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Power requirement for maritime transport with ships powered from hybrid zero-emission system

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***Abstract* – This paper aims to analyze the specific energy requirements of different types of ships, to develop models of hybrid systems adapted to them and to highlight the benefits of integrating renewable sources, such as photovoltaic energy and hydrogen, with efficient energy storage systems. The objectives of the paper focus on exploring and implementing zero-emission hybrid solutions in shipping, aiming to increase energy efficiency and reduce environmental impact. The paper also aims to provide an economic rationale by calculating deployment costs, depreciation and operational savings, as well as to identify the technological and infrastructure challenges required for the widespread adoption of these innovative technologies. The case studies featured in this article look at the deployment of hybrid systems on ships of different sizes and purposes, including a 5 kW PV-battery yacht and a 2 MW hydrogen-based hybrid tugboat.**

Keywords- maritime transport; zero-emission system; ships; fuel cell; battery

I. INTRODUCTION

Maritime transport is a fundamental element of international trade, facilitating about 90% of the volume of global trade [1]. An essential aspect in its efficient operation is the power requirement of the ships, which influences not only operational performance, but also the impact on the environment. This analysis examines the drivers of power demand in shipping, optimization methods, and current technology trends.

Shipping not only affects the global economy, but has a significant impact on port regions and local communities. Ports are major economic hubs, generating direct and indirect jobs. For example, the Port of Rotterdam, the largest port in Europe, is a major employer, with more than 385,000 jobs generated directly and indirectly [2]. The development of port infrastructure contributes to regional economic growth by attracting investment and supporting the logistics and industrial sector.

Another important aspect is the economic benefits brought by maritime transport by reducing transport costs. Due to the high transport capacity and energy efficiency of ships, the cost of maritime transport per ton kilometer is lower compared to other modes of transport, such as air or road transport [3]. This economic advantage is crucial for developing countries, which depend on commodity exports to sustain their economies.

The power requirement for propulsion of ships is determined by several interrelated factors. Of these, the main components include:

- The size and design of the vessel knowing that the weight and hydrodynamic characteristics of the hull significantly influence the power requirements [4]. For example, optimizing the hull shape can reduce drag by up to 20%.
- Drag resistance due to friction, waves and wind. Modern designs use advanced materials and anti-fouling coatings to mitigate these effects [5].
- The type and efficiency of the propulsion system being known as diesel engines and hybrid systems are predominant, although alternative solutions such as LNG or hydrogen propulsion are gaining ground[6].

Reducing the power requirement for maritime transport involves the adoption of innovative practices and technologies:

- Use of software for hydrodynamic simulations: These tools allow for the optimization of hull and propeller design to minimize energy losses [7].
- Implementation of fuel management systems: Continuous monitoring of energy consumption allows for the identification and correction of inefficiencies[8].
- Renewable energy-assisted propulsion: Technologies such as modern sails or the use of solar energy contribute to reducing dependence on fossil fuels[9].

The adoption of alternative fuels and electrification should be the dominant trends for reducing power requirements and environmental impact. According to a recent study, ships equipped with fuel cell-based electric motors could reduce greenhouse gas emissions by up to 50% by 2030 [6].

II. POWER REQUIREMENTS FOR SHIPS

A. *Classification of ships used in maritime transport*

Commercial vessels are classified based on the type of cargo transported and the specific technical characteristics. The main classification includes: general cargo ships, container ships, oil tankers, gas transport ships (LNG and LPG), bulk carriers, Ro-Ro ships, passenger ships and specialized ships [10], [11], [12].

1) General Cargo Ships

General cargo ships are intended to transport goods that do not require specialized storage, such as industrial equipment, consumer goods, and building materials.

Usually, the length of cargo ships varies between 100 and 200 meters, with a width of 15-25 meters. The load capacity it is between 5,000 and 50,000 deadweight tons (DWT) and these cargos have diesel engines with a power between 5,000 and 20,000 kW are standard, ensuring cruising speeds of 12-18 knots.

Figure 1. Operated by the Norwegian company Nor Lines, this vessel transports general cargo along the Norwegian coast and to other European ports

2) Container Ships

Container ships are used for transporting standardized containers, in different sizes: 20 feet (TEU) and 40 feet (FEU).

Figure 2. Tønsberg: Owned by Wallenius Wilhelmsen Logistics, it is one of the largest Ro-Ro/Container ships in the world, used for the transport of vehicles

3) Oil Tankers

Oil tankers are specialized for transporting crude oil or refined products. The classification is based on the load capacity.

Figure 3. **Navion Britannia:** Operated by the Norwegian company Teekay, this vessel transports crude oil from the North Sea to refineries in Europe

4) Roll-on/Roll-off Ships (Ro-Ro)

Ro-Ro vessels are intended for the transport of vehicles, trailers and other cargo on wheels. These vessels have length of 150-250 meters and width of 20-30 m, the capacity from 2,000 to 8,000 vehicles and are powered by 15,000-30,000 kW engine power, with speeds of 16-22 knots.

Figure 4. Höegh Trapper: Owned by Höegh Autoliners, it is one of the largest Ro-Ro vessels in the world, used to transport vehicles and heavy equipment

5) Ferry Boats and Passenger Ships

Passenger ships include ferries and cruise ships. Ferries can be 50-200 meters long; cruise ships can reach up to 350 meters. Their capacity is between 100 and 5,000 passengers, with space for vehicles on ferries and are powered by engines with powers between 10,000-70,000 kW.

Figure 5. Color Line, it is a passenger ferry that connects Oslo to Kiel, offering cruise facilities and vehicle transport

Among the specialized vessels, we list: Heavy-Lift Ships, Gas Transport Vessels (LNG and LPG Carriers), Dredging Vessels, Vessels for Offshore Drilling, Research and Exploration Vessels.

According to the existing data, we can appreciate that the most important types of maritime transport vessels, like those in Figures 1-5, with their weight characteristics, are those presented in Table I.

TABLE I. TYPES OF SHIPS USED IN MARITIME ACTIVITY

Type of Vessel	**Maximum Tonnage (DWT)**			**Engine Power (kW)**		
	min	**max**	**average**	**min**	**max**	**average**
Motor boat	0.5	2	1.25	10	100	55
Small yacht	5	50	27.5	100	1500	800
Small fishing vessel	50	200	125	500	2000	1250
Tug	100	500	300	1500	5000	3250
Passenger ferry	200	1500	850	2000	10000	6000
Industrial fishing ship	500	5000	2750	2000	8000	5000
Litle cargo	1000	5000	3000	3000	10000	6500
Small cargo ship	5000	15000	10000	10000	20000	15000
Bulk carrier medium	15000	60000	37500	10000	25000	17500
Tanker medium	20000	80000	50000	15000	30000	22500
Medium cargo ship	20000	100000	60000	20000	50000	35000
Large bulk carrier	80000	200000	140000	25000	60000	42500
Large tanker	150000	300000	225000	30000	75000	52500
Large cargo	100000	200000	150000	40000	80000	60000
Very large bulk carrier	200000	400000	300000	50000	100000	75000
Super-tanker	300000	550000	425000	70000	100000	85000
Cruise ship	10000	100000	55000	20000	50000	35000
Large cruise ship	100000	250000	175000	50000	100000	75000

B. *Ships usage data*

In maritime transport, the frequency of journeys and the distances travelled annually vary significantly depending on the type of vessel and its specific role. Of the aforementioned categories, ferries (ferry boats) and passenger ships make the most annual trips [10], [11]. A summary of the frequency of trips and annual distance travelled can be found in Table II.

TABLE II. FREQUENCY OF DISPLACEMENTS AND ANNUAL DISTANCE TRAVELLED

	Ferries and Passenger Ships	**Container Ships and General Cargo Ships**	**Oil Tankers and Gas Transport Ships**	**Bulk Carriers**	**Specialized Ships (Heavy-Lift Ships, Dredgers, Research Ships)**
Frequency of displacements	These vessels operate on fixed routes, with multiple daily or weekly crossings, depending on the distance and demand on that route	These ships make longer but less frequent trips compared to ferries	These ships make long and infrequent journeys, carrying large quantities of liquids or gases	Similar to oil tankers, these ships make long and infrequent trips	These ships have specific missions, and therefore the frequency and distance of displacements vary considerably
Annual distance travelled	Estimates indicate that a ferry can travel between 100,000 and 200,000 km per year.	Depending on trade routes and transport demand, these ships can travel between 80,000 and 150,000 km annually	Estimates suggest that these ships travel between 70,000 and 120,000 km per year	It is estimated that bulk carriers travel between 60,000 and 110,000 km annually	It can vary from 30,000 to 80,000 kilometers, depending on the projects and missions assigned

By making a correlation between the types of shipping vessels presented in Table I and the frequency of displacements and annual distance travelled, we obtain information regarding the fuel consumption required (see Table III) [10], [11], [12].

For boat engines. fuel consumption can be estimated based on factors such as engine power, engine type, speed, and efficiency. A common relationship used is:

$$FCon = EP \times SCF \qquad (1)$$

FCon = Fuel consumption in liters/hour

EP = Engine power (Horse Power)

SCF = Specific consumption factor

Engine power is measured in horsepower (HP) or kilowatts (kW) with the following conversion ratio: 1 HP ≈ 0.745 kW.

The specific consumption factor differs depending on the type of fuel. If for diesel engines the typical factor is between **0.15 and 0.25 liters/HP/hour**, in the case of gasoline engines the factor can vary between **0.25 and 0.40 liters/hp/hour**, because these engines are less efficient than diesel engines.

At the same time, the cumulation also varies depending on the operating regime. At economy speed (about 60-80% of the maximum speed) consumption is more efficient, while at maximum speed consumption increases significantly.

TABLE III. ANNUAL FUEL CONSUMPTION FOR SHIPPING VESSELS

Type of Vessel	Annual distance travelled (km / year)			Fuel consumption (l/km)			Fuel consumption (tones/year)
	min	max	average	min	max	average	tones/year
Motor boat	1000	5000	3000	2	10	6	18
Small yacht	3000	15000	9000	10	50	30	270
Small fishing vessel	5000	20000	12500	50	150	100	1250
Tug	80000	150000	115000	100	300	200	23000
Passenger ferry	100000	200000	150000	200	500	350	52500
Industrial fishing ship	50000	100000	75000	150	400	275	20625
Litle cargo	80000	150000	115000	300	800	550	63250
Small cargo ship	80000	150000	115000	500	1200	850	97750
Bulk carrier medium	60000	110000	85000	800	2000	1400	119000
Tanker medium	70000	120000	95000	1000	2500	1750	166250
Medium cargo ship	80000	150000	115000	1200	3000	2100	241500
Large bulk carrier	60000	110000	85000	2000	4000	3000	255000
Large tanker	70000	120000	95000	2500	5000	3750	356250
Large cargo	80000	150000	115000	3000	6000	4500	517500
Very large bulk carrier	60000	110000	85000	4000	7000	5500	467500
Super-tanker	70000	120000	95000	5000	10000	7500	712500
Cruise ship	80000	150000	115000	1500	3500	2500	287500
Large cruise ship	80000	150000	115000	3500	7000	5250	603750

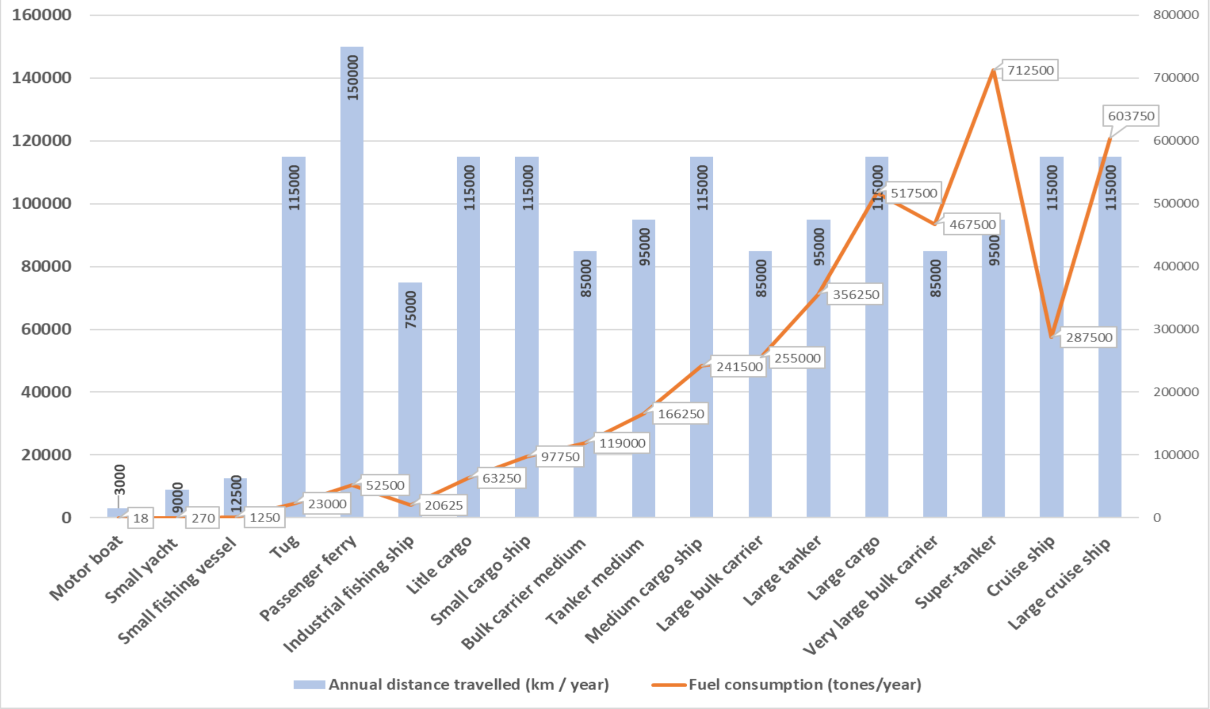

Figure 6. Annual distance travelled & Fuel consumption

The annual consumption, for each category, was calculated as the product values the average distance traveled and the consumption in (l/km). In the case of consumption in l/km, the average value of the engine power (in Table I) is taken into account.

It should be pointed out that additional factors influencing consumption were not taken into account, such as: the shape and weight of the boat, the sailing conditions, the maintenance of the engine or the load of the boat. A heavier boat or one with an inefficient hull requires more energy, waves and strong winds can greatly increase consumption, well-maintained engines are more efficient, and extra weight can increase consumption.

Looking at Figure 6, there is a clear relationship between ship size and annual fuel consumption. The larger and more loaded the ship, the higher the annual consumption, but the specific efficiency per km/ton transported tends to be better. Tanker and cargo ships have the highest absolute consumption, but offer economic and logistical advantages through their high transport capacity.

III. HYBRID ZERO-EMISSION SYSTEMS USED IN MARITIME TRANSPORT

Hybrid propulsion in the maritime industry is the combined use of several energy sources to ensure the movement of ships, with the aim of optimizing energy efficiency and reducing pollutant emissions. The concept of hybrid propulsion involves the integration of a conventional engine, usually a diesel engine, with alternative energy sources such as battery-powered electric motors or fuel cells. The main goal is to ensure flexible and efficient operation while reducing fuel consumption and environmental impact [13].

The general principles of hybrid propulsion systems include the intelligent operation of different energy sources so as to maximize efficiency according to navigation conditions and power requirements. For example, during maneuvers in port or at low speeds, hybrid ships can run exclusively on electricity, eliminating greenhouse gas emissions and reducing noise pollution. On the other hand, at high speeds or in open sea conditions, the diesel engine can be activated to provide the necessary power, while the surplus energy can be used to charge the batteries[14].

A practical example of hybrid propulsion is the system installed on cruise ships "Hurtigruten", which uses lithium-ion batteries to ensure emission-free navigation in protected areas of the Norwegian fjords [15]. This system allows them to comply with strict environmental protection regulations in ecologically sensitive regions, demonstrating the effectiveness of such technology in reducing the ecological footprint.

Next will be presented two hybrid systems with zero emissions used in maritime transport.

A. A photovoltaic - battery hybrid system for a 20 DTW marine yacht with an installed capacity of 5 kW

The diagram of the hybrid system analyzed is shown in Figure 7. The characteristics of each component of the scheme can be found in Table IV

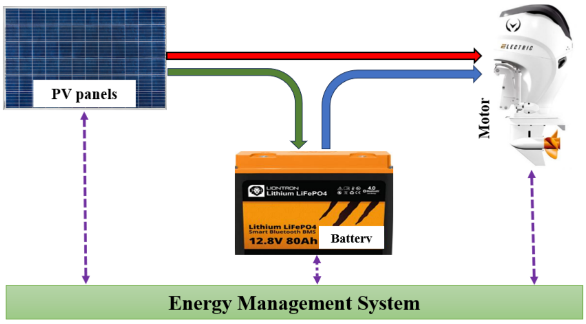

Figure 7. Bloc diagram of a photovoltaic - battery hybrid system

TABLE IV. CHARACTERISTICS OF PHOTOVOLTAIC - BATTERY HYBRID SYSTEM COMPONENTS

Photovoltaic panels	*An efficient photovoltaic panel has a power of about 300-400 If' per panel, with a size of 1.6* m^2. *In order to produce a significant amount of energy (10-20 kW per day depending on solar conditions), about 20-30 photovoltaic panels (6-10 kW total power) should be installed. Total area required: -40-50* m^2*, preferably on the roof and sides of the yacht*	High-efficiency monocrystalline photovoltaic panels, SunPower or LG
Batteries-	*Lithium-ion or LiFeP04 are preferred due to their higher energy density and long lifespan.* *If the yacht needs 35-40 kW for one hour of maximum operation, and the system needs to work S hours a day. then the battery capacity should be around 280-320 kWh.* *This allows for a decent range under normal conditions and a backup in case of bad weather*	Deep Blue Battery 40
EMS - *Energy Management System*	*An energy management system (EMS) is required to control the flow of energy between panels, batteries, and consumers.* *EMS should prioritize the use of solar energy when available and automatically switch to batteries or generator when needed*	
Hybrid powertrain:	*Powerful electric motor: delivers between 25 and 100 kW of continuous power at 360 V* *Available as inboard, outboard or sail drive*	DB25i 1400 Systems from Torqeedo
Auxiliary components	*Power inverters and controllers which can handle both direct current (DC) and alternating current (AC)*	Victron. SMA or Schneider Electric

1) Lifetime analysis

The analysis of the lifespan of a hybrid photovoltaic-battery system used for the propulsion of a yacht consists of optimizing the performance, sustainability and economic viability of environmentally friendly marine propulsion solutions. Such an analysis makes it possible to identify critical factors that influence the degradation of components, such as photovoltaic panels and batteries. Through a detailed understanding of the system's lifecycle, one can determine the total cost of ownership, including both initial acquisition costs and maintenance, repair, and replacement expenses. Moreover, such an analysis facilitates the optimization of the system design to extend the efficient service life and reduce the ecological footprint, thus contributing to the transition to sustainable navigation. This approach is essential in assessing the technological and economic feasibility of the large-scale deployment of hybrid systems in the maritime industry, supporting the adoption of solutions that meet both technical performance requirements and global carbon reduction targets (see Table V).

TABLE V. ANALYTICAL DATA ON THE LIFETIME OF A HYBRID PHOTOVOLTAIC-BATTERY SYSTEM

Average values for yacht use	Average Solar Production	Equipment lifespan
Annual duration of use: 150 days per year (active sailing season).	**Average solar irradiation:** 5 hours of full sun per day (in good maritime areas such as the Mediterranean).	**Photovoltaic panels:** 25-30 years (with a decrease in efficiency of about 0.5% per year).
Average operating hours of the electrical system: 8 hours per day (including propulsion and auxiliary consumption).	**Daily energy production per kW of solar panels:** 5 kWh.	**LiFePO4 batteries:** 10-15 years (or 3,000-5,000 charge cycles).
Estimated daily consumption: 35 kWh.	**Total photovoltaic panels installed:** 10 kW. **Total daily energy production:** 10 kW x 5 hours = 50 kWh	**Inverters and EMS:** 10-15 years

2) Analysis of economic indicators

To calculate the annual savings made by using solar energy and batteries, we need to compare the costs with and without the solar system.

In scenario without photovoltaic system, cost with diesel for propulsion and power supply of the electrical system we have: **Diesel consumption:** 5 liters/hour (for a 15-20 kW diesel generator); **Diesel cost:** $1.5/liter; **Operating hours per day:** 8 hours; **Daily cost of diesel:** 5 liters/hour x 8 hours x $1.5/liter = $60; **Annual cost of diesel:** $60/day x 150 days = $9,000.

In scenario with photovoltaic system we have, **Total power of photovoltaic panels**: 10 kW; **Average hours of sunshine per day:** 5 hours (in good sunny conditions); **Daily energy production:** 10 kW×5 hours=50 kWh/day

Resulting an annual savings by approximately $9,000 (by significantly reducing diesel use).

The investment costs are as follows: **Photovoltaic panels (10 kW):** $10,000-15,000 ($1,000-1,500/kW), **LiFePO4 battery (300 kWh):** $80,000-$100,000 ($250-$350/kWh), **MPPT inverters and controllers:** $5,000-$10,000, **Energy Management System (EMS):** $3,000-$5,000, **Installation and wiring costs:** $10,000-$15,000. This results in an initial cost of: $108,000-$145,000

For the calculation of the investment depreciation, we have taken into account:

$$\text{Amortization period} = \frac{\text{Invest Initial}}{\text{Annual Savings}} \quad (2)$$

where:

Initial investment: $120,000 (average value).

Annual savings: $9,000.

We get a amortization period of:

$$\text{Amortization period} = \frac{120.000}{9.000} \approx 13{,}3\ years \ (3)$$

B. A hydrogen-based hybrid propulsion system for a 500 DTW marine tug with an installed capacity of 2 MW

To equip a 500-ton marine tug with a hydrogen hybrid system, it is essential to select commercially available components that ensure the desired performance and efficiency. Here is a detailed proposal of the necessary components, together with their approximate parameters and prices Table VI.

TABLE VI. HYDROGEN HYBRID SYSTEM

Hydrogen fuel cells	Ballard FCveloCity®-HD	**Power per module:** 100 kW **Electrical efficiency:** up to 55% **Dimensions:** 1.000 x 860 x 626 mm **Weight:** 256 kg **Estimated price per module:** approximately $100,000	20 modules $2 million
Hydrogen storage tanks	Hydrogen tanks Hexagon Composites	**Capacity:** 50 kg of H_2 **Operating pressure:** 350 bar **Dimensions :** 2.500 x 1.000 mm **Weight:** approx. 500 kg **Estimated price per tank:** about 50.000 USD	For an autonomy of 24 hours at maximum consumption, estimating a consumption of 50 kg of hydrogen/hour, 24 tanks would be needed, totaling a cost of approximately USD 1,200,000
Batteries for energy storage	Lithium-ion batteries Corvus Energy Orca Energy	**Capacity per module:** 6.5 kWh **Continuous power:** 3.3 kW **Dimensions:** 743 x 650 x 197 mm **Weight:** 83 kg **Estimated price:** about $5,000 per module	To provide a total capacity of 1,000 kWh, approximately 154 modules would be required, totaling a cost of approximately $770,000
Inverter & Energy Management System	Siemens SINAMICS S120	**Rated power:** up to 1,500 kW **Efficiency:** over 98% **Dimensions:** variable **Estimated price:** about $200,000	To handle the full power, two such systems would be required, totaling a cost of approximately $400,000
	ABB AMZ 5000	**Rated power:** 2,000 kW	

Electric propulsion motor		**Efficiency:** over 96% **Dimensions :** approx. 3 x 2 x 2 m **Weight:** Approx.10.000 kg	**Estimated price:** approx.1.000.000 USD
Control and monitoring system	Kongsberg Maritime K-Chief 700	**Functionalities:** integrated monitoring and control of propulsion and auxiliary systems **Estimated price:** about $500,000	

Adding up the costs of the mentioned components, we get a total of about $5,870,000. Installation, integration, and testing costs are not included in this estimate and can add significantly to the total cost of the project.

Hydrogen fuel cells

- **Estimated service life:** between 10,000 and 30,000 hours of operation, depending on the quality of the hydrogen used and maintenance
- **Impact on lifespan:** If the tug operates, on average, 8 hours a day, 300 days a year, the fuel cells could have a lifespan of about 4-10 years

Hydrogen tanks

- **Estimated lifespan:** between 15 and 20 years, with regular inspections to verify structural integrity
- **Impact on lifespan:** Tanks are relatively durable, but it is important that they undergo regular testing to prevent degradation due to pressure

Lithium-ion batteries

- **Estimated service life:** between 5,000 and 10,000 charge/discharge cycles
- **Impact on lifespan:** If batteries are used daily with a full cycle, the lifespan could be around 7-10 years

Electric propulsion motor

- **Estimated service life:** 20-30 years, with periodic maintenance and stable operating conditions
- **Impact on lifespan:** The durability of the electric motor is high, but its efficiency and performance can only be maintained through regular inspections and eventual repairs

Control and monitoring system

- **Estimated lifespan:** 10-15 years, with software updates and hardware maintenance
- **Impact on lifespan:** Control and monitoring systems can become technologically outdated, requiring upgrades to remain effective.

Figure 8. Lifetime of a hydrogen hybrid system

The service life of a hydrogen hybrid system for a marine tug can be influenced by several factors, such as operating cycles, maintenance, and operating conditions (see Figure 8). To make a realistic estimate, let's look at each main component individually. In an ideal scenario, most major system components should have a service life of at least 10-15 years, provided they are properly maintained (se Table VII). However, components with a shorter lifespan, such as batteries and fuel cells, should be replaced or refurbished after 7-10 years of use.

TABLE VII. FINANCIAL ANALYSIS OF A HYDROGEN HYBRID SYSTEM

Average Usage Values for a Marine Tug	Initial Investment in the Hydrogen Hybrid System	Estimating Savings from Using the Hybrid System	Estimated Savings by Using the Hydrogen Hybrid System	Calculation of the depreciation of the investment
Hours of operation per year: 3,000 - 4,000 hours (assuming a use of approximately 8-11 hours per day, for 300-350 days per year)	**Total estimated cost of the system:** $5,870,000 It includes fuel cells, hydrogen tanks, lithium-ion batteries, electric propulsion motor, control and monitoring system.	**Average fuel consumption of a conventional tug boat:** Approximately 200-300 liters/hour of diesel.	**Reduced fuel costs:** Assuming a 40% reduction in costs, the annual savings would be: $\frac{\$1.312.500}{1\ year} * 0,4 =$ $= \$525.000$	**Depreciation period:** $\frac{\$5.870.000}{\$525.000} \approx 11,2\ years$
Average lifespan: 20-30 years.		**Average cost of diesel** (2024): About $1.5/liter		
Operation and maintenance (O&M) costs: Approximately 5-10% of the initial cost of equipment per year.		Annual diesel consumption: $250\ \frac{liters}{hour} * 3.500\ \frac{hours}{year} =$ $= 875.000\ \frac{liters}{year}$ **Annual fuel cost:** $875.000\ \frac{liters}{year} * \frac{\$1.5}{liter} =$ $ 1.312.500 / year		

Savings from using hydrogen are harder to estimate, but it is estimated that a hydrogen system can reduce fuel costs by 30-50%, depending on the price of hydrogen and the efficiency of the system.

Under normal operating conditions, the investment in a hybrid hydrogen system for a 500-ton marine tug could be amortized in about 11-12 years. This is a conservative estimate and depends on fluctuating fuel costs, system maintenance, and possible subsidies.

The total service life of the tug is 20-30 years, which means that the hybrid system can generate significant savings after the payback period is over, helping to reduce the carbon footprint and operate efficiently in the long term.

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CONCLUSION

The proposals presented in this article include the adoption of hybrid solutions that combine renewable energy sources with efficient energy storage systems, such as LiFePO4 batteries and hydrogen fuel cells. The energy models developed take into account the variability of renewable sources, emphasizing the importance of integrating smart energy management systems for performance optimization. Economic analyses provide estimates of initial costs, payback life and annual savings, demonstrating economic feasibility and contribution to reducing carbon footprint.

The article highlights the challenges related to the energy density of storage systems and their impact on ship architecture. The adaptability and scalability of hybrid solutions are identified as essential factors for large-scale deployment in industry, alongside collaboration between the maritime and energy sectors.

The analysis of the lifetime of hybrid systems provides a solid basis for informed decision-making and the advancement of research in the field of renewable energy applied to maritime transport. The total service life of a hydrogen hybrid system for a 500-tonne marine tug can be estimated to be between 10 and 15 years, with the need to replace certain components during this timeframe. For maximum lifespan, investments in maintenance and technology upgrades are essential.

In conclusion, the paper promotes investments in zero-emission hybrid technologies as a viable solution for reducing fossil fuel consumption, increasing energy efficiency, and protecting the environment in shipping.

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