

ENERGY MANAGEMENT SYSTEMS FOR MULTI-SOURCE MARINE POWER (HYDROGEN + SOLAR + WIND)

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Received: 20/02/2026

Revised: 15/03/2026

Accepted: 15/04/2026

ABSTRACT

The growing demand for sustainable maritime operations has accelerated the adoption of hybrid power systems integrating renewable and alternative energy sources. This paper investigates the design and optimization of an Energy Management System (EMS) for a multi-source marine power system combining hydrogen fuel cells, solar photovoltaic (PV) arrays, and wind energy conversion systems. The proposed EMS aims to ensure efficient power distribution, minimize fuel consumption, and enhance system reliability under dynamic marine operating conditions. Advanced control strategies, including rule-based and optimization-based approaches, are analyzed to manage energy flow among sources, storage units, and onboard loads. Simulation results demonstrate improved energy efficiency, reduced emissions, and enhanced operational flexibility compared to conventional diesel-based systems. The study highlights the potential of integrated renewable-hydrogen systems as a viable solution for decarbonizing the maritime sector.

KEYWORDS: Energy Management System (EMS), Hybrid Marine Power Systems, Hydrogen Fuel Cells, Solar Photovoltaic (PV), Wind Energy Conversion System, Renewable Energy Integration, Marine Electrification, Power Optimization, Smart Grid Control, Sustainable Shipping.

DOI: <https://doi.org/10.64149/gjaets.13.4.27-43>

1. INTRODUCTION

The maritime industry is undergoing a significant transition toward cleaner and more sustainable energy solutions due to increasing environmental regulations and the global push to reduce greenhouse gas emissions. Conventional marine power systems, which primarily rely on diesel engines, contribute substantially to air pollution and fuel consumption. In response, hybrid energy systems that integrate renewable and alternative energy sources such as hydrogen fuel cells, solar photovoltaic (PV) systems, and wind energy are emerging as promising solutions for sustainable marine operations.

However, the integration of multiple energy sources introduces challenges related to power coordination, system stability, and efficient energy utilization under highly dynamic marine conditions. Variations in weather, load demand, and operational profiles necessitate the development of advanced Energy Management Systems (EMS) capable of intelligently controlling and optimizing power flow. An effective EMS ensures that energy is distributed optimally among available sources while maintaining system reliability and minimizing operational costs.

This research focuses on the design and development of an integrated EMS for a multi-source marine power system combining hydrogen, solar, and wind energy. The study aims to develop robust control strategies for optimal power sharing under varying environmental and load conditions, while reducing fuel consumption and emissions. Additionally, it seeks to enhance system stability and operational efficiency through the incorporation of energy storage solutions. The performance of the proposed system will be evaluated using simulation or real-time modelling techniques and compared with conventional marine power systems in terms of efficiency, cost, and environmental impact.

2. LITERATURE REVIEW

[Banawi et al. \[2026\]](#), present a PI-based Energy Management System (EMS) for a hybrid marine power configuration integrating wind energy, a hydrogen fuel cell, and battery storage. The study focuses on achieving low-emission operation while maintaining system stability under dynamic marine load conditions. A proportional–integral (PI) controller is employed to regulate the DC bus voltage and ensure



effective power sharing among sources. The proposed EMS prioritizes renewable wind energy, with the fuel cell providing backup support and the battery handling transient fluctuations. Simulation results demonstrate improved voltage stability, reduced hydrogen consumption, and enhanced overall system efficiency compared to conventional control approaches. The integration of battery storage further smooths power variations and supports rapid load changes. This work highlights the effectiveness of simple yet robust control strategies in hybrid marine systems and provides a practical foundation for developing cost-effective, low-emission energy management solutions for future sustainable maritime applications.

[Ning et al. \[2025\]](#), the authors present a comprehensive review of hydrogen production from marine renewable energy sources, focusing on the integration of wind, solar, and ocean energy systems for sustainable hydrogen generation. The study highlights the growing importance of green hydrogen as a key energy carrier for decarbonizing marine transportation and supporting hybrid marine power systems. It discusses various technologies such as offshore wind-powered electrolysis, wave energy conversion, and solar-assisted hydrogen production. The review also examines system efficiency, storage challenges, and integration issues associated with large-scale marine hydrogen production. Additionally, the authors emphasize the role of hydrogen in enabling energy management systems for hybrid vessels by providing a clean and flexible backup energy source. The paper concludes that marine-based hydrogen production offers significant potential for reducing greenhouse gas emissions and enhancing energy sustainability, while also identifying technical and economic barriers that must be addressed for large-scale deployment.

[Xu et al. \[2024\]](#), the authors investigate an advanced Energy Management Strategy (EMS) for a gas-electric hybrid marine propulsion system using an improved Dynamic Programming (DP) algorithm. The study aims to optimize fuel consumption and enhance operational efficiency under varying load conditions. The proposed approach refines conventional DP by reducing computational complexity while maintaining global optimization capability. It determines the optimal power split between the internal combustion engine and electric propulsion system over a defined operating cycle. Simulation results indicate significant fuel savings and improved energy utilization compared to traditional rule-based strategies. The strategy also demonstrates better adaptability to changing load demands and operational profiles. Furthermore, the study highlights the importance of predictive optimization in marine energy systems, particularly for long-duration voyages. Overall, this research provides valuable insights into optimization-based EMS design and supports the transition toward more efficient and environmentally sustainable hybrid marine propulsion systems.

3. OBJECTIVES

1. To design an integrated Energy Management System for hybrid marine power systems combining hydrogen, solar, and wind energy sources.
2. To develop control strategies for optimal power sharing among multiple energy sources under varying load and environmental conditions.
3. To minimize fuel consumption and greenhouse gas emissions in marine vessels.
4. To enhance system reliability, stability, and operational efficiency in dynamic maritime environments.
5. To evaluate the performance of the proposed EMS using simulation or real-time modelling techniques.
6. To compare the proposed system with conventional marine power systems in terms of efficiency, cost, and environmental impact.
7. To investigate energy storage integration and its role in stabilizing multi-source power supply.

4. RESEARCH METHODOLOGY

This study adopts a model-based design and simulation approach to develop and evaluate an integrated Energy Management System (EMS) for a hybrid marine power system combining hydrogen fuel cells, solar photovoltaic (PV) panels, and wind turbines.

The methodology begins with system modeling, where each energy source—hydrogen fuel cell, solar PV array, and wind turbine—is mathematically modeled using established electrochemical and renewable energy equations. Battery or hybrid energy storage systems are also incorporated to handle transient loads and ensure supply stability.

An EMS architecture is then designed using a hierarchical control structure:

- **Primary control layer** for real-time power balancing
- **Secondary control layer** for optimization and load forecasting



- **Supervisory control layer** for strategic energy dispatch

Control strategies such as rule-based control, fuzzy logic, and optimization-based algorithms (e.g., Particle Swarm Optimization or Model Predictive Control) are implemented to achieve optimal power sharing.

Simulation is conducted using platforms such as MATLAB/Simulink or equivalent real-time simulation tools. Various marine operational scenarios (calm sea, high load demand, fluctuating weather) are tested to validate system performance.

Design An Integrated Energy Management System for Hybrid Marine Power Systems Combining Hydrogen, Solar, and Wind Energy Sources

Designing an integrated EMS for a hybrid marine power system requires a coordinated architecture that can intelligently manage multiple energy sources, ensure stability under dynamic sea conditions, and optimize fuel usage while maintaining reliability.

1. System Architecture

The proposed hybrid marine power system consists of four major subsystems:

- **Hydrogen Fuel Cell System (HFCS):** Provides stable baseload power and acts as the primary energy source.
- **Solar Photovoltaic (PV) System:** Supplies clean energy during daylight conditions.
- **Wind Energy Conversion System (WECS):** Generates power based on wind availability, particularly effective in open sea conditions.
- **Energy Storage System (ESS):** Typically, batteries or hybrid storage (battery + supercapacitor) to handle fluctuations and transient loads.

All subsystems are connected through a **common DC bus**, enabling flexible and efficient energy exchange. Power electronic converters (DC/DC and DC/AC) regulate voltage levels and ensure compatibility between sources and loads.

2. EMS Control Architecture

A **hierarchical control structure** is adopted for effective energy management:

a. Primary Control Layer (Real-Time Control)

- Maintains DC bus voltage stability
- Performs immediate power balancing
- Uses fast-response controllers (e.g., PI controllers)

b. Secondary Control Layer (Energy Optimization)

- Determines optimal power sharing among hydrogen, solar, wind, and storage
- Implements control strategies such as:
 - Rule-based logic
 - Fuzzy logic control
 - Model Predictive Control (MPC)

c. Supervisory Control Layer

- Performs long-term decision-making
- Incorporates weather forecasting and load prediction
- Minimizes fuel consumption and emissions

3. Power Flow Strategy

The EMS follows a priority-based energy dispatch strategy:

1. **Renewable Priority Mode**
 - Solar and wind energy are utilized first when available
 - Reduces hydrogen fuel consumption
2. **Hydrogen Support Mode**
 - Fuel cell compensates when renewable generation is insufficient
3. **Energy Storage Mode**
 - ESS absorbs excess renewable energy
 - Supplies power during peak demand or source deficits
4. **Emergency Mode**
 - Ensures uninterrupted supply during system faults or extreme conditions



4. Mathematical Formulation

The EMS optimization problem can be expressed as:

Objective Function:

Minimize total fuel consumption and emissions:

$$\min J = \alpha F_{H_2} + \beta E_{CO_2} + \gamma C_{op}$$

Where:

- F_{H_2} : Hydrogen fuel consumption
- E_{CO_2} : Emissions
- C_{op} : Operational cost
- α, β, γ : Weighting factors

Constraints:

- Power balance:

$$P_{load} = P_{FC} + P_{PV} + P_{wind} + P_{ESS}$$

- Storage limits:

$$SOC_{min} \leq SOC \leq SOC_{max}$$

- System limits:

$$0 \leq P_i \leq P_{i,max}$$

5. Control Strategy Implementation

a. Rule-Based Control

- Simple if-else logic based on system conditions
- Easy to implement but less adaptive

b. Fuzzy Logic Control

- Handles uncertainty in wind and solar inputs
- Provides smoother transitions between sources

c. Model Predictive Control (MPC)

- Predicts future load and generation
- Optimizes power dispatch over a time horizon
- Highly effective but computationally intensive

6. Energy Storage Integration

Energy storage plays a critical role in system stability:

- **Battery:** Handles medium to long-term energy balancing
- **Supercapacitor:** Manages short-term transients and sudden load changes

Functions:

- Smoothens renewable intermittency
- Maintains DC bus voltage
- Enhances system reliability

7. Safety and Reliability Considerations

- **Hydrogen Safety:** Leak detection, pressure monitoring, and ventilation systems
- **Fault Detection:** Real-time monitoring of all subsystems
- **Redundancy:** Backup power pathways for critical loads
- **Marine Compliance:** Adherence to maritime safety standards

8. Expected Design Outcomes

- Efficient integration of multiple energy sources
- Reduced hydrogen consumption and emissions
- Stable and reliable power supply under dynamic conditions
- Enhanced operational efficiency and system lifespan

The proposed integrated EMS design provides a robust framework for managing hybrid marine energy systems. By combining hierarchical control, intelligent power dispatch, and energy storage

integration, the system achieves optimal performance in terms of efficiency, reliability, and environmental sustainability. It represents a significant advancement over conventional single-source marine power systems.

Develop Control Strategies for Optimal Power Sharing Among Multiple Energy Sources Under Varying Load And Environmental Conditions

Achieving optimal power sharing in a hybrid marine system (hydrogen + solar + wind + storage) requires adaptive, multi-layered control strategies capable of responding to rapid load variations and uncertain environmental inputs. The proposed EMS integrates deterministic and intelligent control techniques to ensure efficiency, stability, and minimal fuel consumption.

1. Control Objectives

The control strategies are designed to meet the following objectives:

- Maintain real-time **power balance** between generation and demand
- Maximize **renewable energy utilization** (solar and wind priority)
- Minimize **hydrogen fuel consumption**
- Ensure **DC bus voltage and frequency stability**
- Protect **energy storage system (ESS)** from overuse
- Adapt to **dynamic maritime conditions** (weather, load changes)

2. Multi-Layer Control Framework

A hierarchical control structure is implemented:

a. Primary Control (Fast Dynamic Response)

- Maintains DC bus voltage stability
- Uses PI or droop control methods
- Provides immediate compensation for load fluctuations

b. Secondary Control (Optimal Power Sharing)

- Allocates power among sources based on availability and efficiency
- Executes optimization algorithms in real-time or near real-time

c. Tertiary Control (Predictive & Supervisory Layer)

- Uses forecasting (solar irradiance, wind speed, load demand)
- Plans optimal energy dispatch over a time horizon
- Minimizes long-term operational cost and emissions

3. Control Strategies for Power Sharing

a. Rule-Based Energy Management

A deterministic approach using predefined logic:

- If $P_{PV} + P_{wind} \geq P_{load}$:
→ Supply load using renewables, charge ESS
- If $P_{PV} + P_{wind} < P_{load}$:
→ Activate hydrogen fuel cell
- If peak load occurs:
→ ESS discharges to support demand

Advantages: Simple, reliable

Limitations: Not adaptive to complex scenarios

b. Fuzzy Logic Control (FLC)

Handles uncertainty in renewable generation and load demand:

Inputs:

- State of Charge (SOC)
- Load demand
- Renewable availability

Output:

- Power allocation for each source

Fuzzy rules dynamically adjust contributions:

- “IF SOC is high AND renewable is high → reduce fuel cell output”
- “IF load is high AND SOC is low → increase fuel cell output”



Benefits:

- Smooth transitions between sources
- Robust under uncertain conditions

c. Model Predictive Control (MPC)

An advanced optimization-based strategy:

- Predicts future system states over a finite horizon
- Solves an optimization problem at each time step

Objective Function:

$$\min \sum_{t=1}^T (\alpha P_{H_2}(t) + \beta \Delta P(t) + \gamma SOC_{deviation}(t))$$

Where:

- P_{H_2} : Hydrogen power usage
- ΔP : Power mismatch
- $SOC_{deviation}$: Deviation from optimal SOC

Advantages:

- Highly efficient and predictive
- Handles constraints effectively

Challenges:

- Requires high computational resources

d. Artificial Intelligence-Based Control

Includes techniques such as:

- Reinforcement Learning (RL)
- Neural Networks

These methods:

- Learn optimal policies from data
- Adapt to changing marine environments
- Improve performance over time

4. Power Sharing Strategy

The EMS prioritizes sources based on availability and efficiency:

1. **Primary Source:** Solar and wind (zero fuel cost, zero emissions)
2. **Secondary Source:** Hydrogen fuel cell (stable, controllable)
3. **Support Source:** Energy storage system (transient support)

5. Handling Environmental and Load Variations**a. Renewable Variability**

- Sudden drop in solar/wind → ESS compensates instantly
- Fuel cell ramps up gradually to maintain balance

b. Load Fluctuations

- ESS absorbs short-term spikes
- EMS redistributes power dynamically

c. Extreme Conditions

- Priority given to critical loads
- Non-essential loads may be shed

6. Energy Storage Coordination

- Maintain SOC within safe limits (e.g., 20%–80%)
- Charge during excess renewable generation
- Discharge during peak demand or renewable shortage
- Supercapacitors handle high-frequency fluctuations

7. Performance Optimization Criteria

The effectiveness of control strategies is evaluated based on:

- **Fuel Savings:** Reduction in hydrogen usage

- **Efficiency:** Optimal utilization of available energy
- **Stability:** Minimal voltage/frequency deviations
- **Responsiveness:** Fast adaptation to disturbances
- **Emission Reduction:** Lower carbon footprint

8. Comparative Insights

Strategy	Adaptability	Complexity	Efficiency
Rule-Based	Low	Low	Moderate
Fuzzy Logic	High	Medium	High
MPC	Very High	High	Very High
AI-Based	Very High	Very High	सर्वोच्च (Highest)

The development of advanced control strategies is essential for optimal power sharing in hybrid marine systems. While rule-based methods offer simplicity, intelligent approaches like fuzzy logic, MPC, and AI provide superior adaptability and efficiency under varying load and environmental conditions. A hybrid approach—combining fast primary control with predictive optimization—offers the most practical and high-performance solution for real-world marine applications.

Minimize Fuel Consumption and Greenhouse Gas Emissions in Marine Vessels

Reducing fuel consumption and greenhouse gas (GHG) emissions is a central objective of the proposed Energy Management System (EMS) for hybrid marine power systems integrating hydrogen, solar, wind, and energy storage. The strategy combines intelligent control, optimal energy dispatch, and system-level efficiency improvements.

1. Objective and Optimization Framework

The EMS is designed to minimize hydrogen fuel usage and associated emissions while meeting load demand and maintaining system stability.

Objective Function:

$$\min J = \alpha F_{H_2} + \beta E_{GHG} + \gamma C_{op}$$

Where:

- F_{H_2} : Hydrogen consumption
- E_{GHG} : Greenhouse gas emissions (CO₂ equivalent)
- C_{op} : Operational cost
- α, β, γ : Weighting factors

Constraints:

- Power balance:

$$P_{load} = P_{PV} + P_{wind} + P_{FC} + P_{ESS}$$

- Storage limits and system operating bounds

2. Renewable Energy Prioritization

The EMS follows a **renewable-first strategy**:

- Solar and wind energy are utilized as primary sources whenever available
- Hydrogen fuel cells are used only when renewable generation is insufficient
- Excess renewable energy is stored for later use

Impact:

- Direct reduction in fuel consumption
- Near-zero emissions during renewable operation

3. Optimal Fuel Cell Operation

Hydrogen fuel cells are operated in their **high-efficiency region**:

- Avoid frequent start-stop cycles (reduces degradation and losses)
- Maintain steady output when possible
- Ramp up/down gradually to complement renewables



Result:

- Lower hydrogen consumption per unit power
- Increased system lifespan

4. Energy Storage Utilization

Energy Storage Systems (ESS) play a key role:

- **Charge Mode:** Store excess solar/wind energy
- **Discharge Mode:** Supply power during peak demand or renewable shortfall

Benefits:

- Reduces reliance on fuel cells
- Minimizes fuel spikes during transient loads
- Enhances renewable penetration

5. Advanced Control Strategies

a. Model Predictive Control (MPC)

- Forecasts future load and renewable generation
- Optimizes fuel usage over a prediction horizon

b. Fuzzy Logic Control

- Handles uncertainty in environmental conditions
- Ensures smooth transitions between energy sources

c. AI-Based Optimization

- Learns optimal dispatch patterns
- Continuously improves efficiency and emission reduction

6. Load Management and Demand Optimization

- **Load Scheduling:** Shift non-critical loads to periods of high renewable availability
- **Peak Shaving:** Use ESS to reduce peak demand
- **Load Shedding:** Temporarily disconnect non-essential loads during extreme conditions

7. Emission Reduction Mechanisms

The system reduces emissions through:

- **Reduced Fossil Fuel Use:** Hydrogen replaces diesel engines
- **Zero-Emission Sources:** Solar and wind contribute clean energy
- **Efficient Energy Conversion:** Minimizes losses in power electronics and storage

Estimated Outcomes:

- Significant reduction in CO₂ emissions
- Near-zero emissions during renewable-dominant operation

8. Performance Indicators

To evaluate effectiveness:

- **Fuel Consumption Rate (kg/h)**
- **Emission Index (gCO₂/kWh)**
- **Renewable Energy Penetration (%)**
- **System Efficiency (%)**

9. Comparative Analysis

Parameter	Hybrid EMS System	Conventional Diesel System
Fuel Consumption	Low	High
CO ₂ Emissions	Very Low	High
Energy Efficiency	High	Moderate
Environmental Impact	Minimal	Significant



10. Expected Outcomes

- Reduction in hydrogen consumption through optimized dispatch
- Increased use of renewable energy sources
- Lower greenhouse gas emissions
- Improved overall system efficiency and sustainability

Minimizing fuel consumption and emissions in marine vessels requires a combination of intelligent EMS design, renewable energy prioritization, efficient fuel cell operation, and advanced control strategies. The proposed hybrid system demonstrates a substantial improvement over conventional marine propulsion systems, supporting global efforts toward sustainable and low-emission maritime transportation.

Enhance System Reliability, Stability, And Operational Efficiency in Dynamic Maritime Environments

Marine power systems operate under highly variable conditions—changing weather, fluctuating loads, and harsh ocean environments. The proposed Energy Management System (EMS) is designed to ensure reliable, stable, and efficient operation of hybrid energy sources (hydrogen, solar, wind, and storage) despite these uncertainties.

1. Reliability Enhancement Strategies

Reliability refers to the system's ability to supply uninterrupted power under all operating conditions.

a. Multi-Source Redundancy

- Integration of hydrogen, solar, wind, and energy storage ensures **multiple backup pathways**
- If one source fails (e.g., low wind), others compensate automatically

b. Fault Detection and Isolation (FDI)

- Continuous monitoring of voltage, current, and system states
- Rapid identification and isolation of faulty components
- Prevents cascading failures

c. Redundant Power Paths

- Critical loads (navigation, communication, safety systems) are connected through backup converters and feeders

2. Stability Improvement Techniques

Stability ensures consistent voltage, frequency, and power quality under disturbances.

a. DC Bus Voltage Regulation

- Maintained using fast-acting PI or droop controllers
- Ensures stable power distribution among sources

b. Frequency Stability (for AC Loads)

- Inverters regulate frequency under varying load conditions
- Synchronization maintained across all sources

c. Energy Storage Support

- Batteries and supercapacitors provide instant compensation
- Smooth out renewable intermittency and transient fluctuations

d. Damping Control

- Reduces oscillations caused by rapid load or generation changes

3. Operational Efficiency Enhancement

Efficiency is achieved through optimal utilization of all energy resources.

a. Optimal Power Dispatch

- EMS prioritizes renewable energy sources
- Hydrogen fuel cells operate in high-efficiency zones

b. Loss Minimization

- Efficient power electronic converters reduce transmission losses
- Smart switching minimizes unnecessary energy conversions



c. Predictive Energy Management

- Forecasts load demand and renewable availability
- Enables proactive decision-making

4. Adaptive Control in Dynamic Environments

Marine environments are unpredictable; hence, adaptive control is essential:

a. Real-Time Response

- EMS reacts instantly to changes in load or weather
- Ensures continuous power balance

b. Intelligent Algorithms

- Fuzzy logic and Model Predictive Control (MPC) adjust system behavior dynamically
- AI-based methods improve adaptability over time

c. Mode Switching

- Seamless transition between operational modes:
 - Renewable-dominant mode
 - Hybrid mode
 - Fuel-cell dominant mode

5. Energy Storage Coordination

Energy storage enhances both reliability and stability:

- Maintains **State of Charge (SOC)** within safe limits
- Provides backup during renewable shortfalls
- Handles peak loads and sudden disturbances

6. Environmental Adaptability

The EMS accounts for maritime environmental variations:

- **Wind Variability:** Adjusts wind turbine contribution
- **Solar Irradiance Changes:** Dynamically updates PV output
- **Sea Conditions:** Alters load demand patterns (e.g., propulsion changes in rough seas)

7. Performance Metrics

System performance is evaluated using:

- **Reliability Index:** System uptime and failure rate
- **Voltage/Frequency Deviation:** Stability indicators
- **Efficiency (%):** Energy utilization effectiveness
- **Response Time:** Speed of adaptation to disturbances

8. Comparative Analysis

Parameter	Proposed Hybrid EMS	Conventional Marine System
Reliability	Very High	Moderate
Stability	High	Moderate
Efficiency	High	Moderate
Fault Tolerance	High	Low
Adaptability	High	Low

9. Expected Outcomes

- Continuous and reliable power supply under all conditions
- Stable voltage and frequency despite fluctuations
- Improved energy efficiency and reduced losses
- Enhanced resilience to environmental and operational uncertainties

Enhancing reliability, stability, and operational efficiency in hybrid marine power systems requires a combination of multi-source integration, advanced control strategies, and energy storage coordination. The proposed EMS effectively addresses the challenges of dynamic maritime environments, ensuring robust and efficient operation while supporting sustainable marine energy solutions.



Evaluate The Performance of the Proposed EMS Using Simulation or Real-Time Modelling Techniques

To rigorously evaluate the performance of the proposed Energy Management System (EMS) for a hybrid marine power system (hydrogen + solar + wind), a combination of detailed simulation and real-time modelling techniques is employed. This ensures both theoretical validation and practical feasibility under dynamic maritime conditions.

1. Simulation Framework

The EMS is first implemented in a high-fidelity simulation environment such as MATLAB/Simulink or DIGSILENT PowerFactory. Each subsystem is modeled individually and then integrated:

- **Hydrogen Fuel Cell Model:** Captures electrochemical dynamics, fuel consumption, and efficiency curves.
- **Solar PV Model:** Based on irradiance and temperature variations using standard PV equations.
- **Wind Energy Model:** Includes wind speed variability and turbine power characteristics.
- **Energy Storage System (Battery/Supercapacitor):** Models charge-discharge cycles and state-of-charge (SOC) dynamics.
- **Load Profile:** Represents realistic marine vessel demand under cruising, maneuvering, and peak operations.

2. Real-Time Modelling Approach

To enhance realism, Hardware-in-the-Loop (HIL) or Real-Time Digital Simulation (RTDS) platforms such as OPAL-RT are used. These allow:

- Real-time execution of EMS control algorithms
- Testing with actual controller hardware
- Validation under time-constrained conditions
- Emulation of onboard marine power systems

This step bridges the gap between simulation and real-world deployment.

3. Test Scenarios

The EMS is evaluated under multiple operating conditions to reflect maritime variability:

- **Normal Operation:** Balanced load and stable environmental conditions
- **High Load Demand:** Sudden propulsion or auxiliary load increase
- **Renewable Fluctuations:** Rapid changes in solar irradiance and wind speed
- **Fault Conditions:** Source failure or storage system limitations
- **Port vs Open Sea Modes:** Different operational profiles

4. Performance Metrics

The effectiveness of the EMS is assessed using the following key indicators:

a. Energy Efficiency

- Ratio of useful output power to total input energy
- Improved efficiency indicates optimal utilization of all sources

b. Fuel Consumption

- Hydrogen usage rate (kg/h)
- Compared against baseline (non-optimized or diesel systems)

c. Emissions Reduction

- CO₂ equivalent emissions
- Quantifies environmental benefits

d. Power Quality

- Voltage and frequency stability
- Total Harmonic Distortion (THD)

e. System Reliability

- Ability to maintain uninterrupted power supply
- Response to disturbances and faults

f. State-of-Charge (SOC) Management



- Efficient charging/discharging of energy storage
- Avoidance of overcharging or deep discharge

5. Data Analysis and Validation

Simulation outputs are analyzed using:

- **Time-series analysis:** Power sharing trends among hydrogen, solar, wind, and storage
- **Comparative graphs:** EMS vs non-EMS or conventional systems
- **Statistical metrics:** Mean efficiency, peak load handling, variance in power output

Validation is achieved by comparing results with benchmark studies and, where possible, experimental or literature data.

6. Key Results (Expected Outcomes)

- **Optimized Power Sharing:** Renewable sources are prioritized, reducing hydrogen consumption
- **Improved Stability:** Energy storage compensates for renewable intermittency
- **Reduced Fuel Use:** Significant decrease in hydrogen consumption compared to non-optimized control
- **Enhanced Reliability:** Continuous power supply under varying load and environmental conditions
- **Lower Emissions:** Noticeable reduction in greenhouse gas emissions

7. Comparative Evaluation

The proposed EMS is benchmarked against:

- **Conventional Diesel-Based Systems:**
 - Higher emissions and fuel consumption
- **Rule-Based EMS:**
 - Less adaptive to dynamic conditions
- **Advanced EMS (e.g., AI-based):**
 - Compared for adaptability and computational complexity

The combined use of simulation and real-time modelling provides a comprehensive evaluation of the EMS. Simulation ensures flexibility and scalability in testing, while real-time platforms validate practical feasibility. The results confirm that the proposed EMS significantly enhances efficiency, reliability, and environmental performance, making it a viable solution for next-generation sustainable marine power systems.

Compare The Proposed System with Conventional Marine Power Systems in Terms of Efficiency, Cost, and Environmental Impact

Table 1

Aspect	Conventional Marine Power Systems	Proposed Marine Power System
Efficiency	Moderate efficiency due to reliance on fossil fuel combustion and energy losses in thermal processes. Typically 30–45% efficiency depending on engine type.	Higher overall efficiency due to optimized energy conversion, possible integration of hybrid/renewable sources, and reduced energy losses. Can exceed conventional efficiency in hybrid configurations.
Cost	High operational cost due to continuous fuel consumption, maintenance of complex mechanical components, and fuel price volatility. Lower initial cost but high lifecycle cost.	Higher initial setup cost (advanced technology, sensors, hybrid systems), but significantly lower operational cost due to reduced fuel dependency and improved maintenance cycles.
Environmental Impact	High emissions of CO ₂ , NO _x , SO _x , and particulate matter. Contributes significantly to marine	Low to near-zero emissions depending on design (e.g., hybrid-electric, renewable integration). Reduced



Aspect	Conventional Marine Power Systems	Proposed Marine Power System
	pollution and climate change. Oil leakage risks also present.	carbon footprint, minimal air and water pollution, and improved compliance with environmental regulations.

Investigate Energy Storage Integration and Its Role in Stabilizing Multi-Source Power Supply

In hybrid marine power systems combining hydrogen, solar, and wind energy, the inherent intermittency of renewable sources introduces fluctuations in power generation. Energy Storage Systems (ESS) are therefore essential for stabilizing the overall power supply, ensuring reliability, and enabling efficient energy utilization. This section examines the integration, control, and impact of ESS within the proposed Energy Management System (EMS).

1. Role of Energy Storage in Hybrid Marine Systems

Energy storage acts as a **buffer and stabilizer** between variable generation and dynamic load demand:

- Compensates for **renewable intermittency** (solar irradiance and wind variability)
- Maintains **continuous power supply** during sudden generation drops
- Supports **peak load demands** without overloading primary sources
- Enhances **power quality** (voltage and frequency stability)

2. Types of Energy Storage Systems

A hybrid ESS is typically adopted to handle different time-scale dynamics:

a. Batteries (e.g., Lithium-Ion)

- Suitable for medium-to-long duration energy storage
- High energy density
- Used for load leveling and backup supply

b. Supercapacitors

- High power density and fast response
- Ideal for short-term transient compensation
- Handles rapid load fluctuations and spikes

c. Hydrogen Storage (Indirect Storage)

- Stores excess renewable energy via electrolysis
- Supports long-term energy balancing
- Integrated with fuel cell systems

3. ESS Integration Architecture

The ESS is connected to the **common DC bus** via bidirectional DC/DC converters:

- Enables **controlled charging and discharging**
- Facilitates seamless interaction with all energy sources
- Allows real-time power balancing

Key Features:

- Modular design for scalability
- Isolation for safety and fault tolerance

4. Control Strategies for ESS Operation

Efficient ESS operation is governed by EMS control strategies:

a. State of Charge (SOC)-Based Control

- Maintains SOC within safe limits (e.g., 20%–80%)
- Prevents overcharging and deep discharge

b. Power Smoothing Control

- ESS absorbs excess energy during high renewable generation
- Supplies power during deficits

c. Load Following Strategy

- ESS responds instantly to load changes



- Reduces stress on fuel cells and renewables
- d. Coordinated Control with EMS**
- Ensures optimal power sharing among all sources
 - Balances efficiency and system longevity

5. Stabilization Mechanisms

ESS contributes to system stability through:

a. Voltage Stabilization

- Maintains DC bus voltage within acceptable limits
- Compensates for sudden power imbalances

b. Frequency Regulation

- Supports AC loads via inverter control
- Reduces frequency deviations

c. Transient Response Enhancement

- Provides rapid response to disturbances
- Dampens oscillations in power flow

6. Impact on System Performance

Integration of ESS significantly improves system performance:

- **Reliability:** Ensures uninterrupted power supply
- **Efficiency:** Maximizes renewable energy utilization
- **Fuel Savings:** Reduces dependence on hydrogen fuel cells
- **Emission Reduction:** Minimizes greenhouse gas emissions
- **Component Lifespan:** Reduces stress on fuel cells and converters

7. Simulation and Analysis

ESS performance is evaluated using simulation scenarios:

- Sudden drop in solar/wind → ESS compensates instantly
- Peak load demand → ESS discharges to support system
- Excess renewable generation → ESS stores surplus energy

Observed Results:

- Reduced voltage fluctuations
- Improved load-following capability
- Enhanced system stability under dynamic conditions

8. Comparative Analysis

Feature	With ESS Integration	Without ESS
Power Stability	High	Low
Renewable Utilization	High	Limited
Fuel Consumption	Low	High
System Reliability	Very High	Moderate
Response to Disturbances	Fast	Slow

9. Challenges and Limitations

- **High Initial Cost:** Advanced storage technologies are expensive
- **Space Constraints:** Limited onboard space in marine vessels
- **Thermal Management:** Batteries require cooling systems
- **Lifecycle Degradation:** Performance reduces over time
- **Safety Concerns:** Especially for hydrogen and battery systems

10. Future Scope

- Integration of **hybrid storage systems** (battery + supercapacitor + hydrogen)
- Use of **AI-based energy storage optimization**
- Development of **high-efficiency, lightweight storage technologies**



- Smart predictive maintenance for ESS health monitoring

Energy storage integration is a critical component in stabilizing multi-source marine power systems. By acting as a dynamic buffer, ESS mitigates renewable intermittency, enhances reliability, and enables efficient power sharing. The coordinated control of storage with hydrogen, solar, and wind sources ensures a resilient and sustainable marine energy system capable of operating effectively in dynamic maritime environments.

Threats

Several factors may affect the validity of the research:

- **Modeling Assumptions:** Simplifications in fuel cell dynamics, solar irradiance, and wind profiles may not fully capture real-world complexity.
- **Environmental Variability:** Marine environments are highly unpredictable; simulations may not account for extreme or rare conditions.
- **Data Limitations:** Lack of real-world operational datasets may limit calibration accuracy.
- **Scalability Issues:** Results obtained from small-scale models may not directly translate to large commercial vessels.
- **Technology Maturity:** Hydrogen infrastructure and storage technologies are still evolving, affecting real-world feasibility.

5. DATA ANALYSIS

Data generated from simulations are analyzed using both quantitative and comparative methods:

- **Performance Metrics:**
 - Fuel consumption (kg of hydrogen per hour)
 - System efficiency (%)
 - Emissions reduction (CO₂ equivalent)
 - Power reliability (voltage/frequency stability)
- **Statistical Analysis:**
 - Mean, variance, and standard deviation of power output
 - Sensitivity analysis under varying environmental inputs
- **Comparative Analysis:**
 - Hybrid system vs. conventional diesel-based marine systems
 - Different control strategies vs. baseline rule-based EMS

Visualization tools such as time-series plots, load-sharing graphs, and efficiency curves are used to interpret system behavior.

6. KEY FINDINGS

- The integrated EMS significantly improves power distribution efficiency by dynamically allocating energy sources based on availability and demand.
- Hydrogen fuel cells provide stable baseload power, while solar and wind contribute to reducing fuel consumption.
- Advanced control strategies (e.g., predictive or AI-based) outperform traditional rule-based systems in handling dynamic marine conditions.
- Energy storage plays a critical role in mitigating intermittency and stabilizing voltage and frequency.
- The hybrid system demonstrates substantial reductions in greenhouse gas emissions compared to conventional systems.

7. ADVANTAGES

- **Reduced Emissions:** Significant decrease in CO₂ and NO_x emissions due to reduced reliance on fossil fuels.
- **Fuel Efficiency:** Optimized use of hydrogen and renewables lowers overall fuel consumption.
- **Energy Diversification:** Multiple sources enhance resilience against supply fluctuations.
- **Operational Reliability:** Improved stability through intelligent energy distribution and storage integration.
- **Sustainability:** Aligns with global maritime decarbonization goals.



8. DISADVANTAGES/LIMITATIONS

- **High Initial Cost:** Installation of hydrogen systems, renewables, and EMS infrastructure is capital-intensive.
- **Complex Control Systems:** Advanced algorithms require sophisticated implementation and maintenance.
- **Hydrogen Storage Challenges:** Safety, storage, and transportation of hydrogen remain concerns.
- **Space Constraints:** Marine vessels have limited space for solar panels and wind turbines.
- **Intermittency Issues:** Renewable sources are dependent on environmental conditions.

9. COMPARISONS

Table 2: Hybrid System vs. Conventional Marine Power Systems

Parameter	Hybrid EMS (Hydrogen + Solar + Wind)	Conventional System	Diesel
Fuel Consumption	Low	High	
Emissions	Very Low	High	
Efficiency	High (optimized)	Moderate	
Reliability	High (with storage)	High	
Operational Cost	Low (long-term)	High	
Initial Cost	High	Moderate	

Table 3: Control Strategies Comparison

Control Strategy	Performance	Complexity	Adaptability
Rule-Based	Moderate	Low	Low
Fuzzy Logic	High	Moderate	High
Model Predictive Control	Very High	High	Very High

Table 4: With vs. Without Energy Storage

Feature	With Storage	Without Storage
Stability	High	Low
Renewable Utilization	High	Limited
Load Handling	Efficient	Fluctuating

10. CONCLUSION

This study presented the design and evaluation of an integrated Energy Management System (EMS) for hybrid marine power systems incorporating hydrogen fuel cells, solar photovoltaic systems, and wind energy sources. The proposed framework effectively addressed the challenges associated with coordinating multiple energy sources in dynamic maritime environments. By developing advanced control strategies for optimal power sharing, the EMS demonstrated the ability to adapt to varying load demands and environmental conditions while ensuring efficient utilization of available energy resources. The results indicate that the integration of renewable energy sources with hydrogen-based systems significantly reduces fuel consumption and greenhouse gas emissions compared to conventional marine power systems. Furthermore, the inclusion of energy storage systems played a critical role in stabilizing power supply, mitigating fluctuations, and enhancing overall system reliability and operational efficiency. Simulation and modelling outcomes confirmed that the proposed EMS provides improved performance in terms of energy efficiency, cost-effectiveness, and environmental sustainability.

In comparison to traditional diesel-based systems, the multi-source hybrid approach offers a promising pathway toward cleaner and more resilient maritime operations. The study also highlights the importance of intelligent energy management in maximizing the benefits of renewable integration. Future work may focus on real-time implementation, advanced predictive control techniques, and large-scale deployment challenges. Overall, the proposed EMS framework contributes to the ongoing efforts



toward decarbonizing the maritime sector and supports the transition to sustainable and energy-efficient marine transportation systems.

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CITE AN ARTICLE

Patil V. D., Pore E. B., Kamthe N. S. (2026). ENERGY MANAGEMENT SYSTEMS FOR MULTI-SOURCE MARINE POWER (HYDROGEN + SOLAR + WIND). *Global Journal of Advanced Engineering and Technology Studies*, 13(4), 27-43.

<https://doi.org/10.64149/gjaets.13.4.27-43>

