Rocking the Boat: Alt-Fuels and the Super Yacht Industry

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Dissertation written under the supervision of

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I. Abstract

The superyacht industry, traditionally associated with luxury and exclusivity, is under pressure. With rising public scrutiny, changing climate regulations, and demands from different stakeholders, it is essential to promote the adoption of alternative fuels. This study used a literature review, twelve semi-structured expert interviews, and a survey with 179 respondents to investigate drivers of alternative fuels for the superyacht industry.

The findings indicated that regulatory frameworks were the leading driver of the transition to alternative fuels, outweighing incentives from yacht owners or market forces. Although younger, more environmentally conscious owners expressed interest in lower-emission propulsion systems, they remain reluctant to invest substantially in new technologies without regulatory mandates and sufficient infrastructure. Furthermore, contrary to the findings of the literature, the *Veblen effect* does not apply to superyachts. Among the alternative fuels, methanol, and hydrotreated vegetable oil appeared to be practical transitional options, while hydrogen and other advanced solutions are hampered by high costs and infrastructural challenges.

Growing pressure from stakeholders, including increased scrutiny from environmental groups and the adoption of transparent lifecycle assessment tools, highlights the need for credible sustainability measures to avoid accusations of greenwashing. In conclusion, the superyacht sector is at a turning point. Decisive policy intervention, stakeholder collaboration, and a strategic focus on established alternative fuels provide a clear pathway to integrating environmental responsibility with luxury maritime experiences.

Keywords: Superyachts, Drivers for Alternative Fuel Adoption, Environmental Impact, Economic Impact, Alternative Marine Fuels, Lifecycle Assessment, Hydrogen, Hydrotreated Vegetable Oil, Biodiesel, Methanol, Dynamic Capabilities, Sustainable Supply Chain Management, Willingness-to-Pay

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II. Resumo

A indústria de superiates, tradicionalmente associada ao luxo e à exclusividade, está sob pressão. Com o aumento do escrutínio público, mudanças nas regulamentações climáticas e demandas de diferentes partes interessadas, é essencial promover a adoção de combustíveis alternativos. Neste estudo, uma revisão de literatura, doze entrevistas semiestruturadas com especialistas e uma pesquisa com 179 respondentes foram utilizadas para investigar os fatores que impulsionam combustíveis alternativos na indústria de superiates.

Os resultados indicaram que marcos regulatórios são o principal motor da transição para combustíveis alternativos, superando incentivos dos proprietários de iates ou das forças de mercado. Embora proprietários mais jovens e ambientalmente conscientes demonstrem interesse por sistemas de propulsão com menor emissão, eles permanecem relutantes em realizar investimentos substanciais em novas tecnologias sem mandatos regulatórios e infraestrutura adequada. Além disso, contrariamente às descobertas da literatura, o efeito Veblen não se aplica aos superiates. Entre os combustíveis alternativos, o metanol e o óleo vegetal hidrotratado surgiram como opções transitórias práticas, enquanto hidrogênio e outras soluções avançadas enfrentam desafios relacionados a custos elevados e infraestrutura insuficiente.

O crescente pressionamento por parte de stakeholders, incluindo o aumento do escrutínio de grupos ambientais e a adoção de ferramentas transparentes de avaliação do ciclo de vida, destaca a necessidade de medidas sustentáveis credíveis para evitar acusações de greenwashing. Em conclusão, o setor de superiates está em um ponto crítico. Uma intervenção política robusta, colaboração entre stakeholders e foco em combustíveis alternativos já estabelecidos fornecem um caminho claro para integrar responsabilidade ambiental com experiências de luxo.

Palavras-chave: Superiates, Direcionadores da Adoção de Combustíveis Alternativos, Impacto Ambiental, Impacto Econômico, Combustíveis Alternativos, Combustíveis Marítimos, Avaliação de Ciclo de Vida, Hidrogênio, Óleo Vegetal Hidrotratado, Biodiesel, Metanol, Capacidades Dinâmicas, Gestão Sustentável da Cadeia de Suprimentos, Disposição a Pagar

Título: Balançando o Barco: Combustíveis Alternativos e a Indústria de Superiates

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Obrigadíssimo!

Jerome J. Hirtenlehner

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VI. List of Abbreviations

AIS	Automatic Identification System
BRIC	Brazil, Russia, India, China
CAGR	Compound Annual Growth Rate
CO2	Carbon Dioxide
CO2-Eq	Carbon Dioxide Equivalent
DAC	Direct Air Capture
ECAs	Emission Control Areas
EGR	Exhaust Gas Recirculation
EMODNET	European Marine Observation and Data Network
EU	European Union
FC	Football Club
GHG	Greenhouse Gas
HNWIs	High Net Worth Individuals
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engines
IMF	International Monetary Fund
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships (Marine Pollution)
MGO	Marine Gas Oil
MPAs	Marine Protected Areas
NOx	Nitrogen Oxides
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cells
PM	Particulate Matter
R&D	Research and Development
RQ	Research Question
SMR	Steam Methane Reforming
SOx	Sulfur Oxides
SSCM	Sustainable Supply Chain Management
TTW	Tank-to-Wake
U.S.	United States
UHNWIs	Ultra High Net Worth Individuals
UNESCO	United Nations Educational, Scientific and Cultural Organization
VOCs	Volatile Organic Compounds
WPAEL	Wind-Powered Alkaline Electrolysis
WTP	Willingness to Pay
WTT	Well-to-Tank
WTW	Well-to-Wake

1 Introduction

Luxury at a Crossroads—The Superyacht Industry's Sustainability Challenge

"Luxury is not a product but a set of values and experiences." — (Kapferer & Bastien, 2012).

Yachts and superyachts are an impressive spectacle worldwide. Whether at the Monaco Grand Prix, the Cannes Film Festival, or the Caribbean Azure, these vessels are recognized symbols of status and luxury. Far from mere means of transportation, they align with Kapferer and Bastien's (2012) notion that luxury transcends tangible products to embody values and experiences.

As quintessential *Veblen goods*, superyachts are consumed not purely for utility but also to convey social status. Thus, demand increases as price rises, a phenomenon known as the *Veblen effect* (Currid-Halkett, Lee, & Painter, 2019). This contrasts with ordinary goods, where higher prices typically suppress demand. Superyachts' exclusivity positions them as potent symbols of socioeconomic status, consumed in the spirit of "conspicuous consumption" as visible status markers.

Moreover, owners replace current vessels with larger, more commanding ones. This yearning for exclusivity and the elevation of social standing illustrates how cultural contexts and financial capacity drive ever more lavish luxury assets (Dubois & Duquesne, 1993). The yacht-size race illustrates how ownership is interwoven with displaying social status and prestige.

As seen in Figure-1, the market is expected to grow, reaching an estimated $14.58 billion by 2030 (Next Move Strategy Consulting, 2024), evincing increasing demand among the world's elite.

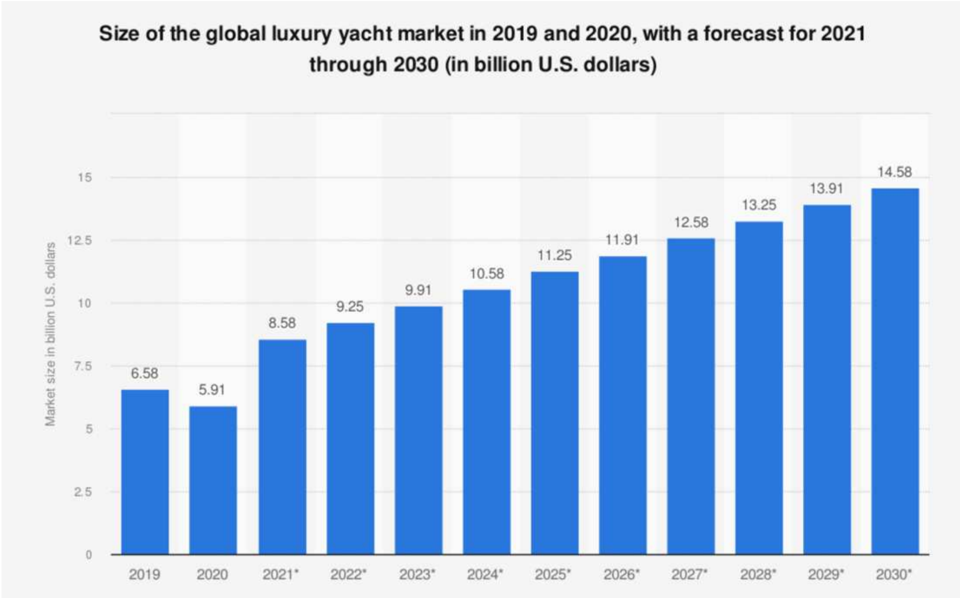


Figure-1: Global Number of Superyachts (in billion U.S. dollars) (Next Move Strategy Consulting, 2024).

Superyachts tend to be associated with the world's wealthiest individuals, founders, oligarchs, and members of royal families. For example, Amazon founder Jeff Bezos reportedly bought one of the largest private sailing yachts, the 125.8-meter *Koru*, for $500 million. He celebrated the acquisition with his fiancée, Lauren Sanchez, and friends such as Bill Gates, Leonardo DiCaprio, and Katy Perry. Additionally, details have emerged about *Koru's* 75-meter support vessel, *Abeona*. Meanwhile, rumors suggest that tech billionaires like Mark Zuckerberg are making secretive purchases of massive yachts originally designed for sanctioned Russian oligarchs. On the other hand, for now, Elon Musk has been seen only chartering, including a mere 24-meter yacht in Greece, costing $7,000 a day, despite owning a $70 million private jet (Duffy, 2022; Berg & Kay, 2024).

Figure-2: 125,8m Koru (left) & 75m support vessel Abeona (right) (Boat International, 2023).

Beyond their impressive size, the environmental impact of superyachts is gaining attention. Despite their relatively small share of the overall maritime industry (0.2% emissions of the shipping industry, which is responsible for 3% of the global emissions (Sciorilli Borrelli, 2024), superyachts are significant consumers of fossil fuels. As industries across the globe face pressure to meet net-zero targets, the maritime sector is particularly implicated in the fight against climate change. Alternative fuels and technologies are key for more sustainable operations (Wang et al., 2022) while also preserving sea life in areas affected by intense recreational yachting (Carreño & Lloret, 2021).

The following Research Question was interrogated:

RQ: What are the drivers for adopting Alternative Fuels in the Super Yacht Industry?

2 Literature Review

2.1 Superyachts: From Opulence to Responsibility

An estimated 10 million yachting holidays are taken annually (Ajagunna & Casanova, 2022). Of all pleasure crafts worldwide, 90% are vessels under 24 meters (Carreño & Lloret, 2021). Even though there is no settled definition, yachts above this length are known as superyachts, a term from the 1990s referring to the "increasingly large professionally crewed pleasure yachts built by private individuals" (Wang et al., 2022, p.1). The term is often used interchangeably with "large yacht" but typically refers to vessels that surpass a size criterion. Some of the largest superyachts even exceed 160 meters, such as the *Fulk Al Salamah* (164m), *Eclipse* (162.5m), and *Azzam* (181m).[1] According to estimates, in 2016, the global fleet included over 10,000 superyachts exceeding 24 meters. By 2020, 5,565 of these yachts exceeded 30 meters, while the fleet of vessels longer than 40 meters had grown to 2,050 (Wang et al., 2022).

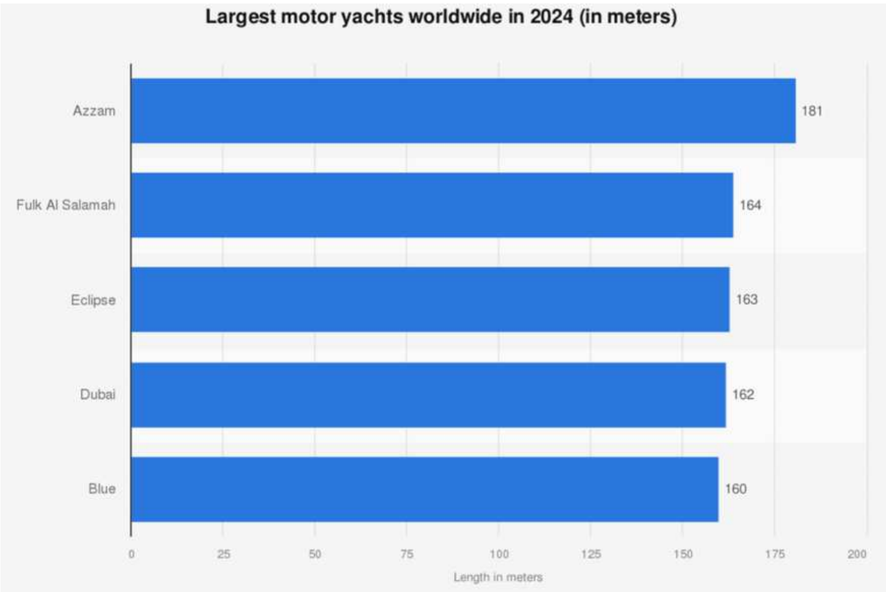


Figure-3: Largest motor yachts worldwide in 2024 (in meters) (Statista, 2024).

[1] Fulk Al Salamah is owned by the Sultan of Oman, Sultan Haitham bin Tariq (SuperYachtFan, n.d.; Yachting Pages, 2016). Azzam was originally owned by Sheikh Khalifa bin Zayed Al Nahyan, the late President of the United Arab Emirates and Ruler of Abu Dhabi, until his death in 2022. Following his passing, it passed his family (SuperYachtFan, n.d.; Yacht Rental UAE, n.d.; Ship Technology, n.d.).

Despite its relative insignificance compared to the approximately 1.3 billion ICE cars globally (Robinet, 2023), excluding support vessels, chase boats, or similar craft, the average 71-meter yacht burns roughly 500 liters of diesel per hour during standard operations (Wang et al., 2022). A notable example is the 162.5 m *Eclipse*, designed for the former owner of FC Chelsea, Roman Abramovich. It is estimated to emit more carbon dioxide in a year than the entire island nation of *Tuvalu*, with a population of about 10,000 (Gemenne, 2010). Another example is the 138-meter *Rising Sun*, which has an annual carbon footprint equivalent to an average American (Haneman, 2024).

Figure-4: Roman Abramovich's 162.5 m Eclipse, the second largest superyacht in the world (Campbell, 2023).

2.1.1 Rising Tides: Unprecedented Growth of Luxury Yachts

Despite environmental concerns, the yachting industry remains strong in the global economy. A leading yacht management company stated that after reaching over $450 million in yacht sales in 2020, it had the most substantial market expansion in four years during Q1 2021. Brokerage sales rose 45% year-over-year, surging 152% in March, driven partly by first-time buyers who found yachts to be secure, controlled environments for travel and leisure during the pandemic (Ajagunna & Casanova, 2022). Between 2020 and 2021, superyacht sales rose by 77% (Haneman, 2024).

Other experts predict further growth. According to *Grand View Research* in 2021, the global yacht market, worth \$8.15 billion in 2020, is projected to reach \$12.16 billion by 2028 at a 5.2% CAGR. The global yacht charter market, valued at \$6.83 billion in 2020, is expected to hit \$10.82 billion by 2027 at a 6.6% CAGR (Ajagunna & Casanova, 2022) and \$14.58 billion by 2030 (Next Move Strategy Consulting, 2024). These gains are associated with more HNWIs and intermediaries, higher living standards, corporate tourism, international yacht shows, marine sports events, and Formula 1 tie-ins (Ajagunna & Casanova, 2022).

Once reserved for aristocrats, yacht tourism's exclusivity now appeals to a broader demographic, including the middle class. Activities range from fishing trips to scenic tours and leisure sailing—the most popular option. The industry's evolution has sparked more luxury yacht orders and steady ownership and rental growth, mirroring changing tastes and broadening consumption of luxury leisure (Allied Market Research, 2023).

2.1.2 The New Wave of Eco-Conscious Ownership: Younger Clients Demand Sustainability

As the superyacht industry transforms, sustainability is becoming a significant driver. Over the next two decades, superyacht owners are projected to be 10–15 years younger, seeking luxury brands that also embrace environmental responsibility. This shift requires manufacturers and designers to rethink strategies, with sustainability evolving from an optional feature to a fundamental enterprise mandate. Consumers now demand concrete and measurable carbon reductions, leaving no room for half-measures (Ansaloni, Bionda, & Ratti, 2024; Sciorilli Borrelli, 2024). Consequently, shipbuilders must integrate eco-friendly technologies, embedding sustainability as a core principle. As yachting aligns with social responsibility, the industry must balance luxury with accountability. Failure to adapt is not an option (Ansaloni, Bionda, & Ratti, 2024).

2.1.3 Navigating Economic Waves: The Anti-Cyclical Nature of Luxury Yachting

The luxury yacht market is often considered anti-cyclical as UHNWIs (those possessing assets over \$30 million) often see their net worth rising during recessions. This suggests that demand remains resilient through business cycles. Yet, empirical evidence does not entirely confirm this. The Global Financial Crisis, for instance, saw declines in yacht sales and orders, revealing how broader economic forces contour behavior and can cool demand. While UHNWIs making money in down cycles theoretically supports anti-cyclicality in the sector, this factor alone has not insulated the market from contracting (Merendino, 2013).

2.1.4 Stakeholders at the Helm: Influencers and Affected Parties

Socio-political and economic changes in the late 20th century, notably Thatcher and Reagan-era Milton-Friedman-based models, generated wealth for certain entrepreneurial sectors. The "Washington Consensus," led by the World Bank, IMF, and U.S. Treasury, promoted market-driven processes, reducing government regulation and benefiting a global elite (Connors, 2023). Inequality grew alongside wealth, creating a "super-rich strata" (Connors, 2023, p.342). Rising affluence in BRIC nations and the Middle East now drives luxury yacht demand (Connors, 2023; Allied Market Research, 2023).

By 2017, UHNWIs reached 255,810, a 13% increase over the previous year, holding $31.5 trillion in wealth (Allied Market Research, 2022). Their influence is evident in the luxury yacht market. The industry also employs thousands worldwide in design, construction, maintenance, and operations (Ajagunna & Casanova, 2022).

In the EU's nautical tourism sector, up to 234,000 jobs produce about €28 billion annually, with 59% centered in the Mediterranean (Carreño & Lloret, 2021). Yacht manufacturing employs architects, engineers, and artisans, often in the hundreds per vessel for months or years (Connors, 2023). Once launched, superyachts require 10–20 crew members, with larger vessels needing more (Ajagunna & Casanova, 2022). Regular refits demand skilled trades, sustaining economies in Italy, Turkey, and France (Carreño & Lloret, 2021).

Supporting industries, from luxury catering to hospitality and supplies, thrive around yachting hubs like the Mediterranean and Caribbean, creating high-paying, often seasonal jobs (Ajagunna & Casanova, 2022; Connors, 2023). Although smaller than the global cruise industry (around €4 billion annually in Europe), the superyacht sector remains a specialized niche fueling regional economic activity (Connors, 2023).

2.2 The Environmental Wake: Impacts of Conventional Yachting

As mentioned in Chapter 2.1.1, the recreational boating industry is currently thriving. This means increasing numbers of vessels, resulting in busier boating areas. While this contributes to regional economies, it also dramatically impacts coastal environments (Carreño & Lloret, 2021).

The Mediterranean is one of the world's most popular yachting destinations thanks to its warm climate, extensive marinas, refit and repair facilities, and yacht management companies. Unfortunately, it is also most affected by yachting's impacts, with an average annual growth rate of superyachts increasing by 3.5%. This expansion raises environmental concerns.

For instance, during peak season, the Gulf of St. Tropez has over 350 leisure boats and over 100 superyachts sailing or anchoring in a single day. This pressure on coastal and maritime tourism is reaching peak capacity in many popular destinations. In Spain, France, and Italy, marinas can accommodate up to 100 moorings per kilometer of coastline. The western Mediterranean’s high traffic means superyachts are present for more than 100 hours per square kilometer annually (Carreño & Lloret, 2021). Additional details from 2021 can be found in Figure-5.

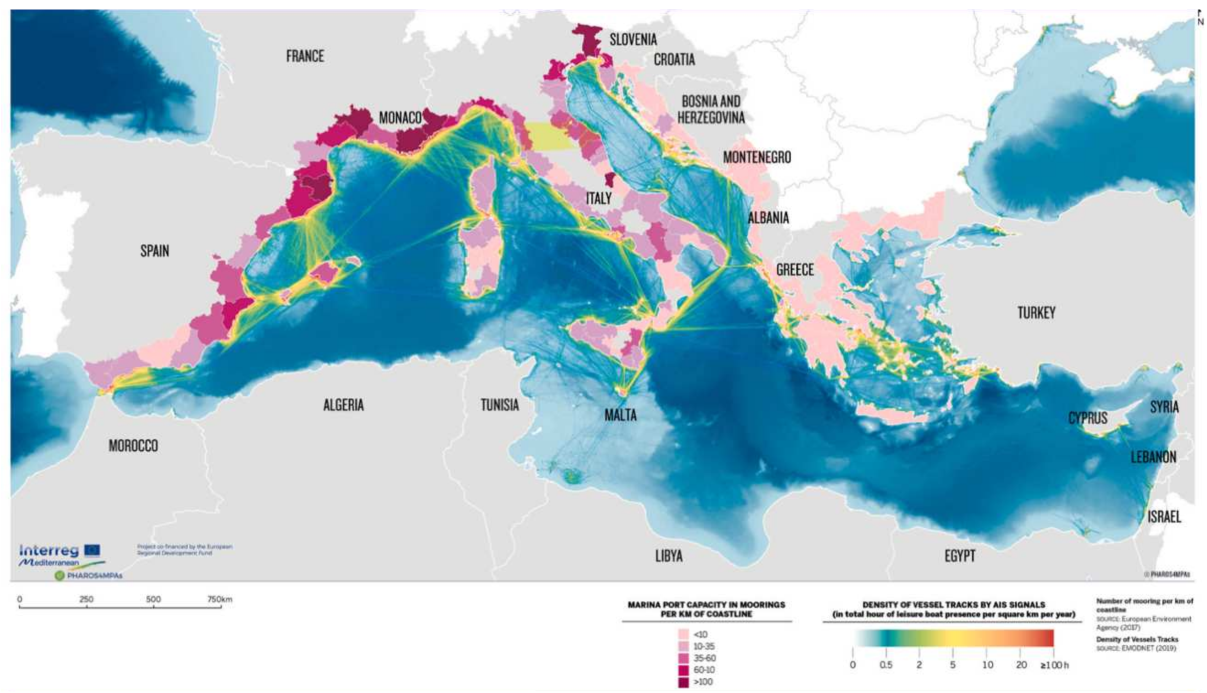


Figure-5: “Marina port capacities in number of moorings per km of coastline in EU countries (except Cyprus), and sailing and pleasure craft routes using Automatic Identification System (AIS) signals (crafts > 24m). Source: Interreg Pharos4MPAs; Alessandro Mulazzani. Adapted from the European Environment Agency (2017) and EMODNET (2019)” (Carreño & Lloret, 2021; p.2).

A second overseas example demonstrating the continuing growth in superyacht visits is the famous Port of Gustavia in Saint-Barthélemy. Over the 2024–2025 New Year's Eve period, the island confirmed a record-breaking 450 superyachts and boats, highlighting its status as a premier destination for high-end luxury clientele (Fadel & Stimpfling, 2025). Figure-6, based on data from SuperYachtFan (2025), illustrates this trend from 2021 to 2024 by charting the rising number of superyachts frequenting the island during the holiday season.

Figure-6: Trends of Superyacht Presence for New Year's Eve in Saint-Barthélemy (2021-2024) (SuperYachtFan, 2025).

2.2.1 Impacts Related to Conventional Yacht Engines

Conventional yacht engines mainly operate on marine diesel or marine gas oil (MGO). Combusting these fuels releases high CO_2, SO_x, NO_x, and PM levels, harming marine ecosystems, human health, and local environments. Transitioning to cleaner alternative fuels can mitigate these adverse effects (Lloyd's Register, 2023).

2.2.1.1 Underwater Noise Disturbance:

Among the environmental impacts of yacht engines, underwater motor noise threatens marine mammals, particularly dolphins. Documented effects include altered travel direction, longer dive durations, and shifts in behavioral states and group dynamics, such as changes in cohesion and synchronized breathing patterns, behaviors commonly associated with evasive responses.

Dolphins often approach vessels, further disrupting their natural activities (Carreño & Lloret, 2021). By avoiding or approaching boats, dolphins may inadvertently reduce time spent on socializing, feeding, or resting, potentially affecting overall population viability.

Furthermore, dolphins in areas such as Croatia's Cres–Lošinj archipelago have been abandoning affected habitats. This highlights the importance of managing motor noise disturbances, as prolonged exposure may compel dolphins to seek quieter environments, placing additional strains on already vulnerable populations (Carreño & Lloret, 2021).

2.2.1.2 Air pollution:

Yacht engines running on MGO emit sulfur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter (PM), affecting air quality, ocean acidification, marine ecosystems, and human health (Lloyd's Register, 2023; Carreño & Lloret, 2021). SO_x (mainly SO_2) from sulfur-rich fuels contributes to acid rain, water acidification, and infrastructure damage, disproportionately harming children, older people, and those with pre-existing conditions (Syrek-Gerstenkorn, Syrek-Gerstenkorn, & Paul, 2024). NO_x (e.g., NO, NO_2), generated at high combustion temperatures, contributes to urban smog, acid deposition, reduced crop yields, and respiratory issues; it also facilitates PM and ground-level ozone formation.

PM, formed both directly and indirectly from SO_x, NO_x, and VOCs, penetrates deep into human respiratory systems, increasing cardiovascular and respiratory disease risks and leading to premature mortality. Yacht-related VOC emissions can be up to 500% higher than commercial ships during the boating season (Carreño & Lloret, 2021). Although improved engine technology, catalytic converters, and stricter standards have advanced emission control, cleaner fuels and propulsion methods remain necessary. With the growth of boating, the superyacht sector must adopt sustainable practices to mitigate environmental impacts (Syrek-Gerstenkorn et al., 2024; Lloyd's Register, 2023).

2.2.1.3 Fuel Spills and Water Contamination:

Yacht engines pollute marine environments, discharging bilge water contaminated with fuel, oil, and other harmful substances (Carreño & Lloret, 2021). Fuel contains heavy metals and polycyclic aromatic hydrocarbons (PAHs), which accumulate in marine organisms, enter the food chain, and ultimately affect human health. Even low PAH concentrations can induce genetic damage in marine life, with bottom-dwelling fish especially vulnerable. Thus, the whole boating industry degrades marine ecosystems.

2.3 Charting a Sustainable Course: Alternative Fuels for the Future

The superyacht industry faces mounting regulatory pressure following the 2016 Paris Agreement, which mandates net zero carbon strategies for all sectors. In 2018, the International Maritime Organisation (IMO) introduced comparable measures (Neilson et al., 2022), seeking to reduce total annual GHG emissions from international shipping by at least 40% by 2030 and by 70% by 2050, using 2008 as the baseline (Wang et al., 2022).

The European Green Deal (2019) and the European Climate Law (2021) reinforced the goal of achieving climate neutrality by 2050, with a targeted 55% emission reduction by 2030 (Krantz et al., 2023; Law and Climate Atlas, n.d.; van ’t Lam & van der Maden, 2021). To reach this, the EU introduced the Fitfor55 package, including FuelEU Maritime, which aims to reduce shipping emissions by 2% in 2025, 6% by 2030, and 75% by 2050 compared to 1990 levels (Krantz et al., 2023). These regulations “exist within The International Convention for the Prevention of Pollution from Ships (MARPOL)” (Neilson et al., 2022, p.1).

However, superyachts are currently not obligated to adhere to rules enforcing lower GHG emissions or imposing energy efficiency standards. Despite the exemption, superyachts' energy consumption and emissions are becoming increasingly visible to the global community. This prompts owners and yacht builders to seek technological solutions during this energy transition. Consequently, new yacht designs and low-carbon fuels are becoming essential (Neilson et al., 2022).

Structural constraints limit the adoption of low-carbon fuels, especially regarding bunkering facilities for options like hydrogen. Without proper infrastructure, decarbonization efforts in maritime industries will stall. For superyachts, this infrastructure gap highlights the need for investment in storage, handling, and safety (Levander, 2022).

Until recently, superyachts— “unique in the manner in which they operate […]”—were often designed to exceed MARPOL regulations for local pollutant emissions. Yet, as “non-essential leisure items which do not undertake useful transport work” (Neilson et al., 2022, p. 2), the rationale for exempting them from stricter standards is increasingly tenuous, mainly when their pollution serves purely recreational purposes (Sciorilli Borrelli, 2024).

Zero-emission propulsion is considered ideal to be more socially responsible. Retrofitting or building new vessels with advanced technologies carries the risk of depreciating a yacht's value, but superyachts' extensive operational lifespan offers some reassurance—some have remained in use for over a century. Contemporary yachts built today may still be active in 2125, making flexibility for future sustainability solutions crucial. This flexibility must be weighed against added costs and any design constraints it imposes (Neilson et al., 2022).

Figure-7: Built in 1902, the 55.4-meter Madiz is one of the oldest classic superyachts still in operation (Camper & Nicholsons, n.d.).

Various alternative fuel solutions are available to the maritime sector, and they differ in feasibility, sustainability, and technological readiness. Before evaluating fuel options, it is essential to consider the Life Cycle Assessment (LCA) framework to understand their broader impacts, from production to consumption (Altosole et al., 2023; Neilson et al., 2022; Wang et al., 2022).

2.3.1 Life Cycle Assessment (LCA): A Compass for Evaluating Marine Fuels

- LCA is a comprehensive method evaluating the environmental consequences of a product or process from cradle to grave—from resource extraction to end-use. This means looking beyond the emissions and instead considering the entire fuel cycle. LCA typically focuses on two key stages: Well-to-Tank (WTT) and Tank-to-Wake (TTW) (Wang et al., 2022):
- WTT refers to emissions generated during fuel production, refining, transportation, and storage. It accounts for everything before fuel reaches a ship's tank and is essential for evaluating fuel effectiveness.
- TTW, on the other hand, deals with emissions produced during the fuel's actual use on board.

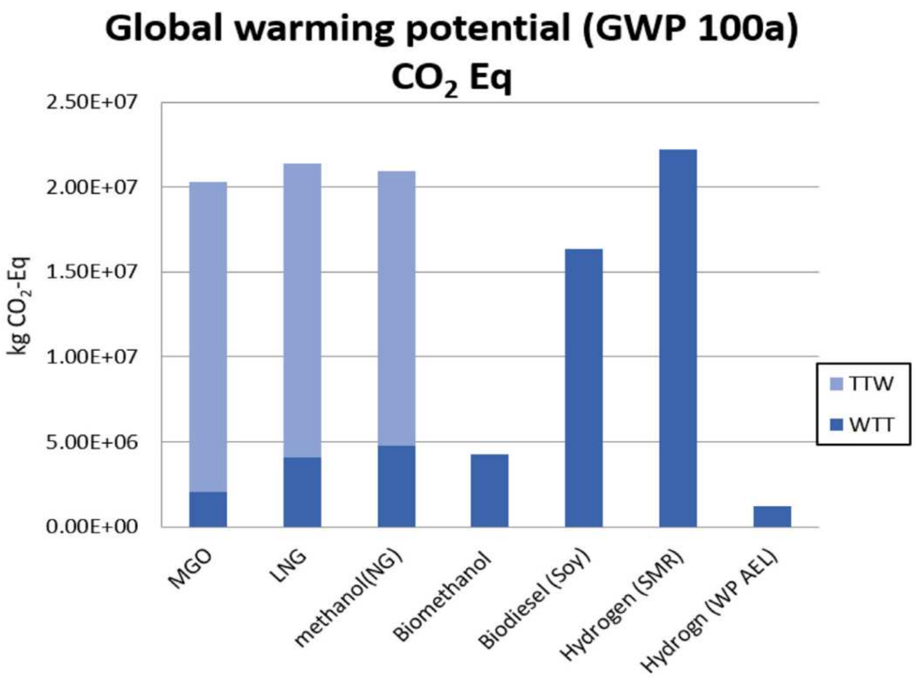


Figure-8: Evaluating the Global Warming Potential of Some Leading Alternative Fuels (Wang et al., 2022, p. 11).

Superyachts and sustainability necessitate evaluating alternative fuels' Global Warming Potential (GWP). As shown in Figure-7, GWP is assessed across each fuel's life cycle, covering both WTT and TTW phases. Expressed in kilograms of CO2-equivalent (kg CO2-Eq), this metric converts emissions into an equivalent amount of CO2 (Wang et al., 2022).

Figure-7 illustrates differing GWP contributions for alternative fuels in both phases. Conventional fuels like MGO and liquefied natural gas (LNG) exhibit higher GWP values than biodiesel (soy-based) and bio-methanol. Hydrogen production methods also matter significantly: steam-methane-reforming (SMR)[2] results in higher GWP, whereas green hydrogen, produced via wind-powered alkaline electrolysis (WPAEL), yields one of the lowest GWPs (Wang et al., 2022).

Combining WTT and TTW provides well-to-wake (WTW) emissions, offering a holistic fuel's environmental impact. Even if TTW reductions are significant, high WTT emissions can offset overall sustainability gains. LCA clarifies these trade-offs, ensuring a comprehensive view of environmental impacts (Altosole et al., 2023; Neilson et al., 2022; Wang et al., 2022).

The IMO's LCA guidelines highlight the need to evaluate fuels Well-to-Wake, incorporating all production-related impacts (Lloyd's Register, 2023).

2.3.2 Breaking the Diesel Dependency: The Case for Transition

Marine Diesel or Marine Gas Oil (MGO) is a standard fuel for ships due to its high energy density and vast availability (Wang et al., 2022). Although diesel engines in these vessels operate on principles like cars/trucks, maritime fuels differ significantly from land-based diesel fuels (McGill et al., 2013).

One key difference is the viscosity (or "fluidity") of MGO, which can reach up to 700 centistokes, whereas road diesel fuel rarely exceeds 5 centistokes. This also affects combustion quality. For comparison, the viscosity of water and honey at room temperature is approximately 1 centistoke and 10,000 centistokes, respectively (Bhandari et al.,1999). The quality of marine fuels is generally lower and more variable than that of land fuels. As a result, marine engines must be capable of handling a wide range of fuel grades, many with high sulfur content that would severely damage the exhaust gas recirculation (EGR) and catalytic systems in automotive engines (McGill et al., 2013).

[2] Steam Methane Reforming (SMR) is an industrial process that produces hydrogen by converting hydrocarbons, such as methane, into hydrogen through a reaction with steam at high temperatures and pressures (Barelli et al., 2008).

Burning MGO in marine engines releases, as mentioned previously, large quantities of CO_2, SO_x, NO_x, and PM. Furthermore, it has a high WTW footprint in terms of LCA. Although more efficient for energy conversion, its environmental cost is substantial. The growing global regulatory focus on reducing emissions makes it clear that alternative fuels must be considered (Wang et al., 2022).

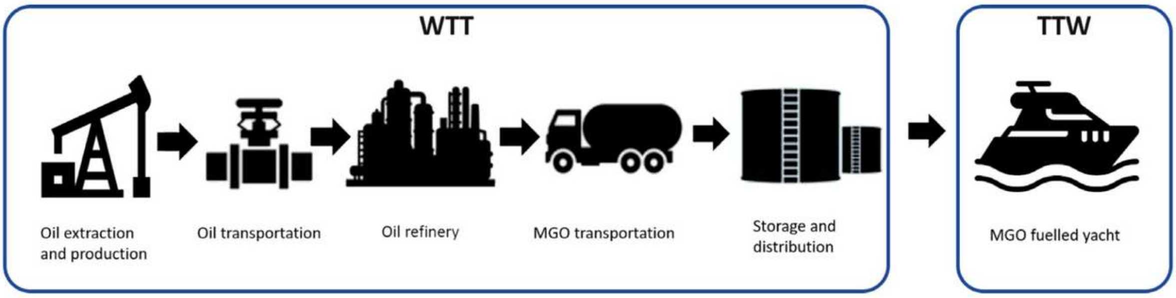


Figure-9: LCA (= WTT + TTW = WTW) of a Diesel Fueled Yacht (Wang et al., 2022).

2.3.3 Exploring Promising Alternative Fuels

Several alternative fuels can replace or supplement MGO while nearly maintaining performance and range. Methanol, biodiesel, liquefied natural gas (LNG), and hydrogen are the most promising. Each has its advantages and challenges, which were all examined through an LCA (Altosole et al., 2023; Neilson et al., 2022; Wang et al., 2022).

2.3.3.1 Methanol:

Methanol is gaining traction as a viable alternative maritime fuel. Known chemically as CH_3OH, this light, volatile, and colorless alcohol offers a cleaner combustion profile than MGO (Lloyd's Register, 2023). Importantly, it functions as a liquid energy carrier and hydrogen carrier, enhancing overall attractiveness (Van Antwerpen et al., 2023).

Methanol's adaptability stems from its varied feedstock options. It can be derived from fossil fuels, such as natural gas and coal, as well as from renewable sources like biomass and captured CO_2, enabling a more seamless transition toward greener energy solutions (Wang et al., 2022). However, its predominant reliance on natural gas and coal remains less sustainable, highlighting a need for more renewable supply chains (Van Antwerpen et al., 2023).

What truly sets methanol apart is its liquid state under ambient conditions. Eliminating the need for costly and energy-intensive compression or cooling systems—essential steps when dealing with hydrogen—simplifies storage and transport logistics. Furthermore, methanol can power ICE with relatively minor modifications (Tian et al., 2022), resulting in far fewer emissions of SO_x, NO_x, and PM than MGO. When sourced from renewable inputs, methanol's GHG emissions can be cut by as much as 97% (Altosole et al., 2023; Neilson et al., 2022). Beyond its compatibility with ICE, methanol also shows promise for integration with fuel cells, broadening its potential applications even further (Van Antwerpen et al., 2023).

However, methanol's lower energy density challenges superyacht design and operation. It requires approximately 2.2 times more storage volume than diesel to achieve the same energy output, which can affect the yacht's internal space allocation (Lloyd's Register, 2023). Additionally, methanol is flammable with a flashpoint of 37°C. It is moderately toxic, necessitating enhanced safety measures onboard, such as cofferdams around fuel tanks, advanced fire suppression systems, and improved ventilation to manage potential leaks (Neilson et al., 2022).

Methanol production methods vary, leading to different classifications based on the feedstock and process used:

- **Grey Methanol**: Produced from natural gas without carbon capture, resulting in higher lifecycle emissions.
- **Blue Methanol**: Produced from fossil sources with carbon capture, reducing overall CO_2 emissions.
- **Green Methanol**: Produced using renewable energy sources, such as biomass (bio-methanol) or by combining captured CO_2 with green hydrogen from electrolysis (e-methanol), leading to significantly lower lifecycle emissions (Lloyd's Register, 2023).

The transition to green methanol is crucial for reducing GHGs. According to the Methanol Institute, renewable methanol must be derived from sustainable bio-sources or synthesized using green hydrogen and carbon extracted from the environment, such as through Direct Air Capture (DAC) technology. However, bio-derived methanol alone is unlikely to meet the entire demand. While DAC is technically developed, it remains energy-intensive and has not been viable on a large industrial scale (Neilson et al., 2022). Significant amounts of renewable energy would be required to support DAC at such levels, presenting challenges for large-scale adoption at this stage.

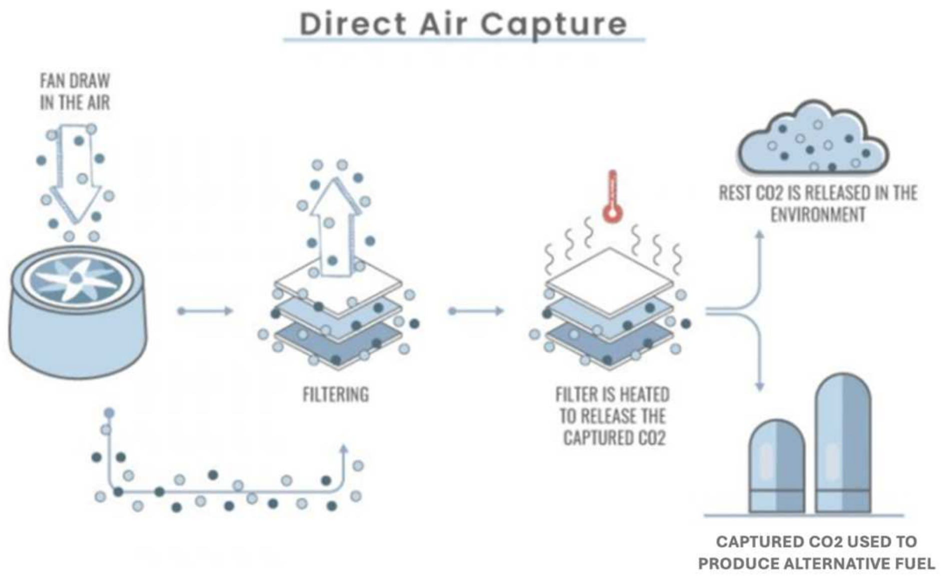


Figure-10: Carbon extraction with DAC (Ingenious e-Brain, n.d.).

Methanol's LCA shows that achieving WTW reductions that align with zero emissions is only possible if methanol is produced from renewable sources. Fossil-derived methanol has higher WTW emissions compared to diesel-powered yachts. Low-carbon blue methanol offers an intermediate option and a transitional pathway toward decarbonization (Neilson et al., 2022).

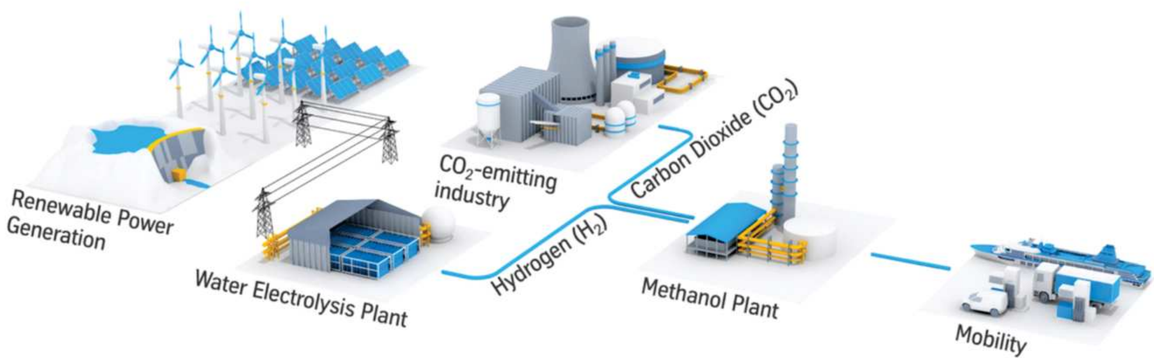


Figure-11: Production Process of Green-Methanol/E-Methanol (KZN Industrial & Business News, 2023).

Adopting methanol as a superyacht fuel necessitates structural adjustments. The increased storage volume affects layout, potentially reducing luxury space or requiring additional hull volume to maintain range. Optimizing the double-bottom structure can boost storage capacity, with needed gross tonnage (GT) increasing by up to 7%, depending on yacht size and configuration (Neilson et al., 2022).

Furthermore, methanol can be used in hybrid propulsion systems, where it powers fuel cells to generate electricity with minimal emissions. Yachts would operate in a so-called *green mode*, reducing noise and pollution, particularly in sensitive coastal areas. However, fuel cells require additional technical space, again influencing needed GT (Altosole et al., 2023).

Despite these challenges, methanol's flexibility supports a gradual transition in yacht design, with dual-fuel systems enabling operation on methanol or diesel during the energy transition. As green methanol's availability increases, yachts can adapt accordingly. Engine manufacturers are advancing methanol-compatible engines, including dual-fuel options. The growing adoption of methanol, reflected in rising orders for methanol-fueled commercial vessels, indicates potential for the superyacht sector (Lloyd's Register, 2023).

2.3.3.2 Liquid Natural Gas (LNG):

LNG is valued for its cleaner combustion compared to MGO. Primarily composed of methane, LNG is stored in a liquefied state at an extreme temperature of -163°C, enabling it to be transported and stored in bulk. Its use notably reduces emissions of SO_x, NO_x, and PM. Compared to MGO, LNG can lower CO_2 emissions by roughly 20%. However, this is tempered by so the called *methane slip*, a process where unburnt methane escapes during combustion (Neilson et al., 2022; Wang et al., 2022).

Integrating LNG storage systems on superyachts requires special insulated cryogenic tanks, which can substantially influence yacht design. With a lower energy density than MGO, LNG demands approximately 1.8 times more storage volume (Wang et al., 2022). Additionally, handling LNG onboard involves complex infrastructure, including enhanced insulation, double-walled piping, and venting systems to manage boil-off gas. These can constrain GT, leading to potential design compromises between operational and luxury areas.

From a lifecycle emissions perspective, LNG cuts WTW emissions, mainly if methane slip is effectively controlled. Depending on the engine type, LNG may reduce NO_x emissions by up to 90% over MGO, offering cleaner operation in emission control areas (ECAs). Yet, the overall GHG reduction capacity of LNG is limited by methane slip; if not managed, methane slip can diminish the CO_2 reduction advantage that LNG otherwise provides (Neilson et al., 2022; Wang et al., 2022). Consequently, LNG is generally viewed as a transitional solution offering moderate GHG reductions unless paired with advanced methane control technologies.

LNG is compatible with both dual-fuel and pure gas engine configurations for propulsion. Dual-fuel systems afford flexibility, allowing superyachts to shift between LNG and diesel based on fuel availability or operational needs. This dual-fuel capability permits yachts to leverage LNG's lower emissions profile while retaining the operational security of diesel engines, presenting LNG as a pragmatic choice for balancing emissions reduction with operational versatility during the ongoing energy transition (Neilson et al., 2022; Wang et al., 2022).

2.3.3.3 Biodiesel:

Biodiesel, a renewable, biodegradable, and non-toxic fuel derived from vegetable oils, animal fats, and waste oils, is a viable alternative to MGO. It can reduce WTW GHG by up to 82%, depending on feedstock and production methods (Neilson et al., 2022; Wang et al., 2022). Synthetic biodiesel, such as Hydrotreated Vegetable Oil (HVO), achieves up to 94% emission reductions. HVO, a second-generation biofuel, is produced from renewable raw materials, including waste oils, residues, and expired margarine, and emits 30% less PM, 9% less NO_x, and no SO_x or aromatic compounds (Sikora & Orliński, 2024).

A key advantage of biodiesel is its compatibility with existing marine engines. HVO is suitable for use without modifications and can be blended with traditional diesel in varying proportions, enabling a gradual transition to higher blends as availability increases (Sikora & Orliński, 2024). Biodiesel's slightly lower energy density reduces range by about 5% compared to MGO. However, this is a relatively minimal reduction compared to other alternative fuels (Neilson et al., 2022).

The environmental benefits of biodiesel vary with feedstock. First-generation biodiesels from food crops can cause indirect land use changes and food security concerns. In contrast, second and third-generation biodiesels, derived from non-edible crops, waste oils, and algae, are more sustainable (Wang et al., 2022). HVO represents second-generation biofuels, relying on renewable feedstocks and waste products to minimize environmental impacts and carbon footprints (Sikora & Orliński, 2024).

The shipping industry's demand for sustainable biofuels is rising, but liquid biofuels alone may not suffice for achieving low-carbon goals by 2030–2050 (Krantz et al., 2023). Biodiesel, while reducing lifecycle emissions, still produces some carbon and local pollutants. Stricter regulations, such as the zero-carbon emissions mandate for UNESCO World Heritage Fjords starting in 2026, may limit superyachts using bio-derived fuels, even if considered net-zero (Neilson et al., 2022).

Yacht designs can integrate biodiesel with minimal modifications to storage and handling systems, though adjustments to filtration systems may be needed to address higher water content and lower oxidation stability (Altosole et al., 2023). Despite these challenges, biodiesel, particularly HVO, offers a flexible, lower-risk option for superyachts transitioning to sustainable fuels.

2.3.3.4 Hydrogen:

Hydrogen is increasingly recognized as a potential zero-emission alternative fuel since it produces only water vapor at the TTW. Its primary advantage lies in its clean operation in fuel cells or ICE and its availability as the simplest and most abundant element. However, hydrogen's benefits largely depend on production methods, as it does not occur naturally in pure form. Hydrogen produced through steam methane reforming (SMR), without carbon capture, generates significant CO_2 emissions, while hydrogen derived from renewable sources, such as WPAEL, presents a more sustainable solution (Wang et al., 2022). Green hydrogen is generated by electrolyzing water (H_2O) by splitting it into hydrogen and oxygen gases ($2H_2$ + O_2) (Ursúa, Gandía, & Sanchis, 2012). This enables a vessel to emit no carbon or other pollutants (zero-emission). This results in a 96% reduction in WTW emissions (Neilson et al., 2022). Additionally, by employing special production techniques—such as DAC with natural gas and steam reforming-based hydrogen production—overall GHG emissions can be reduced by 85% (Wang et al., 2022).

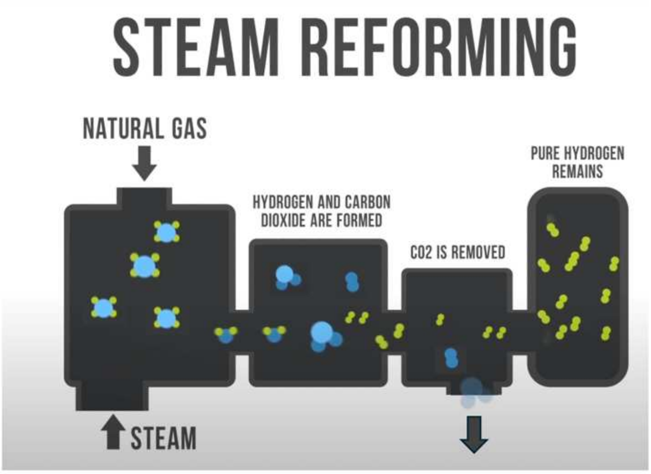


Figure-12: Hydrogen production through SMR (Student Energy, n.d.)

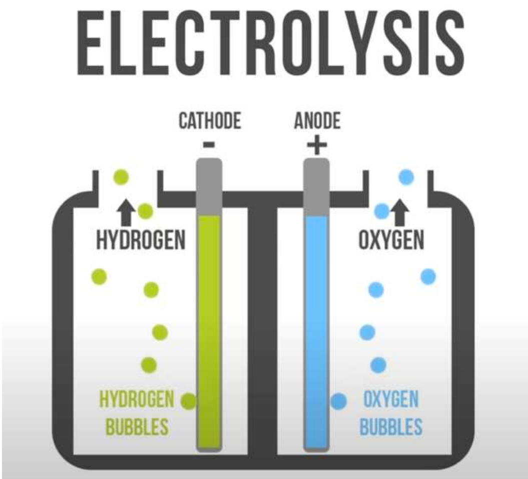


Figure-13: Hydrogen production through Water-Electrolysis (Student Energy, n.d.)

The feasibility of liquid hydrogen as a fuel has been explored in concept projects like the 2019 motor yacht Project *Aqua*. In conjunction with *Sinot Yacht Architecture & Design*, *Lateral Naval Architects* developed a large yacht powered entirely by low-temperature Proton Exchange Membrane (PEM) hydrogen fuel cells. The vessel addresses the challenge of onboard volumetric energy density, leveraging the high technology readiness level (TRL) of storage tanks and fuel cells, which have already obtained approval as a class of vessels. Although there are no formal regulations for hydrogen storage, a clear regulatory pathway exists (Brealey et al., 2022).

Figure-14: Project Aqua - 110m Fully Hydrogen-Powered Super Yacht Concept (Brealey et al., 2022).

Hydrogen's low volumetric energy density necessitates compression or liquefaction for onboard storage. Liquid hydrogen requires cryogenic temperatures of around −252.8°C and involves larger storage volumes compared to MGO (Wang et al., 2022). While this increases energy density, specialized insulated tanks occupy considerable onboard space, potentially impacting the overall layout and GT (Neilson et al., 2022). Furthermore, although PEMs offer high efficiency and quiet operation, making them particularly suitable for environmentally sensitive areas, they typically require more space than ICEs (Neilson et al., 2022).

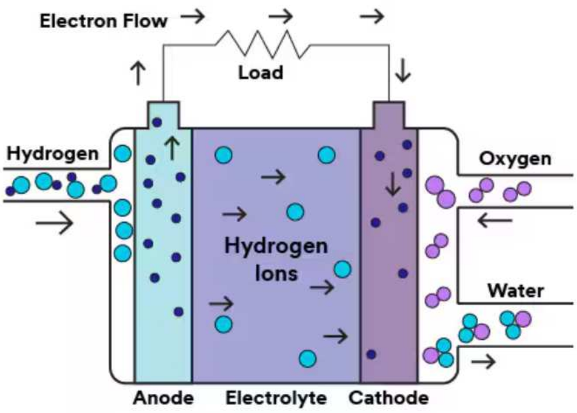


Figure-15: Proton Exchange Membrane Fuel Cells (PEMFCs) or Polymer Electrolyte Membrane Fuel Cells (3M, n.d.)

Conversely, using hydrogen in internal combustion engines allows for easier integration with existing technologies; however, this method still produces NO_x, necessitating emissions control measures (Wang et al., 2022). The technology for storage tanks and fuel cells is at a reasonably mature TRL, supporting the feasibility of hydrogen-powered yachts (Brealey et al., 2022).

Despite the promising aspects of hydrogen as a marine fuel, challenges hinder its widespread adoption. The current use of hydrogen as a marine fuel is primarily confined to pilot and demonstration activities, with no established network of bunkering or port production facilities. Existing hydrogen production is overwhelmingly derived from fossil sources, known as grey hydrogen, which can result in higher CO_2 emissions than MGO when considered in an LCA. Relying on grey hydrogen would be counterproductive for emission reduction goals. While blue hydrogen—produced from fossil sources with DAC—is used in some industries to reduce emissions. However, it is not considered desirable for superyachts compared to other marine fuels that rely on DAC (Brealey et al., 2022).

To meet the highest sustainability targets, green hydrogen derived from renewable power sources and created by electrolysis and subsequent liquefaction is needed. Although around 460 electrolysis-related projects are under development globally, many are at early stages and may not reach projected capacities. Furthermore, few projects are dedicated to producing hydrogen for marine fuel, and most proposed schemes do not consider liquefaction, which is essential for superyacht applications. The amount of liquid hydrogen required by a superyacht is comparatively high, and the locations of proposed projects often are not in areas where yachts require refueling (Brealey et al., 2022).

Safety is another consideration. Hydrogen's flammability and the cryogenic conditions required for storage demand sophisticated onboard safety systems, including enhanced fire suppression and gas detection mechanisms (Neilson et al., 2022). Despite these challenges, green hydrogen produced from renewable energy sources is viewed as a promising long-term solution (Wang et al., 2022). To develop a green hydrogen network supporting large yacht operations, stakeholders within the superyacht industry must invest in yachting “green corridors”, facilitating future sustainable operations (Brealey et al., 2022).

2.4 Management Theories Navigating the Sustainability Transition

2.4.1 Sustainable Supply Chain Management: Integrating Sustainability from Well-to-Wake

Sustainable Supply Chain Management (SSCM) integrates conventional supply chain practices with sustainability principles, addressing environmental, social, and economic impacts under the triple bottom-line framework of environmental protection, social responsibility, and economic resilience (Carter & Rogers, 2008). In the alternative fuels sector, SSCM can apply throughout the WTW phase, encompassing all stages in the fuel's lifecycle. This holistic approach can minimize environmental impact and enhance lifecycle sustainability (Seuring & Müller, 2008).

Sustainable sourcing within SSCM focuses on reducing emissions during extraction, refinement, and transport. Utilizing renewable feedstocks, optimizing supply routes, and employing energy-efficient processing technologies can lower the carbon intensity of fuel production (Hassini, Surti, & Searcy, 2012; Zhu, Sarkis, & Lai, 2008).

Collaboration across supply chains drives innovation in emissions reduction and lifecycle efficiency. Partnerships between suppliers, processors, and distributors strengthen advancements in sustainable processing and emissions management systems, which are critical for the WTW phase. Regulatory frameworks like the IMO's emissions targets and the EU's Fitfor55 package also influence SSCM strategies, compelling companies to adopt compliance-driven approaches to meeting lifecycle emission goals (Brandenburg, Govindan, Sarkis, & Seuring, 2014; Pagell & Wu, 2009).

By applying SSCM principles to the WTW phase, alternative fuel producers can align economic performance, environmental stewardship, and social responsibility at every stage, building resilience to meet the growing demand for sustainable fuel solutions (Carter & Rogers, 2008; Ahi & Searcy, 2013).

2.4.2 Stakeholder Theory

Donaldson and Preston (1995) outlined three dimensions of stakeholder theory: descriptive, instrumental, and normative. The descriptive dimension captures the firm's role within a network of relationships. Instrumentally, it links stakeholder management to benefits like stability and profitability. The normative dimension highlights the ethical duty to value stakeholder interests, promote accountability to a broader community, and balance competing interests for organizational success.

Mitchell, Agle, and Wood (1997) argued that stakeholder salience hinges on power, legitimacy, and urgency. Stakeholders with all three attributes command significant managerial attention and influence decisions more directly. This framework helps managers prioritize stakeholder demands and adapt to shifting expectations.

In the superyacht industry, key stakeholders include yacht owners, environmental organizations, regulatory bodies, employees, and communities affected by pollution and resource use (Freeman, 1984). Environmental groups and regulators drive change through stricter emissions standards and green incentives. Aligning stakeholders around alternative fuels could steer the industry toward innovations that satisfy clients while meeting societal obligations (Frooman, 1999; Phillips et al., 2019; Hillman & Keim, 2001).

2.4.3 Willingness-to-Pay

Willingness-to-Pay (WTP) is the premium a consumer is willing to spend on a product, reflecting its perceived value (Mitchell & Carson, 1989). In our context, WTP reveals how clients value sustainable technologies, such as hydrogen fuel cells, over traditional ICE. Understanding WTP is important in high-end markets, where luxury buyers balance functional and symbolic value. Consequently, sustainable superyachts could emerge as both valuable investments and symbols of ecological responsibility (Breidert et al., 2006).

Luxury consumers' attitudes toward sustainability influence WTP. Some perceive sustainability as incompatible with luxury, seeing it as a mass-market concept that undermines exclusivity (Kapferer & Michaut-Denizeau, 2013). Thus, sustainable features must reinforce the yacht's prestige. Innovations like energy-efficient engines or responsibly sourced fuels can attract buyers if portrayed as exclusive and consistent with luxury.

Conspicuous consumption, driven by the desire to signal status, further shapes WTP in luxury markets. Status-oriented consumers will pay a premium for products that highlight distinction. Accordingly, sustainable yachts may command higher WTP if eco-friendly features elevate their elite status (Amatulli et al., 2018). For instance, cutting-edge sustainable technology can position owners as forward-thinking and responsible, appealing to conspicuous consumers.

Balancing luxury and sustainability in high-visibility products like superyachts, where exclusivity and opulence remain paramount, requires strategically framing social responsibility as a status marker. This heightens appeal without diminishing the luxury positioning (Kapferer, 2014). Ultimately, WTP hinges on the intersection of ecological innovation and conspicuous consumption.

2.4.4 Dynamic Capabilities

Dynamic capabilities (DC) offer a framework for describing how firms navigate significant transitions, such as the shift to alternative fuels and sustainable industry practices. In today's volatile and competitive environments, firms must respond swiftly to external pressures like climate change regulations and shifts in consumer demand. Firms deploying DC anticipate trends and proactively invest in R&D that aligns with a sustainable future (Teece, Pisano, & Shuen, 1997).

The multidimensional nature of DC was stressed by Barreto (2010) in his effort to sharpen the concept beyond sensing and seizing opportunities. He pointed out that the firm needs to promptly respond to opportunities and threats, make market-oriented decisions, and transform the resource base accordingly in high-velocity environments (Barreto, 2010). This highlights that a firm's resources are not static but must be deployed opportunistically to exploit emerging opportunities and mitigate threats. By iteratively testing new technologies and business models, firms can remain flexible and responsive to industry shifts (Eisenhardt & Martin, 2000). Being responsive to emerging environmental demands ensures long-term viability in markets increasingly driven by sustainability (Zollo & Winter, 2002).

3 Research & Methodology:

3.1 Research Design and Approach

We conducted semi-structured expert interviews, a survey, and secondary data analysis to examine structural and strategic changes required for the superyacht-energy transition. This mixed-methods approach accords with best practices for capturing industry drivers based on descriptive insights (Bryman & Bell, 2007; Rowley, 2012).

Our Research Question was: **What are the drivers for adopting Alternative Fuels in the Super Yacht Industry?**

This question implicated ancillary considerations such as: What environmental challenges are facing the superyacht industry today? Which stakeholders exert the most influence on sustainability practices within the industry? What technological, regulatory, or operational changes could improve sustainability outcomes?

3.2 Data Collection Methods

We conducted twelve semi-structured interviews with industry experts and a survey and reviewed secondary data, including industry reports, regulatory documents, and academic literature. To enhance the robustness of our conclusions, we triangulated findings from the literature, interviews, and the survey.

3.2.1 Semi-Structured Expert Interviews

Interviewees of superyacht stakeholders—manufacturers, engineers, alternative fuel experts, captains, naval architects, and environmental regulatory representatives—ensured diverse perspectives on sustainability and covered both technical and strategic facets (Seidman, 2006; Rowley, 2012).

Sample and Recruitment: The twelve interviews presented diverse opinions consistent with achieving adequacy and avoiding saturation (Rowley, 2012). Interviewees were recruited from industry networks and professional associations to ensure representation.

Expert-Interview Partners:

Interview	Position	Interview Date
Interview_1	CEO of a Sustainable Solutions StartUp in the Superyacht Industry	13.11.24
Interview_2	Head of Sales at a Leading Superyacht Services Company (1)	07.11.24
Interview_3	CEO of a Leading Superyacht Services Company (2)	02.12.24
Interview_4	Head of Sales at a Leading Engine Manufacturer	26.11.24
Interview_5	Senior Marina Director at a Leading Sustainable Marina	04.12.24
Interview_6	Superyacht Captain and CEO of a Company Focused on Sustainability in the Industry	19.11.24
Interview_7	Sales Manager at a Hydrogen Fuel Cell Technology Company	25.11.24
Interview_8	Harbor Master of a Major Port in the Gulf of Saint-Tropez	25.11.24
Interview_9	Naval Architect and Manager-Position Representative of a Leading Shipyard specializing in the Design and Construction of Custom Luxury Superyacht (1)	08.11.24
Interview_10	Manager-Position Representative of a Leading Shipyard specializing in the Design and Construction of Custom Luxury Superyacht (2)	30.10.24
Interview_11	Manager-Position Representative at a Leading Nautical Organization (1) Dedicated to Promoting Eco-Friendly Initiatives	05.12.24
Interview_12	Manager-Position of a Leading Nautical Organization (2) Promoting Sustainable Yachting	03.12.24

Interview Guide: Following Rowley's (2012), an interview guide was developed to address key themes from the Literature relevant to the Research Question, including:

- Current sustainability challenges in superyacht production and operation.
- Technological advancements in sustainable fuel and propulsion systems.
- The role of regulations in shaping sustainable practices within the industry.
- Difficulties concerning the adoption of alternative fuels, etc.

Each question was formulated to test assumptions about barriers and drivers within the industry, providing a framework for confirming or challenging hypotheses (Rowley, 2012; Seidman, 2006).

3.2.2 Survey

A survey with n=179 participants was conducted, and the data were analyzed in R.

3.2.3 Secondary Data Analysis

In addition, we consulted industry reports, whitepapers, regulatory guidelines, and academic literature on sustainable maritime practices. This provided historical and emerging information on the industry's sustainability (Krippendorff, 2004) and identified gaps.

Scope and Sources: Reports from regulatory bodies, studies on alternative maritime fuels, and technical specifications from leading superyacht manufacturers, engineers, and architects provided a comprehensive view of challenges and opportunities, as well as potential benchmarks from related fields.

3.3 Data Analysis

The study employed thematic content analysis to extract insights to address the Research Question (Krippendorff, 2004; Mayring, 2004).

3.3.1 Thematic Analysis of Interview Data

We identified recurring themes regarding the barriers, drivers, and perceptions of sustainability, highlighting patterns and emergent themes relevant to industry change (Rowley, 2012). Coding was done in two stages:

Open Coding: Initial coding identified basic themes and sub-themes related to sustainability barriers, regulatory influences, and potential innovations.

Axial Coding: The initial codes were refined through an iterative review into more specific categories, allowing for deeper insights into the interconnected factors influencing sustainable practices.

This dual-stage coding supported an evidence-based response to the Research Question (Seidman, 2006).

3.3.2 Content Analysis of Secondary Data

Content analysis of secondary data identified trends and contextual factors within existing industry publications to extract data efficiently from various sources (Krippendorff, 2004).

Coding Framework: The coding framework was based on derived categories that included "sustainability regulations," "fuel alternatives," and "barriers." This supported or contrasted findings from the thematic analysis, adding rigor to the data triangulation.

3.4 Validity and Reliability

Several strategies were employed to address validity and reliability:

Triangulation: By combining interviews, survey data, and secondary data, the study enhanced its validity through corroboration from multiple sources (Krippendorff, 2004; Rowley, 2012).

Member Checks: Interview participants were provided with summaries to confirm the accuracy of interpretations, enhancing the credibility of qualitative research (Seidman, 2006).

Peer Review: Throughout the analysis phase, peer debriefings with academic supervisors or colleagues helped identify and minimize potential biases, contributing to the transparency and reliability of the findings (Bryman & Bell, 2007).

3.5 Ethical Considerations

This research followed ethical guidelines. Participants were informed of the study's purpose, assured anonymity, and provided with consent forms outlining rights to withdraw at any time. Confidentiality was maintained to protect participants' privacy, especially given the sensitivity of discussing proprietary projects (Rowley, 2012).

3.6 Summary

The methodology described above provided a comprehensive approach for addressing the Research Question.

4 Analysis & Discussion

4.1 Interview Analysis

The superyacht industry has experienced remarkable growth, with over 10,700 yachts above 24 meters currently in operation and approximately 400 to 450 new builds delivered yearly (Interview_2). Demand soared after COVID-19, peaking in 2021 and 2022 before slightly declining in 2023, revealing the sector's sensitivity to external events despite its general uptrend. There is also an increasing emphasis on customization, innovative materials, and eco-friendly options, mirroring broader luxury market shifts toward sustainability and aesthetic innovation (Interview_9).

4.1.1 Shifting Ownership Profiles and Expectations

Experts noted a significant generational shift. Many younger owners, often under 50 and associated with the tech sector, increasingly prioritize environmental responsibility (Interview_2; Interview_3). However, actual investments in sustainable solutions hinge on each owner's "appetite for change" (Interview_6). Although numerous professionals argued that superyachts remain symbols of opulence, there is a growing conviction that owners—and the institutions guiding them—are growing more attuned to environmental concerns. Clubs, associations, and third-party assessment frameworks (TPAF) (Interview_11) reinforced these shifts, establishing norms and incentives that encourage sustainable investments.

This generational wave shapes purchasing behaviors, though it also encounters pockets of skepticism. Some within the industry regard talk of sustainability as insincere unless one avoids purchasing a yacht altogether (Interview_2). Nevertheless, some owners are still interested in sustainable/hybrid technologies (Interview_2; Interview_9).

4.1.2 Economic Realities and Market Dynamics

While superyachts often appear recession-proof, industry resilience is nuanced. A market sector above 60 meters exhibits "anticyclical" behavior, remaining robust despite economic downturns (Interview_2). Yet, vessels below this threshold are more susceptible to cyclical market pressures. Regulation, existential threats, and reputational risks undermine any assumption of unassailable stability (Interview_3; Interview_6). Increasingly stringent environmental standards—especially around carbon emissions—could impact future resale values, pushing owners to adopt more sustainable builds and refits earlier than they otherwise might (Interview_3). Moreover, experts maintained that the *Veblen effect* does not directly apply to superyachts, as owners tend to avoid incurring additional costs (Interview_2).

4.1.3 Environmental Impacts of Conventional Yachting

Although the superyacht industry contributes only 0.2% to global maritime pollution, its underwater noise emissions, fuel spills, and potential harm to marine life remain a reputational and ecological concern. Experts have noted the importance of preserving the oceans' "regenerative capacity" (Interview_1). Acidification, toxic spills, and other pollutants can jeopardize delicate marine ecosystems that superyachts rely on for pristine cruising grounds (Interview_12). Smaller, underregulated vessels aggravate coastal pollution, highlighting the need for uniform regulations across vessel sizes (Interview_1).

Superyachts also face rising scrutiny over carbon emissions. Public perception and societal pressures may increasingly turn against owners unwilling to curb their yachts' pollution, especially as impacts become more visible. Simultaneously, some owners worry yachting is unfairly singled out, pointing to its minimal share of global emissions. Nevertheless, sector leaders acknowledge the need to address any pollution—no matter how relatively small—due to mounting public awareness and social responsibility (Interview_1; Interview_6).

4.1.4 Transitioning Toward Alternative Fuels

Many stakeholders now look beyond diesel dependency and start evaluating alternative fuels (Interview_3; Interview_4; Interview_10; Interview_11). Comprehensively assessing these from WTW perspectives has gained prominence (Interview_4; Interview_9). Although some owners fear new technologies and "stick to what they know" (Interview_1), regulation emerges as the most powerful driver of change, compelling exploration of new fuel systems (Interview_3).

Methanol commands significant attention due to its liquid state at ambient temperature, high hydrogen content, and relative ease of storage (Interview_1; Interview_3; Interview_11). While it produces NO_x emissions upon combustion and entails energy losses during conversion processes, many consider it a feasible medium-term solution (Interview_4; Interview_10; Interview_11). HVO is attractive, given its compatibility with existing diesel engines, but its adoption is limited by feedstock and price (Interview_1; Interview_5; Interview_12). LNG, requiring specialized infrastructure, is considered more suitable for larger (cargo) engines (Interview_4; Interview_7). Hydrogen represents a "huge story" with high long-term potential for zero emissions, yet substantial obstacles—including bunkering, storage, and safety—defer near-term viability (Interview_7; Interview_9; Interview_11).

The rise of TPAF reflects the growing insistence on rigorous life-cycle analysis. These tools measure carbon emissions and energy intensity, offering quantifiable guidelines and potential incentives for low-emission vessels (Interview_11; Interview_12). By integrating these metrics, both owners and shipyards gain clearer baselines for navigating technology investments and regulatory compliance.

4.1.5 Management Theories and Strategic Approaches

Supply Chain Management and LCA: SSCM has gained traction as builders, owners, and regulators increasingly recognize the importance of collaborative LCA efforts (Interview_11; Interview_12). Undertaking LCA studies (Interview_3) and verifying environmental product declarations help reduce the sector's ecological footprint. However, the diverse and fragmented superyacht supply chain complicates standardization and transparency (Interview_9).

Stakeholder Theory: The industry features a prominent network of owners, yacht clubs, and regulatory bodies, all exerting varied degrees of influence (Interview_6; Interview_11). Early adopters among owners can steer sustainable transformations, while influential associations push best practices and unify norms. Several experts argued for balancing interests across these stakeholder groups to build an environmentally responsible "culture" in yachting (Interview_11; Interview_12).

Willingness-to-Pay and Dynamic Capabilities: Despite emergent sustainability demands, many clients refuse to pay sizable upfront premiums without a clear economic logic (Interview_2). Hybrid propulsion and alternative fuel technologies sometimes prove costlier, especially in uncertain regulatory environments, and even more for customized superyachts (Interview_2; Interview_12). Consequently, financial and policy incentives play decisive roles in advancing green technologies. From a "dynamic capabilities" perspective, shipyards can rapidly innovate, adapt, and leverage new fuels to position themselves for future market leadership (Interview_7).

4.1.6 Regulatory Pressures, Infrastructure, and Cultural Shifts

Regulation repeatedly emerges as the most urgent and influential driver of change (Interview_1; Interview_3). Current frameworks often prioritize commercial shipping, leaving superyachts unregulated or insufficiently covered in certain size categories (Interview_1; Interview_6). Nonetheless, looming carbon and emissions regulations will likely pressure the sector to adopt alternative fuels or risk obsolescence (Interview_3; Interview_11). Experts predicted that consistent regulations are essential for scaling bunkering infrastructure, spurring engine development, and ensuring stable fuel supply chains (Interview_1; Interview_4).

Infrastructure hurdles are critical. Alternative fuel production and bunkering for green methanol and hydrogen remains limited, deterring owners from committing to new propulsion systems (Interview_7; Interview_11; Interview_12). Ports and marinas must invest significantly in fuel handling systems and secure storage, often in partnership with government agencies and private suppliers (Interview_5; Interview_8).

Cultural transformations also prove crucial. Established traditions of opulence and the allure of unrestrained cruising can clash with the discipline of reduced emissions and new operational procedures (Interview_6). Some experts fear "greenwashing" when limited sustainability measures are disproportionately marketed (Interview_6). Authentic change demands collaborative efforts: educational programs, demonstration projects, and pilot initiatives that illustrate the viability of lower-impact yachting (Interview_1; Interview_11; Interview_12).

4.1.7 Collaboration, Consulting, and Practical Projects

A tension exists between those who believe in "regulation over collaboration" (Interview_1) and those who champion multi-stakeholder efforts (Interview_11; Interview_12). Both approaches can complement each other. Robust regulation, combined with industry working groups, can drive tangible results. Numerous pilot projects, such as new bunkering stations and demonstration vessels, are underway to test technologies like methanol fuel cells, hydrogen propulsion, and advanced hybrid systems (Interview_1; Interview_6; Interview_9; Interview_10).

Consulting services and alliances with classification societies (Interview_12) help stakeholders navigate complexities—design requirements, bunkering logistics, and safety protocols—while avoiding ad hoc decision-making. Some leading marinas and ports now offer incentives for sustainability leaders and invest in creative infrastructure solutions (Interview_1; Interview_5). These steps, though incremental, can lay the foundations for the broader adoption of alternative fuels and greener operations.

4.1.8 Persistent Supply Chain Challenges

Switching to greener fuels requires robust supplier networks. Availability, feedstock limitations, and volatile pricing remain persistent barriers (Interview_1; Interview_10). Logistical constraints—like inadequate port infrastructure or inconsistent fuel supply—compound owners' hesitancy (Interview_1; Interview_12). Experts also highlighted the higher costs of biofuels and synthetic fuels compared to diesel (Interview_10), and the scale-dependent nature of alternative-fuel production stifles widespread uptake.

4.1.9 Evolving Mindsets and the Future of Sustainable Yachting

Overcoming cultural resistance and short-term thinking is central to a meaningful green transition (Interview_6). Forward-thinking shipyards and owners believe robust solutions necessitate integrated designs, flexible fuel systems, improved energy efficiency, and ongoing education. They also anticipate that younger generations, raised in an era of climate consciousness, will increasingly demand transparency and accountability—leading to major structural shifts in the industry (Interview_2; Interview_3).

Experts converged on a vision where superyachts can incorporate low or zero-carbon propulsion, cutting-edge technologies, and resource-efficient interiors, all supported by advanced bunkering facilities (Interview_11; Interview_12). Crucially, some experts noted that superyachts spend most of their time at anchor and that up to 90% of their overall emissions occur during this period—for the "hotel load"—which is currently powered by generators running on MGO (Interview_1; Interview_6). As a result, adapting these onboard generators to operate with alternative fuels or comparable technologies could substantially reduce overall emissions (Interview_1; Interview_6). Tools like TPAF (Interview_11; Interview_12) will likely become standard, providing measurable frameworks for continuous improvement. Although significant obstacles remain—especially around infrastructure and owner willingness to incur additional costs—stakeholders appear to be moving toward a future in which sustainability is integral rather than optional.

4.2 Survey Analysis

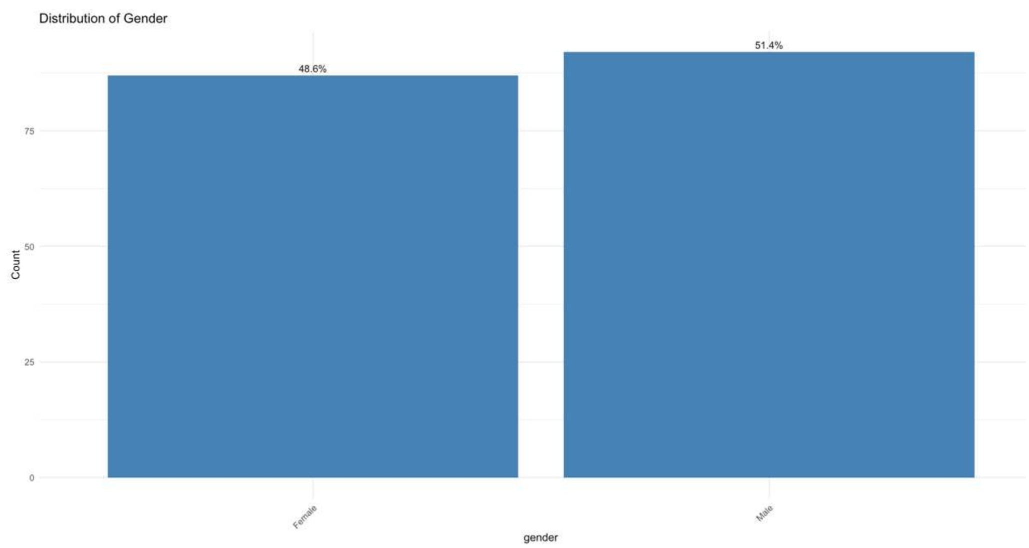
Survey data from the final, corrected sample of n=179 exploring perceptions, awareness, and attitudes toward sustainability and alternative fuels in the superyacht industry and perceived barriers to more sustainable practices.

4.2.1 Demographic Profile of Respondents

Gender (N = 179)

The gender distribution was fairly balanced: 92 (51.4%) identified as male and 87 (48.6%) as female. No respondent selected non-binary or preferred not to say.

Table-1



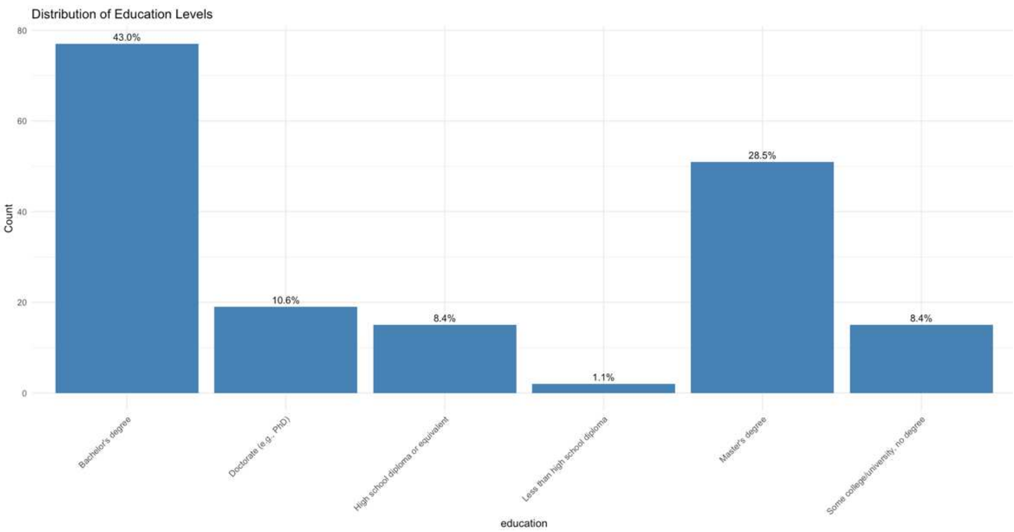
Occupation (N = 179)

About half were students (91; 50.8%), while 65 (36.3%) held roles usually requiring higher education (e.g., engineers, teachers, managers). Ten (5.6%) were in roles not needing a degree, 10 (5.6%) were self-employed, and 3 (1.7%) were unemployed. The strong student presence may reflect a younger demographic with keen academic interest in sustainability.

Education Level (N = 179)

A large portion held bachelor's or higher degrees: bachelor's (77; 43.0%), master's (51; 28.5%), and doctorate-level (19; 10.6%). Smaller groups had some college/university without a degree (15; 8.4%), a high school diploma or equivalent (15; 8.4%), or less than high school (2; 1.1%).

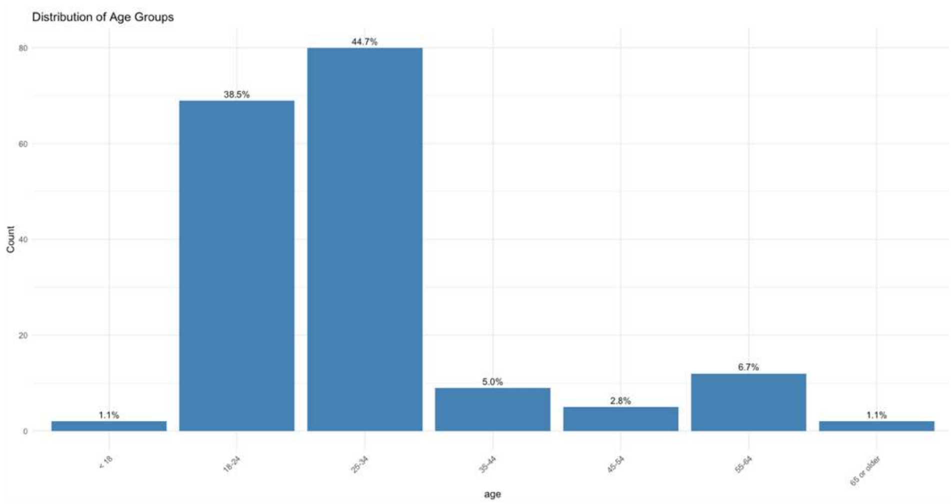
Table-2



Age Distribution (N = 179)

The majority of participants were 18–34 years old. Specifically, 2 (1.1%) were under 18, 69 (38.5%) were 18–24, 80 (44.7%) were 25–34, 9 (5.0%) were 35–44, 5 (2.8%) were 45–54, 12 (6.7%) were 55–64, and 2 (1.1%) were 65 or older. Over 80% were under 35, indicating a predominantly younger sample.

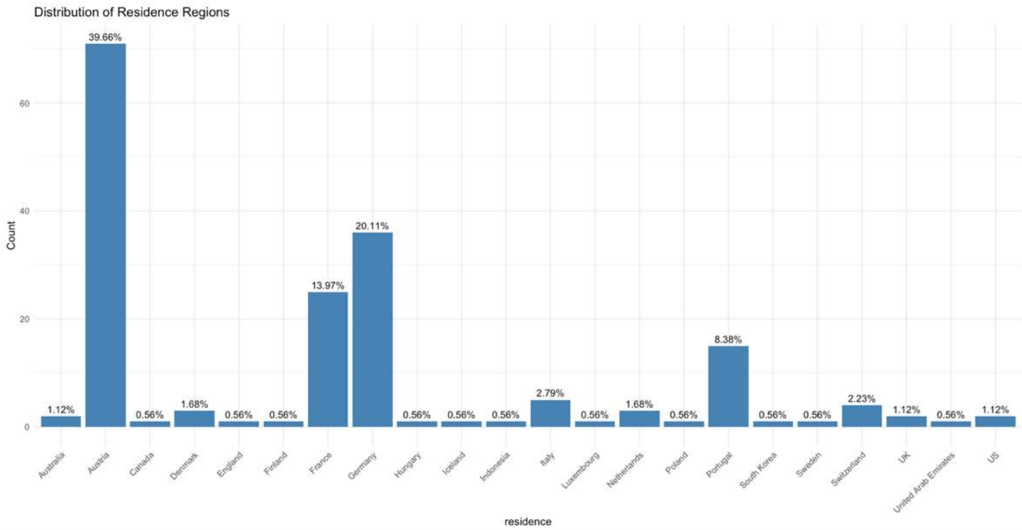
Table-3



Country of Residence (N = 179)

Respondents came from numerous countries, mainly in Europe. Austria (63; 35.2%) and Germany (30; 16.8%) dominated, followed by France (24; 13.4%) and Portugal (14; 7.8%). Other European and some non-European nations (e.g., Australia, Canada, US, Indonesia, South Korea) also appeared in smaller numbers.

Table-4



4.2.2 Environmental Awareness and Perceptions of Superyachts

Environmental Awareness

Most respondents were at least moderately familiar with environmental issues. The majority were “Moderately” (79; 44.1%) or “Very familiar” (72; 40.2%), with fewer “Extremely” (17; 9.5%), “Slightly” (9; 5.0%), or “Not at all” (2; 1.1%) familiar.

Table-5

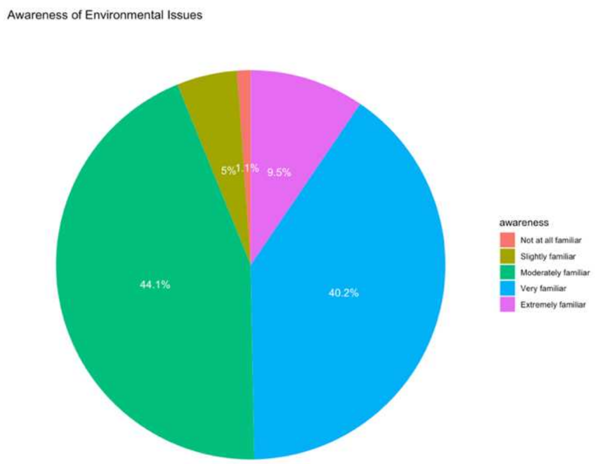
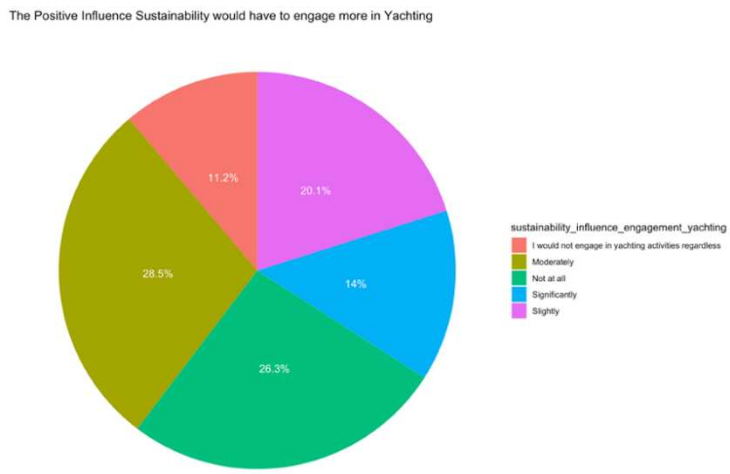


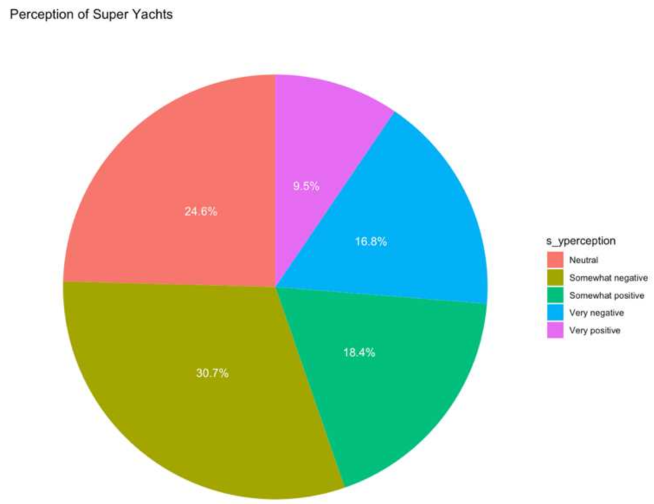
Table-6



Perception of Superyachts

Attitudes ranged widely: 46.8% viewed superyachts negatively ("Very negative" 16.8%, "Somewhat negative" 30.7%), 24.6% were neutral, and 27.9% were positive ("Somewhat positive" 18.4%, "Very positive" 9.5%). Nearly half were critical, with over a quarter favorable and a quarter neutral.

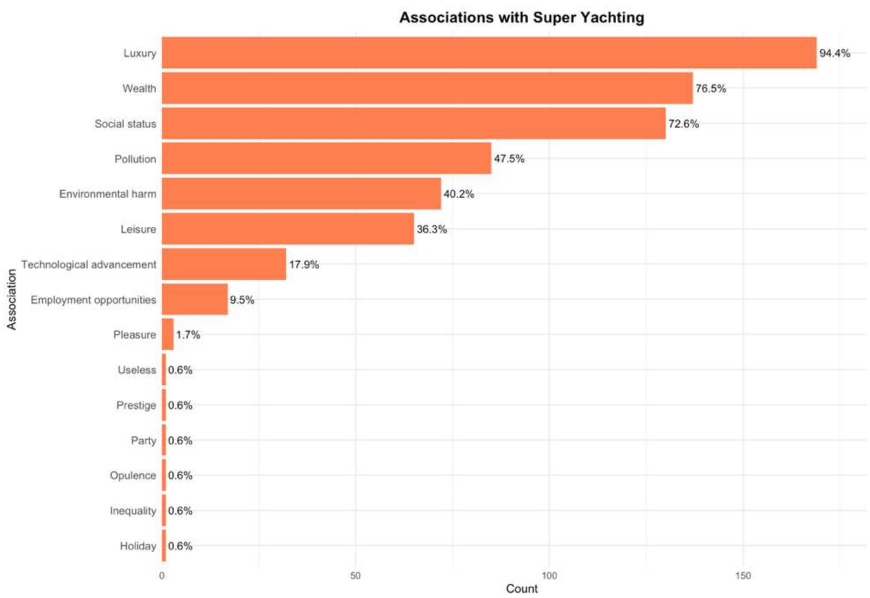
Table-7



Associations with Superyachts

Respondents mainly linked superyachts with luxury (169; 94.4%), wealth (137; 76.5%), and social status (130; 72.6%), followed by leisure (65; 36.3%), environmental harm (72; 40.2%), and pollution (85; 47.5%). Fewer mentioned technological advancement (32; 17.9%) or employment (17; 9.5%). Open-ended responses, such as “Useless,” “Inequality,” “Ultimate feeling of freedom,” and “Party, good times with good people,” illustrated varied interpretations.

Table-8



Concern About Environmental Impact

Among respondents, 7.3% (13) were “Extremely concerned,” 15.6% (28) “Very,” 39.7% (71) “Moderately,” 21.8% (39) “Slightly,” and 15.6% (28) “Not at all” concerned about superyachts’ environmental impact. Over half showed at least moderate concern.

Table-9

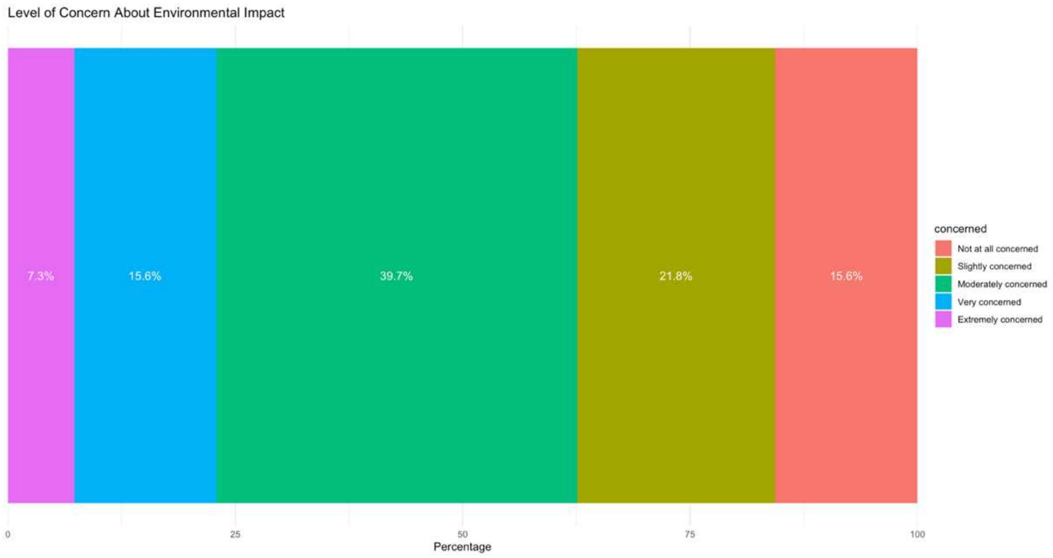
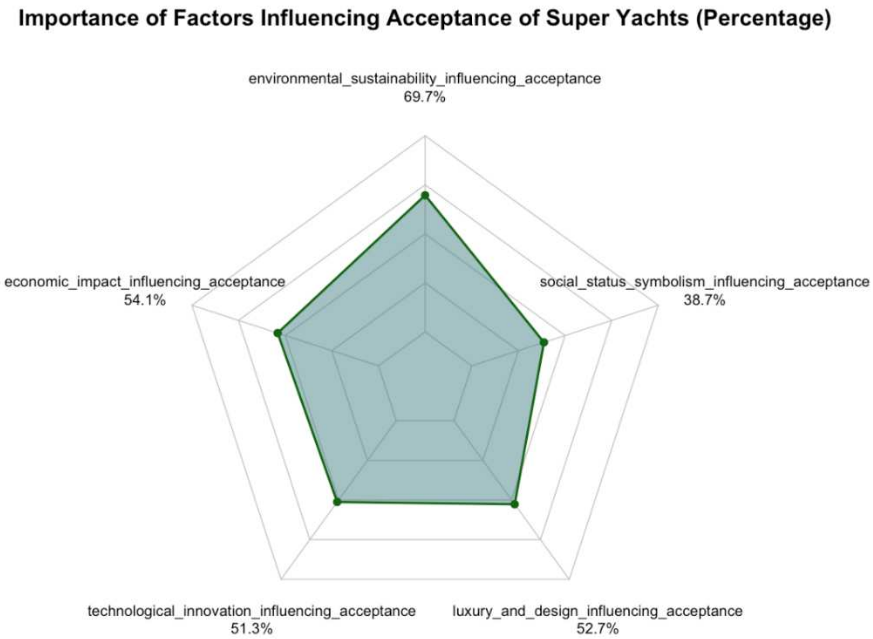


Table-10



4.2.3 Environmental Concerns Specific to Superyachts

Respondents ranked the severity of environmental issues associated with superyachts on a 1–5 scale (1 = least concerning, 5 = most concerning). The average ratings highlight priorities:

- **Air Pollution (Emissions):** Mean rating ≈ 3.29

  Distribution was fairly even: about one-fifth rated this as most concerning (5), while a plurality assigned mid-range concern.

- **Water Pollution (Oil Spills, Waste Discharge):** Mean rating ≈ 3.75

  Over 60% rated this a 4 or 5, making it one of the top concerns.

- **Noise Pollution:** Mean rating ≈ 2.11

  Most respondents (over two-thirds) considered this relatively less concerning, rating it a 1 or 2.

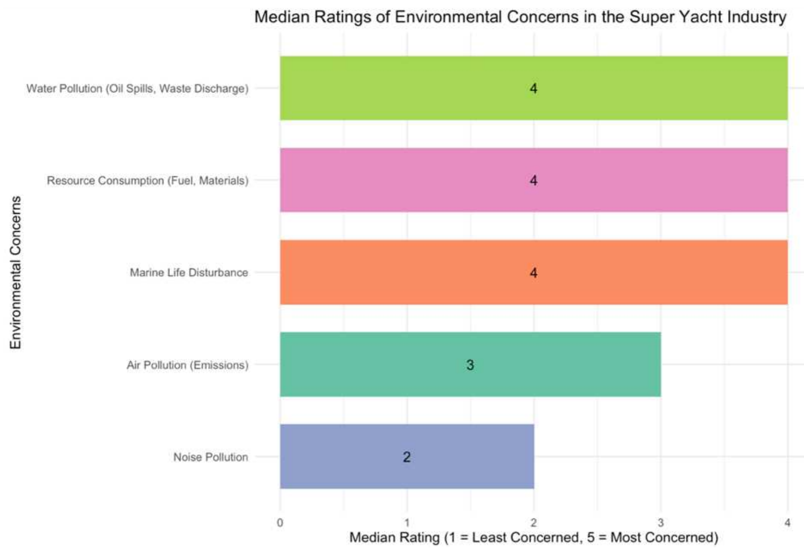
- **Marine Life Disturbance:** Mean rating ≈ 3.50

  Moderately high levels of concern, with a substantial share rating 4 or 5.

- **Resource Consumption (Fuel, Materials):** Mean rating ≈ 3.75

  Similar to water pollution, resource consumption garnered high concern, with many rating it toward the upper end (4 or 5).

Table-11

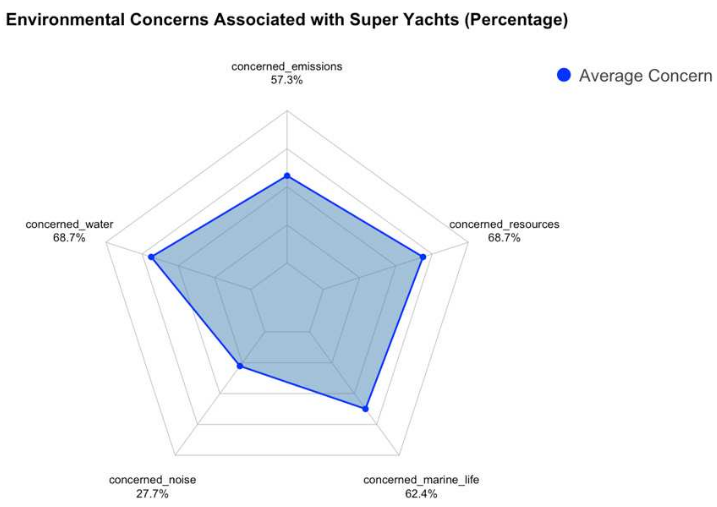


To address the potential impact of outliers on the survey data regarding environmental concerns in the superyacht industry, medians were calculated and compared with the mean values (Table-11). The median ratings revealed:

- Water Pollution (Oil Spills, Waste Discharge): Median = 4, consistent with the mean rating of 3.75, indicating symmetry in responses and high concern overall.
- Resource Consumption (Fuel, Materials): Median = 4, aligning with the mean rating of 3.75, again confirming high concern without significant skewness.
- Marine Life Disturbance: Median = 4, slightly higher than the mean rating of 3.50, suggesting a possible slight skew toward lower ratings.
- Air Pollution (Emissions): Median = 3, matching the mean rating of 3.29, indicating balanced responses with moderate concern.
- Noise Pollution: Median = 2, matching the mean rating of 2.11, further emphasizing that this issue is of relatively low concern for most respondents.

The medians closely aligned with the mean values, suggesting that the data is largely free from significant skew caused by outliers. The exception might be Marine Life Disturbance, where the slight difference between the mean and median could hint at a minor skew in the distribution.

Table-12



4.2.4 Responsibility, Awareness of Alternative Fuels, and Support for Sustainable Practices finished here

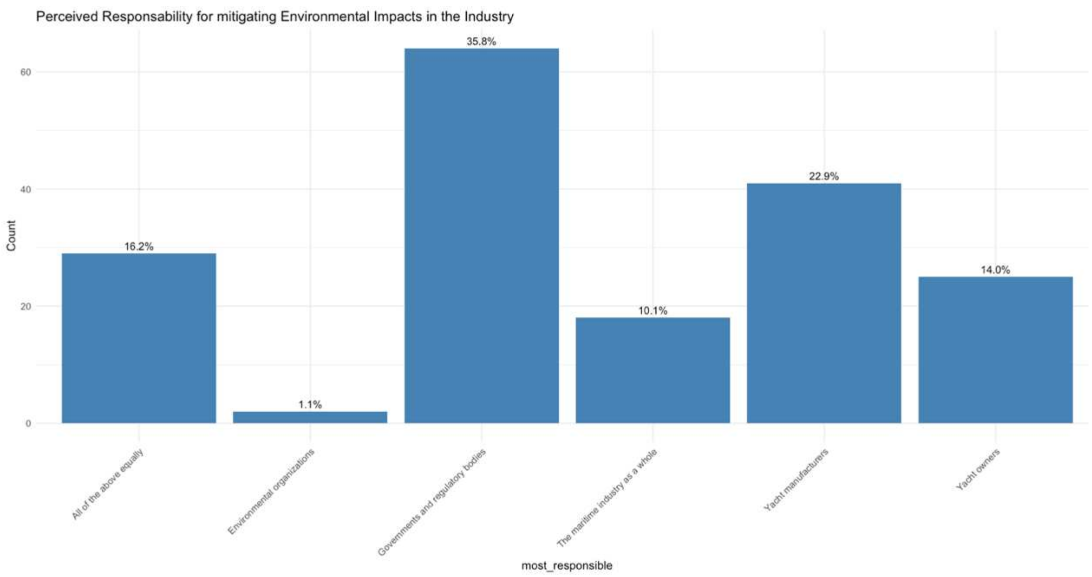
Perceived Responsibility

When asked about responsibility for mitigating environmental impacts, responses highlighted the importance of collective action:

- Maritime industry: 18 (10.1%)
- Yacht owners: 25 (14%)
- Yacht manufacturers: 41 (22.9%)
- Governments/regulatory bodies: 64 (35.8%)
- Environmental organizations: 2 (1.1%)
- All of the above equally: 29 (16.2%)

These findings emphasized the role of governance and the industry, with many respondents advocating a shared approach.

Table-13



Awareness and Support for Alternative Fuels

Before the survey, 57 respondents (31.8%) were unaware that alternative fuels could reduce environmental impacts, while 122 (68.2%) were aware. When asked about supporting alternative fuels, over 70% expressed varying degrees of support, indicating a favorable attitude toward sustainable innovations.

Table-14

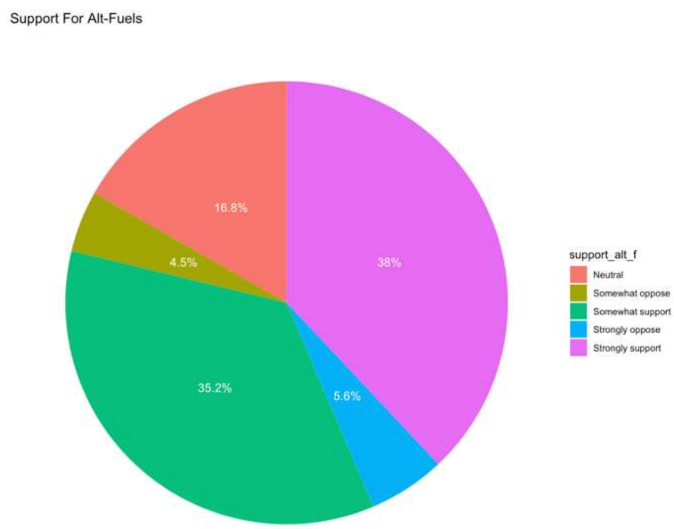


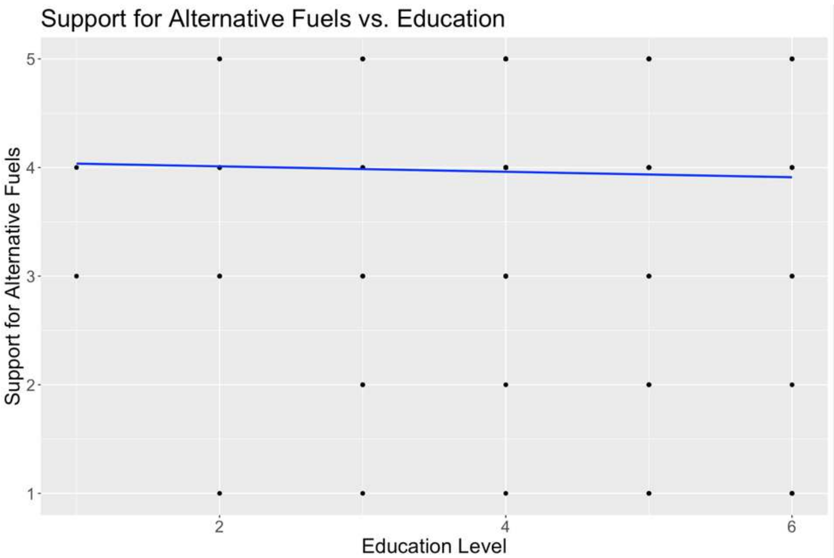
Table-15

Support for Alternative Fuels by Education Level

education	Neutral	Somewhat oppose	Somewhat support	Strongly oppose	Strongly support
Bachelor's degree	18.2% (14)	1.3% (1)	37.7% (29)	1.3% (1)	41.6% (32)
Doctorate (e.g., PhD)	15.8% (3)	5.3% (1)	26.3% (5)	21.1% (4)	31.6% (6)
High school diploma or equivalent	26.7% (4)	0.0% (0)	40.0% (6)	6.7% (1)	26.7% (4)
Less than high school diploma	50.0% (1)	0.0% (0)	50.0% (1)	0.0% (0)	0.0% (0)
Master's degree	7.8% (4)	7.8% (4)	37.3% (19)	5.9% (3)	41.2% (21)
Some college/university, no degree	26.7% (4)	13.3% (2)	20.0% (3)	6.7% (1)	33.3% (5)

The support for alternative fuels correlated with education (Table-15). Respondents with bachelor's or master's degrees exhibited the strongest support, with over 41% strongly supporting. Those with a high school diploma or less were more neutral or somewhat supportive, while doctorate holders had mixed views (31.6% strongly supporting, 21.1% strongly opposing). Overall, higher education was not linked to stronger support, inside the survey data (Table-16). However better education could indicate higher purchase power, hence Willingness-to-Pay for a conventional superyacht.

Table-16



Impact of Alternative Fuels on Perception

If superyachts adopted alternative fuels to reduce environmental impact, 129 respondents (72%) reported an improved perception, 42 (23.5%) indicated no change, and 8 (4.5%) noted a negative shift. These findings highlighted the potential for environmental advancements to enhance public image.

Importance of Sustainability in Luxury Industries

When asked how important it is that luxury industries adopt sustainable practices:

- Extremely important: 53 (29.6%)
- Very important: 67 (37.4%)
- Moderately important: 37 (20.7%)

- Slightly important: 14 (7.8%)
- Not at all important: 8 (4.5%)

Over two-thirds considered it very or extremely important, indicating strong normative pressure for sustainable transitions.

4.2.5 Influence on Consumer Behavior and Policy Support

Decision to Engage in Yachting Activities

Would sustainable practices influence decisions to charter a yacht?

- Not at all: 47 (26.3%)
- Slightly: 36 (20.1%)
- Moderately: 51 (28.5%)
- Significantly: 25 (14.0%)
- Would not engage regardless: 20 (11.2%)

While some consumers remained disengaged, approximately 43% reported moderate to significant influence, indicating sustainability's potential to attract environmentally conscious buyers.

Policy Support for Alternative Fuels

When asked about support for policies mandating alternative fuels:

- Strongly support: 60 (33.5%)
- Somewhat support: 62 (34.6%)
- Neutral: 42 (23.5%)
- Somewhat oppose: 12 (6.7%)
- Strongly oppose: 3 (1.7%)

A majority supported (somewhat or strongly) regulatory interventions to require alternative fuels, indicating favorable conditions for policy measures.

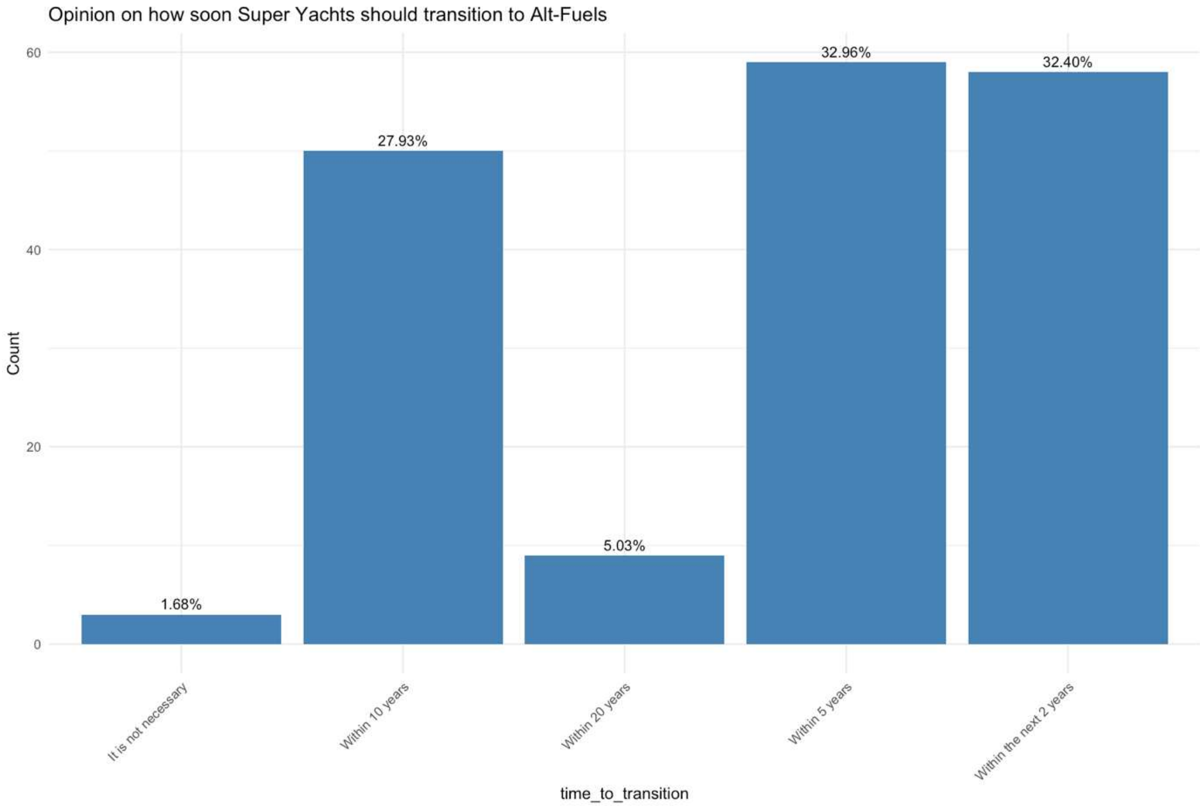
Timeline for Transition to Alternative Fuels

A clear sense of urgency emerged:

- Within 2 years: 58 (32.4%)
- Within 5 years: 59 (33%)
- Within 10 years: 50 (28%)
- Within 20 years: 9 (5%)
- Not necessary: 3 (1.7%)

Almost two-thirds supported a transition within 5 years, underscoring strong momentum for rapid change.

Table-17



4.2.6 Trust in Industry Commitment and Factor Importance

Trust in Industry Commitment

When asked how much they trust the superyacht industry's commitment to sustainability:

- Not at all: 63 (35.2%)

- Slightly: 68 (38%)
- Moderately: 38 (21.2%)
- Very much: 8 (4.5%)
- Completely: 2 (1.1%)

Trust was low, with most respondents expressing little or no trust in the industry's sustainability efforts.

Importance of Various Factors

Respondents rated the importance of environmental sustainability, economic impact, technological innovation, luxury and design, and social status symbolism for their acceptance of superyachts (1=Not important; 5=Very important):

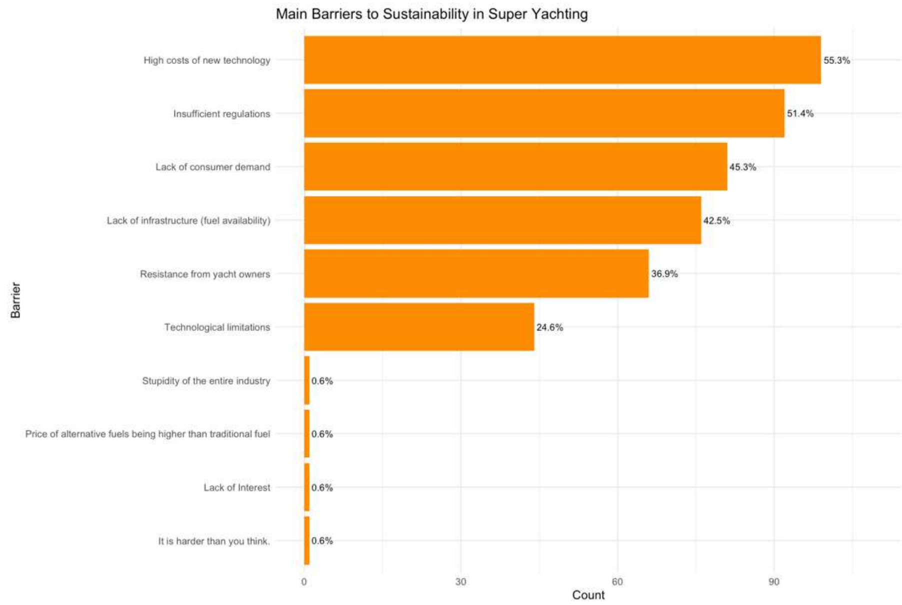
- **Environmental Sustainability:** Mean ≈ 3.79. The majority rated this as important (4 or 5).
- **Economic Impact:** Mean ≈ 3.16. Moderately influential but less than sustainability.
- **Technological Innovation:** Mean ≈ 3.05. Mid-level importance.
- **Luxury and Design:** Mean ≈ 3.11. Opinions varied, with some considering it important and others not.
- **Social Status Symbolism:** Mean ≈ 2.55. Of least importance, reflecting that status appeal is not as strong a driver of acceptance compared to environmental factors.

4.2.7 Perceived Barriers to Adopting Alternative Fuels

Finally, respondents identified barriers to the uptake of alternative fuels, selecting up to two:

- High costs of new technology: Selected by 99 (55.3%)
- Insufficient regulations: 92 (51.4%)
- Lack of infrastructure (fuel availability): 76 (42.5%)
- Resistance from yacht owners: 66 (36.9%)
- Lack of consumer demand: 81 (45.3%)
- Technological limitations: 44 (24.6%)

Table-18



The open-ended responses revealed frustration and complexity, citing “stupidity of the entire industry” (1 respondent), “it is harder than you think” (1 respondent), the “price of alternative fuels being higher than traditional fuel” (1 respondent), and “lack of interest” (1 respondent). Key concerns included costs, regulations, infrastructure, and consumer demand.

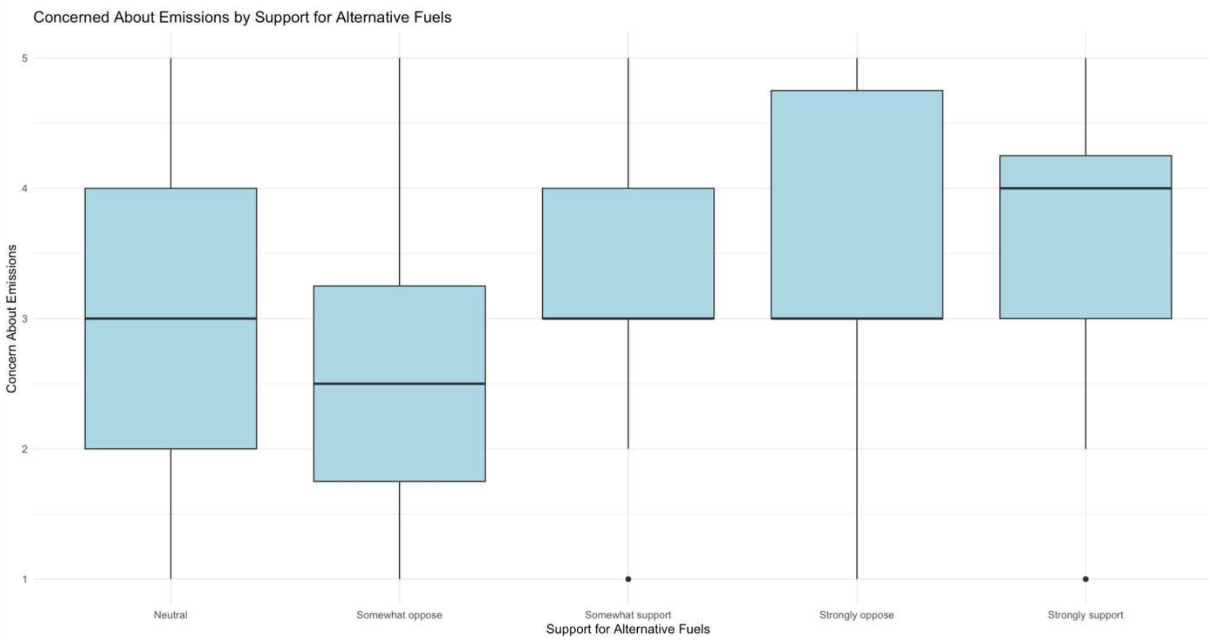
4.2.8 Patterns and Correlations

- Age and Environmental Concern: Younger respondents (18-34) expressed greater environmental concern and support for transitioning to alternative fuels.
- Education and Sustainability: Higher education is correlated with a greater emphasis on sustainability and regulatory support.
- Trust Deficit: Despite support for alternative fuels, trust in the industry was low, requiring transparent commitments and verifiable progress.
- Demand for Action: Strong majorities favored external governance (e.g., government regulations) and rapid adoption timelines, reflecting a desire for policy frameworks alongside technological solutions.

Open-ended responses revealed mixed sentiments about superyachts. Some labeled them “useless” or symbols of excess (“I have too much money to know what to do with”). In contrast, others highlighted positive experiences (“Ultimate feeling of freedom,” “Holiday,” “Party, good times"). These perspectives showcase both symbolic and experiential value but underscore environmental concerns.

The data indicated widespread awareness and significant concern about superyachts' environmental impact. Most respondents supported alternative fuels, seeing adoption to improve the industry's image. However, they cited barriers like high costs, weak regulations, infrastructure gaps, owner resistance, and limited demand, questioning the industry's willingness to change. The findings emphasize the need for policy-driven, industry-wide measures to meet public expectations for sustainability and accountability.

Table-19



Support for alternative fuels correlates positively with concern about emissions, with higher support linked to greater environmental awareness. The box plot indicates that respondents strongly supporting alternative fuels have the highest median concern about emissions. Meanwhile, those who are neutral or opposed show lower concern, suggesting other factors that influence their views. Variation within groups reflects diverse respondent priorities.

Table-20

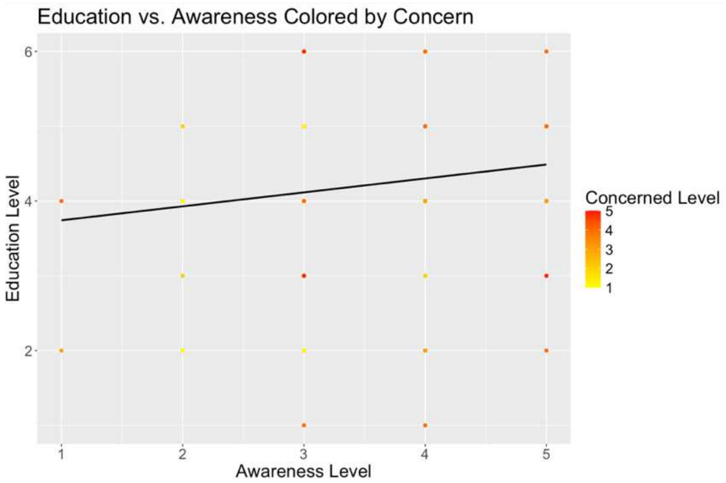


Table-20 shows a positive relationship between education and awareness of alternative fuels, with color intensity indicating concern levels. Higher education correlated with greater awareness (upward trend), and the color gradient reveals that individuals with higher awareness also exhibited increased emission concerns, linking education, understanding, and environmental concerns.

Table-21

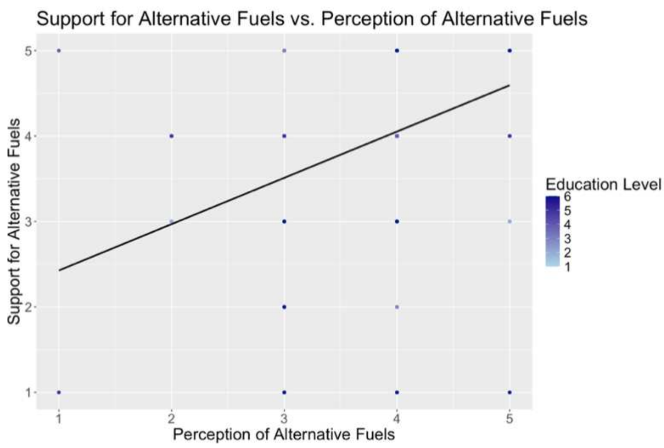


Table-21 reveals a positive correlation between perceptions of alternative fuels and support for their adoption, indicated by the upward trend. Higher perceptions corresponded to stronger support. The color gradient suggests higher education often aligns with both greater perception and support, underscoring education's role in fostering positive attitudes toward alternative fuels.

Table-22

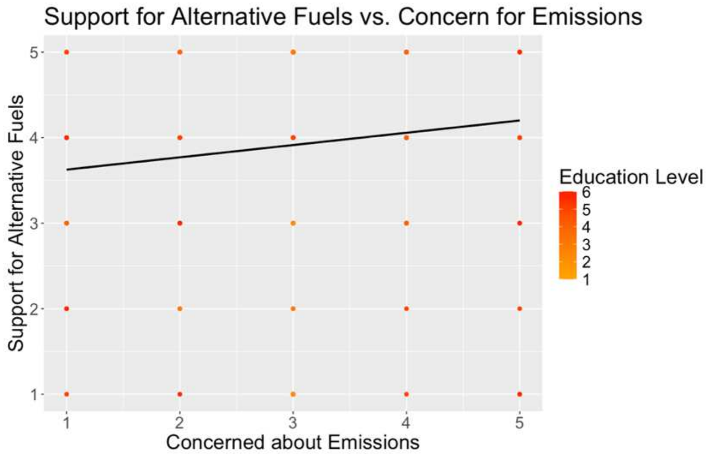


Table-22 shows a positive relationship (upward trend) between emission concerns and support for alternative fuels. Higher concern about emissions correlates with greater support, and the color gradient indicates that this trend spans all education levels. Thus, emission concerns emerged as a key driver of support across various educational backgrounds.

Table-23

Linear Model Summary

```
Call:
lm(formula = support_alt_f_num_new ~ age_num + education_num +
    gender_num + focused_num + occupation_num + awareness_num +
    concerned_water + concerned_noise + concerned_marine_life +
    concerned_resources + concerned_emissions + s_yassociation_Luxury +
    s_yassociation_Wealth + s_yassociation_Holiday + s_yassociation_Inequality +
    s_yassociation_Party + s_yassociation_Leisure + s_yassociation_Technological_advancement +
    s_yassociation_Social_status + s_yassociation_Employment_opportunities +
    s_yassociation_Environmental_harm + s_yassociation_Pleasure +
    s_yassociation_Prestige + s_yassociation_Useless + s_yassociation_Pollution +
    most_responsible_Maritime + most_responsible_Manufacturers +
    most_responsible_Gov_and_Reg + most_responsible_All + most_responsible_Owners +
    main_barriers_High_costs_new_technology + main_barriers_Insufficient_regulations +
    main_barriers_Technological_limitations + main_barriers_Lack_of_consumer_demand +
    main_barriers_Resistance_from_yacht_owners + main_barriers_Lack_of_infrastructure +
    main_barriers_Lack_of_interest + main_barriers_Hader_than_you_think +
    awareness_before_survey_num + perception_alt_f_num + sustainable_lux_num +
    sustainability_influence_engagement_num + support_regulations_num +
    time_to_transition_num + industry_committed_to_sustainability_num +
    environmental_sustainability_influencing_acceptance + economic_impact_influencing_acceptance +
    technological_innovation_influencing_acceptance + luxury_and_design_influencing_acceptance +
    social_status_symbolism_influencing_acceptance + residence_Austria +
    residence_Canada + residence_Denmark + residence_England +
    residence_Finland + residence_France + residence_Germany +
    residence_Hungary + residence_Iceland + residence_Indonesia +
    residence_Italy + residence_Luxembourg + residence_Netherlands +
    residence_Poland + residence_Portugal + residence_Sweden +
    residence_Switzerland + residence_UK + residence_US, data = survey_data2)

Residuals:
    Min      1Q  Median      3Q     Max
-2.3029 -0.4338  0.0000  0.5282  1.5351

Coefficients:
                                                     Estimate Std. Error t value Pr(>|t|)
(Intercept)                                         0.3578466  1.3747696   0.260 0.795141
age_num                                            -0.2407496  0.1023837  -2.351 0.020549 *
education_num                                      -0.0468026  0.0976220  -0.479 0.632623
gender_num                                          0.2459759  0.1832745   1.342 0.182425
focused_num                                        -0.1027064  0.1606960  -0.639 0.524114
occupation_num                                      0.1544285  0.0766516   2.015 0.046470 *
awareness_num                                      -0.0975938  0.1267930  -0.770 0.443184
concerned_water                                     0.1543584  0.0937741   1.646 0.102712
concerned_noise                                    -0.0293997  0.0993823  -0.296 0.767943
concerned_marine_life                              -0.0385196  0.0895069  -0.430 0.667812
concerned_resources                                -0.0148575  0.0814995  -0.182 0.855694
concerned_emissions                                 0.1268380  0.0898058   1.412 0.160774
s_yassociation_Luxury                               0.4583862  0.4644490   0.987 0.325916
s_yassociation_Wealth                               0.2725414  0.2211508   1.232 0.220534
s_yassociation_Holiday                             -0.4279174  1.2932349  -0.331 0.741381
s_yassociation_Inequality                           0.8140029  1.4508383   0.561 0.575943
s_yassociation_Party                                0.0411360  1.6535182   0.025 0.980199
s_yassociation_Leisure                              0.2553260  0.1846985   1.382 0.169757
s_yassociation_Technological_advancement           -0.4573299  0.2470433  -1.851 0.066923 .
s_yassociation_Social_status                        0.0762725  0.2195416   0.347 0.728967
s_yassociation_Employment_opportunities             0.3624537  0.3188858   1.137 0.258258
s_yassociation_Environmental_harm                  -0.1405380  0.2073912  -0.678 0.499472
s_yassociation_Pleasure                             1.7270608  1.1990904   1.440 0.152727
s_yassociation_Prestige                             1.3804754  1.0828904   1.275 0.205165
s_yassociation_Useless                             -2.4474479  1.2353568  -1.981 0.050163 .
s_yassociation_Pollution                            0.0915265  0.2060959   0.444 0.657878
most_responsible_Maritime                           0.7452293  0.8544363   0.872 0.385077
most_responsible_Manufacturers                      0.4822638  0.7840552   0.615 0.539814
most_responsible_Gov_and_Reg                       -0.1309770  0.8076030  -0.162 0.871473
most_responsible_All                                0.2239208  0.8107308   0.276 0.782935
most_responsible_Owners                             0.1107375  0.8315966   0.133 0.894317
main_barriers_High_costs_new_technology            -0.0731669  0.1969329  -0.372 0.710983
main_barriers_Insufficient_regulations             -0.2450177  0.1810304  -1.353 0.178787
main_barriers_Technological_limitations            -0.0040283  0.2082515  -0.019 0.984603
main_barriers_Lack_of_consumer_demand              -0.0709540  0.2033046  -0.349 0.727779
main_barriers_Resistance_from_yacht_owners         -0.3489205  0.1784927  -1.955 0.053238 .
main_barriers_Lack_of_infrastructure               -0.2008487  0.1731168  -1.160 0.248577
main_barriers_Lack_of_interest                      0.8635030  1.0983301   0.786 0.433507
main_barriers_Hader_than_you_think                 -0.7885659  1.6925671  -0.466 0.642243
awareness_before_survey_num                         0.0947672  0.1811572   0.523 0.601981
perception_alt_f_num                                0.2754002  0.1292872   2.130 0.035473 *
sustainable_lux_num                                 0.2386521  0.0945442   2.524 0.013077 *
sustainability_influence_engagement_num             0.0609929  0.0775103   0.787 0.433096
support_regulations_num                             0.3796852  0.1101686   3.446 0.000816 ***
time_to_transition_num                              0.0518235  0.1156132   0.448 0.654888
industry_committed_to_sustainability_num           -0.0437825  0.1210605  -0.362 0.718327
environmental_sustainability_influencing_acceptance -0.0237419  0.1070137  -0.222 0.824851
economic_impact_influencing_acceptance             -0.1043853  0.0871566  -1.198 0.233715
technological_innovation_influencing_acceptance    -0.0592818  0.0936513  -0.633 0.528093
luxury_and_design_influencing_acceptance           -0.0006241  0.0843743  -0.007 0.994112
social_status_symbolism_influencing_acceptance      0.0513957  0.0802823   0.640 0.523432
residence_Austria                                   0.0764396  0.5604216   0.136 0.891766
residence_Canada                                    0.4488756  1.2171793   0.369 0.713025
residence_Denmark                                  -0.0419362  0.9720448  -0.043 0.965669
residence_England                                   0.3306557  1.3661465   0.242 0.809220
residence_Finland                                  -0.0365365  1.1316908  -0.032 0.974306
residence_France                                   -0.2706431  0.5963257  -0.454 0.650864
residence_Germany                                   0.3249231  0.5803403   0.560 0.576740
residence_Hungary                                  -0.6972137  1.1898640  -0.586 0.559147
residence_Iceland                                  -0.2053239  1.2691048  -0.162 0.871782
residence_Indonesia                                -1.1371558  1.2004806  -0.947 0.345666
residence_Italy                                     0.3089902  0.7461330   0.414 0.679621
residence_Luxembourg                               -0.3577243  1.1426721  -0.313 0.754851
residence_Netherlands                               0.5560886  0.9298740   0.598 0.551098
residence_Poland                                    1.2545119  1.1674802   1.075 0.285018
residence_Portugal                                  0.3096689  0.6237599   0.496 0.620601
residence_Sweden                                   -0.4389091  1.1821228  -0.371 0.711163
residence_Switzerland                              -0.7501444  0.7820620  -0.959 0.339647
residence_UK                                        0.2658472  0.8911534   0.298 0.766044
residence_US                                        0.5096932  1.0081702   0.506 0.614213
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.9091 on 106 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R-squared:  0.5905,    Adjusted R-squared:  0.3239
F-statistic: 2.215 on 69 and 106 DF,  p-value: 0.0001097
```

The linear regression model (Table-23) explores factors influencing support for alternative fuels in the superyacht industry. Key insights from the model include the following:

Significant Predictors:

- **Age**: Younger individuals were more likely to support alternative fuels ($p<0.01$).
- **Perception of Alternative Fuels**: A positive perception of alternative fuels strongly enhanced support ($p<0.01$).
- **Sustainability Influence on Engagement**: This factor significantly boosted support, reflecting the importance of sustainability in decision-making ($p<0.01$).
- **Perceived Transition Time**: A longer transition time reduced support for alternative fuels, indicating that perceived delays or inefficiencies discourage adoption ($p<0.05$).

Barriers:

- **Resistance from Yacht Owners**: Resistance negatively impacted support, though its effect was marginally significant ($p\approx0.05$). This suggests the need to engage stakeholders to overcome resistance effectively.
- **Barriers Related to High Costs of New Technology**: These barriers negatively impacted support ($p>0.05$).

Sustainability and Technological Associations:

- Individuals associating sustainability with progress and environmental responsibility exhibited stronger support. Meanwhile, concerns about technological limitations had a negative but less significant impact ($p>0.05$).
- Associations with luxury and inequality showed less consistent or non-significant effects on support.

Geographical Variability:

- Residency in countries like Austria, Canada, and Denmark positively correlated with higher support, while negative associations were observed for countries such as Finland, Germany, and Hungary. This highlighted potential regional differences in attitudes toward alternative fuels.

Model Performance:

- The model explained approximately **32.4% of the variation** in support for alternative fuels ($R^2_{adj} = 0.3239$).
- The F-statistic ($p=0.0001$) confirmed the model's overall significance, ensuring that the predictors collectively had explanatory power.

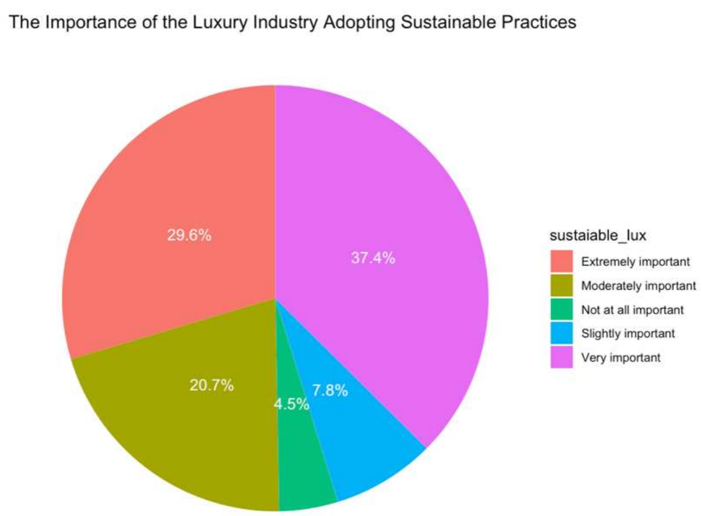
4.3 Discussion

This research integrated a literature review, expert interviews, and a survey to examine the superyacht industry's opulent history and growing sustainability pressures (Ajagunna & Casanova, 2022; Wang et al., 2022). With about 10,700 yachts over 24 meters worldwide and annual deliveries of 400–450, only a tiny fraction are genuinely "green" (Interview_2). Despite the market worth billions, the adoption of alternative fuels and low-emission designs remains limited (Neilson et al., 2022; Wang et al., 2022).

4.3.1 Economic Context and Perceptions of Luxury

The literature positions superyachts as part of a luxury sector driven by wealth and exclusivity (Currid-Halkett, Lee, & Painter, 2019), yet not necessarily operating as classic *Veblen goods*, where higher prices stimulate demand purely for conspicuous status. Several interviewees highlighted that superyachts, although symbols of grandeur, do not strictly follow the *Veblen* dynamic as buyers are more influenced by utility, personal taste, and lifestyle than by mere price-signaling (Interview_2; Interview_3). Survey data (N=179)—primarily young, educated respondents—shows that while over 60% consider sustainability "very or extremely important," environmental awareness does not automatically increase Willingness-to-Pay for greener, pricier vessels. The link between high price and desirability remains tenuous.

Table-24

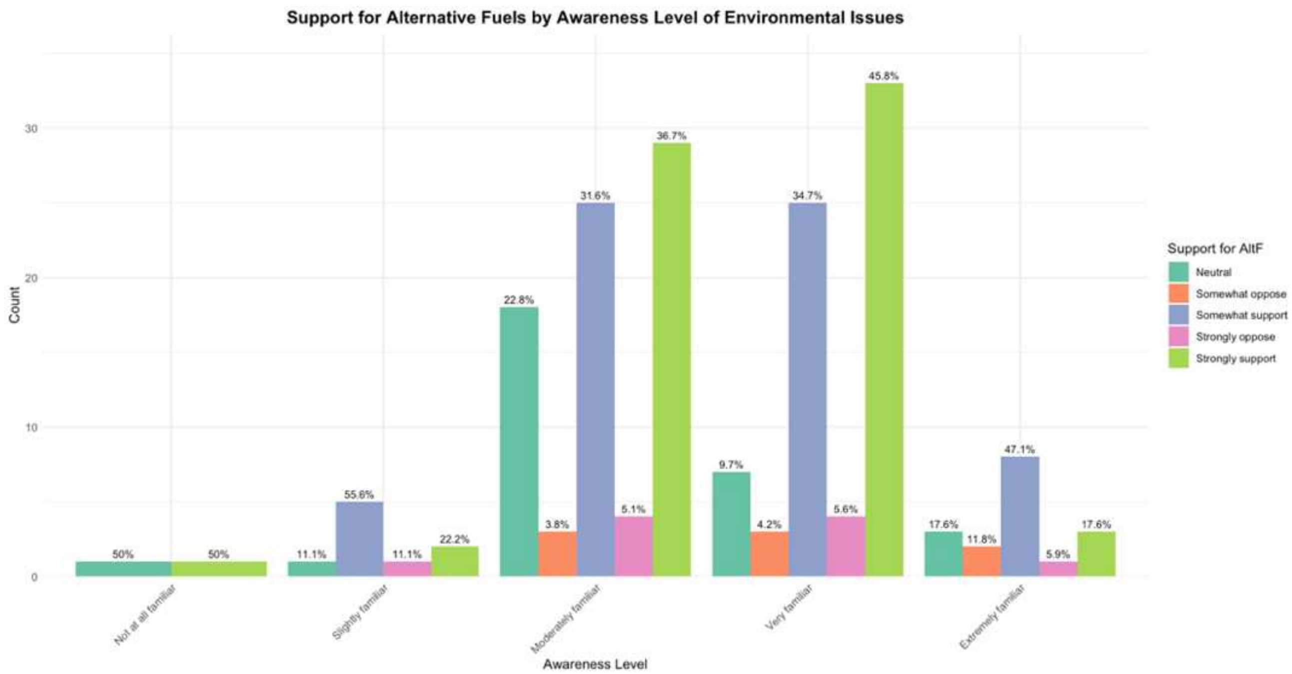


The industry's behavior during economic downturns is somewhat anticyclical, though not uniformly (Interview_2; Merendino, 2013). Higher-end segments (60m+) may be resilient, but market fluctuations, regulations, and reputational pressures challenge the idea of superyachts as safe havens (Interview_2; Interview_6).

4.3.2 Shifting Demographics and Social Pressures

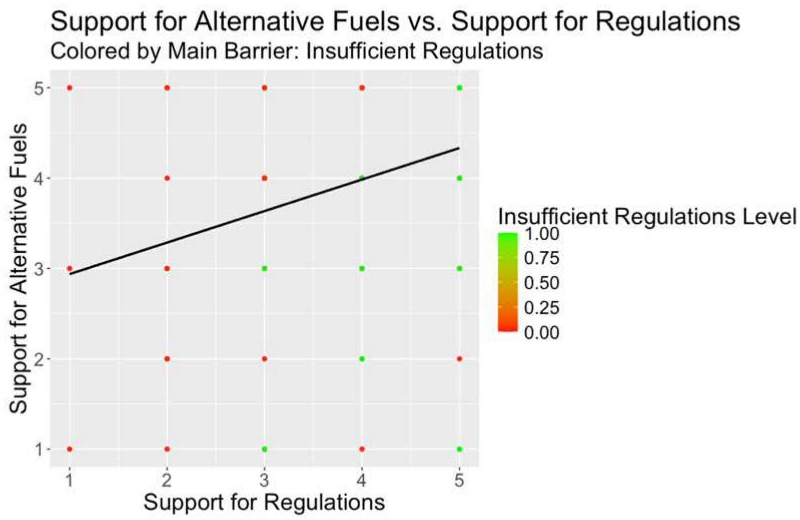
Emerging client demographics—often under 50 and from tech sectors—strongly shape sustainability agendas (Ansaloni, Bionda, & Ratti, 2024; Sciorilli Borrelli, 2024; Interview_2). Literature predicts growing environmental concern, yet interviews reveal a preference for incremental measures (e.g., eliminating plastic bottles on board) rather than costly alternative fuel solutions (Interview_2; Interview_3; Interview_6). Survey data confirms that higher environmental awareness correlates with stronger support for alternative fuels (Table-25).

Table-25



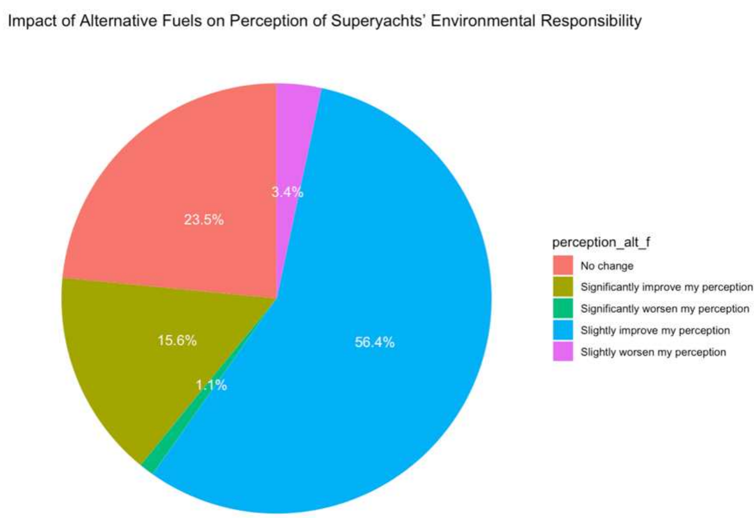
Support for alternative fuels correlated positively with support for regulations, especially when insufficient regulations were identified as the primary barrier (Table-26).

Table-26



Non-owners, including environmental organizations and online communities, push influence through social media and public scrutiny (Interview_11; Interview_12). Survey data showed that 72% of respondents viewed superyachts more favorably if environmental impacts were substantially reduced (Table-27). Literature and interviews highlight mounting reputational pressures, driving the industry to pursue credible sustainability efforts to avoid "greenwashing" (Interview_6; Sciorilli Borrelli, 2024).

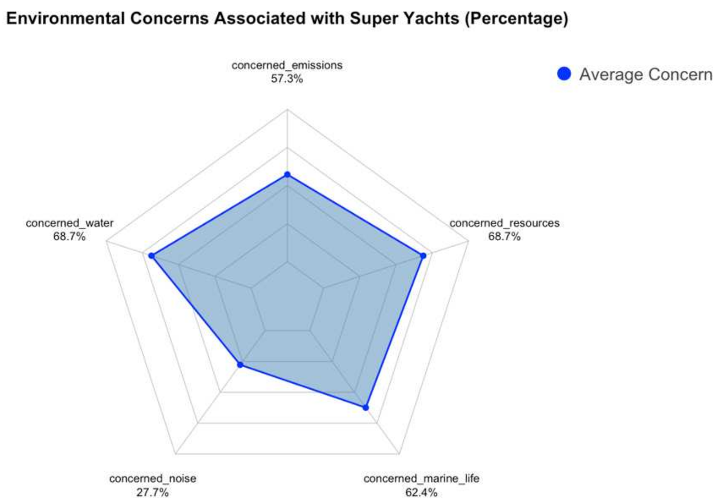
Table-27



4.3.3 Environmental Considerations, Greenwashing Risks, and Transparency

Ecologically, superyachts contribute to CO_2 emissions, air and water pollution, and underwater noise affecting marine mammals (Wang et al., 2022; Carreño & Lloret, 2021). Though a small fraction of maritime emissions overall, they are seen as conspicuous symbols of excess (Interview_1; Interview_2; Interview_12). Survey respondents identified resource consumption, water pollution, and marine life disturbance as major concerns, with specialized issues like underwater noise receiving less attention (Table-28).

Table-28

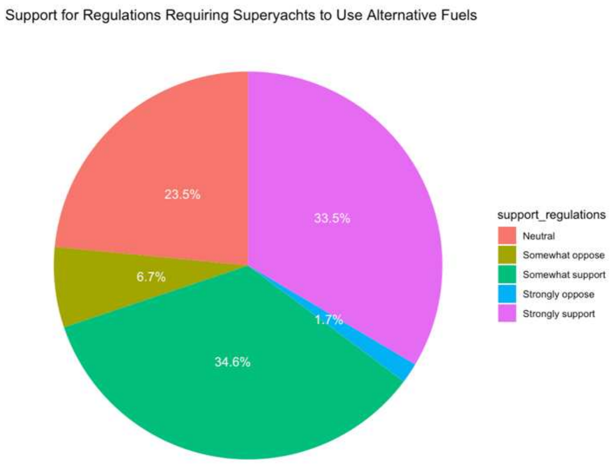


Yet, superficial solutions risk greenwashing (Interview_6; Interview_9). Multiple interviewees warn that minor efforts without addressing core fuel emissions undermine credibility and can backfire. Drawing on Stakeholder Theory (Freeman, 1984) and Sustainable Supply Chain Management (Seuring & Müller, 2008), experts emphasize the need for transparent LCA and robust TPAF (Interview_11; Interview_12) to capture WTW impacts.

4.3.4 Drivers for Adopting Alternative Fuels: Regulation, Technological Feasibility, Cost, and Stakeholder Pressure

A central insight was that regulatory frameworks are the primary driver of alternative fuel adoption (Neilson et al., 2022; Wang et al., 2022). Experts emphasized, “Regulation is driving everything" (Interview_1; Interview_3), indicating that market-led efforts could stall without stringent policy. Strict regulations encourage consideration of efficient alternative fuels (Neilson et al., 2022; Wang et al., 2022). However, these policies should explicitly include superyachts to ensure compliance (Interview_5; Interview_6). Survey results also support regulatory measures—over two-thirds favor mandated alternative fuels—highlighting the necessity of top-down policy enforcement (Table-29).

Table-29



Technological and infrastructural readiness is crucial. While hydrogen has near-zero TTW emissions, its adoption is limited by underdeveloped bunkering infrastructure (Interview_1; Interview_9; Brealey et al., 2022). Green methanol provides a transitional option but depends on scalable production (Interview_5; Lloyd's Register, 2023; Neilson et al., 2022; Wang et al., 2022). HVO, as a cleaner drop-in fuel, is feasible in the short- to mid-term due to compatibility with existing engines and infrastructure (Interview_11; Sikora & Orliński, 2024).

Economic factors also play a major role. Retrofitting older yachts is cost-prohibitive, so owners prefer new builds with sustainability in mind (Interview_1; Interview_2; Interview_12). This aligns with Dynamic Capabilities theory (Barreto, 2010; Teece, Pisano, & Shuen, 1997), highlighting the need for flexible, future-proof yacht designs. Additionally, stakeholder and reputational pressures drive change. Younger owners' moderate environmental concerns and social media scrutiny encourage incremental adoption of alternative fuels to protect brand image (Interview_11; Survey data). Although Willingness-to-Pay remains limited, neglecting sustainability risks alienating clients and the public.

4.3.5 Promising Fuels and the Future of Refit vs. New Builds

Among examined fuels, green methanol and HVO appear to be most viable in the near term (Interview_4; Interview_11; Neilson et al., 2022). Their ambient liquid state eases storage, and compatibility with current engines makes them effective bridge solutions. However, ensuring their availability remains challenging due to production limitations. While LNG lowers emissions compared to MGO, especially in dual-fuel systems, methane slip, storage requirements, including cryogenic tanks and boil-off gas management, and infrastructure complexity reduce its attractiveness in this niche market and is currently more interesting outside the recreational yachting sector (Interview_4; Interview_6; Wang et al., 2022).

Green hydrogen offers zero emissions but presents significant technical and logistical barriers, including cryogenic storage and limited bunkering infrastructure (Interview_1; Interview_3; Interview_7; Interview_9). These hurdles, plus onboard integration complexities, position green hydrogen as a longer-term solution contingent on maturing regulatory frameworks and port facilities (Interview_1; Interview_3; Interview_7).

Refitting older yachts remains rare because of the expense and technical complexity. As interviews clarify, owners prefer ordering new builds featuring alternative propulsion designs rather than undertaking costly retrofits (Interview_1; Interview_12). Since superyacht owners often only retain their vessels for a few years before upgrading to a different one, the notion of “future-proofing” is hardly a priority from their perspective. The additional expense associated with designing a yacht to accommodate future technological and regulatory shifts holds limited appeal for owners who do not plan to operate the same vessel long-term (Interview_2). Consequently, the responsibility shifts to the yacht builders, who must integrate flexible and cost-effective solutions at the outset—ensuring that new designs can adapt to evolving environmental and regulatory requirements while reducing reliance on costly refits. This preference suggests an evolving industry norm: future-proof from inception rather than retrofit later. Firms that embrace SSCM and Dynamic Capabilities frameworks could be well-positioned to incorporate modular engine rooms and flexible fuel systems, thereby reducing long-term costs and enhancing adaptability as regulations tighten (Neilson et al., 2022; Seuring & Müller, 2008; Teece et al., 1997).

4.3.6 Moving Toward a Multivariate Model

Table-30

Horizontal Axis / Vertical Axis	Exogenous / Industry-Level	Exogenous / Firm-Level	Endogenous / Industry-Level	Endogenous / Firm-Level
First-Order Variables	Regulatory Mandates	Fuel Supplier Relationships, Infrastructure Constraints, Fuel Accessibility	Industry Collaborations on Fuel Technology, Shared Maintenance Infrastructures	Internal Dynamic Capabilities, Cost Management Strategies
Second-Order Variables	Social Reputation, Measurement Standards	Technology Partnerships	Norms for Sustainable Practices, Collective Industry Initiatives	Strategic Resource Allocation, Branding and Marketing Approaches to Sustainability
Mediators	Institutionalized Measurement Tools, Sustainable Supply Chain Practices	Supplier Relationships	Shared Infrastructure for Technology	R&D Capabilities, Operational Practices
Moderators	Technological Innovations	Market Perception and Willingness-to-Pay	Industry-Wide Standards	Design Flexibility in New Builds
Confounders	Global Economic Fluctuations, Geopolitical Instability	Supply Chain Variability	Macro-Level Industry Trends	Capital Availability

When integrated into a multivariate model (Table-30), these factors demonstrate how alternative fuel adoption unfolds in the superyacht industry.

First-order variables directly drive alternative fuel adoption, for example, through regulatory frameworks imposing emissions limits or cost strategies guiding resource allocation. These tangible factors form the core of the adoption process.

Second-order variables, such as societal norms, reputational considerations, and industry initiatives, shape the broader ecosystem. Collaborative efforts, like technology partnerships and sustainable practice norms, influence perceptions and actions within the industry.

Mediators link drivers to outcomes by translating pressures into practical measures. Tools like carbon accounting aid firms in meeting regulations, while R&D capabilities turn sustainability goals into innovations, thus enabling fuel integration. Supplier dynamics and shifting consumer preferences give firms anticipating these changes competitive advantages.

Moderators affect the strength or direction of these relationships. Technological advances can ease regulatory compliance, and market perceptions guide responses to sustainability demands. Industry-wide collaboration on fuel technology and shared infrastructure can accelerate systemic progress, shaping the conditions for driver effectiveness.

Confounders are external, uncontrollable factors that add uncertainty, such as economic shifts, geopolitical unrest, or supply chain disruptions. Although these can obscure expected outcomes, tighter regulations, and better institutional tools can ultimately strengthen the industry's capacity for change.

At the industry level, regulations drive compliance with stricter environmental standards, supported by institutional tools and sustainable supply chain practices. Technological innovations and market perceptions influence how quickly firms comply, while global economic and political volatility introduces variability.

At the firm level, relationships with suppliers and infrastructure constraints shape responses. Industry-wide collaborations on fuel technology and shared infrastructure further accelerate progress while dynamic capabilities and cost strategies boost the adoption of alternative fuels. Research and development and design flexibility in new builds promote continued innovation.

Heightened sustainability demands from younger generations intensify compliance pressures, prompting greater R&D investment and more sustainable practices. Understanding how external pressures, internal capabilities, and systemic factors interact improves predictive accuracy and informs strategic decisions. Thus, this framework provides a roadmap for future research and policy in the superyacht industry.

5 Conclusion

Based on the literature, twelve expert interviews, and 179 survey responses, this study found the superyacht industry on the verge of transformation. Historically defined by luxury and exclusivity, it now faces increasing pressure to embrace sustainability, mainly through alternative fuels. Although the existing fleet vastly outnumbers genuinely "green" vessels, and younger client demand for advanced fuels is not yet universal, several factors are pushing change.

Regulation stood out as the primary catalyst, requiring compliance and accelerating the shift away from traditional engines. Without robust policy frameworks, owner interest and external scrutiny alone may be insufficient to drive systemic change. Technological feasibility and high costs also influence the transition, favoring transitional fuels like HVO and green methanol that are more readily integrated. Meanwhile, reputational concerns—intensified by social media—encourage authentic sustainability rather than superficial greenwashing. Experts noted that nearly 90% of superyacht emissions occur at anchor (from hotel load), highlighting the need to address generator-related emissions before fully transitioning to new propulsion systems. They also stressed that outright obsolescence of the industry is not a viable option, as it employs a vast workforce and drives local economies, raising questions about the fate of these professionals if the sector were "banned" in an exaggerated scenario.

Management theory sheds light on these developments. Stakeholder Theory highlights the broad influences—from owners and builders to environmental organizations, regulators, and the socially conscious public—demanding accountability. Dynamic Capabilities emphasizes firms anticipating regulatory trends, investing in R&D, and designing flexible yachts. Similarly, SSCM principles highlight a WTW approach, ensuring accurate and quantifiable environmental benefits.

Although progress is incremental, converging forces—regulatory mandates, technological advances, economic factors, and stakeholder expectations—are steering the industry toward cleaner propulsion. Ultimately, the superyacht industry is shifting from a purely "opulent leisure sector" to one balancing luxury and responsibility. Regulatory developments, cross-industry collaboration, technological advancements, and generational value changes will determine the pace and breadth of this transition. If key stakeholders commit to rigorous environmental standards, adopt feasible alternative fuels, and champion robust training and education, the industry could become a leader in maritime sustainability—proving that even the most exclusive forms of leisure can evolve toward lower environmental impact. Adopting alternative fuels will determine the superyacht sector's capacity to reconcile its heritage of opulence with growing environmental obligations.

6 Limitations & Further Research

This study faces several constraints. The survey sample size was limited, and most respondents were German-speaking individuals or students, potentially narrowing the range of perspectives. Next, reliance on secondary data, though valuable, may not reflect the most recent advancements in an evolving industry. Finally, some experts may have presented skewed portrayals favoring their organizations. Additionally, even though the experts interviewed were from several European countries and from Asia, the total of twelve interviews may still not suffice to provide a fully holistic perspective on the topic. Also, the research did not fully explore certain propulsion and design options—such as sails, electric/battery systems, and nuclear propulsion—either because they were deemed less relevant, viewed as impractical at present, or considered prohibitively expensive and technologically underdeveloped.

Furthermore, we did not thoroughly investigate immediate measures that could enhance sustainability without major propulsion overhauls, such as improved hull design, better insulation, advanced antifouling, “intelligent” air conditioning systems that manage heat and water heating, or reduced plastic use, as was mentioned in some interviews. These areas deserve further study.

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8 Appendix

8.1 Interview Summaries:

Interview 1: CEO of a Sustainable Solutions StartUp in the Superyacht Industry (November 13, 2024)

The CEO, motivated by a passion for meaningful engineering projects, established a company focused on sustainable innovation in yachting, now expanding to cruise ships and broader maritime sectors. The interviewee highlighted that yachting accounts for just 0.2% of maritime emissions, pointing instead to sea pollution as a major concern. Regulatory mandates are seen as the key driver for adopting new fuels, with inadequate infrastructure and owner skepticism hindering progress. Although hydrogen and methanol show promise, current market and technological limitations impede widespread adoption. The company is engaged in educational programs, technical studies, and consulting to guide the industry toward alternative fuels and sustainability-focused operations.

Interview 2: Head of Sales at a Leading Superyacht Services Company (1) (November 7, 2024)

From this sales executive's perspective, sustainability barely registers among superyacht clients, who often prioritize comfort over environmental considerations. Although younger owners show slightly more interest, most are unwilling to pay premiums for green features, hybrid or alternative-fuel propulsions. Economic considerations, notably rising fuel prices, have shifted focus to fuel efficiency. However, real change is unlikely without regulations such as stricter engine requirements. Sustainable yachts remain a niche, comprising less than 1% of the market, further constrained by limited refit feasibility and insufficient infrastructure. The executive predicts that notable sustainability progress in yachting is at least a decade or two away.

Interview 3: CEO of a Leading Superyacht Services Company (2) (December 2, 2024)

The CEO highlighted the smaller environmental footprint of yachts compared to commercial ships and emphasized owners' significant contributions to innovating new technologies, including hydrogen and carbon capture. A pioneering superyacht project illustrates growing industry ambition, though storage and safety remain major hurdles. While regulation is a principal catalyst, younger owners and proactive collaboration among designers, shipyards, and brokers also drive progress. The CEO advocates persistent exploration of options like hydrogen, methanol, with a collective industry push toward sustainability.

Interview 4: Head of Sales at a Leading Engine Manufacturer (November 26, 2024)

With decarbonization as a core strategy, the company aims to reduce marine CO_2 emissions by designing engines that accommodate alternative fuels. Methanol is favored for its ease of storage, lower pressure needs, and adaptability in dual-fuel engines. However, challenges include limited availability of green methanol, higher costs, and the need for larger onboard tanks. While HVO and hybrid systems can serve as interim solutions, the executive sees regulatory pressures, infrastructure development, and collaborative industry partnerships as essential to making alternative fuel adoption financially and technically viable.

Interview 5: Senior Marina Director at a Leading Sustainable Marina (December 4, 2024)

The director observed rapid technological progress since 2008 but noted that yachting still lags behind automotive electrification. Current batteries lack the capacity and lightness needed for large vessels, limiting electric propulsion. His marina is planning infrastructure adaptations to anticipate future developments, including larger berths and potential biofuel availability. Regulatory incentives and cost benefits are pivotal in encouraging green adoption, and the director sees improved hull design, advanced coatings, and better insulation as immediate strategies for reducing energy consumption. While hydrogen and hybrids spark interest, reliability, storage, and costs remain limiting factors.

Interview 6: Superyacht Captain and CEO of a Company Focused on Sustainability in the Industry (November 19, 2024)

Drawing on decades in the industry, the captain stressed that superyachts, largely unregulated for GHG emissions, still rely heavily on fossil fuels. He predicts that looming regulations and carbon taxes will eventually compel shifts, but owner reluctance to invest in pricier solutions stalls progress. Methanol stands out as the most promising alternative, and HVO offers a near-term transition for existing fleets. Infrastructure challenges, the weight and storage demands of emerging fuels, and prevalent greenwashing hamper genuine reform. The CEO advocates for greater collaboration, open-source innovation, and operational efficiency improvements as crucial steps to securing the sector's social license to operate.

Interview 7: Sales Manager at a Hydrogen Fuel Cell Technology Company (November 25, 2024)

Championing hydrogen as a zero-emission energy carrier, the manager views hybridization—combining fuel cells and batteries—as essential for flexible and efficient marine propulsion. Yet infrastructure gaps, production methods (grey vs. green hydrogen), and high costs hinder mainstream adoption. Regulators drive interest by restricting polluting vessels from sensitive zones, and superyachts, with budgets and prestige, can serve as early testbeds for new technology. Despite integration complexities and limited refueling options, hydrogen's long-range potential and suitability for high-energy loads position it as an attractive choice for the industry's decarbonization roadmap.

Interview 8: Harbor Master of a Major Port in the Gulf of Saint-Tropez (November 25, 2024)

The harbor master, transitioning from hospitality to maritime operations, has introduced a suite of environmental measures. These include a desalination station to conserve freshwater, grey and black water pumping services, and a drive toward the "Clean Port" label. Electrification is a priority, with plans for expanded charging infrastructure and eventual electric harbor vessels, though hydrogen and methanol remain impractical for now. High infrastructure costs and regulatory uncertainties pose challenges, yet collaborations—such as solar-powered yachts feeding surplus energy back to the port—demonstrate growing interest in sustainability. The harbor master estimates a 10- to 15-year timeline for broader alternative fuel adoption, closely tied to advances in automotive technology and regulatory frameworks.

Interview 9: Naval Architect and Manager-Position Representative of a Leading Shipyard specializing in the Design and Construction of Custom Luxury Superyacht (1) (November 8, 2024)

He brings deep expertise in naval architecture and maritime research. His leadership focuses on sustainable yacht construction, emphasizing multi-fuel flexibility to accommodate future energy transitions. While larger yachts heighten challenges around scaling, materials, and emissions, he sees promising momentum—driven by eco-conscious owners, shipyards, and some industry groups—to adopt low-carbon fuels and greener materials. The company invests in life cycle assessments and is shifting toward methanol over hydrogen due to practicality. Ultimately, yacht designs must remain adaptable to whichever non-fossil fuels gain traction. He highlights the need for regulation, supply chain collaboration, and cultural shifts to advance sustainability, predicting that environmental accountability will become essential for attracting talent and maintaining social acceptance.

Interview 10: Manager-Position Representative of a Leading Shipyard specializing in the Design and Construction of Custom Luxury Superyacht (2) (October 30, 2024)

Sustainability is integrated into design and operations by focusing on moderate cruising speeds, lightweight construction, and hybrid propulsion for efficiency. Methanol emerges as a viable green fuel due to simpler storage and potential renewability, while hydrogen faces safety and handling complexities. Waste heat recovery and genuine, non-superficial sustainability efforts are prioritized. However, most clients still weigh costs and return on investment cautiously, given yachts' limited usage. Though battery power alone is impractical for large yachts, hybrid systems and methanol are promising. Transitioning to new fuels necessitates collaboration with engine manufacturers, classification societies, and regulatory bodies to address storage, safety, and infrastructure demands.

Interview 11: Manager-Position Representative at a Leading Nautical Organization (1) Dedicated to Promoting Eco-Friendly Initiatives (December 5, 2024)

As part of an international yacht club, he champions sustainability by introducing tools to measure yacht CO_2 emissions and offering incentives like berthing discounts for eco-friendly vessels. He mentions pioneering events that showcase emerging technologies—electric propulsion, hydrogen fuel cells, solar power—which are driving collaboration among students, engineers, and marine professionals. Methanol stands out for its storage and emissions benefits, yet wind-assist technologies and AI-driven solutions also hold promise. Key barriers include limited bunkering infrastructure, regulatory gaps for alternative fuels, and owners' unfamiliarity with new systems. By uniting shipyards, tech providers, and regulatory bodies, yacht clubs can accelerate adoption of greener propulsion and strengthen an industry shift toward life cycle sustainability.

Interview 12: Manager-Position of a Leading Nautical Organization (2) Promoting Sustainable Yachting (December 3, 2024)

The organization is very familiar with an environmental assessment tool to quantify superyacht CO_2 emissions from propulsion and hotel loads, motivating owners to adopt lower-impact technologies. Verified by classification societies, the tool is widely embraced, with ports offering incentives for better-rated yachts. While carbon emissions remain the prime concern, noise pollution and waste management are also relevant. The industry's shift to alternative fuels requires updated regulations, bunkering facilities, and continuing R&D. By facilitating collaboration among stakeholders—owners, shipyards, regulators—the tool drives transparency and continuous improvement. Future plans include expanding metrics beyond CO_2, encouraging real-time monitoring, and reinforcing the business case for investing in greener propulsion and design.

8.2 R-Code For Statistics and Tables

```
### Analysis Of Survey Data On Sustainability in The Super Yacht
Industry

# Load libraries
library(stargazer)
library(ggthemes)
library(GGally)
library(skimr)
library(corrr)
library(knitr)
library(infer)
library(janitor)
library(naniar)
library(magrittr)
library(plm)
library(lmtest)
library(mfx)
library(sandwich)
library(survival)
library(broom)
library(data.table)
library(ggplot2)
library(dplyr)
library(readr)
library(stringr)
library(forcats)
library(AER)
library(tidyr)
library(kableExtra)
library(fmsb)
library(MASS)
library(fastDummies)
library(scales)
library(RColorBrewer)

## Load data manually

# View the first few rows
head(survey_data)

# Rename columns for consistency
survey_data <- survey_data %>%
  rename(
    Awareness = Awerness,
    ConcernedMarineLife = ConcernedMsrineLife,  # Correcting typo
    ConcernedResources = ConcernedRessources,
    AwarenessBeforeSurvey = AltFAwernessBeforeSurvey,
```

```
    SustainabilityInfluenceEngagementYachting =
SustainabilityInfluenceEngagementYachting,
    Environmental_sustainability_influencingAcceptance =
`Environmental_sustainability_influencingAcceptance`,
    Economic_impact_influencingAcceptance = `Economic
impact_influencingAcceptance`,
    Technological_innovation_influencingAcceptance = `Technological
innovation_influencingAcceptance`,
    Luxury_and_design_influencingAcceptance = `Luxury and
design_influencingAcceptance`,
    Social_status_symbolism_influencingAcceptance = `Social status
symbolism_influencingAcceptance`
  )

# Clean column names to make them R-friendly
survey_data <- survey_data %>%
  clean_names()

# View cleaned column names
names(survey_data)

# **Correction Step: Replace "18- 24" with "18-24" in the age column**
survey_data <- survey_data %>%
  mutate(age = as.character(age)) %>%                           #
Convert to character
  mutate(age = str_trim(age)) %>%                               # Trim
whitespace
  mutate(age = str_replace(age, "18-\\s*24", "18-24")) %>%        #
Replace "18- 24" with "18-24"
  mutate(age = factor(age, levels = c(
    "< 18", "18-24", "25-34", "35-44", "45-54", "55-64", "65 or older"
  )))

# **Optional: Verify the replacement**
unique(survey_data$age)

# Convert other categorical variables to factors
survey_data <- survey_data %>%
  mutate(
    education = factor(education),
    occupation = factor(occupation),
    gender = factor(gender),
    residence = factor(residence),
    awareness = factor(
      awareness,
      levels = c(
        "Not at all familiar",
        "Slightly familiar",
        "Moderately familiar",
        "Very familiar",
        "Extremely familiar"
```

```
      )
    ),
    s_yperception = factor(s_yperception),
    s_yassociation = factor(s_yassociation),
    concerned = factor(
      concerned,
      levels = c(
        "Not at all concerned",
        "Slightly concerned",
        "Moderately concerned",
        "Very concerned",
        "Extremely concerned"
      )
    ),
    focused = factor(focused),
    most_responsible = factor(most_responsible),
    support_alt_f = factor(support_alt_f),
    perception_alt_f = factor(perception_alt_f),
    sustaiable_lux = factor(sustaiable_lux),
    sustainability_influence_engagement_yachting =
factor(sustainability_influence_engagement_yachting),
    support_regulations = factor(support_regulations),
    time_to_transition = factor(time_to_transition),
    industry_committed_to_sustainability =
factor(industry_committed_to_sustainability),
    main_barriers = factor(main_barriers)
  )

# Convert Likert scale variables to numeric
survey_data <- survey_data %>%
  mutate_at(vars(
    concerned_emissions, concerned_water, concerned_noise,
    concerned_marine_life, concerned_resources,
    environmental_sustainability_influencing_acceptance,
    economic_impact_influencing_acceptance,
    technological_innovation_influencing_acceptance,
    luxury_and_design_influencing_acceptance,
    social_status_symbolism_influencing_acceptance
  ), as.numeric)

# Check for missing values again
skim(survey_data)

# Visualize missing data
vis_miss(survey_data)

#### No data Missing = AMAZING!!


############Summary statistics
```

```
summary(survey_data)

# Detailed summary with skimr
skim(survey_data)

# Define the variables of interest
variables <- c(
  "concerned_emissions", "concerned_water", "concerned_noise",
  "concerned_marine_life", "concerned_resources"
)

# Inspect for any out-of-range values
outlier_counts <- survey_data %>%
  select(all_of(variables)) %>%
  summarise_all(~ sum(. < 1 | . > 5, na.rm = TRUE))

# Calculate medians for each variable
medians <- survey_data %>%
  summarise(across(all_of(variables), median, na.rm = TRUE))

print("Medians for each concern variable:")
print(medians)

# Calculate medians and reshape for plotting
medians <- survey_data %>%
  summarise(across(all_of(variables), median, na.rm = TRUE)) %>%
  pivot_longer(cols = everything(), names_to = "Variable", values_to =
"Median") %>%
  mutate(Variable = case_when(
    Variable == "concerned_emissions" ~ "Air Pollution (Emissions)",
    Variable == "concerned_water" ~ "Water Pollution (Oil Spills, Waste
Discharge)",
    Variable == "concerned_noise" ~ "Noise Pollution",
    Variable == "concerned_marine_life" ~ "Marine Life Disturbance",
    Variable == "concerned_resources" ~ "Resource Consumption (Fuel,
Materials)",
    TRUE ~ Variable
  ))

# Create the bar plot
median_plot <- ggplot(medians, aes(x = reorder(Variable, Median), y =
Median, fill = Variable)) +
  geom_bar(stat = "identity", width = 0.7, show.legend = FALSE) +
  coord_flip() +  # Flip coordinates for better readability
  scale_fill_brewer(palette = "Set2") +  # Use a color palette from
RColorBrewer
  labs(
    title = "Median Ratings of Environmental Concerns in the Super
Yacht Industry",
```

```
    x = "Environmental Concerns",
    y = "Median Rating (1 = Least Concerned, 5 = Most Concerned)"
  ) +
  theme_minimal(base_size = 14) +  # Use a minimal theme with larger
text
  geom_text(aes(label = Median),
            position = position_stack(vjust = 0.5),
            color = "black",
            size = 5)  # Add median labels on the bars

# Display the plot
print(median_plot)

############ Visualisations

### 1. Bar Charts with Percentage Labels

# Function to create bar charts with percentage labels
create_bar_chart <- function(data, variable, title) {
  ggplot(data, aes(x = {{ variable }})) +
    geom_bar(fill = "steelblue") +
    geom_text(
      stat = "count",
      aes(label = scales::percent(..count.. / sum(..count..))),
      vjust = -0.5,
      size = 3.5
    ) +
    theme_minimal() +
    labs(
      title = title,
      x = deparse(substitute(variable)),
      y = "Count"
    ) +
    theme(
      axis.text.x = element_text(angle = 45, hjust = 1)
    )
}

# Create bar charts for demographic variables with percentage labels
create_bar_chart(survey_data, gender, "Distribution of Gender")
create_bar_chart(survey_data, education, "Distribution of Education
Levels")
create_bar_chart(survey_data, age, "Distribution of Age Groups")
create_bar_chart(survey_data, residence, "Distribution of Residence
Regions")
create_bar_chart(survey_data, time_to_transition, "Opinion on How Soon
Super Yachts Should Transition to Alt-Fuels")
create_bar_chart(survey_data, most_responsible, "Perceived
Responsibility for Mitigating Environmental Impacts in the Industry")
```

```
### 2. Likert Bar Charts with Percentage Labels

# Function to create a Likert bar chart with percentage labels
create_likert_bar <- function(data, variable, title) {
  data %>%
    group_by({{ variable }}) %>%
    summarise(Count = n()) %>%
    mutate(Percentage = Count / sum(Count) * 100) %>%
    ggplot(aes(x = "", y = Percentage, fill = {{ variable }})) +
    geom_bar(stat = "identity", width = 1) +
    coord_polar("y") +
    geom_text(
      aes(label = paste0(round(Percentage, 1), "%")),
      position = position_stack(vjust = 0.5),
      color = "white",
      size = 4
    ) +
    theme_void() +
    labs(
      title = title,
      fill = deparse(substitute(variable))
    ) +
    theme(legend.position = "right")
}

# Create Likert bar charts
create_likert_bar(survey_data, awareness, "Awareness of Environmental
Issues")
create_likert_bar(survey_data, s_yperception, "Perception of Super
Yachts")
create_likert_bar(survey_data,
sustainability_influence_engagement_yachting, "The Positive Influence
Sustainability Would Have to Engage More in Yachting")
create_likert_bar(survey_data, support_regulations, "Support for
Regulations Requiring Superyachts to Use Alternative Fuels")
create_likert_bar(survey_data, support_alt_f, "Support For Alt-Fuels")
create_likert_bar(survey_data, sustaiable_lux, "The Importance of the
Luxury Industry Adopting Sustainable Practices")
create_likert_bar(survey_data, perception_alt_f, "Impact of Alternative
Fuels on Perception of Superyachts’ Environmental Responsibility")

### 3. Stacked Bar Chart with Percentage Labels

# Function to create a stacked bar chart with percentage labels
create_stacked_bar1 <- function(data, variable, title) {
  # Calculate the counts and percentages for each category
  summary_data <- data %>%
    group_by({{ variable }}) %>%
    summarise(count = n()) %>%
    mutate(percentage = count / sum(count) * 100)
```

```
  # Create the stacked bar chart
  ggplot(summary_data, aes(x = 1, y = percentage, fill = {{ variable
}})) +
    geom_bar(stat = "identity") +  # Use stat="identity" since we're
providing pre-summarized data
    geom_text(aes(label = paste0(round(percentage, 1), "%")),
              position = position_stack(vjust = 0.5),
              color = "white",
              size = 4) +  # Add percentage labels
    coord_flip() +  # Flip coordinates for a horizontal bar
    theme_minimal() +  # Apply a minimal theme
    labs(
      title = title,
      x = "",
      y = "Percentage",
      fill = deparse(substitute(variable))
    ) +
    scale_y_continuous(expand = c(0, 0)) +  # Remove extra space on y-
axis
    theme(
      axis.text.y = element_blank(),
      axis.ticks.y = element_blank(),
      panel.grid.major.y = element_blank(),  # Remove horizontal grid
lines
      panel.grid.minor.y = element_blank()
    )
}

# Create stacked bar chart for 'concerned' variable
create_stacked_bar1(survey_data, concerned, "Level of Concern About
Environmental Impact")

### 4. Associations with Super Yachting Bar Chart

# Define the total number of respondents
total_respondents <- 179

# Split the multiple responses into long format and calculate counts
and percentages
s_yassociation_long1 <- survey_data %>%
  separate_rows(s_yassociation, sep = ",\\s*") %>%  # Split multiple
responses
  group_by(s_yassociation) %>%                      # Group by each
association
  summarise(Count = n()) %>%                         # Count
occurrences
  ungroup() %>%
  arrange(desc(Count)) %>%
  mutate(Percentage = (Count / total_respondents) * 100)  # Calculate
percentages
```

```
# Plot horizontal bar chart with counts and percentage labels
ggplot(s_yassociation_long1, aes(x = reorder(s_yassociation, Count), y
= Count)) +
  geom_bar(stat = "identity", fill = "coral") +
  geom_text(aes(label = paste0(round(Percentage, 1), "%")),  # Add
percentage labels
            hjust = -0.1,
            color = "black",
            size = 3.5) +
  coord_flip() +
  theme_minimal() +
  labs(
    title = "Associations with Super Yachting",
    x = "Association",
    y = "Count"
  ) +
  scale_y_continuous(
    expand = expansion(mult = c(0, 0.1)),
    labels = comma
  ) +
  theme(
    axis.text.y = element_text(size = 10),
    plot.title = element_text(hjust = 0.5, size = 14, face = "bold")
  )

### 5. Radar Charts for Importance Factors and Concerns

# Function to create radar charts
create_radar_chart <- function(data, title, color_border, color_fill,
legend_title = NULL) {
  radarchart(
    data,
    pcol = color_border,
    pfcol = color_fill,
    plwd = 2,
    cglcol = "grey",
    cglty = 1,
    axislabcol = "grey",
    caxislabels = seq(0, 100, 20),
    cglwd = 0.8,
    vlcex = 0.8,
    title = title
  )

  if (!is.null(legend_title)) {
    legend("topright", legend = legend_title, bty = "n", pch = 20, col
= color_border, text.col = "grey25", cex = 1.2, pt.cex = 3)
  }
}
```

```
# Radar Chart for Importance of Factors Influencing Acceptance
importance_factors <- survey_data %>%
  select(
    environmental_sustainability_influencing_acceptance,
    economic_impact_influencing_acceptance,
    technological_innovation_influencing_acceptance,
    luxury_and_design_influencing_acceptance,
    social_status_symbolism_influencing_acceptance
  ) %>%
  summarise_all(list(mean = mean, sd = sd)) %>%
  pivot_longer(
    cols = everything(),
    names_to = c("Factor", ".value"),
    names_pattern = "(.*)_(.*)"
  ) %>%
  mutate(percentage = ((mean - 1) / 4) * 100)

radar_data <- importance_factors %>%
  select(Factor, percentage) %>%
  pivot_wider(names_from = Factor, values_from = percentage)

# Add max and min for the radar chart
radar_chart_data <- rbind(
  rep(100, ncol(radar_data)),
  rep(0, ncol(radar_data)),
  radar_data
)

# Rename Columns to Include Percentage Values in Labels
colnames(radar_chart_data) <- paste0(
  colnames(radar_chart_data), "\n",
  round(radar_data[1, ], 1), "%"
)

# Plot the radar chart
create_radar_chart(
  radar_chart_data,
  "Importance of Factors Influencing Acceptance of Super Yachts
(Percentage)",
  "darkgreen",
  rgb(0.2, 0.5, 0.5, 0.5),
  "Average Importance"
)

# Radar Chart for Environmental Concerns
concern_factors <- survey_data %>%
  select(
    concerned_emissions,
    concerned_water,
    concerned_noise,
```

```
    concerned_marine_life,
    concerned_resources
  ) %>%
  summarise_all(list(mean = mean, sd = sd)) %>%
  pivot_longer(
    cols = everything(),
    names_to = c("Factor", ".value"),
    names_pattern = "(.*)_(.*)"
  ) %>%
  mutate(percentage = ((mean - 1) / 4) * 100)

radar_data_concern <- concern_factors %>%
  select(Factor, percentage) %>%
  pivot_wider(names_from = Factor, values_from = percentage)

radar_chart_data_concern <- rbind(
  rep(100, ncol(radar_data_concern)),
  rep(0, ncol(radar_data_concern)),
  radar_data_concern
)

colnames(radar_chart_data_concern) <- paste0(
  colnames(radar_chart_data_concern), "\n",
  round(radar_data_concern[1, ], 1), "%"
)

create_radar_chart(
  radar_chart_data_concern,
  "Environmental Concerns Associated with Super Yachts (Percentage)",
  "blue",
  rgb(0.2, 0.5, 0.7, 0.5),
  "Average Concern"
)

# Add a legend if needed
legend("topright", legend = "Average Concern", bty = "n", pch = 20, col
= "blue", text.col = "grey25", cex = 1.2, pt.cex = 3)

### 6. Main Barriers to Sustainability

# Total number of participants
total_participants <- 179

# Split into long format and calculate counts and percentages
main_barriers_long <- survey_data %>%
  separate_rows(main_barriers, sep = ",\\s*") %>%
  group_by(main_barriers) %>%
  summarise(Count = n()) %>%
  mutate(Percentage = (Count / total_participants) * 100) %>%
  arrange(desc(Count))
```

```
# Frequency Table with Percentages
main_barriers_long %>%
  mutate(Percentage = sprintf("%.1f%%", Percentage)) %>%  # Format
percentage
  rename(
    Barrier = main_barriers,
    `Number of Responses` = Count,
    `Percentage of Participants` = Percentage
  ) %>%
  kable(format = "html", caption = "Frequency and Percentage of Main
Barriers") %>%
  kable_styling(full_width = FALSE)

# Horizontal Bar Chart with Percentages
ggplot(main_barriers_long, aes(x = reorder(main_barriers, Count), y =
Count)) +
  geom_bar(stat = "identity", fill = "darkorange") +
  geom_text(aes(label = sprintf("%.1f%%", Percentage)),  # Add
percentage labels
            hjust = -0.1,
            size = 3) +
  coord_flip() +
  theme_minimal() +
  labs(
    title = "Main Barriers to Sustainability in Super Yachting",
    x = "Barrier",
    y = "Count"
  ) +
  ylim(0, max(main_barriers_long$Count) * 1.1)  # Adjust y-axis to
accommodate labels

### 7. Crosstabulation between SupportAltF and Education

# Crosstabulation table
survey_data %>%
  tabyl(education, support_alt_f) %>%
  adorn_percentages("row") %>%
  adorn_pct_formatting() %>%
  adorn_ns() %>%
  kable(format = "html", caption = "Support for Alternative Fuels by
Education Level") %>%
  kable_styling(full_width = FALSE)

### 8. Support for Alternative Fuels by Awareness Level

# Summarize counts and calculate percentages
support_awareness_summary <- survey_data %>%
  group_by(awareness, support_alt_f) %>%
  summarise(Count = n(), .groups = 'drop') %>%
```

```
  group_by(awareness) %>%
  mutate(Percentage = (Count / sum(Count)) * 100) %>%
  ungroup()

# Create grouped bar chart with percentage labels
ggplot(support_awareness_summary, aes(x = awareness, y = Count, fill =
support_alt_f)) +
  geom_bar(stat = "identity", position = position_dodge(width = 0.9)) +
  geom_text(aes(label = paste0(round(Percentage, 1), "%")),  # Add
percentage labels
            position = position_dodge(width = 0.9),
            vjust = -0.5,
            size = 3,
            color = "black") +
  theme_minimal() +
  labs(
    title = "Support for Alternative Fuels by Awareness Level of
Environmental Issues",
    x = "Awareness Level",
    y = "Count",
    fill = "Support for AltF"
  ) +
  theme(
    axis.text.x = element_text(angle = 45, hjust = 1),
    plot.title = element_text(hjust = 0.5, size = 14, face = "bold")
  ) +
  scale_y_continuous(
    expand = expansion(mult = c(0, 0.1)),
    labels = comma
  ) +
  scale_fill_brewer(palette = "Set2")  # Optional: Use a color palette
for better aesthetics

### 9. Box Plot: Concerned Emissions by Support for Alternative Fuels

ggplot(survey_data, aes(x = support_alt_f, y = concerned_emissions)) +
  geom_boxplot(fill = "lightblue") +
  theme_minimal() +
  labs(
    title = "Concerned About Emissions by Support for Alternative
Fuels",
    x = "Support for Alternative Fuels",
    y = "Concern About Emissions"
  )


############ CORRELATIONS

# Select numerical variables
numerical_vars <- survey_data %>%
```

```
  select(
    concerned_emissions,
    concerned_water,
    concerned_noise,
    concerned_marine_life,
    concerned_resources,
    environmental_sustainability_influencing_acceptance,
    economic_impact_influencing_acceptance,
    technological_innovation_influencing_acceptance,
    luxury_and_design_influencing_acceptance,
    social_status_symbolism_influencing_acceptance
  )

# Compute correlation matrix
cor_matrix <- numerical_vars %>%
  correlate(diagonal = 1)

# Format the correlation matrix
cor_matrix_formatted <- cor_matrix %>%
  rearrange() %>%              # Rearrange variables by correlations
  shave() %>%                  # Remove upper triangle for clarity
  fashion(decimals = 3)        # Format to 3 decimal places

# Display the correlation matrix as a nicely formatted table
cor_matrix_formatted %>%
  kable(format = "html", caption = "Correlation Matrix of Numerical 
Variables") %>%
  kable_styling(full_width = FALSE, bootstrap_options = c("striped", 
"hover"))

############# Data Cleaning For Regression

## Encoding Categorical Variables

survey_data2 <- survey_data %>%
  mutate(
    # Encode 'age' as ordinal
    age_num = case_when(
      age == "< 18" ~ 1,
      age == "18-24" ~ 2,
      age == "25-34" ~ 3,
      age == "35-44" ~ 4,
      age == "45-54" ~ 5,
      age == "55-64" ~ 6,
      age == "65 or older" ~ 7,
      TRUE ~ NA_real_
    ),

    # Encode 'education' as ordinal
    education_num = case_when(
```

```
      education == "Less than high school diploma" ~ 1,
      education == "High school diploma or equivalent" ~ 2,
      education == "Some college/university, no degree" ~ 3,
      education == "Bachelor's degree" ~ 4,
      education == "Master's degree" ~ 5,
      education == "Doctorate (e.g., PhD)" ~ 6,
      TRUE ~ NA_real_
    ),

    # Encode 'occupation' as ordinal
    occupation_num = case_when(
      occupation == "Unemployed" ~ 1,
      occupation == "Student" ~ 2,
      occupation == "Employed in a role that typically does not require
a college or university degree (e.g., administrative support, service
industry, manual labor)" ~ 3,
      occupation == "Self-employed" ~ 4,
      occupation == "Employed in a role that typically requires a
college or university degree or specialized professional training
(e.g., doctor, engineer, teacher, manager)" ~ 5,
      TRUE ~ NA_real_
    ),

    # Encode 'awareness' as ordinal
    awareness_num = case_when(
      awareness == "Not at all familiar" ~ 1,
      awareness == "Slightly familiar" ~ 2,
      awareness == "Moderately familiar" ~ 3,
      awareness == "Very familiar" ~ 4,
      awareness == "Extremely familiar" ~ 5,
      TRUE ~ NA_real_
    ),

    # Encode 's_yperception' as ordinal
    s_yperception_num = case_when(
      s_yperception == "Very negative" ~ 1,
      s_yperception == "Somewhat negative" ~ 2,
      s_yperception == "Neutral" ~ 3,
      s_yperception == "Somewhat positive" ~ 4,
      s_yperception == "Very positive" ~ 5,
      TRUE ~ NA_real_
    ),

    # Encode 'concerned' as ordinal
    concerned_num = case_when(
      concerned == "Not at all concerned" ~ 1,
      concerned == "Slightly concerned" ~ 2,
      concerned == "Moderately concerned" ~ 3,
      concerned == "Very concerned" ~ 4,
      concerned == "Extremely concerned" ~ 5,
```

```
  TRUE ~ NA_real_
),

# Encode 'focused' as ordinal
focused_num = case_when(
  focused == "Not at all" ~ 1,
  focused == "Slightly" ~ 2,
  focused == "Moderately" ~ 3,
  focused == "Very" ~ 4,
  focused == "Extremely" ~ 5,
  TRUE ~ NA_real_
),

# Encode 'support_alt_f' as ordinal
support_alt_f_num_new = case_when(
  support_alt_f == "Strongly oppose" ~ 1,
  support_alt_f == "Somewhat oppose" ~ 2,
  support_alt_f == "Neutral" ~ 3,
  support_alt_f == "Somewhat support" ~ 4,
  support_alt_f == "Strongly support" ~ 5,
  TRUE ~ NA_real_
),

# Encode 'industry_committed_to_sustainability' as ordinal
industry_committed_to_sustainability_num = case_when(
  industry_committed_to_sustainability == "Not at all" ~ 1,
  industry_committed_to_sustainability == "Slightly" ~ 2,
  industry_committed_to_sustainability == "Moderately" ~ 3,
  industry_committed_to_sustainability == "Very much" ~ 4,
  industry_committed_to_sustainability == "Completely" ~ 5,
  TRUE ~ NA_real_
),

# Encode 'perception_alt_f' as ordinal
perception_alt_f_num = case_when(
  perception_alt_f == "Significantly worsen my perception" ~ 1,
  perception_alt_f == "Slightly worsen my perception" ~ 2,
  perception_alt_f == "No change" ~ 3,
  perception_alt_f == "Slightly improve my perception" ~ 4,
  perception_alt_f == "Significantly improve my perception" ~ 5,
  TRUE ~ NA_real_
),

# Encode 'sustainable_lux' as ordinal
sustainable_lux_num = case_when(
  sustaiable_lux == "Not at all important" ~ 1,
  sustaiable_lux == "Slightly important" ~ 2,
  sustaiable_lux == "Moderately important" ~ 3,
  sustaiable_lux == "Very important" ~ 4,
  sustaiable_lux == "Extremely important" ~ 5,
```

```
      TRUE ~ NA_real_
    ),

    # Encode 'sustainability_influence_engagement_yachting' as ordinal
    sustainability_influence_engagement_num = case_when(
      sustainability_influence_engagement_yachting == "Not at all" ~ 1,
      sustainability_influence_engagement_yachting == "Slightly" ~ 2,
      sustainability_influence_engagement_yachting == "Moderately" ~ 3,
      sustainability_influence_engagement_yachting == "Significantly" ~
4,
      sustainability_influence_engagement_yachting == "I would not
engage in yachting activities regardless" ~ 0,
      TRUE ~ NA_real_
    ),

    # Encode 'support_regulations' as ordinal
    support_regulations_num = case_when(
      support_regulations == "Strongly oppose" ~ 1,
      support_regulations == "Somewhat oppose" ~ 2,
      support_regulations == "Neutral" ~ 3,
      support_regulations == "Somewhat support" ~ 4,
      support_regulations == "Strongly support" ~ 5,
      TRUE ~ NA_real_
    ),

    # Encode 'time_to_transition' as ordinal
    time_to_transition_num = case_when(
      time_to_transition == "Within the next 2 years" ~ 1,
      time_to_transition == "Within 5 years" ~ 2,
      time_to_transition == "Within 10 years" ~ 3,
      time_to_transition == "Within 20 years" ~ 4,
      time_to_transition == "I do not know" ~ 5,
      TRUE ~ NA_real_
    )
  )

## Check for missing values
vis_miss(survey_data2)

## Encode Binary Variables
survey_data2 <- survey_data2 %>%
  mutate(
    # Encode 'gender' as binary
    gender_num = case_when(
      gender == "Male" ~ 1,
      gender == "Female" ~ 0,
      TRUE ~ NA_real_
    ),

    # Encode 'awareness_before_survey' as binary
```

```
    awareness_before_survey_num = case_when(
      awareness_before_survey == "yes" ~ 1,
      awareness_before_survey == "no" ~ 0,
      TRUE ~ NA_real_
    )
  )

skim(survey_data2)

############ Variables which cannot be transformed....

####### Nominal variables (without inherent order):
# occupation, residence

# Create dummy variables for 'residence'
survey_data2 <- survey_data2 %>%
  dummy_cols(select_columns = c("residence"),
             remove_first_dummy = TRUE,
             remove_selected_columns = TRUE)

skim(survey_data2)

##### Multi-Selection Variables (where respondents can select multiple
options):
# s_yassociation, most_responsible, main_barriers

survey_data2 <- survey_data2 %>%
  mutate(
    # Handle 's_yassociation' multiple selections
    s_yassociation_Luxury = if_else(str_detect(s_yassociation,
"Luxury"), 1, 0),
    s_yassociation_Wealth = if_else(str_detect(s_yassociation,
"Wealth"), 1, 0),
    s_yassociation_Holiday = if_else(str_detect(s_yassociation,
"Holiday"), 1, 0),
    s_yassociation_Inequality = if_else(str_detect(s_yassociation,
"Inequality"), 1, 0),
    s_yassociation_Oppulence = if_else(str_detect(s_yassociation,
"Oppulence"), 1, 0),
    s_yassociation_Party = if_else(str_detect(s_yassociation, "Party"),
1, 0),
    s_yassociation_Leisure = if_else(str_detect(s_yassociation,
"Leisure"), 1, 0),
    s_yassociation_Technological_advancement =
if_else(str_detect(s_yassociation, "Technological advancement"), 1, 0),
    s_yassociation_Social_status = if_else(str_detect(s_yassociation,
"Social status"), 1, 0),
    s_yassociation_Employment_opportunities =
if_else(str_detect(s_yassociation, "Employment opportunities"), 1, 0),
    s_yassociation_Environmental_harm =
if_else(str_detect(s_yassociation, "Environmental harm"), 1, 0),
```

```
    s_yassociation_Pleasure = if_else(str_detect(s_yassociation,
"Pleasure"), 1, 0),
    s_yassociation_Prestige = if_else(str_detect(s_yassociation,
"Prestige"), 1, 0),
    s_yassociation_Useless = if_else(str_detect(s_yassociation,
"Useless"), 1, 0),
    s_yassociation_Pollution = if_else(str_detect(s_yassociation,
"Pollution"), 1, 0),

    # Handle 'main_barriers' multiple selections
    main_barriers_High_costs_new_technology =
if_else(str_detect(main_barriers, "High costs of new technology"), 1,
0),
    main_barriers_Insufficient_regulations =
if_else(str_detect(main_barriers, "Insufficient regulations"), 1, 0),
    main_barriers_Technological_limitations =
if_else(str_detect(main_barriers, "Technological limitations"), 1, 0),
    main_barriers_Lack_of_consumer_demand =
if_else(str_detect(main_barriers, "Lack of consumer demand"), 1, 0),
    main_barriers_Resistance_from_yacht_owners =
if_else(str_detect(main_barriers, "Resistance from yacht owners"), 1,
0),
    main_barriers_Lack_of_infrastructure =
if_else(str_detect(main_barriers, "Lack of infrastructure"), 1, 0),
    main_barriers_Stupidity_of_industry =
if_else(str_detect(main_barriers, "Stupidity of the entire industry"),
1, 0),
    main_barriers_Lack_of_interest = if_else(str_detect(main_barriers,
"Lack of Interest"), 1, 0),
    main_barriers_Price_alt_fuel = if_else(str_detect(main_barriers,
"Price of alternative fuels being higher than traditional fuel"), 1,
0),
    main_barriers_Hader_than_you_think =
if_else(str_detect(main_barriers, "It is harder than you think."), 1,
0),
    main_barriers_Other = if_else(str_detect(main_barriers, "Other"),
1, 0),

    # Handle 'most_responsible' multiple selections
    most_responsible_Maritime = if_else(str_detect(most_responsible,
"The maritime industry as a whole"), 1, 0),
    most_responsible_Manufacturers =
if_else(str_detect(most_responsible, "Yacht manufacturers"), 1, 0),
    most_responsible_Gov_and_Reg = if_else(str_detect(most_responsible,
"Governments and regulatory bodies"), 1, 0),
    most_responsible_All = if_else(str_detect(most_responsible, "All of
the above equally"), 1, 0),
    most_responsible_Owners = if_else(str_detect(most_responsible,
"Yacht owners"), 1, 0),
    most_responsible_Envir_Orgs = if_else(str_detect(most_responsible,
"Environmental organizations"), 1, 0),
    most_responsible_Other = if_else(str_detect(most_responsible,
"Other"), 1, 0)
```

```
  )

skim(survey_data2)

## Remove the original categorical columns if they are no longer needed
survey_data2 <- survey_data2 %>%
  select(-c(
    age, education, gender, awareness,
    s_yperception, concerned, focused,
    support_alt_f, perception_alt_f,
    sustaiable_lux, sustainability_influence_engagement_yachting,
    support_regulations, time_to_transition,
industry_committed_to_sustainability,
    s_yassociation, main_barriers, most_responsible,
awareness_before_survey, occupation
  ))

# View the first few rows of the transformed dataset
head(survey_data2)

# Check the structure of the dataset
str(survey_data2)
skim(survey_data2)

## Looks perfect!!!!!


############ REGRESSIONS ##


# Linear Regression predicting 'support_alt_f_num_new' based on other
variables
model <- lm(
  support_alt_f_num_new ~
    # Demographic Variables
    age_num +
    education_num +
    gender_num +
    focused_num +
    occupation_num +

    # Concerned
    awareness_num +
    concerned_water +
    concerned_noise +
    concerned_marine_life +
    concerned_resources +
    concerned_emissions +

    # Associations with Super Yachting
```

```
s_yassociation_Luxury +
s_yassociation_Wealth +
s_yassociation_Holiday +
s_yassociation_Inequality +
s_yassociation_Oppulence +
s_yassociation_Party +
s_yassociation_Leisure +
s_yassociation_Technological_advancement +
s_yassociation_Social_status +
s_yassociation_Employment_opportunities +
s_yassociation_Environmental_harm +
s_yassociation_Pleasure +
s_yassociation_Prestige +
s_yassociation_Useless +
s_yassociation_Pollution +

# Most Responsible Entities
most_responsible_Maritime +
most_responsible_Manufacturers +
most_responsible_Gov_and_Reg +
most_responsible_All +
most_responsible_Owners +
most_responsible_Envir_Orgs +

# Main Barriers to Sustainability
main_barriers_High_costs_new_technology +
main_barriers_Insufficient_regulations +
main_barriers_Technological_limitations +
main_barriers_Lack_of_consumer_demand +
main_barriers_Resistance_from_yacht_owners +
main_barriers_Lack_of_infrastructure +
main_barriers_Stupidity_of_industry +
main_barriers_Lack_of_interest +
main_barriers_Price_alt_fuel +
main_barriers_Hader_than_you_think +

# Additional Factors
awareness_before_survey_num +
perception_alt_f_num +
sustainable_lux_num +
sustainability_influence_engagement_num +
support_regulations_num +
time_to_transition_num +
industry_committed_to_sustainability_num +
environmental_sustainability_influencing_acceptance +
economic_impact_influencing_acceptance +
technological_innovation_influencing_acceptance +
luxury_and_design_influencing_acceptance +
social_status_symbolism_influencing_acceptance +
```

```
    # Dummy Variables for Residence
    residence_Austria +
    residence_Canada  +
    residence_Denmark +
    residence_England +
    residence_Finland +
    residence_France +
    residence_Germany +
    residence_Hungary +
    residence_Iceland +
    residence_Indonesia +
    residence_Italy +
    residence_Luxembourg +
    residence_Netherlands +
    residence_Poland +
    residence_Portugal +
    residence_Sweden +
    residence_Switzerland +
    residence_UK +
    residence_US,
  data = survey_data2
)

# Summarize the model
summary(model)

# Capture the summary output as text
model_summary <- capture.output(summary(model))

# Combine the captured text into a single string with line breaks
model_summary_text <- paste(model_summary, collapse = "\n")

# Create HTML content with preformatted text
html_content <- paste0(
  "<!DOCTYPE html>",
  "<html>",
  "<head><title>Model Summary</title></head>",
  "<body>",
  "<h1>Linear Model Summary</h1>",
  "<pre>", model_summary_text, "</pre>",
  "</body>",
  "</html>"
)

# Write the HTML content to a file
writeLines(html_content, "model_summary.html")

# Open the HTML file in the default browser
browseURL("model_summary.html")
```

```
############ Scatter Plots

# Scatter Plot 1: Support for Alternative Fuels vs. Awareness
ggplot(data = survey_data2, aes(x = awareness_num, y =
support_alt_f_num_new)) +
  geom_point() +
  geom_smooth(method = "lm", se = FALSE, color = "blue") +
  theme(text = element_text(size = 20)) +
  labs(
    title = "Support for Alternative Fuels vs. Awareness",
    x = "Awareness Level",
    y = "Support for Alternative Fuels"
  )

# Scatter Plot 2: Support for Alternative Fuels vs. Education
ggplot(data = survey_data2, aes(x = education_num, y =
support_alt_f_num_new)) +
  geom_point() +
  geom_smooth(method = "lm", se = FALSE, color = "blue") +
  theme(text = element_text(size = 20)) +
  labs(
    title = "Support for Alternative Fuels vs. Education",
    x = "Education Level",
    y = "Support for Alternative Fuels"
  )

# Scatter Plot 3: Education vs. Awareness Colored by Concern
ggplot(data = survey_data2, aes(x = awareness_num, y = education_num,
color = concerned_num)) +
  geom_point() +
  geom_smooth(method = "lm", se = FALSE, color = "black") +
  theme(text = element_text(size = 20)) +
  labs(
    title = "Education vs. Awareness Colored by Concern",
    x = "Awareness Level",
    y = "Education Level",
    color = "Concerned Level"
  ) +
  scale_color_gradient(low = "yellow", high = "red")  # Customize color
gradient

# Scatter Plot 4: Support for Alternative Fuels vs. Perception of
Alternative Fuels
ggplot(data = survey_data2, aes(x = perception_alt_f_num, y =
support_alt_f_num_new, color = education_num)) +
  geom_point() +
  geom_smooth(method = "lm", se = FALSE, color = "black") +
  theme(text = element_text(size = 20)) +
  labs(
    title = "Support for Alternative Fuels vs. Perception of
Alternative Fuels",
```

```
    x = "Perception of Alternative Fuels",
    y = "Support for Alternative Fuels",
    color = "Education Level"
  ) +
  scale_color_gradient(low = "lightblue", high = "darkblue")  #
Customize color gradient

# Scatter Plot 5: Support for Alternative Fuels vs. Support for
Regulations Colored by Insufficient Regulations
ggplot(data = survey_data2, aes(x = support_regulations_num, y =
support_alt_f_num_new, color = main_barriers_Insufficient_regulations))
+
  geom_point() +
  geom_smooth(method = "lm", se = FALSE, color = "black") +
  theme(text = element_text(size = 20)) +
  labs(
    title = "Support for Alternative Fuels vs. Support for
Regulations",
    subtitle = "Colored by Main Barrier: Insufficient Regulations",
    x = "Support for Regulations",
    y = "Support for Alternative Fuels",
    color = "Insufficient Regulations Level"
  ) +
  scale_color_gradient(low = "red", high = "green")  # Customize color
gradient

# Scatter Plot 6: Support for Alternative Fuels vs. Concern for
Emissions Colored by Education
ggplot(data = survey_data2, aes(x = concerned_emissions, y =
support_alt_f_num_new, color = education_num)) +
  geom_point() +
  geom_smooth(method = "lm", se = FALSE, color = "black") +
  theme(text = element_text(size = 20)) +
  labs(
    title = "Support for Alternative Fuels vs. Concern for Emissions",
    x = "Concerned about Emissions",
    y = "Support for Alternative Fuels",
    color = "Education Level"
  ) +
  scale_color_gradient(low = "green", high = "red")  # Customize color
gradient
```