifetime	30 years
Crystalline Silicon Module Efficiency	
Mono-crystalline	14.0%
Multi-crystalline	13.2%
Thin Film Module Efficiency	
Amorphous silicon (a-Si)	6.3 %
Cadmium telluride (CdTe)	10.9%
Copper indium gallium diselenide (CIGS)	11.5%
Performance Ratio	
Ground-Mounted	0.80
Rooftop	0.75

Table 5: Harmonization parameters for LCA of solar PV emissions. Source: NREL[11]

Harmonized results translate into 65% lower variability in the interquartile range of LCA emissions. Solar PV results in ~40 gCO2eq/kWh LCA emissions, being upstream processes (incl. raw materials extraction, materials production, manufacturing and construction/installation of PV arrays) responsible for 60-70% of emissions. Compared to coal, solar PV plants lead to ~60% lower LCA emissions per output energy (kWh). During the production of electricity from coal, the operational process emits the greatest share of CO2 +98%, revealing the attractiveness of solar PV technologies for decarbonization of electricity generation. Indeed, among the existing RES, solar PV and concentrated solar power (CSP) could be the least polluting technologies. CSP may lead to lower LCA emissions thanks to its potential to generate greater amounts of electricity than solar PV under the same geographical conditions.

Furthermore, the efficiency of solar PV modules is limited to 10-20% depending on the raw material used. Monocrystalline silicon has proven the greatest efficiency which could range from 18%-20% in Spain and lead to greater GHG emission reduction potential [22]. Various solutions to increase the efficiency of solar PV modules include perovskites, graphene-based, tandem or multi-junction solar cells, bifacial solar panels, building integrated solar PV, hybrid systems of solar and storage, and smart systems enabling more efficient inverter and solar PV system operation.

2.2. Green Hydrogen

Green hydrogen could play a pivotal role in decarbonizing the transport sector by offering a zero-emission energy source produced from renewable sources (wind and solar). Indeed, green hydrogen could be used as a clean and efficient energy to power fuel-cell vehicles, where it is stored in tanks and then fed into fuel cells, where it reacts with oxygen from the air to produce electricity, powering the vehicles propulsion system. This process emits only water vapor as a byproduct, making fuel cell boats environmentally friendly with zero greenhouse gas emissions.

There is a strong momentum for green hydrogen projects globally where Spain represents one of the green hydrogen frontrunners in Europe, together with Denmark, Netherlands and Germany [23]. Thanks to its natural endowments and capacity to produce renewable energy at lower costs than other European countries, Spain had already announced ~20% of total green hydrogen projects globally, being only behind the US. Among the Projects of Common Interest selected by the EU Commission in 2024, many of them are related to hydrogen development, interconnection and production scale-up which reveals the upcoming importance of hydrogen for decarbonization [24]. In Spain, the PNIEC has set a target of 11GW electrolyzer capacity by 2030, updating the previous target (4GW of electrolyzer capacity) set in the Spanish hydrogen strategic plan: *"Hoja de Ruta del Hidrógeno Renovable"* [11]. Furthermore, an addendum to the Spanish Recovery and Resilience Plan included additional funding of 5.5Bn€ for Renewables, Hydrogen and Storage, reinforcing the Spanish efforts to develop green hydrogen infrastructure.

Regarding the application of green hydrogen to the maritime industry, fuel cells can provide significant advantages as they offer longer ranges and faster refueling times compared to traditional batteries, making them a promising solution for decarbonizing maritime transport, and attaining the IMO's net-zero objectives in the sector. There is an opportunity for hydrogen fuel cells to reduce GHG emissions of small, short-haul vessels (including ferries, recreational boats, and cargo ships) serving as a catalyst for innovation. The scale-up of FC technology to power larger vessels poses a technical and logistical challenge as significant storage capacity is required for propulsion due to the H2 low energy density.

2.1.3 Energy consumption

The tank-to-propeller efficiency for hydrogen fuel cell boats encapsulates the seamless energy flow from onboard hydrogen storage tanks to the propulsion system. Hydrogen, stored onboard in tanks, is fed into fuel cells where it undergoes electrochemical reactions with oxygen from the air (electrolysis process), generating electricity to power the vessel's electric motors. At this step, the electricity undergoes a similar process as in the electric vessels, the DC electricity is stored in a battery and later converted into the AC electricity used in the electric motor driving the propeller. The whole process is represented in Figure 2.

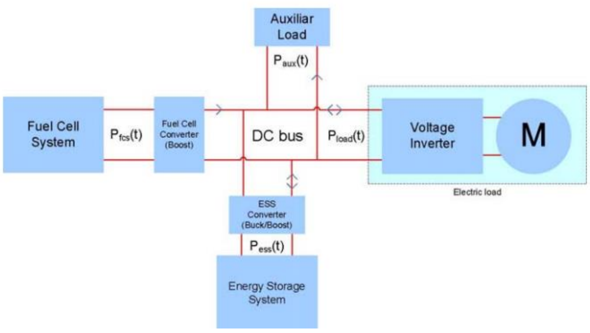

Figure 2: Energy flow diagram for hydrogen FC boats. Source: Feroldi et. al [25]

Fuel cells are categorized based on the electrolyte used in their electrochemical process. Proton Exchange Membrane (PEM) fuel cells, although less efficient compared to alternatives like Alkaline Fuel Cells (AFC), are widely adopted and easily accessible in the market. PEM fuel cells are favored for their quick startup, high power density, and compact design, making them ideal for applications such as vehicles and portable electronics. In contrast, AFCs, despite their potential for higher efficiency, are less prevalent due to their larger size, complexity, and restricted availability [26]. Hence, FC technology's efficiency influences the tank-to-propeller efficiency as follows:

$$\eta_{TTP\,FC} = \eta_{FC} \cdot \eta_{Battery\ input} \cdot \eta_{DC/ACconverter} \cdot \eta_{electric\ motor/generator} \cdot \eta_{mechanical\ transmission}$$

Components	Unit	Minimum efficiency	Maximum efficiency
Fuel cell	%	35%	65%
Battery input	%	90%	99%
DC/AC converter	%	96%	98%
Electric motor/generator	%	81%	95%
Mechanical transmission	%	89%	98%
Tank to propeller	**%**	**22%**	**59%**

Table 6: Efficiency range of each component of the value chain form tank to propeller of hydrogen FC boats. Source: Travesset-Baro et. al (2015) [13]

Compressed hydrogen tanks are essential components of fuel cell systems that hold the fuel needed to generate energy. Fueling time has a significant impact on both user convenience and operational effectiveness. However, the compression process might cause higher temperatures as a result of faster fueling, which raises safety concerns [27]. For fueling operations to be both safe and efficient, effective temperature management solutions are necessary to reduce the possibility of temperature spikes throughout the operation. Therefore, temperature in the cylinder has been limited to 85ºC, leading to a maximum fueling rate of 3.6 kg/min as stated by SAE J2601 protocol [28].

Assuming the hydrogen tank used for recreational vessels traveling small distances has a working pressure at 15ºC of 350 bar and a total capacity of 8 kg at the same pressure, the refueling time is calculated by dividing the total tank capacity by the fueling rate. For safety reasons and to avoid overfilling the tank, the state of charge (SOC) should be between 95% and 100%. Consequently, leading to a charging duration of 2-3 minutes. In case the tank was bigger, the refueling time would be higher, but still faster than the equivalent for an electric battery.

2.1.4 Fuel production analysis

Similar to the equivalent section included above for RES, a cost analysis of the levelized cost of producing green hydrogen is conducted to understand the competitiveness of this technology. In addition, technology readiness is considered as another KPI as it could be a differentiating factor when considering other alternative fuel technologies. Finally, a LCA analysis is presented to understand the impact of green hydrogen compared to fossil production of hydrogen from steam methane or power from the electricity grid. The goal is to understand quantitatively and qualitatively the role of green hydrogen to decarbonize small, short-haul vessels in the maritime industry in Spain.

2.1.4.1 Cost analysis

In recent years, several ambitious projects have been announced globally, aiming to scale up green hydrogen production and drive down costs. Leveraging some of these pioneering initiatives in Spain as reference points, this section focuses on the analysis of levelized cost calculations for green hydrogen, offering insights into the key factors influencing the affordability and scalability of green hydrogen production on a large scale.

Currently, three distinct electrolyzer technologies dominate the market: alkaline, PEM (proton exchange membrane), and SOEC (solid oxide electrolyzer cell). Among these, alkaline and PEM electrolyzers stand out as the most mature technologies, albeit with lower energy efficiencies compared to SOEC. Regardless of the chosen technology, electrolyzers constitute the largest proportion of CAPEX for green hydrogen production

~50-60% [29]. Additional CAPEX components encompass engineering, construction, and commissioning expenses, alongside costs associated with storage tanks and grid fees. According to IRENA, maximum PEM electrolyzer CAPEX would be ~1.6 Mn€/MW of electrolyzer capacity. These costs are used as a reference for the below annualized estimation per kg of green hydrogen assuming 50% utilization with an energy density of 33.3 kWh/kg H2 and average efficiency of 50%.

OPEX is also considered for the production costs calculation of green hydrogen. It should be noted that the greatest OPEX is related to the price of electricity plus the amount of electricity required as feedstock for the electrolyzer. Overall energy costs are significantly variable and could represent +60% of green hydrogen production costs. The electricity required for green hydrogen production is ~67 kWh/kg of H2 as indicated by IRENA [30]. As a proxy in this thesis, the electricity is assumed to be produced ~40% by solar PV and ~60% by wind under the aim of avoiding the need for grid connection. Solar PV electricity costs are assumed to be equal to the LCOE estimated in the previous section and the equivalent LCOE for wind is assumed to be ~2 times higher than solar PV [31]. Furthermore, other opex include operation and maintenance and it is normally ~2-4% of direct capital expenditures depending on whether stack replacement costs are included [29].

As a whole, the levelized cost of green hydrogen production is estimated to be ~5.1 €/kg of H2 calculated as per the equation shown below.

$$LCOH_{2030} = \frac{CAPEX_{2030} + \sum_{n=1}^{N} OPEX_{annual} \cdot \frac{1 - \left(\frac{1+g}{1+WACC}\right)^{n}}{WACC - g}}{\sum_{n=1}^{N} Green\ H2\ output_{annual} \cdot \frac{1-(1+WACC)^{-n}}{WACC}}$$

$$g = growth\ rate\ of\ OPEX; n = lifecycle\ of\ the\ plant$$

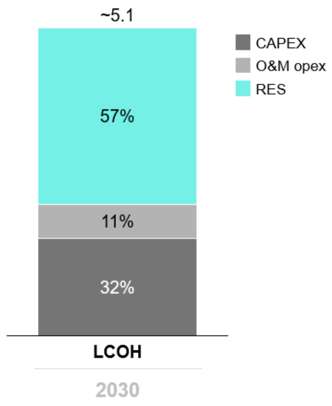

Figure 3: Levelized Costs of Producing Green Hydrogen. Source: Own elaboration.

2.1.4.2 Technology maturity

Green hydrogen can provide a clean and sustainable pathway to transition from fossil fuels to green energy sources in the maritime industry. Furthermore, liquid hydrogen can become a very attractive alternative for small, short-haul vessels thanks to its fast-refueling capacity and the possibility to travel longer ranges compared to electric vessels thanks to a higher energy density.

On the other hand, there is not enough green hydrogen capacity developed at scale to transition from internal combustion engines. In Spain, there are currently more than 70 green H2 projects publicly announced according to IEA, but less than 0.1% of the capacity is already operational. The lack of operational green hydrogen capacity hampers its immediate use to power vessels. Without sufficient infrastructure for green hydrogen production and distribution, vessels may continue to rely on traditional fuels, delaying the adoption of hydrogen-powered propulsion systems.

Transitioning from pilot and demonstration projects to commercial-scale operations remains unrealized globally, only 4% of the global potential production capacity has at least taken final investment decision (FID). Furthermore, there is significant uncertainty on the deployment of these projects due to the lack of manufacturing capacity and expertise, the long permitting process and a potential scarcity of feedstock required (RES and water). In addition, the most used electrolyzer is the PEM which may result in lower efficiencies than other technologies. Independently of the electrolyzer technology used, significant CAPEX and RES are required which may hinder the deployment of these projects unless funding is available. For this reason, Spain became one of the early movers in Europe by providing government funding to some of the hydrogen projects while increasing 5.5 Bn€ the government funding for the Strategic Project for Recovery and Economic Transformation on Renewable Energy, Hydrogen and Storage [23].

In general, greater efforts are required to provide funding for the development of green H2 projects, boost innovation to enhance cost and technical efficiency, plus shorter permitting timelines.

2.1.4.3 GHG emissions

Green hydrogen used as fuel source for powering vessels is a carbon neutral alternative considering the emissions in the pipe. Therefore, it is one of the most promising alternatives for decarbonization of the maritime sector. A LCA comparing green and grey hydrogen production methods reveals significant differences in their environmental impacts. While the primary source of GHG emissions in grey hydrogen stems from the production process, typically involving steam methane reforming or grid-powered electrolysis, green hydrogen demonstrates a substantial reduction in GHG emissions, estimated at 75-80%. Notably, among electrolyzer technologies, Proton Exchange Membrane (PEM) exhibits the lowest system efficiency compared to alkaline and solid oxide electrolysis, necessitating higher electricity consumption. Despite PEM's environmental impact stemming from platinum use in electrolysers, the overarching factor influencing environmental footprint remains electricity input. Solid oxide electrolysis emerges as the most efficient technology across impact categories, albeit reportedly underdeveloped relative to PEM and alkaline electrolysis. Nonetheless, PEM and alkaline electrolysis, owing to their maturity and relative advantages, remain favored options [32].

Efficiency enhancement in green hydrogen production is crucial for reducing the LCA. Strategies such as integrating large-scale renewable energy sources (potentially combining several technologies to increase utilization of the electrolyzer) and advancing electrolyzer technologies can significantly improve efficiency. Investing in research for advanced catalysts and electrolyzer scale-up, along with waste heat recovery and electrolyte recycling, further contributes to efficiency gains. Grid connection could improve electrolyzer utilization, but it may result in higher volatility, connectivity challenges and higher GHG emissions in case the Spanish grid is not 100% renewable in the upcoming future. By maximizing energy utilization and minimizing losses throughout the production process, green hydrogen becomes more competitive as a sustainable energy carrier, driving the transition towards a net-zero future.

2.3. Biofuels

Biofuels can play a pivotal role for decarbonizing the transport sector as they can substitute fossil fuels in most internal combustion engines (ICEs), which are still the most common alternative used in cars, ships, and planes. Biofuels are produced with bio-based feedstocks. Depending on the origin of the feedstock used to produce biofuels, they can be classified into 1st generation biofuels, when produced from edible crops of food-based feedstocks (e.g., corn, sugarcane, palm oil), or 2nd generation biofuels, when produced from biomass or residues (e.g., animal fats, used cooking oil (UCO), agricultural waste). The EU has set a 7% cap on 1st generation feedstocks as there is a growing concern regarding land use, environmental damage, or competition with food supplies. Indeed, RED III states that high-ILUC risk feedstocks should be phase-out by 2030 [33].

Compared to fossil fuels, these bio-based feedstocks enable a significant GHG emissions reduction which makes them an attractive alternative for short-term reduction of the carbon footprint for ICEs. Indeed, Spain has set an objective of 11% share of biofuels in the transport sector or 2024, increasing up to 12% by 2026 which reveals their increasing importance for the energy transition [34].

Currently, over 95% of maritime vessels rely on internal-combustion engines (ICEs) fueled by a range of petroleum products, including heavy fuel oil (HFO), marine gas oil (MGO), and marine diesel oil (MDO). These conventional fuels have long been the backbone of the maritime industry, powering various types of ships across the globe.

However, this reliance on fossil fuels contributes significantly to greenhouse gas emissions and other environmental concerns which presents as short-term opportunity for biofuels as these fuels can leverage the existing infrastructure of boats and ports ensuring reliable and sustainable energy sources for maritime transportation [35]. Biodiesel and biomethanol are the most attractive alternative fuels for powering vessels. Its future use will vary depending on cost competitiveness and feedstock availability.

2.3.1 Energy consumption

The analysis of internal combustion engine (ICE) two key factors are taken into account to estimate the tank to propeller efficiency: engine efficiency and mechanical transmission efficiency. Engine efficiency assesses how effectively the engine converts fuel energy into mechanical power, considering factors such as combustion efficiency and friction losses. Meanwhile, mechanical transmission efficiency evaluates the effectiveness of transferring this mechanical power from the engine to the propeller, accounting for losses in components like gears and shafts. By multiplying both, the tank-to-propeller efficiency in determined, providing a comprehensive measure of the engine's performance in converting fuel energy into useful thrust for propulsion. For the purpose of this thesis, a range of 39-47% efficiency is considered as per the calculations shown in Table 7.

ICE diesel	Unit	Minimum efficiency	Maximum efficiency
Diesel engine efficiency	%	20%	40%
Mechanical transmission	%	89%	98%
Tank to propeller	**%**	**18%**	**39%**

Table 7: ICE Tank-to-propeller efficiency. Source: Travesset-Baro et. al (2015) [13]

When evaluating the refueling time of diesel vehicles and comparing it to hydrogen and electric vehicles, notable differences emerge that shape the overall convenience and usability of each fueling option. Short-haul ICE vessels typically requires ~6 minutes to refuel, a process involving pumping liquid fuel into the vehicle's tank [36]. It must also be considered the difference in the availability of refueling stations in national ports. As ICEs have been the most popular engines used to power vessels, the refueling infrastructure is already present at national ports, providing a significant advantage to sustainable fuels that are compatible with existing infrastructure such as biodiesel, biomethanol and the equivalent synthetic fuels.

2.3.2 Fuel production analysis

In this section, fuel production of both biodiesel and biomethanol are considered since these alternative fuels are considered the most viable fuels for short-haul vessels which are the focus on this thesis.

2.3.2.1 Cost analysis

In this section, comprehensive assessments of the production costs of biodiesel and biomethanol are conducted, drawing insights from various facilities. This comparative analysis sheds light on the relative competitiveness of biodiesel and biomethanol production, offering valuable insights for consumption in the maritime sector.

In Spain, biodiesel production has long been synonymous with Fatty Acid Methyl Esters (FAME), a blend of biodiesel (~10-15%) and conventional gasoil. As a result, there's been a notable shift towards the production of HVO which is a renewable diesel that does not need to be blended with fossil fuels, representing a significant evolution in the biofuels landscape. Unlike FAME, HVO stands out as a 100% renewable diesel, offering considerable advantages in terms of reduced greenhouse gas (GHG) emissions and improved environmental sustainability. In Spain, this transition towards HVO production is exemplified by the emergence of advanced co-location units within refineries. Notably, one of the largest co-location units for HVO production: Repsol's refinery in Cartagena and Cepsa's refinery in Huelva. These units have been considered as a reference for estimating CAPEX as shown in Figure 4.

CAPEX detail		
Repsol cartagena		
Investment	€	250.000.000,00
Production	ton pa	250.000,00
CAPEX	€/ton pa	1.000,00
Cepsa Huelva		
Investment	€	1.050.000.000,00
Production	ton pa	500.000,00
CAPEX	€/ton pa	2.100,00
CAPEX estimate - average	€/ton pa	1.550,00

Figure 4: CAPEX and production detail of two HVO co-location units. Source: Repsol, Cepsa (2024)

The annual operational expenditure associated with biofuel production is allocated across three primary categories: O&M, hydrogen costs, and feedstock costs. O&M expenses typically represent ~5% of the total CAPEX, covering the routine upkeep and operational management of production facilities. Hydrogen plays a vital role in both purifying the feedstock and transforming it into a high-quality renewable diesel fuel, for producing one ton of HVO ~0.03 tons of H2 are required. Meanwhile, feedstock costs constitute a substantial portion of OPEX and are heavily contingent upon the source material. Second-generation feedstocks, derived from non-food sources such as waste oils or residues, often entail higher costs due to factors like limited availability, specialized processing requirements, and increased logistical complexities. In this context, used cooking oil (UCO) costs have been selected as a reference. UCO prices are particularly susceptible to fluctuations due to the variable nature of its availability and trading, for this analysis a range of ~900-1,700 €/ton has been considered [37].

Taking both capital and operational expenditures into account, the levelized cost of producing HVO is ~1,400-2,200 €/ton HVO, significantly dependent on the market prices of feedstock which are highly volatile.

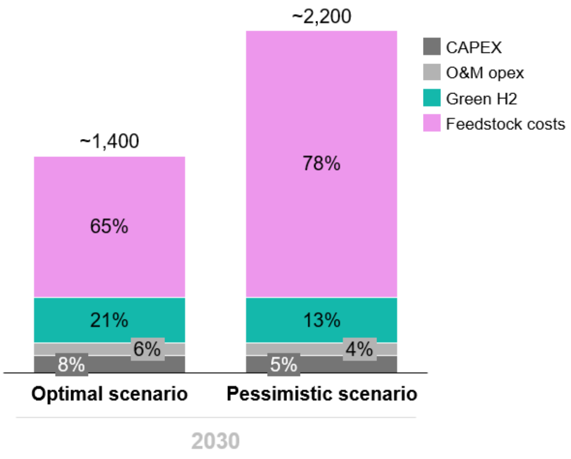

Figure 5: Levelized cost of producing HVO from UCO (€/ton HVO). Source: Own elaboration.

Competitive feedstock sourcing is an essential condition for competitiveness given the share of feedstock market price in total cost of product (~65-80% in net product costs), even small relative advantages in this item may offset any differentials on other items. Indeed, feedstock prices can be largely driven by market conditions, which reflects the importance of securing feedstock and building a resilient supply chain for biofuels at national level.

Furthermore, the production cost analysis of biomethanol is included in this section. There is no operational biomethanol plant in Spain nowadays and there is only one project announced at national level. This project which is currently under development by Enerkem and Repsol, is expected to produce biomethanol from gasification and will start operations in Tarragona by 2026 [38]. Therefore, as a reference of the required costs, several European facilities that are developing biomethanol projects through gasification units are considered, resulting in an average CAPEX of ~2,800 €/ton of biomethanol as shown in Figure 6 [39].

CAPEX estimation		
Repsol Enerkem - Tarragona		
Investment	€	580.000.000,00
Production	ton pa	220.000,00
CAPEX	€/ton pa	2.636,36
Enerkem - Rotterdam		
Investment	€	580.000.000,00
Production	ton pa	215.000,00
MSW	ton pa	400.000,00
CAPEX	€/ton pa	2.697,67
Eni/NextChem - Livorno		
Investment	€	330.000.000,00
Production	ton pa	115.000,00
CAPEX	€/ton pa	2.869,57
CAPEX estimate - average	€/ton pa	2.783,62

Figure 6: CAPEX and production overview of European gasification units producing biomethanol. Source: Ingvar Landälv (2021)

Under the aim of estimating the levelized costs of producing biomethanol, annual operating expenses, which are split into O&M and feedstock costs, should also be considered. The O&M operating expenses are projected to be 5-10% of total capital expenditures, representing the range from an optimistic to a pessimistic scenario. The feedstock required for producing biomethanol can be either biomass or municipal solid waste. For simplicity, this analysis focuses solely on biomass, specifically wood pellets, which are priced around 300-400 €/ton. Given that 1.75 tons of biomass are needed to produce one ton of biomethanol, the feedstock costs form a significant portion of the overall expenses [40].

Therefore, the total costs of producing biomethanol would be ~870-1,200 €/ton biomethanol as represented in Figure 7, with feedstock costs representing the greatest share. This is because the price of biomass feedstock is significantly higher than the combined O&M opex and capital expenditure due to the cost of sourcing and competition from other sectors for bio-based feedstocks.

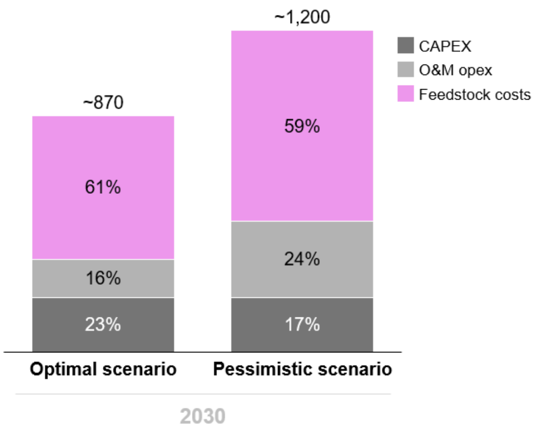

Figure 7: Levelized cost of producing biomethanol from biomass (€/ton biomethanol). Source: Own elaboration.

2.3.2.2 Technology maturity

In Spain, biofuels are already being used in the transport sector blended with traditional fuels as FAME and bioethanol. Demand is expected to increase due to regulation, technology maturity and its emissions reduction potential. Indeed, shipping companies expect that biodiesel and biomethanol represent +13% of total maritime demand in 2030, increasing up to ~25% by 2050 [35].

The establishment of biofuel production facilities demonstrates Spain's dedication to decarbonization efforts. Biodiesel emerges as a near-term alternative for internal ICE vehicles, given its current production. Spain currently operates ~9 standalone, co-processing, or unit conversion biodiesel (HVO) production facilities, indicating a mature technology and a promising avenue for replacing conventional fuels in maritime transportation. Conversely, the construction of only one biomethanol unit is underway, slated for operation by 2026, highlighting a slower progress in this sector compared to biodiesel. In addition, methanol may require the installation of new engine cylinder heads, double-walled piping, and the implementation of monitoring and ventilation systems to detect slippage as it may not be 100% compatible with existing ICEs, unlike biodiesel and HVO [41].

Spain holds a distinct advantage in its biofuel transition due to its existing infrastructure, boasting eight refineries capable of conversion, co-processing, or constructing standalone biofuel units. This versatility offers significant synergistic potential, allowing for seamless integration of biofuel production alongside traditional refining processes. These refineries, collectively representing the third-largest production capacity in Europe, trailing only behind Germany and Italy, provide a robust foundation for Spain's biofuel expansion. Leveraging this established industrial base, Spain stands poised to accelerate its journey towards decarbonization by tapping into its refining expertise and scale to meet domestic demand effectively [42].

Nonetheless, the production of biofuels also presents certain challenges that must be addressed to achieve large-scale production efficiently. Biofuels constitute a capital-intensive industry, with feedstock accounting for over 50% of production expenses, resulting in higher costs compared to traditional fuels [43]. Hence, ensuring the long-term cost competitiveness of the industry necessitates financial incentives and regulatory backing. Such support mechanisms are vital for sustaining the viability of biofuel production and ensuring its continued contribution to the broader energy landscape. Other countries are setting more ambitious biofuel mandates or GHG emissions reduction for the transport sector (e.g., UK, Netherlands, Portugal), higher carbon taxes, penalties, and fiscal incentives (e.g., France, Sweden, UK), increasing the cost competitiveness of biofuels.

2.3.2.3 GHG emissions

LCA studies have highlighted the significant emissions reduction potential of biodiesel and biomethanol compared to their fossil fuel counterparts. Biodiesel, depending on the feedstock utilized, has been shown to mitigate emissions by 50%-90% compared to its equivalent fossil energy source. This reduction stems from factors such as carbon sequestration during feedstock growth and lower emissions during combustion. Conversely, biomethanol is often regarded as a carbon-neutral alternative, as the carbon dioxide emitted during its use is balanced by the carbon absorbed during feedstock growth. These findings underscore the substantial environmental benefits of both biodiesel and biomethanol, positioning them as promising contributors to efforts aimed at mitigating climate change and transitioning towards more sustainable energy systems [44].

2.4. Synthetic Fuels

Synthetic fuels are another drop-in fuel alternative to conventional fossil fuels with higher emissions reduction potential compared to biofuels. These fuels are produced from green hydrogen and CO2 which are then combined through the Reverse Water Gas Swift (RWGS) process to form syngas, carbon monoxide (CO). The syngas is further synthetized under a Fischer Tropsch reaction and further upgraded to produce synthetic fuels, or efuels [45].

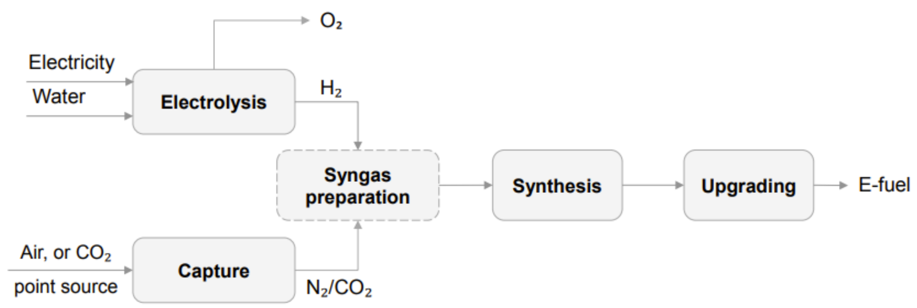

Figure 8: Overview of e-fuel's production process. Source: IEA (2023)

The potential of e-fuels in the maritime sector is substantial, offering significant emissions reduction benefits and enhancing low-carbon energy security for the industry. Similar to biofuels, these alternative fuels require minimal transformation of existing port infrastructure, facilitating their integration into current maritime operations. Given their drop-in compatibility, they can be seamlessly utilized in existing ICEs, with minor adjustments required for e-methanol and e-ammonia, as discussed previously. Notably, the introduction of a 5.5% objective of advanced biofuels and synthetic fuels, with a non-binding 1.2% target for synthetic fuels for maritime industry by 2030 under RED III underscores the pressing need for their adoption in the short term to meet national decarbonization objectives.

2.4.1 Energy consumption

Biofuels' tank to propeller efficiency, refueling time as well as refueling infrastructure are applicable to synthetic fuels as they are also compatible with ICE engines which provides significant opportunities for costs competitiveness as the existing infrastructure can be leveraged for future use.

2.4.2 Fuel production analysis

The fuel production analysis varies depending on the synthetic fuel in question, whether e-methanol or e-diesel. In both cases, green hydrogen (H2) and carbon dioxide (CO2) are used as feedstocks for syngas production, contributing to operating expenses along with plant operation and maintenance. Consequently, capital investments for producing these fuels encompass all necessary machinery and equipment from syngas preparation to the final output of synthetic fuel, as illustrated in Figure 9.

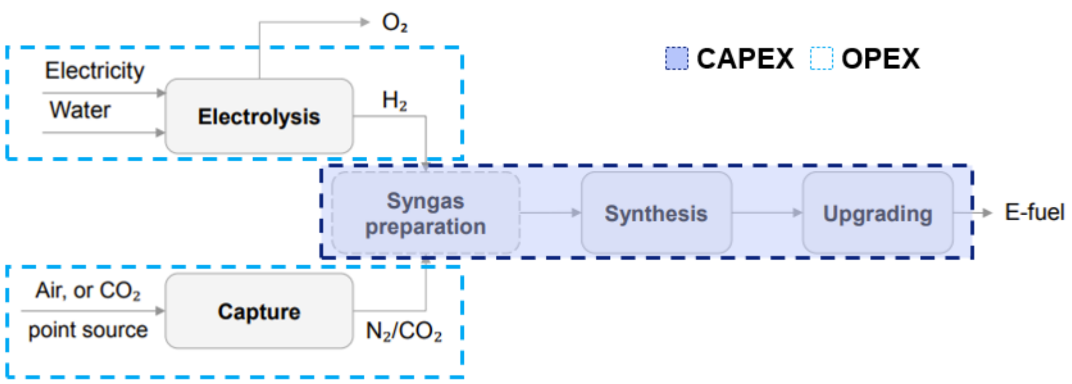

Figure 9: Production costs split between CAPEX and OPEX. Source: Own elaboration.

It should be noted that carbon costs may be quite uncertain in the upcoming years. To provide a realistic estimation, both an optimal and a pessimistic scenario are considered. As of today, carbon costs associated to EU ETS are ~80€/ton of CO2 but are expected to increase due to growing global regulatory measures aimed at GHG emissions reduction. Consequently, a high case scenario or pessimistic scenario is considered where prices are ~200€/ton of CO2 [46]. For simplicity, the costs of green hydrogen are assumed to match the LCOH calculated in Section 2.2. It is important to note that this assumption is conservative, as green hydrogen costs could be significantly higher if the technology scales up at a lower rate.

2.4.2.1 Cost analysis

First, the production costs of e-methanol are estimated considered there are a couple of production units that have already been announced by the main players and could be readily available for use by 2030.

The CAPEX costs considered in the calculation of the levelized costs of producing e-methanol encompass three essential processes: syngas preparation, methanol synthesis, and methanol distillation. These processes are fundamental to the efficient production of e-methanol, starting with the preparation of syngas, which serves as a crucial feedstock, followed by its conversion into methanol through synthesis, and finally, the distillation process to purify the resultant methanol. The total CAPEX for these components amounts to ~203,400€, representing the comprehensive investment required to ensure the operational viability and economic efficiency of the e-methanol production system [47].

Additionally, the annual operational expenditure for the e-methanol production system is divided into two main categories: operations and maintenance (O&M) costs and feedstock costs. The O&M costs account for ~5% of the total CAPEX annually, covering the expenses necessary for the upkeep and efficient functioning of the production facilities. On the other hand, the feedstock costs are a significant component, with the production of one ton of e-methanol requiring approximately 0.19 tons of green H2 and 1.38 tons of CO2 [48]. Assuming no inflation or other factors—such as fluctuations in energy prices, changes in feedstock availability, or advancements in technology—that could impact feedstock prices, the resulting levelized costs of producing e-methanol amount to ~1,260-1,430 €/ton e-methanol by 2030 assuming a WACC of 5%.

$$LCOe - fuels_{2030} = \frac{CAPEX_{2030} + \sum_{n=1}^{N} OPEX_{annual} \cdot \frac{1 - \frac{1+g}{1+WACC}^{n}}{WACC - g}}{\sum_{n=1}^{N} ton\ of\ output_{annual} \cdot \frac{1-(1+WACC)^{-n}}{WACC}} n$$

$$= lifecycle\ of\ the\ plant$$

Feedstock costs represent ~80% of fuel production costs (Figure 10) as a result of the significant green H2 and CO2 requirements for the chemical synthesis. Furthermore, the share of feedstock costs is highly impacted by the market volatility and technology readiness.

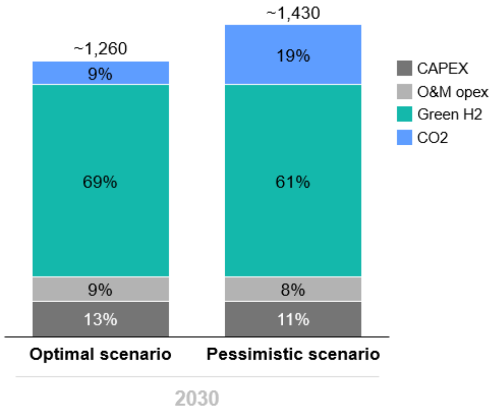

Figure 10: Levelized cost of e-methanol production [€/ton e-methanol]. Source: Own elaboration.

Synthetic diesel is also considered as an attractive alternative to decarbonize the maritime sector since it is a byproduct of the e-jet production under the power to liquid (PtL) process. For every ton of e-jet produced, ~0.33 tons of e-diesel are obtained which would be leveraged for industrial and transport uses.

In this context, the CAPEX includes the reverse water gas shift (RWGS) process for syngas production, Fischer-Tropsch (FT) synthesis, and subsequent fuel upgrading processes such as distillation, isomerization, and hydrocracking, culminating in a total investment of approximately €15,700 per ton of e-diesel. This cost is particularly high because PtL units primarily focus on producing e-jet fuel, one of the few viable options for decarbonizing the aviation sector, resulting in minimal output of e-diesel. As the technology is currently at a pilot stage and yet to be proven in Spain, the capital expenditure is anticipated to decrease significantly, leveraging economies of scale and other efficiencies. Consequently, the optimal scenario in Figure 11 projects a reduction of 50% in CAPEX by 2030, reflecting advancements in technology, increased production scale, and enhanced operational effectiveness [45].

Similar to e-methanol units, the annual O&M OPEX represents a small share of CAPEX (~3% in this case) and the feedstock operating costs are the most relevant. For producing one ton of e-diesel, 0.77 tons of green H2 and 8.24 tons of CO2 are needed [49]. As a result, the levelized cost of producing e-diesel is ~5,250-6,240 €/ton of e-diesel.

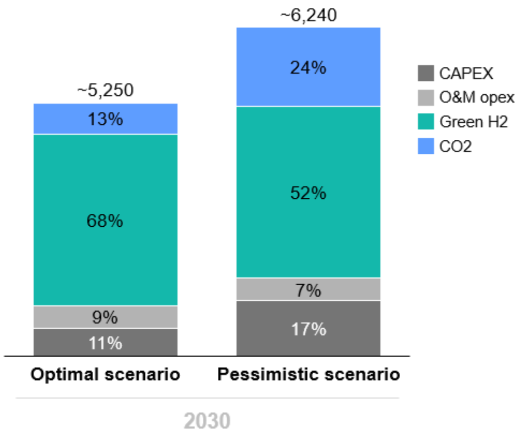

Figure 11: Levelized cost of e-diesel production [€/ton e-diesel]. Source: Own elaboration.

2.4.2.2 Technology maturity

Unlocking the production of synthetic fuels at scale hinges on the deployment of green hydrogen and carbon capture technologies. Spain possesses a competitive edge in green hydrogen production, benefiting from abundant renewable electricity resources and favorable cost dynamics. Nonetheless, green hydrogen production remains in its early stages, as elaborated in Section 2.2. As for CO2, its availability is contingent upon the development of carbon capture technologies, which have yet to be operationalized in Spain. Therefore, the availability of synthetic fuels in abundance and at a competitive cost is not possible as of today.

E-diesel projects have not yet been announced at scale in Spain. Greenalia and Repsol have announced the development of two Power to Liquid (PtL) pilot units that will produce e-diesel as a byproduct. On the other hand, several e-methanol plants have been announced in the country which are expected to be operational before 2030. The biggest investment has been done by the shipping company Maersk and Cepsa expecting a production of 300 Mtpa by 2028 [50].

In conclusion, although a few innovators have begun constructing e-fuels facilities, substantial advancements are still imperative to address the fuel requirements of ICEs within the maritime sector. This entails not only increasing the number of announced e-fuel plants but also ensuring the abundant availability of CO2 and green hydrogen as essential feedstock.

2.4.2.3 GHG emissions

E-fuels offer a compelling solution to mitigate GHG emissions in various sectors. These synthetic fuels have the potential to drastically reduce emissions by over 95% compared to their fossil fuel counterparts. By utilizing renewable electricity and capturing carbon dioxide during production, e-fuels effectively break the cycle of carbon emissions associated with traditional fossil fuels. This substantial reduction positions e-fuels as a key player in the transition towards more sustainable fuels in the maritime industry, more specifically for short-haul vessels which are the main focus of this thesis [51].

2.5. Comparison of fuel feasibility for recreational vessels

This section provides a comprehensive comparison of the fuels analyzed previously — electricity, hydrogen, biofuels, and synthetic fuels — in terms of tank-to-propeller efficiency, levelized costs of fuel production, technology maturity, and GHG emissions reduction relative to their fossil fuel counterparts. Table 8 summarizes these key metrics for each fuel type, offering a clear depiction of their respective advantages and limitations in the context of sustainable energy solutions.

Electricity | Green H2 | Bio/E-Diesel | Bio/E-Methanol

Fuel type	Tank-to-propeller efficiency, %	Refueling time, minutes	Levelized cost of fuel production, €/GJ	LCA GHG emissions reduction vs fossil diesel	Technology maturity	Limitations for recreational vessels
Renewable electricity	**50-85%,** dependent on the electric motor efficiency	~90-340	7 14	100%, net zero energy source	**At scale develop-ment of RES**	**Limited range** and refueling network
Green hydrogen	**20-60%,** significantly influenced by fuel cell efficiency	~3-11	42	100%, net zero energy source	**Some commercial applications**	**Limited refueling network**
Biofuels	**20-40%**	6	76 20	50-90%, depending on the feedstock used	**Some commercial applications**	**Compatible** with existing infrastructure
Synthetic fuels	**20-40%**	6	192 20	~95%	**Early stage,** no announced projects at scale	**Compatible** with existing infrastructure

Conversion factors: 1 MWh = 3.6 MJ; 1 kg H2 = 120 MJ; 1 kg bio/e-diesel = 22.7 MJ; 1 kg bio/e-methanol = 50.2 MJ

Table 8: Comparative analysis of each fuel type. Source: Own elaboration.

In conclusion, despite the high efficiency, low cost, and availability of renewable energy sources for producing electricity as fuel for recreational vessels, their range and refueling limitations could diminish their overall appeal. Conversely, green hydrogen faces significant drawbacks due to its low efficiency and supply limitations. Biofuels and e-fuels, however, present a more favorable option as they are compatible with existing refueling and vessel infrastructure, with methanol proving to be much more cost-efficient than diesel. Nevertheless, the cost of HVO and synthetic fuels are tied to the cost of hydrogen leading to a decrease cost competitiveness until green hydrogen is developed at scale.

As of today, biodiesel and biomethanol appear to be the most promising and readily available fuel alternatives. Nonetheless, the appeal of other fuels may increase with advancements in technology, economies of scale, and the development of refueling infrastructure.

Chapter 3. TOTAL COST OF OWNERSHIP ANALYSIS

Analyzing the Total Cost of Ownership (TCO) for recreational vessels powered by alternative fuels such as green hydrogen, RES, biofuels, and synthetic fuels is essential for a complete evaluation of their techno-economic competitiveness. TCO not only accounts for initial capital expenditures and operating expenses but also includes the costs related to fuel consumption, regulatory compliance, infrastructure, and the potential resale value of the vessels. By providing a holistic view that encompasses long-term financial and environmental costs and benefits, TCO enables stakeholders to make informed investment decisions that align with both economic viability and sustainability goals, thus offering a more nuanced understanding than simply comparing the levelized cost of fuel production.

Therefore, this section includes an overview of the TCO analysis for recreational vessels in Spain per alternative fuel. This analysis is conducted by delineating between initial acquisition costs (CAPEX) and recurring operating expenditures. CAPEX involves the initial purchase price of the vessel and expenditures associated with adapting it for electric/hydrogen propulsion if applicable, such as retrofitting with battery systems and electric motors or fuel cells. Operating costs encompass significant components like fuel expenses, which constitute a substantial portion of TCO, and operational and maintenance costs to provide a comprehensive economic analysis.

3.1. Description of TCO model

First, the TCO model that is used for the comparison of the different leisure vessels depending on the alternative fuel used for propulsion is considered. The TCO is calculated per nautical mile (€/nm) by discounting costs to the present value. The following equation summarizes the calculation approach utilized:

$$TCO/nm = \frac{(IPC - RV) \cdot CRF + \frac{1}{N} \cdot \sum_{n=1}^{N} \frac{AOC}{(1+i)^n}}{ANMT}$$

TCO/nm represents the total cost of ownership per nautical mile travelled (€/nm). The parameters used include the initial purchase cost of the vehicle (IPC) in euros (€), the resale value (RV) in euros (€), and the capital recovery factor (CRF), which is calculated as $CRF = \frac{i \cdot (1+i)^N}{(1+i)^N - 1}$. The annual operating cost (AOC) is expressed in euros (€), i is the discount rate, ANMT represents the annual nautical miles traveled (nm), and N is the leisure vessel average lifetime value.

The parameters CRF, i, N and ANMT are assumed to be the same for all leisure vessels independently of the fuel used for propulsion. The average lifetime value of a leisure vessel in Spain is ~30 years, equal to the duration in which the boat is depreciated ~85% of its initial value ($RV = 0.15 \cdot IPC$) [52]. Additionally, the discount rate considered is 6% assumed to be the same for all technologies as observed in the market.

To estimate the initial purchase price, three type of boats have been defined: battery-electric, which is power by RES; hydrogen fuel cell and ICE recreational vessel. The pricing of ICE recreational vessels in more standardized in Spain due to its significant availability in the market, but it still depends on the materials and characteristics of the boat. In this thesis, a boat of ~7.9 meters of LOA, ~2.55 meters of beam are considered with a capacity to transport 8 people maximum. The equivalent ICE boat with these characteristics would cost ~100-200 k€, an average price of 120 k€ is assumed for simplicity.

The equivalent battery-electric and hydrogen FC boat pricing varies per propulsion system. As previously mentioned, these technologies have not yet taken advantage of economies of scale and there is still room for technological advances that could result in efficiency enhancement. Therefore, these parameters are subject to further sensitivity analysis in the following section. As a base scenario, the pricing of both type of boats has been calculated by estimating how much it would cost to replace the ICE propulsion system (ICE engine plus the fuel tank costs) with the corresponding system required for each technology.

IPC per fuel type	Unit	Value	IPC/IPC ICE
Battery-electric	€	165,200	1.38x
Hydrogen FC	€	189,200	1.58x
ICE	€	120,000	1.00x

Table 9: Initial Purchase Price per technology [Base case]. Source: Own elaboration.

Furthermore, operation and maintenance costs represent ~10% of initial investment for ICE yachts or leisure vessels [53]. However, it should be noted that maintenance costs for ICE are mainly engine and transmission related which are not directly applicable to FC or electric vessels. Battery costs and power electronic costs are commonly lower than ICEs engine costs as they have a longer lifespan, leading to smaller annual costs. Nowadays, FC maintenance costs are comparable to ICEs, but technological advances are expected in terms of fuel cell stack durability resulting in lower O&M costs as summarized in Figure 12.

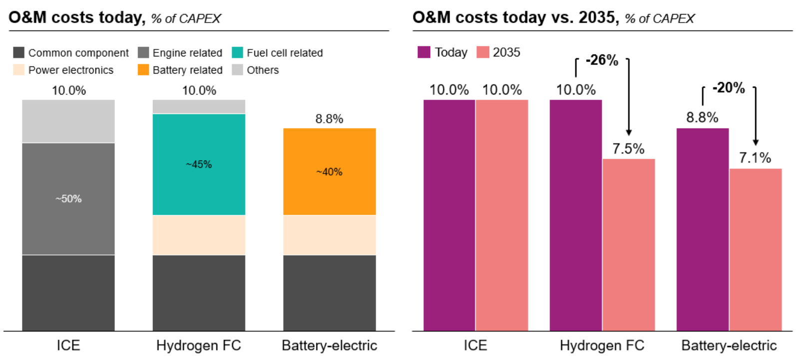

Figure 12: O&M costs as a share of initial investment. Source: [54], Own elaboration.

Other operating expenses that may vary by technology include fuel costs. These expenses are calculated by multiplying the levelized cost of fuel production by the annual fuel consumption, and then adjusting for the tank-to-propeller efficiency. The fuel usage of recreational vessels is highly variable due to factors such as vessel size and weight, engine type and performance, cruising speed, sea conditions, hull design, load carried, and the skill and behavior of the operator. This variability necessitates a detailed analysis of the specific route and prevailing marine conditions. Other operating expenses should be considered such as fuel transport and distribution costs, cargo fees and taxes. The calculation of TCO in this section does not take them into account as they are assumed to be equal for all fuel and vessel types. In a more detailed analysis, fuel transport and distribution costs could be considered based on proximity of the production unit to the corresponding port.

For simplicity, an average consumption of 130 liters per hour could be expected for recreational boats in Spain that are powered by diesel (~36,000 MJ/m^3 according to IDEA [55]). Assuming a leisure vessel is utilized for 60 days per year, at 5 hours per day, and maintains an average speed of 12 nautical miles per hour, this results in ~3,600 nautical miles traveled per year with an estimated annual consumption of approximately 1.4 TJ.

An overview of operating costs considered for the base scenario are summarized in Table 10.

Operating costs	**Unit**	**Battery-electric**	**Hydrogen Fuel Cell**	**Biodiesel**	**Biomethanol**	**E-diesel**	**E-methanol**
Tank-to-propeller efficiency	*%*	69%	40%	29%	29%	29%	29%
Adjusted consumption	*TJ*	2.0	3.5	4.9	4.9	4.9	4.9
Levelized cost of fuel production	*€/TJ*	11,147	42,210	76,363	20,001	192,294	20,271
Annual fuel costs	***€/year***	**22,826**	**147,207**	**376,169**	**98,525**	**947,251**	**99,856**
O&M as share of CAPEX	*%*	9%	10%	10%	10%	10%	10%
Annual O&M costs	***€/year***	**14,538**	**18,920**	**12,000**	**12,000**	**12,000**	**12,000**

Table 10: Annual operating costs per fuel and vessel type [Base case]. Source: Own elaboration.

In conclusion, the base case analysis of the total cost of ownership across various types of alternative fuels and propulsion systems reveals significant differences in economic viability. The main outcome of this analysis is that fuel costs represent +50% of TCO costs in all cases, revealing the importance of large-scale development of each technology to increase attractiveness of decarbonization solutions. Currently, e-diesel ICE vessels exhibit the highest TCO, primarily due to high production costs and limited commercial availability. It should be noted that unless e-diesel is developed at scale, it would not be used to decarbonize the maritime industry.

Furthermore, green H2 FC vessels also represent a higher cost than the remaining ICE vessels. The TCO could be improved with advancements in hydrogen production technologies, and increased adoption leading to economies of scale, potentially making hydrogen a more competitive option in the future.

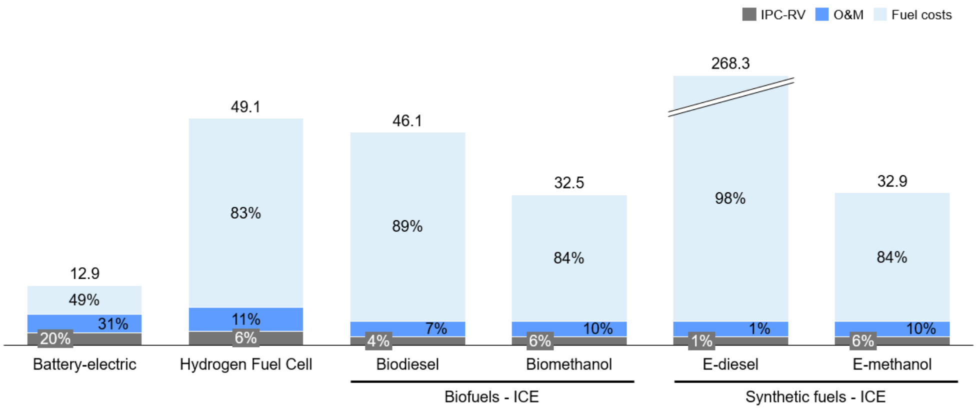

Figure 13: TCO per fuel and vessel type [Base case]. Source: Own elaboration.

3.2. Sensitivity analysis

Once TCO costs per alternative fuel type have been analyzed, several sensitivity analyses are conducted below under the aim of understanding what are the parameters that would unlock battery-electric and hydrogen FC vessels' cost competitiveness.

First, a cost parity analysis for green hydrogen fuel cell vessels relative is conducted based on annual nautical miles travelled and green hydrogen production costs. Table 11 reveals the requirements for green hydrogen TCO cost parity compared to biomethanol ICE vessels. Under the estimated levelized cost of green hydrogen production ~42,000 €/TJ, a FC vessel would need to travel +6,000 nautical miles per year to attain cost parity with biomethanol ICE's base case (~3,600 nautical miles with an average fuel price of ~20,000 €/TJ).

Sensitivity analysis						
		Annual nautical miles traveled				
		3.000,00	4.000,00	5.000,00	6.000,00	7.000,00
Green H2 costs	20.000	33,04	24,78	19,83	16,52	14,16
	30.000	44,67	33,50	26,80	22,33	19,14
	40.000	56,29	42,22	33,78	28,15	24,13
	50.000	67,92	50,94	40,75	33,96	29,11
	60.000	79,54	59,66	47,73	39,77	34,09

Table 11: Cost parity analysis for Hydrogen FC vessels vs. ICE biomethanol. Source: Own elaboration.

Sensitivity analysis						
		Annual nautical miles traveled				
		3.000,00	4.000,00	5.000,00	6.000,00	7.000,00
Green H2 costs	5.000	15,61	11,70	9,36	7,80	6,69
	15.000	27,23	20,42	16,34	13,62	11,67
	25.000	38,86	29,14	23,31	19,43	16,65
	35.000	50,48	37,86	30,29	25,24	21,63
	45.000	62,11	46,58	37,26	31,05	26,62

Table 12: Cost parity analysis for Hydrogen FC vessels vs. battery-electric vessels. Source: Own elaboration.

In addition, the evolution of TCO based on fuel consumption is tested to understand the effect levelized fuel production costs, considered as purchase price of fuel assuming there is no market nor market limitations. ICE vessels powered by e-fuels are not being considered for simplicity.

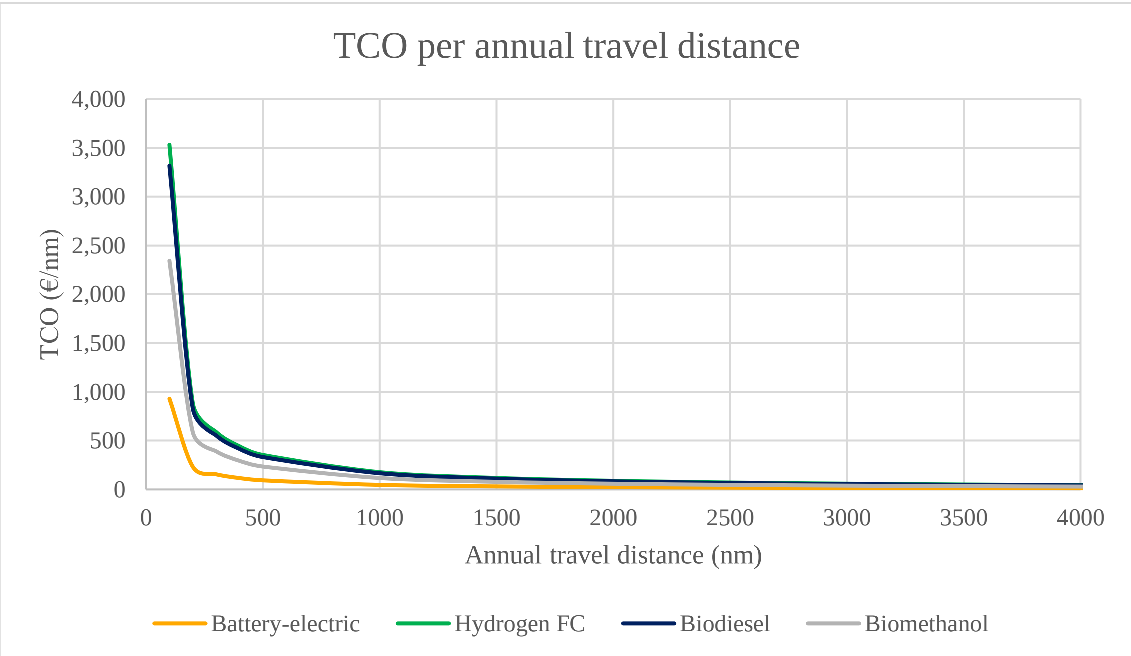

Figure 14: TCO analysis based on fuel consumption. Source: Own elaboration.

It can be inferred that the higher the distance traveled the smaller the TCO is as costs are spread over a higher number of operating hours. As a result, if the distance traveled is lower than 300 nautical miles, the difference between TCO per alternative fuel is significantly exacerbated, where H2 fuel cells and biodiesel ICE vessels would be the least cost competitive. However, if distance travelled is greater than 2,000 nautical miles, there is little difference between the TCO per alternative fuel and vessel.

Chapter 4. BUSINESS CASE: REIAL CLUB MARITIM BARCELONA

Once the levelized costs of alternative fuels production has been analyzed together with its techno-economic feasibility study for usage in recreational vessels, a real-world business case is presented for providing the reader with a view on the importance of maritime decarbonization and the investments required from the point of view of the port's supplier.

The transition to alternative fuels presents significant economic challenges, as these fuels are not cost-competitive without large-scale development. Recognizing this limitation, a Spanish port located near key industrial hubs and established fuel production facilities is considered. Barcelona has been selected as one of the most attractive regions for decarbonization of the recreational maritime industry thanks to its geographical advantage, enabling efficient fuel supply chains, infrastructure integration, cost reduction and facilitating scalable deployment of low-carbon technologies nearby. More specifically, the Reial Club Maritim of Barcelona has been selected due to its significant recreational activities and size of the port.

4.1. Details of the Reial Club Maritim Barcelona

Barcelona, a city with a rich maritime history and a strategic Mediterranean location, is an ideal candidate for pioneering the decarbonization of marina operations. The aim is to capitalize on Barcelona's industrial synergies and logistical strengths, to position the Reial Club Maritim as a leader in sustainable maritime innovation. With a legacy dating back to 1902, the marina is a hub for nautical enthusiasts and a symbol of the city's maritime culture. It boasts 139 moorings, accommodating vessels up to 20 meters in length.

Owners of recreational vessels aiming to moor at the marina would need to pay some fixed costs such as entrance fees and variable costs depending on the size of the boat as summarized in Table 13.

MOORING*	
CONCEPT	TARIFF
Length x Beam (m²)	5,10€ X m² + VAT / Monthly
Boat entrance fees	259,60€ X m² + VAT
Daily fee for T5 boats + permanent mooring water sheet	
Sailing boats < 12m in length or motor boats < 9m in length	0,02794 €/m2/day + VAT
Sailing boats > o = 12m in length or motor boats > o = 9m in length	0,05095 €/m2/day + VAT
Daily rate for navigation aids	
Sailing boats > o = 12m in length or motor boats > o = 9m in length	0,02498 €/m2/day + VAT
+ T5 boat tax and sheet of water	
Sailing boats < 12m in length or motor boats < 9m in length	0,04926 €/m2/day + VAT
Sailing boats > o = 12m in length or motor boats > o = 9m in length	0,1044 €/m2/day + VAT
Daily rate for navigation aids	
Sailing boats > o = 12m in length or motor boats > o = 9m in length	0,02498 €/m2/day + VAT

TOWING SERVICE (prices with VAT)	Members	
	Low season*	High season**
Boats up to 9m in length	€126.68	€168.88
Boats from 9.01 to 11m in length	€163.90	€218.55
Boats from 11.01 to 13m in length	€178.86	€238.44
Boats from 13.01 to 15m in length	€223.56	€298.04
Low season: from August to the end of March **High season: from April to the end of July		

Table 13: Rates, prices and services for members of the marina in 2024. Source: Reial Club Maritim Barcelona [56]

4.2. Overview of local and regional regulatory environment

The combustion of fossil fuels accounts for ~70% of the emissions generated by port activities. Hence, the Port of Barcelona has set ambitious decarbonization goals as part of its commitment to environmental sustainability. These objectives align with global strategies to reduce greenhouse gas emissions and combat climate change. Among the main strategic targets defined for the energy transition, the following are highly related to alternative fuels:

1. **GHG emissions reduction:** 50% GHG emissions reduction compared to 2017 levels and climate neutrality by 2050
2. **Strategic plan for energy transition:** focus on increasing the use of renewable energy in the port with an improvement of energy efficiency and the electrification of the machinery and pier, while promoting the use of alternative fuels

However, the port of Barcelona does not provide any specific requirements on alternative fuels volumes or GHG emissions reduction focused on recreational vessels. Therefore, all alternative technologies are promoted equally for recreational port activity. It should be noted that the Port of Barcelona is a low emissions area since 2020, aiming to reduce the use of ICE motors [57].

4.3. Overview of alternative fuel production units

Mapping alternative fuel production units nearby is crucial for the Reial Club Maritim Barcelona's decarbonization efforts because it enables efficient access to sustainable energy sources, reducing the club's reliance on fossil fuels. Proximity to these units minimizes transportation emissions and logistical costs, ensuring a steady and eco-friendly fuel supply. By identifying and utilizing local alternative fuel resources, the club can significantly lower its carbon footprint, align with environmental regulations, and promote sustainability. This strategic approach could also foster partnerships with green energy producers, potentially enhancing the club's reputation as a leader in environmental stewardship and contributing to broader regional and global decarbonization goals.

Table 14, Table 15, and Table 16 reveal the green hydrogen, HVO, and biomethanol production units near Barcelona respectively. These tables include details regarding the production location, start of operations, production capacity and distance to Reial Maritim Barcelona port. Synthetic fuel production units are not considered in this analysis due to the limited feedstock availability and technology developments. Furthermore, as previously mentioned, RES have already been developed at scale in Spain and there are plenty of production units available around Barcelona as shown in Figure 15. Therefore, it is assumed that there would not be a resource availability issue nor transport costs associated for this case study. It should be noted that there is already a hydrogen production unit in Barcelona, which would be the closest to the port, but its use would be mainly focused on fuel cell buses [58].

Name	Location	Start of operations	Electrolizer capacity [MW]	Distance to port [km]
Repsol, IQOXE, Endesa	Tarragona	2025	150	100
IQOXE	Tarragona	2026	15	100
Endesa	Andorra (Teruel)	2028	15,00	270

Table 14: Green Hydrogen production units near Barcelona. Source: Own elaboration, [59]

Name	Location	Start of operations	HVO production (ktpa)	Distance to port [km]
Repsol-Tarragona	Tarragona	2018	130	100
BP-Castellon (co-processing)	Castellon	2018	80	280
BP-Castellon (standalone)	Castellon	2030	650	280

Table 15: HVO production units near Barcelona. Source: Own elaboration, press search

Name	Location	Start of operations	Biomethanol production (ktpa)	Distance to port [km]
Repsol/Agbar/Enerkem -Tarragona	Tarragona	2026	240	100

Table 16: Biomethanol production units near Barcelona. Source: Own elaboration

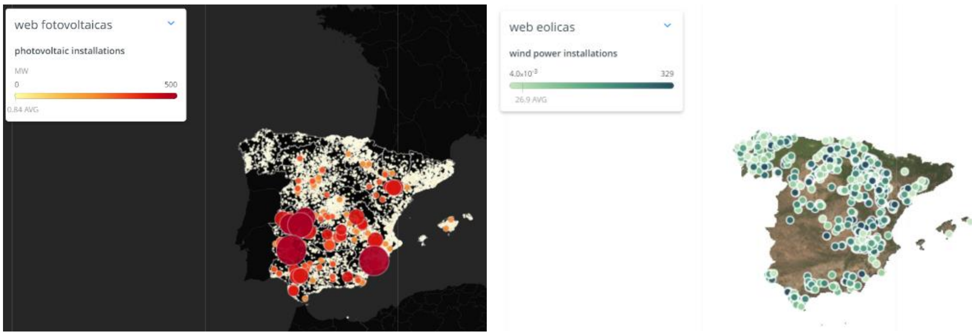

Figure 15: RES deployment in Spain. Source: [60]

Green hydrogen production capacity has been estimated based on unit utilization, efficiency, operating hours, and energy density, using the same parameters as is 2.1.4.1 estimation of LCOH.

4.3.1 Transport costs

Understanding the transport and distribution costs of alternative fuels is essential for the Reial Club Maritim Barcelona's decarbonization efforts because these costs significantly impact the overall feasibility and economic viability of transitioning to sustainable energy sources. Accurate cost assessments ensure efficient budgeting and strategic planning, allowing the club to optimize its fuel procurement process and minimize unnecessary expenses. This is particularly important for alternative fuels, where transport costs can vary widely based on distance and infrastructure. Notably, the transport costs from RES can be disregarded, as there are numerous RES units available nearby, eliminating the need for significant transport and distribution efforts.

Green hydrogen transport costs may vary depending on the method of transportation, the distance, and the infrastructure in place. Below is a detailed qualitative analysis of the various aspects influencing the transport costs of green hydrogen.

Type of transport	Initial investment	Operational costs
Pipeline	• Construction and retrofitting existing pipelines	Low once the infrastructure is in place
Compressed gas	• **Compression equipment** • **High-pressure containers**	**Need for continuous compression** and specialized containers
Liquid hydrogen	• **Liquefaction plants** • **Cryogenic storage tanks**	**Energy-intensive process** of liquefaction and maintaining cryogenic temperatures

Figure 16: Qualitative comparison of green hydrogen transport alternatives. Source: Own elaboration, [61]

For the sake of cost efficiency and minimization of technological developments required across the value chain, it is assumed that green hydrogen is transported as compressed gas by road transport, which is carried out using tanker trucks with a capacity of 360 kg of compressed hydrogen in Spain [61]. The levelized costs of transporting hydrogen is dependent on the distance travelled and hydrogen capacity, ranging from ~0.8-2 €/kg of compressed green hydrogen for compressed hydrogen [62].

Biofuel transport costs would be extremely similar to those being currently paid for gasoil and ethanol. Indeed, according to Repsol, transport and distribution costs represent ~11% of the fuel price ranging from 0.10-0.40 €/liter [63]. Considering that biodiesel density is 0.89 kg/l and 0.80 kg/l for biomethanol, plus the heat densities mentioned in Chapter 2, the transport cost per type of alternative fuel are summarized in Table 17.

Type of fuel	Unit	Minimum	Maximum
Electricity	€/TJ	0	0
Green hydrogen	€/TJ	6,667	16,667
Biodiesel	€/TJ	4,945	19,778
Biomethanol	€/TJ	2,491	9,965

Table 17: Transport costs by fuel type. Source: Own elaboration

4.3.2 Distribution costs

In a port setting, the distribution costs of electricity, green hydrogen, and biofuels are divided into CAPEX and OPEX. CAPEX includes the initial investment in infrastructure refueling infrastructure, required for green hydrogen refueling infrastructure and electric charging stations deployment. In this case, biofuels present a cost advantage as there is no need for additional investment in technology, since the infrastructure and technology for their distribution are already well-developed and established in Reial Club Maritim Barcelona. This reduces the overall capex for biofuels, making them an economically attractive option for ports looking to decarbonize efficiently and in the short-term.

Capital investment needs for electric charging stations vary per type of charger ranging from 10,000€ to 180,000€ [64]. For the decarbonization of the marina, chargers with a nominal power of 22kW will be considered assuming an initial cost of ~30,000€. For these chargers, O&M costs would be ~300€/year (~1% of CAPEX). Furthermore, other operational costs that would be incurred in Spain are network tolls and other regulated tolls split into a fixed and variable term as summarized in Table 18 and Table 19. Additionally, network regulated charges have also been considered including also a fixed and variable term as shown in

Grupo tarifario	Término de potencia del peaje de transporte y distribución (€/kW año)					
	Periodo 1	Periodo 2	Periodo 3	Periodo 4	Periodo 5	Periodo 6
2.0 TD	22,393140	1,150425	–	–	–	–
3.0 TD	10,267292	10,039843	2,651271	2,303199	1,381933	1,381933
6.1 TD	19,108658	17,911151	8,925198	7,158278	0,506199	0,506199
6.2 TD	13,561685	13,526788	5,420822	4,094881	0,374203	0,374203
6.3 TD	9,880203	9,471228	4,796920	3,592008	0,487055	0,487055
6.4 TD	8,443077	7,279110	3,590719	2,751326	0,349732	0,349732

Table 18: Fixed term of power regulated charges (€/kW). Source: BOE, [65]

Grupo tarifario	Término de energía del peaje de transporte y distribución (€/kWh)					
	Periodo 1	Periodo 2	Periodo 3	Periodo 4	Periodo 5	Periodo 6
2.0 TD	0,029098	0,019794	0,000980	–	–	–
3.0 TD	0,019466	0,015685	0,006382	0,004645	0,000412	0,000412
6.1 TD	0,018036	0,014354	0,005965	0,004393	0,000362	0,000362
6.2 TD	0,010719	0,008707	0,003427	0,002349	0,000172	0,000172
6.3 TD	0,008957	0,007052	0,002994	0,002055	0,000197	0,000197
6.4 TD	0,008625	0,006738	0,002988	0,001948	0,000153	0,000153

Table 19: Variable term of energy regulated charges (€/kWh). Source: BOE, [65]

Segmento tarifario	Término de potencia de los cargos (euros/kW año)					
	Periodo 1	Periodo 2	Periodo 3	Periodo 4	Periodo 5	Periodo 6
1	2,989915	0,192288				
2	3,715217	1,859231	1,350774	1,350774	1,350774	0,619203
3	3,856557	1,930027	1,402384	1,402384	1,402384	0,642759
4	2,264702	1,133557	0,823528	0,823528	0,823528	0,377450
5	1,813304	0,907425	0,659281	0,659281	0,659281	0,302217
6	0,887008	0,443874	0,322548	0,322548	0,322548	0,147835

Table 20: Fixed term of electric network charges (€/kW). Source: BOE, [66]

Segmento tarifario	Término de energía de los cargos (euros/kWh)					
	Periodo 1	Periodo 2	Periodo 3	Periodo 4	Periodo 5	Periodo 6
1	0,043893	0,008779	0,002195			
2	0,024469	0,018118	0,009788	0,004894	0,003137	0,001958
3	0,013305	0,009856	0,005322	0,002661	0,001706	0,001064
4	0,006243	0,004624	0,002497	0,001249	0,000800	0,000499
5	0,005117	0,003791	0,002047	0,001023	0,000656	0,000409
6	0,001944	0,001440	0,000778	0,000389	0,000249	0,000156

Table 21: Variable term of electric network charges (€/kWh). Source: BOE, [66]

Regarding green hydrogen investment costs, Natpower's effort in Italy has been used as a reference. The company invested 100Mn€ in the deployment of 100 hydrogen refueling stations (HRS) in 24 different marinas, resulting in a fixed investment of ~1Mn€ per HRS [67]. Additionally, 10% O&M OPEX would be required potentially decreasing thanks to improved and safer operations in the upcoming future.

4.4. Decarbonization of Reial Club Maritim Barcelona

Once the capital and operational efforts required for decarbonization of each alternative fuel type in the Reial Club Maritim Barcelona have been defined, several scenarios are considered for reducing the marina's emissions.

Each scenario hinges critically on the refueling infrastructure because it forms the backbone of any transition to low-carbon fuels. This infrastructure encompasses the systems and facilities necessary to supply, store, and distribute alternative fuels such as hydrogen, electricity, or biofuels. The complexity and expense of developing these systems are influenced by several factors, including the need for new storage tanks, pipelines, refueling stations, and safety protocols to handle different types of fuels. Moreover, the infrastructure must be compatible with various vessel types and their specific fuel requirements, adding another layer of complexity. Investment in refueling infrastructure not only involves significant capital expenditure but also requires rigorous regulatory compliance, ongoing maintenance, and workforce training. Therefore, understanding and accurately estimating the costs associated with establishing and maintaining this infrastructure for each scenario is paramount for assessing the overall financial implications of port decarbonization. This focus ensures a comprehensive analysis that captures the true scale of the economic transition required to achieve sustainable maritime operations.

Each of the 239 vessels of Reial Club Maritim Barcelona are considered to have a very similar size with an average annual consumption of 1.4 TJ, resulting from an average consumption of 130 l/h from the equivalent diesel vessel with 60 operating days per year and 5 hours use per day as described in Chapter 3. Additionally, to transpose consumption to each vessels type, the respective tank-to-propeller efficiency calculated in Chapter 2 is used.

A summary of the number of vessels decarbonized per alternative fuel in each scenario is included in Table 22.

The first scenario considers the decarbonization of the port using only electricity as a fuel source, meaning the port's fleet is assumed to be 239 battery-electric vessels. The second, third and fourth scenarios consider the port is decarbonized fully with green hydrogen, biodiesel or biomethanol respectively.

Number of vessels decarbonized	Unit	Battery-electric	Hydrogen Fuel Cell	Biodiesel	Biomethanol
Scenario 1	#	239	0	0	0
Scenario 2	#	0	239	0	0
Scenario 3	#	0	0	239	0
Scenario 4	#	0	0	0	239

Table 22: Description of the number of vessels decarbonized in each scenario under each of the alternative fuel technologies. Source: Own elaboration.

When decarbonizing a port's fleet using electricity as a fuel, it is essential to install one electric charger per vessel, with these chargers powered by renewable energy sources (RES). This ensures that the electrification of the fleet is both sustainable and aligns with broader environmental goals. For hydrogen fuel cell (FC) vessels, the establishment of at least one hydrogen refueling station (HRS) becomes crucial. The development of this HRS is a key assumption across all scenarios involving green hydrogen FC boats, as it provides the necessary infrastructure to support the transition to hydrogen fuel. In contrast, biofuels present a distinct advantage as they can utilize the existing port infrastructure without necessitating additional capital expenditure (CAPEX). This effectively means that the adoption of biofuels incurs no new infrastructure costs, leveraging the current systems already in place. Consequently, the choice of fuel significantly impacts the infrastructure requirements and associated costs, underscoring the importance of thorough planning and investment in refueling infrastructure to achieve successful port decarbonization.

Figure 17 summarizes the annual operational costs that would be incurred in each of the four scenarios that have been previously mentioned. It should be noted that each fuel would be purchased from a nearby supplier either from Tarragona in the case of green H2, biodiesel and biomethanol, and directly from Barcelona in the case of renewable electricity. Therefore, it should be noted that electricity transport costs are negligible since the only cost incurred would be network charges and tolls for accessing and using electricity from the grid.

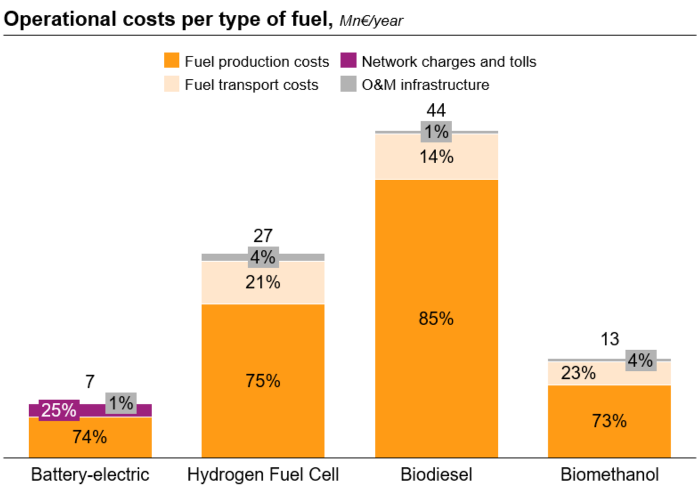

Figure 17: Operational costs incurred for the development of refueling infrastructure. Source: Own elaboration[1]

Similarly to the analysis conducted in Chapter 3, fuel production costs represent the greatest share of operational costs. The main reason behind this is the high expense associated with producing low-carbon fuels. These fuels require significant technological investments and infrastructure development, which contribute to their overall cost. These

[1] Fiscal costs are excluded from this analysis

costs incurred by suppliers would be directly translated to the port's operations in each fuel's purchase price. In this case, no markup is assumed for the sale of these fuels from producers. Still, the economic viability of decarbonizing port operations heavily depends on advancements in fuel production technologies and economies of scale that can reduce these costs over time.

Furthermore, an estimation of a summarized P&L and payback resulting from these infrastructure investments for Reial Club Maritim who would charge consumers ~10% more than operational costs for refueling are presented in Table 23.

Type of vessel	Unit	Battery-electric	Hydrogen Fuel Cell	Biodiesel	Biome-thanol
Annual consumption	*TJ*	489	834	1,177	1,177
Revenues	*M€/year*	7.2	50.5	115.5	34.5
OPEX	*M€/year*	-6.6	-45.9	-105.0	-31.4
Margin	***M€/year***	**0.7**	**4.7**	**10.6**	**3.2**
CAPEX	*M€*	7.2	10.0	0.0	0.0
Payback period	***years***	**11**	**2**	**0**	**0**

Table 23: Overview of the payback period for each scenario (assuming 10% margin). Source: Own elaboration

As expected, the payback period for biodiesel and biomethanol is null because no investment costs have been assumed. For the case of electricity and hydrogen, the payback period would be higher the greater the fuel costs are. For this reason, the payback period is higher for the first scenario decarbonizing the port with battery-electric vessels as annual margin, and operational costs are lower. It can be concluded that the higher the fuel production costs assuming the same margin for all low-carbon technologies, results in a higher margin for those alternative fuels who's operational (production, transportation and tolls) costs are higher.

4.5. Potential low-carbon technologies mix for Reial Club Maritim Barcelona

Two additional scenarios have been considered for the decarbonization of Reial Club Maritim with a mix of low-carbon technologies. These scenarios take into account the production capacity of the low-carbon plants in Tarragona, and the "unlimited" access to electricity from the grid in 2025. For example, by 2025 no biomethanol plant would be operational which means this alternative fuel source is not considered as a decarbonization option for the short-term. In the case of biodiesel, Repsol's refinery in Tarragona is already operating and producing 130 ktpa of HVO. In addition, a 150MW electrolizer would be operational by 2025 in Tarragona in charge of producing green hydrogen.

Assuming an offtake agreement is reached between the Reial Club Maritim Barcelona and these production facilities in Tarragona to provide 10% of its fuel production for the ports use, 33 vessels could be powered by green hydrogen and 59 with biodiesel assuming the same annual consumption as is Chapter 3.

Considering the cost competitiveness of renewable electricity as fuel source, its potential to mitigate noise in the port and nearby maritime areas as well as its decarbonization potential, it is considered as the main alternative fuel in complement to the offtake agreements. As a consequence, scenario 5 considers that offtake agreements are prioritized before cost efficiency, and the fuel should be used for the existing port's fleet. Under the 6th scenario, the cost competitiveness of each low-carbon fuel technology is considered. Therefore, green hydrogen and battery-electric are prioritized as shown in Table 24.

Number of vessels decarbonized	Unit	Battery-electric	Hydrogen Fuel Cell	Biodiesel	Biomethanol
Scenario 5	#	147	33	59	0
Scenario 6	#	206	33	0	0

Table 24: Description of additional decarbonization scenarios using a mix of low-carbon technologies. Source: Own elaboration

A summary of the economic results obtained from each scenario are summarized in Figure 18. Still in both cases, costs associated with the production of the low-carbon fuel represent the greatest share being more significant under scenario 5 as it considers part of the port's fleet would be decarbonized using biodiesel which is the alternative fuel with the greatest production costs.

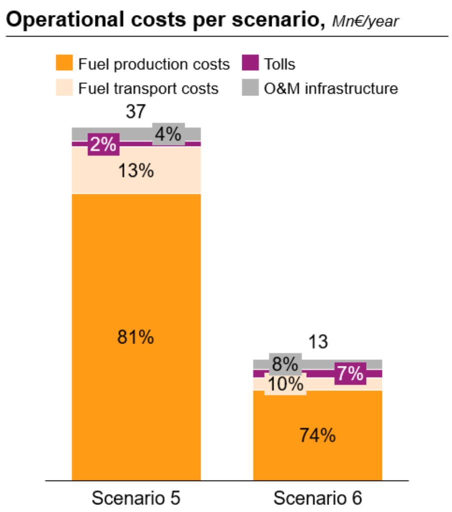

Figure 18: Overview of annual operational costs per scenario. Source: Own elaboration

Having understood the operational cost impact of these two scenarios, the payback period for both scenarios is analyzed under the same assumption as in the previous section: 10% revenue margin.

P&L	Unit	Scenario 5	Scenario 6
Annual consumption	*TJ*	707	540
Revenues	*M€/year*	41	14
Operating costs	*M€/year*	-38	-13
Margin	*M€/year*	4	1
CAPEX	*M€*	-14	-16
Payback period	*years*	4	13

Table 25: Economic analysis of Scenario 5 and 6 (assuming a 10% revenue margin). Source: Own elaboration

It can be inferred that under a similar CAPEX order of magnitude, the scenario with the greatest margin would result in a lower payback period. In this case, it is scenario 5 the one leading to a greater revenue margin in absolute terms due to higher operational costs.

Chapter 5. CONCLUSIONS

This section revisits the initial objectives established at the outset of the thesis to assess their progress and how they have been addressed throughout the research. The main conclusions drawn from the study are highlighted, emphasizing key findings and their implications. Additionally, potential avenues for future work are explored, discussing how the research can be extended or applied in new contexts.

First, a comparison of the sustainable fueling technologies for recreational sailing boats, including biofuels, synthetic fuels, hydrogen, and electricity, was conducted based on economic competitiveness, environmental impact, and operational considerations as key performance indicators. The main conclusions are as follows: Renewable electricity (solar or wind) and green hydrogen demonstrate the lowest levelized costs of fuel production, the greatest emissions reduction potential, and high tank-to-propeller efficiency. However, they have limitations compared to biofuels and e-fuels, which are already scalable for use in existing internal combustion engines and can leverage established refueling infrastructure. For recreational vessels, renewable energy sources offer limited range and significantly high charging times. Additionally, green hydrogen is not yet developed at scale, resulting in limited production supply and insufficient refueling infrastructure.

Furthermore, a financial feasibility assessment regarding the TCO of fuel cell hydrogen powered recreational boats was conducted under the aim of providing a benchmark against TCO of recreational vessels powered by other alternative fuels such as biofuels, synthetic fuels, and electricity. The main conclusions inferred from this analysis that fuel costs constitute +50% of the TCO across technologies, underscoring the necessity for large-scale development of each technology to enhance the attractiveness of decarbonization solutions. Currently, e-diesel ICE vessels have the highest TCO, primarily due to high production costs and limited commercial availability of production plants. Unless e-diesel is developed at scale, it will not be viable for decarbonizing the maritime industry. Additionally, green hydrogen FC vessels also incur higher costs compared to other ICE vessels. However, advancements in hydrogen production technologies and increased adoption could lead to economies of scale, potentially making hydrogen a more competitive option in the future.

A sensitivity analysis was also conducted to assess additional components significantly impacting the TCO. It was found that for shorter distances, the differences between technologies became more pronounced, with biodiesel and green hydrogen vessels being the least competitive. However, when the annual nautical miles traveled exceeded 2000, the TCO differences across technologies became negligible.

Finally, an application to the real-world case scenario was conducted to understand the required investments from the perspective of a port supplier, more specifically, to the Reial Club Maritim of Barcelona. In this case, the port of Barcelona as well the national government are significantly pushing for decarbonization of the territory aiming to reduce emissions by limiting the use of ICE motors as well as promoting the use of alternative fuels.

Several scenarios for decarbonizing the port's fleet were considered, each assuming the use of a single technology: ICE biodiesel, ICE biomethanol, battery-electric, or hydrogen fuel cell vessels; an additional scenario considered the optimal mix based on the alternative fuel production units' capacity nearby and assuming an offtake agreement would be reached for fuel supply. It should be noted that significant upfront investment was required for decarbonizing with electricity and green hydrogen, especially for electricity, as it was assumed that each battery-electric vessel would need its own charger. Regarding operational costs, fuel production costs still represent the greatest share as significant technological investments and infrastructure development are required, which directly impact the port's fuel purchase prices. Furthermore, assuming the port's owner charges its customers a revenue margin of 10%, it can be inferred that under a similar CAPEX order of magnitude, the scenario with the greatest margin in absolute terms would result in a lower payback period. Hence, any scenario considering a share of biodiesel would be positively impacted.

In conclusion, green hydrogen has not yet been developed at scale in Spain, which significantly impacting its cost competitiveness in the short term. The high production costs and limited refueling infrastructure currently make green hydrogen less viable compared to other technologies. However, green hydrogen holds substantial promise as a future decarbonization technology. With continued advancements in production technologies and the establishment of economies of scale, the costs are expected to decrease over time. Additionally, as the infrastructure for hydrogen production and distribution expands, its availability and feasibility will improve. Therefore, while green hydrogen may not be the most competitive option at present, it has the potential to become an attractive and sustainable solution for maritime decarbonization in the long term, thanks to its decarbonization potential that promotes environmental sustainability.

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