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Sustainable Energy Sources For Marine Propulsion: A Comparative Review And Energy-Balance Analysis of A Solar–Wind–Hydrogen Hybrid Plant

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Abstract

Shipping emitted about 2.9% of anthropogenic CO_2 in 2018, and tightening International Maritime Organization (IMO) objectives require a move away from fossil marine fuels. This study compares nine propulsion energy options (conventional fuels, liquefied natural gas, biofuels, ammonia, hydrogen fuel cells, solar photovoltaics, wind assistance, nuclear power and magnetohydrodynamic drives) on a harmonised basis covering conversion efficiency, operational emissions, constraints and readiness. A renewable-only hybrid plant combining solar photovoltaics, wind assistance, proton-exchange-membrane fuel cells and a battery is then assessed with a reproducible 24 h energy-balance model of a constant 1000 kW propulsion demand. A configuration with a fixed 500 kW fuel-cell output leaves 15.7% of the daily energy unmet, because nominal 20/30/50% source shares sum to 100% only at peak solar output and mean wind. A load-following fuel cell rated at 800 kW with a 200 kWh battery meets the demand in the reference case, with the fuel cell supplying 66% of the energy and consuming about 1,000 kg of hydrogen per day. Over 500 stochastic wind realisations, residual shortfalls average 0.3% of daily energy and are largely removed by a 1000 kWh battery. Solar photovoltaics supply only 6% of the energy and need about 1,250 m^2 of deck area. Renewables mainly cut hydrogen use rather than the required fuel-cell capacity; hydrogen cost and onboard storage volume are the dominant barriers for small and medium vessels on short routes.

Keywords Marine propulsion · Hybrid energy system · Hydrogen fuel cell · Wind-assisted propulsion · Shipping decarbonisation · Energy-balance simulation

1 Introduction

International shipping carries the great majority of world trade by volume, and it still runs almost entirely on fossil fuels. The Fourth IMO Greenhouse Gas Study estimated that shipping emitted 1,056 Mt of CO_2 in 2018, about 2.9% of global anthropogenic CO_2 emissions, together with significant quantities of NO_x, SO_x and particulate matter (Faber et al. 2020). These emissions affect climate, air quality in port regions and coastal ecosystems (Bouman et al. 2017; Balcombe et al. 2019).

A broad set of alternatives is under discussion: liquefied natural gas (LNG), biofuels, ammonia, hydrogen and fuel cells, battery-electric drives, wind assistance, onboard solar power and, for specific niches, nuclear propulsion (Hansson et al. 2019; Law et al. 2021; Mallouppas and Yfantis 2021; Inal et al. 2022; Gray et al. 2021). Each option trades off energy density, conversion efficiency, operational emissions, infrastructure needs and cost, and no single option satisfies the requirements of all ship types and routes. Hybrid plants that combine several sources are therefore an obvious candidate for decarbonising vessels with moderate power demand and predictable operating profiles.

Most comparative studies assess fuels on life-cycle emissions and cost, and relatively few link the comparison to an explicit, transparent energy balance of a hybrid plant that shows how nominal source shares translate into delivered propulsion energy. This matters because power shares quoted for renewables at their peak do not equal energy shares over a voyage, and firm capacity requirements differ from energy requirements. The present paper makes three contributions. First, it provides a harmonised comparison of nine energy options for ship propulsion, with an explicit statement of what each efficiency figure refers to. Second, it evaluates a renewable-only solar–wind–hydrogen–battery plant with an open and reproducible 24 h energy-balance model, including a stochastic uncertainty analysis and sensitivity to wind resource, fuel-cell rating and battery size. Third, it quantifies the resulting hydrogen demand, onboard storage volume, indicative fuel cost and avoided emissions, so that the practical barriers can be judged against numbers rather than qualitative statements.

The remainder of the paper is organised as follows. Section 2 reviews the regulatory context and the candidate energy options. Section 3 describes the review approach and the simulation model. Section 4 presents the results, Section 5 discusses implications and limitations, and Section 6 concludes.

2 Comparative review of energy options

2.1 Regulatory context

Two sets of IMO measures frame the problem. The global sulphur limit of 0.50% m/m in fuel oil used outside emission control areas (0.10% inside them) has applied since 1 January 2020 under MARPOL Annex VI (IMO 2008). It addresses SO_x and particulate matter, not CO_2, and is often referred to as "IMO 2020". Compliance has been achieved through low-sulphur fuels or exhaust-gas scrubbers rather than through a change of propulsion technology.

Greenhouse-gas policy is governed by the IMO strategy. The 2018 initial strategy targeted at least a 50% cut in total annual emissions by 2050 relative to 2008. The 2023 revised strategy raised the ambition to net-zero emissions by or around 2050, with indicative checkpoints of at least 20% (striving for 30%) by 2030 and at least 70% (striving for 80%) by 2040 relative to 2008 (IMO 2023). A Net-Zero Framework combining a fuel-intensity standard with an emissions-pricing mechanism was approved at the 83rd session of the Marine Environment Protection Committee (MEPC) in April 2025, but formal adoption was adjourned in October 2025 (DNV 2026). At the time of writing, a decision is expected at a resumed session scheduled for late 2026 (Atchison 2026). The regulatory trajectory is therefore clear in direction but uncertain in detail, which in turn affects investment decisions for new propulsion technology.

2.2 Candidate energy options

Table 1 summarises the nine options considered. Efficiencies are not strictly comparable across rows, because they refer to different conversion steps; the basis of each figure is therefore stated in the table note. The ranges are indicative values drawn from the cited sources rather than results of this study.

Table 1 Comparison of energy options for ship propulsion

Option	Efficiency (%)[a]	Operational emissions	Principal constraints	Cost and readiness
Conventional fuels (HFO, MDO, MGO)	40–50	About 3.1–3.2 t CO_2 per t fuel (IMO 2018); NO_x, SO_x and PM	Regulatory exposure and price volatility	Fully mature; lowest capital cost (Bouman et al. 2017)
LNG (dual-fuel engines)	40–50	Up to about 25% lower tank-to-wake CO_2 per unit energy than HFO; methane slip can offset the gain (Pavlenko et al. 2020; Ushakov et al. 2019)	Cryogenic storage, bunkering network, methane slip	Commercial; moderate
Biofuels (FAME, HVO, bio-LNG, bio-methanol)	40–50, engine-dependent	Biogenic CO_2; life-cycle benefit depends on feedstock and land use (Brynolf et al. 2014; Hansson et al. 2019)	Feedstock availability and competing demand	Partly drop-in; medium to high
Ammonia	30–50 (projected)	No CO_2; NO_x, N_2O and unburnt NH_3 require control (Kobayashi et al. 2019)	Toxicity, corrosivity, slow combustion	Engines at demonstration stage; high (Valera-Medina et al. 2018; Lloyd's Register and UMAS 2020)
Hydrogen with PEM fuel cells	40–60 (system, LHV)	No emissions at point of use; life-cycle depends on hydrogen source (Ball and Weeda 2015)	Low volumetric density, cryogenic or high-pressure storage, bunkering	Demonstration and early commercial; high (van Biert et al. 2016; Elkafas et al. 2023)
Solar photovoltaics	15–22 (module)	None in operation; manufacturing impacts	Low power density, deck area, latitude and weather (Kobougias et al. 2013)	Commercial for auxiliary loads; moderate
Wind assistance (rotor and wing sails, kites)	Not applicable[b]	None in operation	Route and wind dependence, air draft, deck space (Traut et al. 2014; Chou et al. 2021)	Commercial retrofits; low to moderate
Nuclear (small modular reactors)	About 30–35 (steam cycle)	No operational CO_2; radioactive waste	Regulation, security, port access, public acceptance (Hirdaris et al. 2014)	Proven in naval and icebreaker service; very high capital cost
Magnetohydrodynamic (MHD) drive	Below about 20 (experimental)	None in operation	Low seawater conductivity, very strong magnets (Phillips 1962)	Laboratory and prototype scale; very high

[a] Engines and fuel cells: fuel energy (lower heating value) to shaft or electrical power. Photovoltaics: incident irradiance to electricity. Nuclear: thermal energy to electricity. [b] Wind assistance does not convert energy onboard; it displaces propulsion

power, and reported fuel savings are route-dependent and typically in the single digits to about 20% on favourable routes (Traut et al. 2014; Chou et al. 2021). HFO, heavy fuel oil; MDO, marine diesel oil; MGO, marine gas oil; FAME, fatty acid methyl ester; HVO, hydrotreated vegetable oil; PEM, proton-exchange membrane; PM, particulate matter.

2.3 Synthesis and research gap

Three observations follow from Table 1. First, the lowest operational emissions are associated with the options that have the lowest technological readiness or the largest practical constraints: hydrogen, ammonia, nuclear and MHD. Fuels that are mature, such as LNG and conventional oils, remain carbon-intensive, and the climate benefit of LNG depends strongly on methane slip, which has been measured at levels that can neutralise its tailpipe CO_2 advantage (Ushakov et al. 2019; Pavlenko et al. 2020). Second, the zero-emission benefit of hydrogen and ammonia is conditional on how the fuel is produced; hydrogen from steam methane reforming without carbon capture carries a large upstream footprint, whereas hydrogen from renewable electricity does not (Ball and Weeda 2015; IEA 2023). Third, renewable sources captured on board, namely solar and wind, are free of fuel cost but limited in power density and availability, which makes them supplements rather than stand-alone solutions for most ships.

Hybridisation follows naturally from these observations: an onboard renewable contribution reduces consumption of a stored energy carrier, while the carrier provides firm power. What is less often shown quantitatively is how much of the demand each source can really cover over a day, how large the firm-power source must be, and what this implies for hydrogen consumption and storage. These questions are addressed in the remainder of this paper.

3 Methods

3.1 Literature review

Section 2 is a narrative review of peer-reviewed articles, institutional reports (IMO, IEA, Lloyd's Register and UMAS, ICCT) and regulatory documents. Quantitative values in Table 1 were taken from the sources cited in the table and were checked for consistency of definition (what the efficiency refers to) before being compared.

3.2 Hybrid plant model

The plant consists of a solar photovoltaic (PV) array, wind-assist devices whose contribution is expressed as an electrical-equivalent power, a hydrogen-fed PEM fuel-cell system, and a lithium-ion battery, all connected to a DC bus that feeds electric propulsion motors (Fig. 1). A power-management system (PMS) sets the fuel-cell output and the battery balances the remainder. The model simulates 24 h with a time step of 5 min against a constant propulsion demand P_L = 1000 kW at the DC bus. Transmission, motor and propeller losses are not modelled separately; the demand is defined at the bus. All parameters are listed in Table 2.

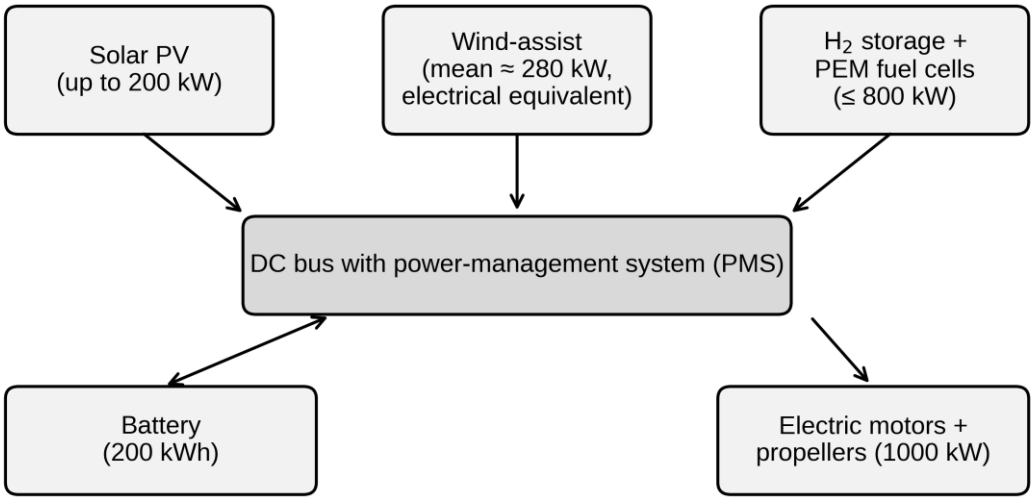


Fig. 1 Architecture of the renewable hybrid propulsion plant modelled in this study. Solar PV, wind assistance and fuel cells feed a DC bus controlled by a power-management system; the battery exchanges power with the bus in both directions and the electric motors draw the propulsion demand

Solar power follows a clear-sky half-sine between 06:00 and 18:00 with peak $P_{pv,peak}$ = 200 kW (20% of the demand):

$$P_{pv}(t) = P_{pv,peak} \sin[\pi(t - 6)/12], \quad 6 \le t \le 18 \text{ h; zero otherwise} \tag{1}$$

Wind-derived power is a mean value plus two first-order autoregressive (AR(1)) fluctuations, a slow component (time constant 2 h, standard deviation 35% of the mean) and a fast gust component (10 min, 10%), truncated between zero and 600 kW:

$$P_w(t) = \min\{\max[\mu_w + x_1(t) + x_2(t), 0], P_{w,max}\} \tag{2}$$

Treating wind assistance as electrical-equivalent power is a simplification: rotor and wing sails reduce the thrust required from the propeller rather than generating electricity. The nominal mean of 300 kW (30% of the demand) is at the upper end of the savings reported for wind assistance and is varied in the sensitivity analysis.

Two fuel-cell control strategies are compared. In the *fixed set-point* strategy, which corresponds to the plant as first specified (solar 20%, wind 30%, fuel cell 50%), the fuel cell delivers 500 kW at all times. In the *load-following* strategy the PMS computes the residual demand $P_{res} = P_L - P_{pv} - P_w$ and drives the fuel cell towards it through a first-order filter with time constant τ = 0.5 h, which limits fuel-cell ramping, with a state-of-charge (SOC) restoring term:

$$\tau \, dP_{ref}/dt = P_{res} + k(SOC_{tgt} - SOC)E_b - P_{ref} \tag{3}$$

$$P_{fc} = \min\{\max[P_{ref}, 0.1 \, P_{fc,rated}], P_{fc,rated}\} \tag{4}$$

where $SOC_{tgt} = 0.5$ is the target, E_b the battery capacity and $k = 1\ h^{-1}$. The fuel-cell system efficiency on a lower-heating-value (LHV) basis falls linearly with load, which is representative of PEM systems including balance of plant and lies within the 40–60% range of Table 1 (van Biert et al. 2016):

$$\eta_{fc} = 0.58 - 0.12\, P_{fc}/P_{fc,rated} \quad (5)$$

Hydrogen consumption follows from $m_{H2} = \int P_{fc}/(\eta_{fc}\, LHV_{H2})\, dt$ with $LHV_{H2} = 33.33$ kWh kg^{-1}. Any difference $P_{net} = P_{pv} + P_w + P_{fc} - P_L$ is taken up by the battery, which is limited by its SOC window, a power limit of 1C, and charge and discharge efficiencies of 0.95. When the battery is full, surplus power is curtailed; when it is empty or at its power limit, the shortfall is recorded as unmet load.

Table 2 Model parameters

Parameter	Value
Propulsion demand	Constant 1000 kW at the DC bus; 24 h horizon; 5 min time step
Solar PV	Peak 200 kW; clear-sky half-sine 06:00–18:00 (upper bound, no cloud)
Wind-derived power	Mean 300 kW before truncation (realised mean 277 kW in the reference realisation); AR(1) components 2 h / 35% and 10 min / 10%; truncated to 0–600 kW
Fuel cell	Rating 500 kW (fixed set-point) or 800 kW (load-following); idle floor 10% of rating; reference filter $\tau = 0.5$ h; η_{fc} from Eq. 5; $LHV_{H2} = 33.33$ kWh kg^{-1}
Battery	200 kWh (1000 kWh in S2); SOC window 10–90%; initial and target SOC 50%; 0.95 charge and discharge efficiency; 1C power limit; SOC gain 1 h^{-1}
Random numbers	Reference realisation: seed 42. Monte Carlo: 500 realisations, seeds 1000–1499

3.3 Scenarios and uncertainty analysis

Three scenarios are defined: S0, fixed 500 kW fuel-cell set-point with a 200 kWh battery; S1, load-following fuel cell rated at 800 kW with a 200 kWh battery; and S2, as S1 with a 1000 kWh battery. Each is run for the reference wind realisation and for 500 independent wind realisations. Sensitivity runs vary the mean wind power (100, 200 and 300 kW) and the fuel-cell rating (600, 800 and 1000 kW), and the battery capacity (100–2000 kWh). A 24 h no-wind stress case shows the firm-power requirement.

3.4 Hydrogen, cost and emission accounting

Onboard hydrogen storage volume is estimated from gravimetric densities of 70.8 kg m^{-3} for liquid hydrogen and 40 kg m^{-3} for 700 bar compressed gas, excluding tank structure and insulation (Züttel 2004). Hydrogen cost is illustrated with USD 4–6 per kg for renewable hydrogen, an order-of-magnitude figure that varies with location and electricity price (IEA 2023). As a reference, the same 24 MWh is supplied by a marine gas oil (MGO) engine of 45% efficiency, with a lower heating value of 11.86 kWh kg^{-1}, a CO_2 factor of 3.206 t per t fuel (IMO 2018) and an assumed illustrative price of USD 700 per t. Grey hydrogen is assumed to carry about 10 kg CO_2 per kg H_2. These accounting assumptions are indicative; they ignore capital cost, maintenance, fuel-cell replacement and upstream emissions of MGO, and mix system boundaries (tank-to-wake for MGO, well-to-tank for grey hydrogen). They are intended to show orders of magnitude only.

3.5 Software and use of AI tools

The model is implemented in Python 3 with NumPy and the script is supplied as Online Resource 1. An AI language model (Claude, Anthropic) was used to help restructure the manuscript, to draft and debug the simulation script, and to propose the control strategy; The authors reviewed and verified the code, results and text and takes full responsibility for the content.

4 Results

4.1 Reference and load-following configurations

Over 24 h the demand is 24,000 kWh. In the reference realisation the solar array delivers 1,528 kWh, only 6.4% of the daily demand, because the 200 kW peak is reached for a short period around noon (Fig. 2). Wind delivers 6,636 kWh (27.7%). Nominal power shares of 20% solar, 30% wind and 50% fuel cell sum to 100% only at solar noon and at mean wind; averaged over the day they sum to about 84%.

With the fixed 500 kW fuel-cell set-point (S0), the plant leaves 3,763 kWh unmet (15.7% of the daily demand) over 22.4 h, with a peak shortfall of 433 kW (Fig. 2a). The 200 kWh battery is exhausted within the first hour and cannot compensate: the average deficit is about 157 kW, and 200 kWh covers it for little more than an hour. With the load-following strategy and an 800 kW fuel cell (S1), the demand is met throughout the reference realisation (Fig. 2b). The fuel cell supplies 15,901 kWh (66.3%) at a mean output of 663 kW, the battery SOC stays between 11% and 72%, and the battery performs 2.4 equivalent full cycles per day.

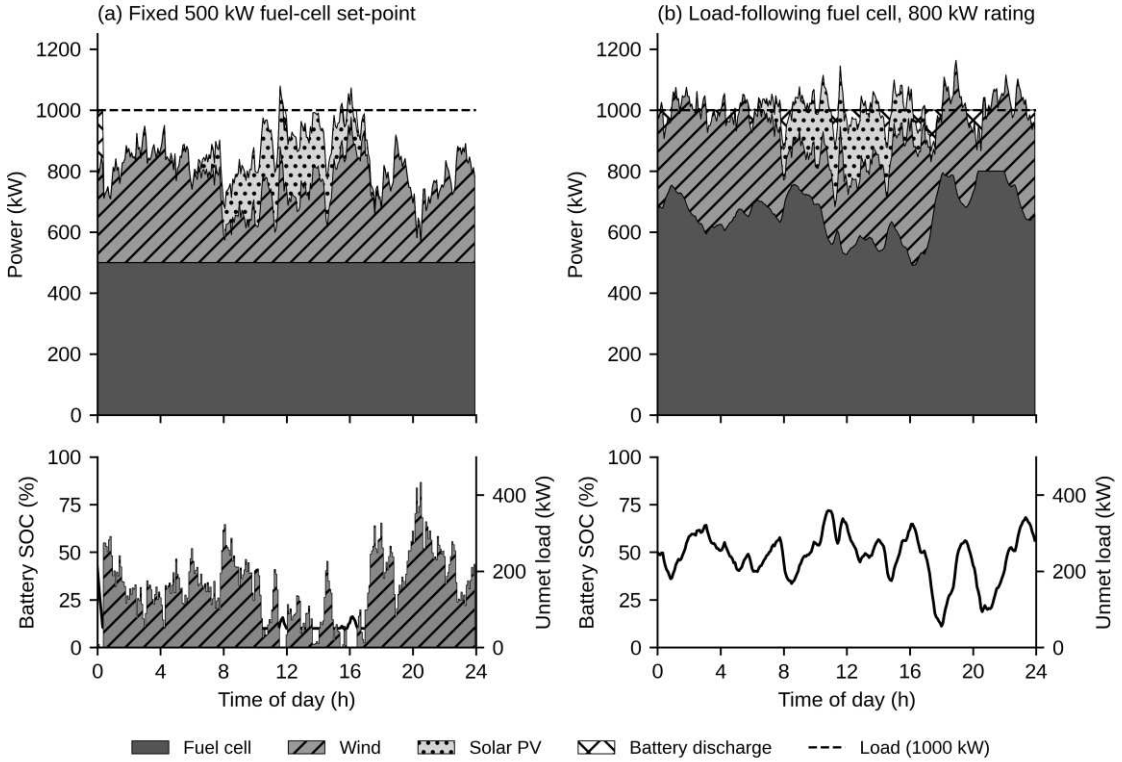


Fig. 2 Simulated 24 h operation for the reference wind realisation: **a** fixed 500 kW fuel-cell set-point (S0) and **b** load-following fuel cell rated at 800 kW (S1). Top, power contributions stacked against the 1000 kW demand

(dashed line); stacked totals above the line indicate surplus used to charge the battery. Bottom, battery state of charge (solid line, left axis) and unmet load (hatched area, right axis)

4.2 Uncertainty and sensitivity

A single wind realisation can hide failures. Across 500 realisations, the load-following plant with the 200 kWh battery (S1) shows no unmet load in 38% of cases, a mean shortfall of 77 kWh (0.32% of daily energy, standard deviation 130 kWh) and a 95th percentile of 317 kWh (Table 3). Raising the battery to 1000 kWh (S2) removes the shortfall in 96% of realisations. The fixed set-point plant (S0) fails in every realisation, with a mean shortfall of 3,276 kWh. Hydrogen use in S1 varies with the wind realisation, with a mean of 946 kg per day and a standard deviation of 67 kg.

Table 3 Daily energy balance and reliability metrics for the three scenarios (reference realisation unless stated)

Metric	S0: fixed 500 kW fuel cell, 200 kWh	S1: load-following 800 kW, 200 kWh	S2: load-following 800 kW, 1000 kWh
Solar share of demand (%)	6.4	6.4	6.4
Wind share of demand (%)	27.7	27.7	27.7
Fuel-cell share of demand (%)	50.0	66.3	66.3
Unmet energy (kWh)	3,763	0	0
Unmet energy (% of demand)	15.7	0.0	0.0
Peak unmet load (kW)	433	0	0
Battery SOC range (%)	10–42	11–72	42–54
Battery equivalent full cycles per day	0.5	2.4	0.5
Hydrogen use (kg per day)	783	996	996
Monte Carlo: mean unmet energy (kWh)	3,276	77	7
Monte Carlo: 95th percentile unmet energy (kWh)	4,687	317	0
Monte Carlo: realisations with no unmet load (%)	0	38	96

Monte Carlo statistics are from 500 wind realisations (Sect. 3.3). S0, S1 and S2 as defined in Sect. 3.3.

The sensitivity runs (Fig. 3, Table 4) show how the required fuel-cell rating depends on the wind resource. With the nominal wind contribution (about 28% of demand), an 800 kW fuel cell is sufficient in the reference realisation, whereas a 600 kW unit leaves 6.4% unmet. If the wind contribution falls to about 9% of demand, which is closer to typical wind-assist savings, an 800 kW unit leaves 5.3% unmet and a 1000 kW unit is required. In the 24 h no-wind stress case, an 800 kW fuel cell leaves 13.3% of the demand unmet, and a fuel cell rated at the full 1000 kW is needed to keep the ship moving, consuming 1,443 kg of hydrogen in the day. Compared with the reference case (996 kg), the solar and wind contribution therefore reduces hydrogen use by about 31%, but it does not reduce the rating of the firm power source unless the wind resource is guaranteed. Battery capacity beyond 200 kWh does not change the daily energy balance in the reference realisation; it only reduces shortfalls in unfavourable realisations (Table 3). A 100 kWh battery leaves 74 kWh unmet in the reference realisation.

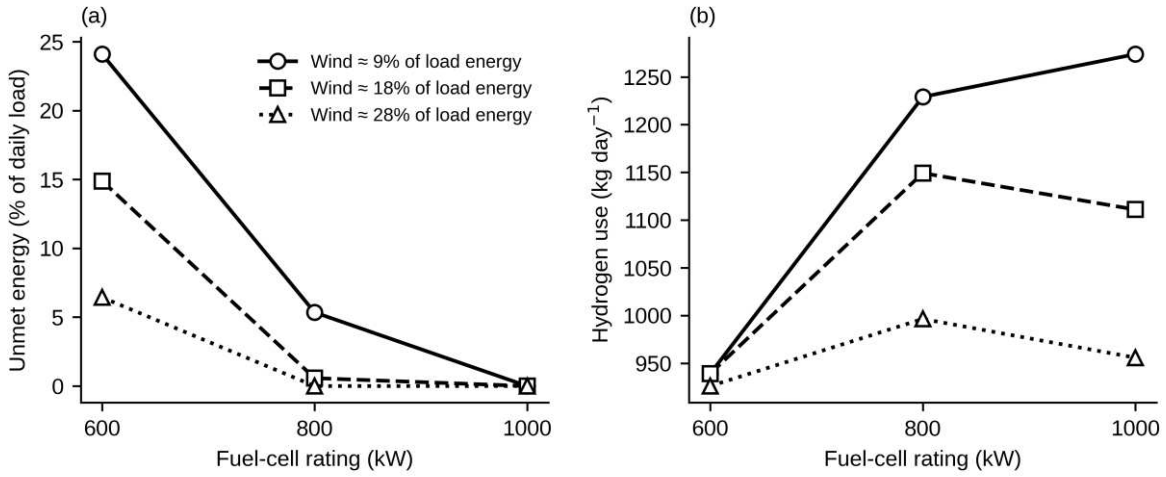


Fig. 3 Sensitivity of the load-following plant with a 200 kWh battery to fuel-cell rating and wind resource: **a** unmet energy as a percentage of the daily demand and **b** hydrogen use. Hydrogen use is only comparable between points with negligible unmet energy; at low ratings part of the demand is not served and hydrogen use is correspondingly lower

Table 4 Unmet energy (% of daily demand) / hydrogen use (kg per day) for different wind contributions and fuel-cell ratings (200 kWh battery, reference seed)

Wind share of demand (%)	Fuel cell 600 kW	Fuel cell 800 kW	Fuel cell 1000 kW
9.2	24.1 / 939	5.3 / 1,229	0.0 / 1,274
18.4	14.9 / 939	0.6 / 1,149	0.0 / 1,111
27.7	6.4 / 926	0.0 / 996	0.0 / 956

4.3 Hydrogen demand, storage, cost and emissions

The reference load-following plant (S1) consumes 996 kg of hydrogen per day. Storing one day of hydrogen requires about 14 m^3 as liquid hydrogen or 25 m^3 as 700 bar gas, before tank structure and insulation; a voyage of several days multiplies this volume accordingly. At USD 4–6 per kg the daily hydrogen cost is USD 4,000–6,000, against about USD 3,100 for the 4,500 kg of MGO that would deliver the same energy at an engine efficiency of 45% and an assumed price of USD 700 per t, that is roughly 1.3–1.9 times as much on a fuel-cost basis alone.

The MGO reference emits about 14.4 t of CO_2 per day at the funnel. The hybrid plant with renewable hydrogen has no operational CO_2 emissions. If the hydrogen were instead produced from natural gas without carbon capture, upstream emissions would be about 10.0 t of CO_2 per day, only about 31% below the MGO funnel emissions and not comparable on a like-for-like boundary. The environmental case for the plant therefore rests on the hydrogen source, as noted in Section 2.3. The solar array that supplies 6.4% of the daily energy requires about 1,250 m^2 of panel area at 20% module efficiency, 1000 W m^{-2} peak irradiance and a performance ratio of 0.8, which is comparable to the entire weather-deck area of a small ferry or coastal vessel.

5 Discussion

5.1 What the simulation shows

Three results are of general relevance. First, nominal power shares are not energy shares. A 200 kW PV array delivers about 6% of a 1000 kW demand over a day, and a plant specified as 20/30/50% by peak power cannot satisfy the demand with a constant 50% fuel-cell output (S0). Designs presented in terms of peak shares should therefore be accompanied by a daily energy balance. Second, the fuel cell must be dispatchable. Load-following operation with a filtered reference closes the gap, and the battery then serves mainly as a buffer that absorbs fluctuations and ramp-rate limits. Third, renewables reduce the energy drawn from the hydrogen store, by about 30% here, but not the firm capacity that must be installed unless the wind resource is guaranteed, which is not the case on most routes.

The comparison with the literature also shows that the nominal wind contribution of 30% is optimistic. Studies of rotor sails and kites report savings that vary strongly with route and ship type and are typically well below 30% (Traut et al. 2014; Chou et al. 2021). The sensitivity analysis (Table 4) covers contributions of 9–28% and shows that a plant sized for the optimistic case would be undersized in less favourable conditions.

5.2 Barriers to adoption

The results are consistent with the barriers identified in the review. Hydrogen storage volume is the first: about 14 m^3 per day of liquid hydrogen implies that voyages of several days need tanks that compete with cargo space, and 700 bar storage needs roughly twice that volume (Züttel 2004; van Biert et al. 2016). The second is cost, because hydrogen at USD 4–6 per kg raises fuel cost per unit energy well above that of MGO, while fuel cells and storage add capital cost. The third is infrastructure: few ports offer hydrogen bunkering, which restricts route flexibility. Fourth, regulation remains in flux, as discussed in Section 2.1, so that the future carbon price that would close part of the cost gap is not yet fixed. Finally, technological maturity of marine fuel-cell systems, in terms of durability, safety standards and class rules, is still evolving (van Biert et al. 2016; Elkafas et al. 2023).

5.3 Implications and research needs

For small and medium vessels with moderate power demand, short routes and access to a hydrogen supply, the hybrid architecture assessed here is technically feasible on the energy-balance level, with a fuel cell rated close to the full propulsion power, a modest battery for buffering, and wind and solar contributions that lower hydrogen consumption. For deep-sea shipping, the energy storage and power requirements are far larger and the options in Table 1 with higher volumetric energy density, such as ammonia and biofuels, remain relevant, while all-battery solutions are limited to specific routes even as battery costs fall (Kersey et al. 2022). Priority research needs are: (i) models with realistic variable load profiles and ship-specific resistance; (ii) validation against measured data from wind-assisted and fuel-cell vessels; (iii) lighter and cheaper hydrogen storage; (iv) fuel-cell durability under marine load

cycling; (v) energy-management strategies, including predictive control using weather routing; and (vi) techno-economic and life-cycle assessment including capital cost.

5.4 Limitations

The energy balance is a simplified, single-day model. Propulsion demand is constant, whereas real ship power varies roughly with the cube of speed and with sea state. Wind assistance is represented as an electrical-equivalent source with synthetic AR(1) fluctuations rather than as site-specific data or an aerodynamic model, and solar output is a clear-sky upper bound. Fuel-cell degradation, ramp limits other than the reference filter, thermal management, hydrogen boil-off and battery ageing are not modelled, and drivetrain losses are not included. The cost and emission figures are order-of-magnitude illustrations with several assumed parameters (Section 3.4). The literature review is narrative rather than a systematic review. The results should therefore be read as a design-level sizing study, and they have not been validated against measurements.

6 Conclusions

A harmonised comparison of nine propulsion energy options shows that the options with the lowest operational emissions currently face the greatest practical constraints, and that onboard solar and wind are best seen as supplements. An energy-balance analysis of a renewable hybrid plant for a 1000 kW constant demand leads to four conclusions. (1) Nominal power shares overstate the contribution of renewables: solar supplied 6% and wind 28% of the daily energy. (2) A fixed fuel-cell set-point at 50% of the demand leaves 15.7% of the energy unmet; a load-following 800 kW fuel cell with a 200 kWh battery meets the demand in the reference realisation, and a larger battery is needed to cover unfavorable wind realizations. (3) Onboard renewables reduce hydrogen consumption by about 30%, but a fuel cell sized near the full load is still needed when wind cannot be guaranteed. (4) Hydrogen supply, about 1,000 kg per day, with a storage volume of 14–25 m^3 per day and a fuel cost around 1.3–1.9 times that of MGO in the assumed conditions, rather than generating capacity, is the main practical barrier. Future work should extend the model to variable load and measured weather data, add degradation and cost models, and validate against operating vessels.

Statements and Declarations

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Competing interests: The author has no relevant financial or non-financial interests to disclose.

Ethics approval: Not applicable.

Author contributions: Both the authors conceived the study, performed the literature review and analysis, and wrote the manuscript equally.

Data availability: All data analyzed in this study were generated by the simulation script provided as Online Resource 1 and can be reproduced by running it with the random seeds stated in Table 2. Literature values are taken from the publications cited.

Code availability The Python script used for the simulations is provided as Online Resource 1. [https://github.com/mabdullahkhan/JOEME]

References

Atchison J (2026) MEPC84: support for Net Zero Framework stabilizes ahead of key decision point in late 2026. Ammonia Energy Association. https://ammoniaenergy.org/articles/mepc84-support-for-net-zero-framework-stabilizes-ahead-of-key-decision-point-in-late-2026/. Accessed 6 Oct 2026

Balcombe P, Brierley J, Lewis C, Skatvedt L, Speirs J, Hawkes A, Staffell I (2019) How to decarbonise international shipping: options for fuels, technologies and policies. *Energy Convers Manag* 182:72–88. https://doi.org/10.1016/j.enconman.2018.12.080

Ball M, Weeda M (2015) The hydrogen economy – vision or reality? *Int J Hydrogen Energy* 40:7903–7919. https://doi.org/10.1016/j.ijhydene.2015.04.032

Bouman EA, Lindstad E, Rialland AI, Strømman AH (2017) State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review. *Transp Res D Transp Environ* 52:408–421. https://doi.org/10.1016/j.trd.2017.03.022

Brynolf S, Fridell E, Andersson K (2014) Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. *J Clean Prod* 74:86–95. https://doi.org/10.1016/j.jclepro.2014.03.052

Chou T, Kosmas V, Acciaro M, Renken K (2021) A comeback of wind power in shipping: an economic and operational review on the wind-assisted ship propulsion technology. *Sustainability* 13:1880, https://doi.org/10.3390/su13041880

DNV (2026) IMO MEPC 84: revisiting the net-zero framework. https://www.dnv.com/news/2026/imo-mepc-84-revisiting-the-net-zero-framework/. Accessed 6 Oct 2026

Elkafas, A. G., Rivarolo, M., Gadducci, E., Magistri, L., & Massardo, A. F. (2023). Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives. Processes, 11(1), 97. https://doi.org/10.3390/pr11010097

Faber J, Hanayama S, Zhang S et al (2020) Fourth IMO greenhouse gas study 2020. International Maritime Organization, London

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., & Murphy, J. D. (2021). Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Advances in Applied Energy, 1, 100008. https://doi.org/10.1016/j.adapen.2021.100008

Hansson J, Månsson S, Brynolf S, Grahn M (2019) Alternative marine fuels: prospects based on multi-criteria decision analysis involving Swedish stakeholders. *Biomass Bioenergy* 126:159–173. https://doi.org/10.1016/j.biombioe.2019.05.008

Hirdaris, S. E., Cheng, Y. F., Shallcross, P., Bonafoux, J., Carlson, D., Prince, B., & Sarris, G. A. (2014). Considerations on the potential use of Nuclear Small Modular Reactor (SMR)

technology for merchant marine propulsion. Ocean Engineering, 79, 101–130. https://doi.org/10.1016/j.oceaneng.2013.10.015

IEA (2023) Global hydrogen review 2023. International Energy Agency, Paris

IMO (2008) Resolution MEPC.176(58): amendments to the annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973 (revised MARPOL Annex VI). International Maritime Organization, London

IMO (2018) Resolution MEPC.308(73): 2018 guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships. International Maritime Organization, London

IMO (2023) Resolution MEPC.377(80): 2023 IMO strategy on reduction of GHG emissions from ships. International Maritime Organization, London

Inal, O. B., Zincir, B., & Deniz, C. (2022). Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia. International Journal of Hydrogen Energy, 47(45), 19888–19900. https://doi.org/10.1016/j.ijhydene.2022.01.189

Kersey, J., Popovich, N. D., & Phadke, A. A. (2022). Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping. Nature Energy, 7(7), 664–674. https://doi.org/10.1038/s41560-022-01065-y

Kobayashi, H., Hayakawa, A., Somarathne, K. D. K. A., & Okafor, E. C. (2019). Science and technology of ammonia combustion. Proceedings of the Combustion Institute, 37(1), 109–133. https://doi.org/10.1016/j.proci.2018.09.029

Kobougias, I., Tatakis, E., & Prousalidis, J. (2013). PV Systems Installed in Marine Vessels: Technologies and Specifications. Advances in Power Electronics, 2013, 1–8. https://doi.org/10.1155/2013/831560

Law, L., Foscoli, B., Mastorakos, E., & Evans, S. (2021). A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost. Energies, 14(24), 8502. https://doi.org/10.3390/en14248502

Lloyd's Register, UMAS (2020) Techno-economic assessment of zero-carbon fuels. Lloyd's Register and University Maritime Advisory Services, London

Mallouppas, G., & Yfantis, E. Ar. (2021). Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals. Journal of Marine Science and Engineering, 9(4), 415. https://doi.org/10.3390/jmse9040415

Pavlenko N, Comer B, Zhou Y, Clark N, Rutherford D (2020) The climate implications of using LNG as a marine fuel. ICCT Working Paper 2020-02. International Council on Clean Transportation, Washington DC

Phillips OM (1962) The prospects for magnetohydrodynamic ship propulsion. *J Ship Res* 5(4):43–51

Traut, M., Gilbert, P., Walsh, C., Bows, A., Filippone, A., Stansby, P., & Wood, R. (2014). Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. Applied Energy, 113, 362–372. https://doi.org/10.1016/j.apenergy.2013.07.026

Ushakov S, Stenersen D, Einang PM (2019) Methane slip from gas fuelled ships: a comprehensive summary based on measurement data. *J Mar Sci Technol* 24:1308–1325. https://doi.org/10.1007/s00773-018-00622-z

Valera-Medina A, Xiao H, Owen-Jones M, David WIF, Bowen PJ (2018) Ammonia for power. *Prog Energy Combust Sci* 69:63–102. https://doi.org/10.1016/j.pecs.2018.07.001

van Biert L, Godjevac M, Visser K, Aravind PV (2016) A review of fuel cell systems for maritime applications. *J Power Sources* 327:345–364. https://doi.org/10.1016/j.jpowsour.2016.07.007

Züttel A (2004) Hydrogen storage methods. *Naturwissenschaften* 91:157–172. https://doi.org/10.1007/s00114-004-0516-x