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PATHWAYS TO MARITIME DECARBONISATION: COMPARATIVE INSIGHTS OF SOLAR POWERED PROVEN DESIGNS

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ABSTRACT

The maritime industry, a significant contributor to global carbon emissions, faces mounting pressure to transition toward sustainable operations through the integration of renewable energy technologies. This study offers a detailed comparative analysis of two solar-powered vessels, MS Tûranor PlanetSolar and Energy Observer, with a focus on their proven design principles, energy systems, and contributions to maritime decarbonization. MS Tûranor PlanetSolar, the first solar-powered vessel to circumnavigate the globe, features a solar-only design powered by 512 m² of photovoltaic panels and a 1,350 kWh lithium-ion battery system. This configuration allows for zero-emission operations but presents limitations in scalability and energy autonomy.In contrast, Energy Observer combines solar panels, wind turbines, and hydrogen fuel cells, showcasing a hybrid energy system capable of producing and storing hydrogen through onboard seawater electrolysis. This approach significantly extends its autonomy and operational versatility, making it more adaptable to diverse environmental conditions. The study evaluates the energy efficiency, environmental impact, and scalability of these vessels, highlighting their role as benchmarks for sustainable maritime engineering. By examining their real-world applications and limitations, the research underscores the importance of hybrid renewable energy systems and optimized designs in accelerating the decarbonization of global shipping. These findings provide critical insights for policymakers, engineers, and industry stakeholders seeking to promote sustainable practices within the maritime sector.

Keywords: renewable energy systems, solar-powered vessels, maritime decarbonisation, hybrid energy technologies, Sustainable shipping.

1. INTRODUCTION

The escalating urgency of climate change and the need to reduce greenhouse gas emissions have driven significant advancements in renewable energy applications across various industries [1]. The maritime sector, traditionally reliant on fossil fuels, has started to explore alternative energy solutions to align with global decarbonization targets [2]. Solar-powered vessels represent an innovative frontier in this pursuit, offering a sustainable means to navigate the seas while minimizing environmental impact [3]. Among the prominent pioneers in this field, the MS Tûranor PlanetSolar and Energy Observer have emerged as exemplary case studies, each demonstrating unique approaches to integrating renewable energy systems into vessel design and operation.

This article undertakes a comparative analysis of these two solar-powered vessels, examining their engineering designs, renewable energy configurations, and their respective contributions to the broader goal of maritime decarbonization. By evaluating their successes and innovations, the discussion aims to highlight the critical role of renewable energy in transforming the maritime industry and addressing the environmental challenges posed by conventional shipping practice.

2. MATERIALS AND METHODS

This section outlines the methodologies and materials employed in a detailed comparative analysis of two solar-powered maritime vessels: MS Tûranor PlanetSolar and Energy Observer. The research emphasizes their design principles, renewable energy technologies, and contributions to maritime decarbonization, incorporating specific data on their operational and environmental performance.

MS Tûranor PlanetSolar: Launched in 2010, this catamaran was the first entirely solar-powered vessel to complete a circumnavigation of the globe. The vessel is equipped with 512 m² of solar panels generating up to 93.5 kW of power, with energy stored in lithium-ion batteries for propulsion.

Energy Observer: Commissioned in 2017, this multi-energy vessel combines solar panels (145 m² generating 28 kW), vertical-axis wind turbines, and hydrogen fuel cells for energy production and storage. The integration of these systems allows zero-emission operation and energy autonomy.

Technical Documentation: Manufacturer specifications, energy system designs, and construction materials were sourced from official vessel reports and academic publications.

Performance Records: Operational data, including energy outputs, voyages, and system performance metrics, were collected from peer-reviewed studies, mission logs, and technical analyses.

Environmental Impact Assessments: Life-cycle analyses (LCAs) and carbon emissions data were obtained from published studies evaluating the vessels' decarbonization contributions.

Structural and Functional Analysis: The vessels' designs were analyzed in terms of hydrodynamic efficiency, material composition, and energy system integration. For MS Tûranor PlanetSolar, its catamaran design was evaluated for stability and energy efficiency, while the Energy Observer's hybrid propulsion system was assessed for versatility and operational flexibility.

Materials Assessment: The hull of MS Tûranor PlanetSolar, constructed from carbon fiber, was analyzed for its lightweight properties and durability, while the Energy Observer's aluminum and composite structures were evaluated for corrosion resistance and weight efficiency.

Solar Energy Utilization: The photovoltaic (PV) panels on both vessels were compared based on total area, panel efficiency, and average energy output under similar operational conditions. For MS Tûranor PlanetSolar, its mono-crystalline silicon panels were examined, while Energy Observer's multi-energy integration was studied for complementary energy generation.

Energy Storage Efficiency: The lithium-ion battery systems of MS Tûranor PlanetSolar were analyzed for capacity (1,350 kWh) and energy retention, while Energy Observer's hybrid storage combining batteries (112 kWh) and hydrogen storage tanks

(62 kg capacity) was evaluated for its extended operational range.

Voyage Comparisons: MS Tûranor PlanetSolar's global circumnavigation (completed in 585 days covering over 60,000 km) and Energy Observer's ongoing missions across 50 countries were compared in terms of range, speed, and energy autonomy.

Efficiency Metrics: Metrics such as energy consumed per nautical mile and percentage of voyage powered entirely by renewable energy systems were calculated and contrasted.

Emission Reduction Analysis: The total CO_2 emissions avoided by each vessel were estimated using voyage data and comparison to diesel-powered vessels of similar size. For example, MS Tûranor PlanetSolar avoided approximately 52 tons of CO_2 during its circumnavigation, while Energy Observer demonstrates potential scalability in renewable energy use for commercial shipping.

Lifecycle Impact: LCAs were conducted for each vessel's energy systems, focusing on resource extraction, manufacturing, operation, and end-of-life phases to estimate their net environmental benefits.

Computational simulations of solar energy capture under varied geographic and climatic conditions were performed using PV simulation software.

Hydrodynamic models were utilized to evaluate energy efficiency based on vessel design and propulsion systems.

MS Tûranor PlanetSolar: Detailed examination of its solar-only propulsion and operational challenges, emphasizing its role as a pioneering model for solar energy in maritime transport.

Energy Observer: Evaluation of its innovative integration of solar, wind, and hydrogen systems, highlighting its adaptability for decarbonized maritime operations and future scalability.

3. CHALLENGES AND CASE STUDIES IN RENEWABLE ENERGY INTEGRATION IN MARITIME TRANSPORT

The integration of renewable energy technologies into maritime transport offers substantial promise for decarbonization but also faces a series of significant challenges that impede widespread adoption. These challenges span technological constraints, economic barriers, operational complexities, and deficiencies in infrastructure and policy frameworks. Addressing these hurdles requires concerted efforts by maritime stakeholders, policymakers, and researchers to fully harness the potential of renewable energy in this sector [4].

Technological Limitations

Renewable energy systems for maritime operations often face technical constraints. For example, photovoltaic panels, though capable of generating up to 250 W/m² under optimal conditions, are limited by available deck space. For large commercial vessels, covering even 5% of total energy demand would require over 2,000 m² of deck area, which is often infeasible.

Hydrogen fuel cells, while offering zero-emission potential, face challenges related to storage and transport. A hydrogen-powered vessel such as the Energy Observer requires 62 kg of hydrogen for a standard voyage, necessitating a compact, cryogenic storage system capable of maintaining temperatures below -253°C [5]. Expanding such systems to large vessels is hampered by limited global bunkering infrastructure and high energy losses during compression and storage.

Economic Constraints

Financial considerations present another critical barrier to adopting renewable energy systems. Integrating solar photovoltaic systems into vessels like MS Turanor PlanetSolar, which involved 512 m² of panels costing approximately $1,000 per square meter, pushed total solar system costs to

$500,000–$700,000 [6], [7].

Hydrogen fuel cell systems represent an even greater investment, with costs ranging from $5 million to $10 million per vessel for installation and commissioning, accounting for the electrolyzer, fuel cells, and storage infrastructure. These costs discourage smaller shipping companies with limited budgets, especially in the absence of substantial government subsidies or incentives [8].

Operational Complexities

Operational challenges compound the difficulty of adopting renewable technologies. Onboard hydrogen production, as implemented by the Energy Observer, requires a high level of technical expertise to manage electrolysis systems that convert seawater into hydrogen at efficiencies of 45–55%. Maintenance of cryogenic storage and hydrogen delivery systems necessitates crew training and advanced safety protocols to mitigate risks of leaks or explosions [9].

Solar systems are subject to variability in environmental conditions. For example, a typical 100 kW photovoltaic system may see energy output drop by 30–40% in overcast weather, requiring auxiliary energy sources to maintain consistent operation [10].

Infrastructure and Policy Gaps

Infrastructure limitations represent a critical challenge to scaling renewable energy in maritime transport. Hydrogen bunkering facilities are currently operational in fewer than 10 major ports globally, leaving most shipping routes without adequate refueling infrastructure [11].

Policy gaps exacerbate these challenges. Although the International Maritime Organization (IMO) has established decarbonization goals, the absence of cohesive international regulations for renewable energy systems has created uncertainty for shipowners. The lack of globally recognized standards for hybrid vessels delays investment and slows adoption rates [12].

MS Turanor PlanetSolar

The MS Turanor PlanetSolar, powered solely by a 512 m² photovoltaic array generating 93 kWp, successfully completed a global circumnavigation, demonstrating the feasibility of 100% solar-powered voyages. While effective on tropical routes with high solar irradiance, its energy independence is limited in regions with low sunlight, where daily output can drop by 50% or more. Insights from this project have driven research into improving photovoltaic efficiency and integrating 1–2 MWh battery systems to address nighttime energy needs [13].

Energy Observer

The Energy Observer integrates 202 m² of solar panels, wind turbines, and hydrogen fuel cells, enabling zero-emission operation through onboard hydrogen production. Its electrolysis system produces up to 1 kg of hydrogen per hour, sufficient to power its hybrid propulsion system for extended voyages. This innovation eliminates dependence on hydrogen refueling infrastructure but increases system complexity, requiring advanced energy management protocols and crew training.

These case studies demonstrate the transformative potential of renewable energy technologies in maritime transport, addressing many of the challenges posed by existing systems. To realize their full potential, sustained investment in research and development, global standardization of hybrid technologies, and the implementation of supportive policy frameworks are essential. Collaboration among industry leaders, researchers, and policymakers will be pivotal in accelerating the adoption of these innovations and redefining the future of maritime sustainability [14] , [15].

4. COMPARATIVE ANALYSIS OF RENEWABLE ENERGY VESSELS

The maritime sector is a significant contributor to global carbon emissions, prompting growing interest in renewable energy solutions to mitigate its environmental impact. This analysis focuses on two innovative vessels—MS Tûranor PlanetSolar and Energy Observer—which represent distinct approaches to integrating renewable technologies into maritime transport. Both vessels provide critical insights into sustainable shipping practices and the potential for achieving zero-emission maritime operations.

The MS Tûranor PlanetSolar is a groundbreaking vessel recognized as the first entirely solar-powered ship to circumnavigate the globe. Equipped with 512 square meters of monocrystalline photovoltaic panels, it generates up to 93.5 kW of power, storing excess energy in 1,350 kWh lithium-ion batteries. This innovative configuration enables the vessel to operate with complete independence from fossil fuels, achieving zero emissions during operation.

The design of the MS Tûranor PlanetSolar is optimized for energy efficiency, with a lightweight carbon-fiber hull that minimizes drag and energy consumption. Operating at a cruising speed of approximately 10 knots, the vessel demonstrates the viability of solar energy for maritime navigation. However, its limited speed and scalability pose challenges for adoption in large-scale commercial shipping. The vessel's reliance on solar irradiance also restricts its performance in less sunlit regions [16].

Despite these limitations, MS Tûranor PlanetSolar has significantly advanced research on solar-powered maritime systems, serving as a model for integrating photovoltaic technologies into vessel design. Its successful circumnavigation highlighted the potential for renewable energy to revolutionize maritime transport, encouraging further investment in solar energy solutions for shipping.

The Energy Observer adopts a hybrid energy approach, integrating solar panels, wind turbines, and hydrogen fuel cells to achieve zero-emission operation. Its 145 square meters of photovoltaic panels generate up to 28 kW of power, which is supplemented by vertical-axis wind turbines. Additionally, the vessel employs seawater electrolysis to produce hydrogen, which is stored in pressurized tanks and converted into energy via fuel cells. This energy mix provides a versatile and sustainable system capable of maintaining operational autonomy under variable environmental conditions [17].

With its onboard energy storage system combining 112 kWh lithium-ion batteries and 62 kilograms of hydrogen capacity, Energy Observer achieves significant operational flexibility. The vessel has been reported to save up to 70% of fuel compared to traditional systems, while also achieving completely carbon-neutral voyages. Its mission as a research and promotional vessel focuses on advancing public awareness of renewable technologies and testing innovative solutions for maritime decarbonization.

The Energy Observer's hybrid design addresses some of the challenges faced by solar-only systems, such as dependence on sunlight and limited scalability. Its ability to generate hydrogen onboard provides a critical advantage in maintaining energy autonomy during extended voyages or in less favorable climatic conditions. This adaptability makes Energy Observer a compelling example of next-generation renewable energy vessels, showcasing the potential for integrating complementary energy systems.

Both MS Tûranor PlanetSolar and Energy Observer exemplify the potential of renewable energy technologies to transform the maritime industry, albeit with distinct approaches and applications. MS Tûranor PlanetSolar demonstrates the feasibility of solar-only propulsion, achieving zero emissions through an elegant and minimalist design. However, its operational speed and dependence on high solar irradiance limit its practicality for broader commercial use [18].

In contrast, Energy Observer adopts a more adaptable hybrid system, combining solar, wind, and hydrogen technologies to achieve energy resilience and extended range. This versatility addresses key challenges faced by solar-only systems, making it a more scalable and practical solution for maritime decarbonisation [19].

Table 1 Renewable energy vessels specifications

Feature	MS Turanor PlanetSolar	Energy Observer
Primary Energy Source	Solar (Photovoltaic Panels)	Hybrid (Solar, Wind, Hydrogen)
Energy Storage	Lithium-ion Batteries	Hydrogen and Lithium-ion Batteries
Design Innovations	512 m^2 of Solar Panels	Onboard Hydrogen Production
Fuel Savings	100%	Up to 70%
Emissions	Zero Emissions	Zero Emissions
Operational Scope	Demonstration and Research	Global Research
Speed	10 knots	10 knots
Technology Level	Fully Operational	Fully Operational
Use Case	Awareness and Demonstration	Research and Promotion

In this study Solar energy is the common renewable energy used on both vessels.

We can agree that the storage of the energy is mandatory to be installed onboard MS Turanor PlanetSolar. This one is using Lithium-ion batteries in order to be able to navigate during nighttime when no solar energy is possible to be harnessed. Energy Observer project also uses Lithium-ion batteries for the same reason.

MS Turanor PlanetSolar is eliminating all the fuel cost with zero emissions by using 512m^2 of solar panels. Due to the hydrogen production onboard, the Energy Observer have an estimated fuel consumption less with up to 70% with zero emissions.

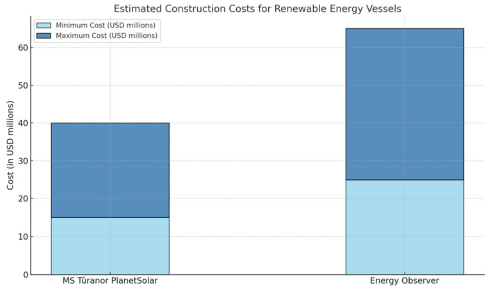

Fig. 1 Estimated Construction Costs for Renewable Energy Vessels

In the above table is presented the minimum and maximum costs for construction of the vessels where we can see that the most expensive vessel to be built from zero, which is Energy Observer, including engineering, construction and delivery will be between 25-40 USD millions.

MS Tûranor PlanetSolar's lower costs reflect its simpler solar-only energy system and lightweight construction, while Energy Observer's higher costs are due to its advanced hybrid system integrating solar, wind, and hydrogen technologies. The close bar placement allows for clear comparison, highlighting the financial implications of more complex renewable energy systems in maritime decarbonization. The graph effectively communicates these differences with a clear and accessible design.

Table 2 Technology and Estimated costs for renewable energy vessels

Vessel	Technology Integration	Estimated Cost (USD)
MS Turanor PlanetSolar	Photovoltaic Panels + Lithium-ion Batteries	$15-25 million
Energy Observer	Solar + Wind + Hydrogen Fuel Cells	$25-40 million

MS Turanor PlanetSolar and Energy Observer both use lightweight composite materials for their hulls, which are more expensive than traditional steel construction but improve energy efficiency. Composite hulls can add 20–30% higher costs compared to steel hulls, ranging from \$5–8 million for medium-sized vessels. If we consider that the cost of lithium-ion batteries for maritime applications is approximately \$500 per kWh, then the estimated cost for their energy storage systems is \$3–5 million, depending on capacity and supplier pricing. MS Turanor PlanetSolar features 512 square meters of photovoltaic panels, while Energy Observer has 202 square meters. Installation costs for high-efficiency solar panels can range from \$200,000 to \$500,000 per 100 square meters, leading to a total of \$2–4 million. As for testing, certification and R&D will reach somewhere between \$3-5 million.

If we are discussing about operation costs, the MS Turanor PlanetSolar it reaches first place in our ranking as it has zero costs since it's using electricity for propulsion which is converted from solar energy.

The final goal of using these resources and technologies is the emissions of this proven designs so we can see that in case of MS Turanor PlanetSolar which is using only solar energy converted into electricity and Energy Observer, which is using hydrogen fuel cells, the emissions will be zero.

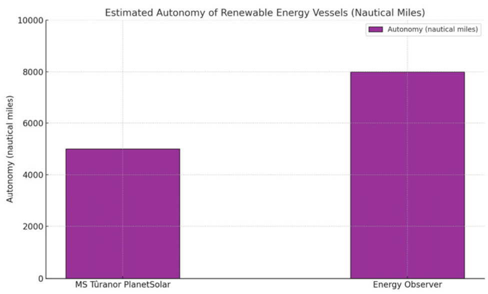

Fig.2 Estimated autonomy of renewable Energy Vessels

When discussing autonomy, if assuming 6 hours of peak sunlight, the solar panels of MS Turanor PlanetSolar are generating approximately 558 kWh/day. At a cruising speed of 5 knots, the vessel likely consumes around 60–70 kWh/day. If it is an efficient energy management then we will have continuous operation for approximately 40–50 days, translating to a theoretical range of 5,000 nautical miles.

At a cruising speed of 5 knots, the vessel consumes approximately 48 kg/day of hydrogen. With a storage capacity of 62 kg, the vessel can operate for approximately 1.3 days on hydrogen alone. As solar and wind systems are reducing hydrogen consumption by up to 50%, then will effectively double the operational range to approximately 8,000 nautical miles.

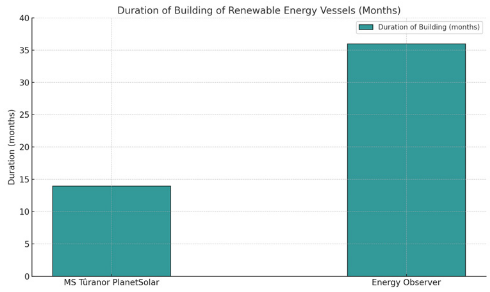

Fig.3 Duration of Building or Retrofiting Renewable Energy Vessels

For MS Turanor PlanetSolar will be necessary between 6-8 months for hull fabrication phase which requires advanced construction techniques. Another 4–5 months will be necessary for installation and calibration of photovoltaic panels. As for the sea trials and certification processes will take 2–3 months which will result into a total of 14 months. This shorter timeline excludes preliminary design or engineering stage which can take up to 10 months more.

The estimated 36 months for Energy Observer encompass all critical stages of the project such as 12 months needed for initial design and conversion planning. The hull modifications and system installation will take for another 18-20 months as the hull was extensively modified to improve hydrodynamic efficiency and supporting photovoltaic panels on 202 m², vertical-axis wind turbines, and a hydrogen electrolysis unit were installed during this phase. Testing and certification will take another 4–6 months.

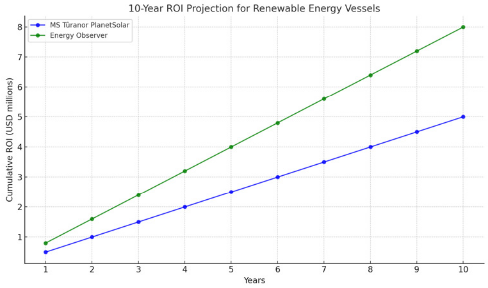

Fig.4 10-year ROI Projection for Renewable Energy Vessels

The projected ROI for MS Tûranor PlanetSolar demonstrates a linear growth rate of 0.5 million USD per year.

By the end of the 10-year period, the vessel's cumulative ROI reaches approximately 5 million USD, aligning with its lower energy demands and reliance on a single renewable source (solar energy).

The modest growth reflects the vessel's limitations in scalability and its primary role as a research and demonstration platform rather than a commercial operation.

Energy Observer's ROI grows at a higher rate of 0.8 million USD per year, reaching a cumulative ROI of 8 million USD by year 10.

The enhanced growth rate is attributed to its hybrid energy system, which integrates solar, wind, and hydrogen technologies, enabling broader applicability and greater operational efficiency.

This projection highlights the vessel's versatility and ability to capitalize on multiple renewable energy sources, resulting in greater financial returns over time.

This analysis highlights the economic potential of renewable energy vessels in reducing operational costs and achieving financial sustainability. While MS Tûranor PlanetSolar demonstrates the feasibility of solar-powered maritime transport, Energy Observer underscores the advantages of hybrid energy systems in achieving greater financial and operational performance.

5. CONCLUSIONS

The maritime industry, a cornerstone of global trade, is undergoing a critical transition toward sustainability to meet international climate goals. This study analyzed two pioneering vessels MS Turanor PlanetSolar and Energy Observer, each of which represents a tested and proven design for integrating renewable energy technologies into maritime operations. These vessels provide valuable insights into the potential of renewable solutions to reduce greenhouse gas emissions, improve fuel efficiency, and pave the way for decarbonized shipping.

The MS Turanor PlanetSolar has been extensively tested as the first fully operational solar-powered vessel to circumnavigate the globe. Its performance during these voyages confirms the feasibility of solar-powered navigation, although its scalability for large commercial vessels remains a challenge.

The Energy Observer showcases a fully operational hybrid renewable energy system that integrates solar, wind, and hydrogen technologies. Its ability to produce hydrogen onboard via seawater electrolysis demonstrates an innovative solution to energy self-sufficiency and zero-emission operations, even on long-haul voyages.

These vessels underscore the transformative potential of renewable energy systems in maritime transport, demonstrating that tested and proven designs can serve as benchmarks for future advancements. Fully renewable solutions, such as those demonstrated by the MS Turanor PlanetSolar and Energy Observer, highlight the possibility of achieving net-zero emissions in maritime operations.

While these vessels demonstrate the viability of renewable energy in maritime applications, challenges persist, including high upfront costs, limited infrastructure, and scalability concerns. Addressing these barriers will require sustained innovation, investment in research and development, and supportive policies to accelerate the adoption of proven technologies. Collaboration across industry stakeholders and international organizations is crucial to ensure the maritime sector aligns with global decarbonization targets.

In conclusion, this study emphasizes that proven and tested renewable energy designs, as exemplified by these two solar powered vessels, are key to redefining the maritime industry. By leveraging the insights gained from these pioneering vessels, the sector can chart a sustainable path forward, balancing technological innovation with operational feasibility to meet the ambitious goals of a zero-emission future.

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