Energy Advancements and Strategies in Energy Management Systems for Hybrid Marine Power Solutions

Nur Amirah binti Ishak a* Ummu Umairah binti Mohamad Ali a Siti Rabi'ah binti Hamzah a

ᵃ Faculty of Marine Engineering, Akademi Laut Malaysia

Abstract - The increasing demand for sustainable energy solutions in maritime transportation has driven the development of hybrid power systems for ships. This review explores the advancements in energy management systems (EMS) designed to optimize hybrid power systems in marine vessels. Emphasis is placed on integration strategies, control methodologies, and the performance metrics of these systems. Key findings highlight the potential of EMS to enhance fuel efficiency, reduce emissions, and improve operational reliability.

Keywords: Emission Reduction, Energy Management System, Hybrid Power System, Ships, Sustainable Maritime Transportation.

*Corresponding Author: nuramirah.ishak@alam.edu.my

1.0 INTRODUCTION

The maritime industry is pivotal to global trade but is also a significant contributor to greenhouse gas emissions. Traditional diesel-powered ships are increasingly being supplemented or replaced by hybrid power systems, which combine conventional engines with renewable energy sources and energy storage systems (Othman et al., 2018). The integration of these diverse power sources necessitates sophisticated EMS to ensure optimal performance and efficiency (Tang et al., 2019). Hybrid power systems for ships typically include components such as diesel engines, batteries, fuel cells, and solar panels. These components need to be managed in a way that balances power generation and consumption while minimizing fuel use and emissions (Hou et al., 2019). The primary challenge lies in developing EMS that can handle the dynamic nature of maritime operations and the varying availability of renewable energy sources (Xie et al., 2024). Recent research has focused on advanced control algorithms, predictive maintenance, and real-time optimization techniques to enhance the functionality of EMS in hybrid ships (Li et al., 2024). These advancements are crucial for achieving the International Maritime Organization's (IMO) targets for emission reduction and energy efficiency (Ammar, 2018).

This review aims to provide a comprehensive overview of the current state of EMS for hybrid power systems in ships, highlighting key technologies, methodologies, and performance outcomes. By synthesizing recent research findings, this paper seeks to identify future research directions and practical applications (Ebrahimi & Eren, 2022).

2.0 ENERGY MANAGEMENT SYSTEM TECHNOLOGIES

Energy management systems for hybrid ships leverage various technologies to optimize power distribution and consumption. These technologies can be broadly categorized into control strategies, power electronics, and communication systems (Yuan et al., 2018).

2.1 Control Strategies

Control strategies are critical for managing the interplay between different power sources and loads in hybrid systems. Model predictive control (MPC) has emerged as a promising approach due to its ability to handle multi-objective optimization problems (Jayachandran & Ravi, 2019). MPC uses real-time data

to predict future states and make informed decisions about power distribution (Ammar, 2018). Another significant strategy is rule-based control, which relies on predefined rules to govern system behavior under various operating conditions. This approach is relatively simple to implement and has been effective in many practical applications (Moretti et al., 2021). However, it may not always achieve optimal performance, especially in complex and dynamic environments (W. Chen et al., 2023). Adaptive control systems are another area of interest, particularly for handling the variability in renewable energy sources. These systems adjust control parameters in real-time to optimize performance under changing conditions (Mokhtar et al., 2022).

2.2 Power Electronics

Power electronics play a crucial role in EMS by facilitating the conversion and control of electrical energy. Key components include inverters, converters, and battery management systems (BMS) (Mahfuz-Ur-Rahman et al., 2021). These components ensure that power from different sources is compatible with the ship's electrical grid and can be efficiently distributed (Paduraru et al., 2023). Recent advancements in wide-bandgap semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), have significantly improved the efficiency and reliability of power electronics in hybrid ships (Department of Energy, 2015). These materials offer superior thermal performance and higher switching frequencies, which are essential for maritime applications. Emerging technologies like solid-state transformers and advanced magnetic materials are also being explored to further enhance the performance of power electronic systems (Rahman et al., 2020).

2.3 Communication Systems

Effective communication systems are vital for coordinating the various elements of an EMS. These systems enable real-time data exchange between sensors, controllers, and actuators, ensuring seamless operation (Naji et al., 2020).The integration of Internet of Things (IoT) technologies has further enhanced the capabilities of EMS by providing detailed insights into system performance and facilitating predictive maintenance (Alves et al., 2020). The use of machine learning algorithms to analyze data from communication systems has shown promise in improving the accuracy and efficiency of EMS. These algorithms can identify patterns and anomalies, allowing for proactive management of power systems (Li et al., 2024). 5G technology is also being investigated for its potential to enhance the speed and reliability of communication systems in hybrid ships (Ait Allal et al., 2020). Figure 1 shows the overview for energy management systems.
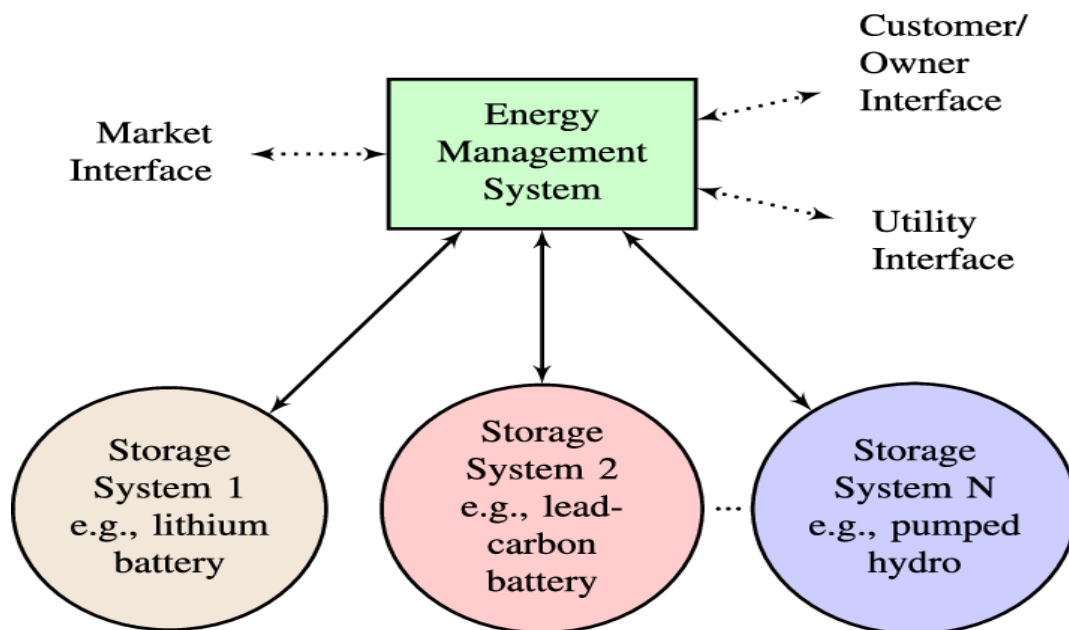

Fig. 1. Overview of Energy Management System Components (Byrne et al., 2017)

3.0 INTEGRATION STRATEGIES

Integrating various power sources and storage systems into a cohesive hybrid power system requires meticulous planning and execution. Effective integration strategies ensure that all components work harmoniously to achieve desired performance metrics (Ebrahimi & Eren, 2022).

3.1 System Architecture

The architecture of a hybrid power system significantly impacts its performance and reliability. Common architectures include series, parallel, and series-parallel configurations (Papadopoulos et al., 2022).Each configuration has its advantages and challenges, depending on the specific requirements of the ship and its operational profile (German-Galkin & Tarnapowicz, 2023). Series configurations are typically used when the primary goal is to minimize emissions, as they allow for efficient use of renewable energy sources (Al-Rawashdeh et al., 2023). Parallel configurations, on the other hand, are preferred for applications where reliability and redundancy are critical (Sadeghi et al., 2021). Series-parallel configurations offer a balance between these two approaches, providing flexibility in power management (Liu & Ruan, 2020).

3.2 Load Management

Load management is essential for optimizing the performance of hybrid power systems. Techniques such as demand-side management (DSM) and load forecasting are used to balance power generation and consumption (Amir et al., 2022). DSM involves adjusting the operation of non-critical loads based on the availability of power, while load forecasting uses historical data and predictive models to anticipate future power needs (Scarabaggio et al., 2022). Effective load management can significantly reduce fuel consumption and emissions by ensuring that renewable energy sources are used to their full potential (Bizon et al., 2015). It also enhances the reliability of the power system by preventing overloads and ensuring a stable supply of electricity (Hou et al., 2019).

Table 1. Comparison of Hybrid Power System Configurations (Geertsma et al., 2017)

Configuration	Advantages	Challenges
Series	High efficiency, low emissions	Complexity in control and integration
Parallel	High reliability, redundancy	Increased fuel consumption
Series-Parallel	Balanced performance, flexibility	Moderate complexity and control requirements

Table 1 shows a comparison of hybrid power system configurations. For situation of hybrid power system, for example the Solar-Wind Hybrid System combines solar and wind energy, leveraging their complementary nature to ensure a more consistent power supply. This setup requires significant space for both solar panels and wind turbines and involves high initial setup costs. It is ideal for areas that have both ample sunlight and wind resources (Abo-Alela, 2018). The Solar-Diesel Hybrid System integrates solar panels with diesel generators, providing reliable backup power and reducing fuel consumption and operational costs. However, diesel generators cause pollution and require regular maintenance, and fuel costs can be high. This configuration is best suited for remote locations with unreliable grid power where solar alone isn't sufficient (Esobinenwu, 2023).The Wind-Diesel Hybrid System uses wind turbines to reduce diesel fuel consumption and associated costs, offering a reliable power supply. The main challenges include the intermittency of wind resources and the pollution from diesel generators.

3.3 Control Coordination

Coordinating control actions across different components of a hybrid power system is crucial for maintaining optimal performance. Hierarchical control architectures, which include primary, secondary, and tertiary control levels, are commonly used to manage this complexity (Alam et al., 2023). Primary control handles real-time adjustments, secondary control focuses on maintaining system stability, and tertiary control optimizes long-term performance (Sedhom et al., 2020). Advanced control algorithms, such as decentralized and distributed control, have been developed to enhance the coordination of hybrid power systems. These algorithms enable individual components to operate semi-independently while still achieving overall system objectives (Bandla & Padhy, 2020). Figure 2 shows the hierarchical control architecture for hybrid power systems. Hierarchical control architecture in hybrid power systems ensures stability, efficiency, and reliability by dividing control into different levels. Primary control manages real-time voltage and frequency regulation with components like inverters and converters, responding within milliseconds to seconds. Secondary control adjusts primary control set points to correct frequency and voltage deviations from load changes, with response times of seconds to minutes. Tertiary control optimizes overall system operation using energy management systems, managing power flows and scheduling generators, responding within minutes to hours. Quaternary control focuses on long-term strategic planning, regulatory compliance, and infrastructure development, with response times of months to years. This architecture offers enhanced stability, scalability, efficiency, and resilience. It is crucial for applications like microgrids, smart grids, and remote power systems, ensuring smooth, efficient, and reliable operations.
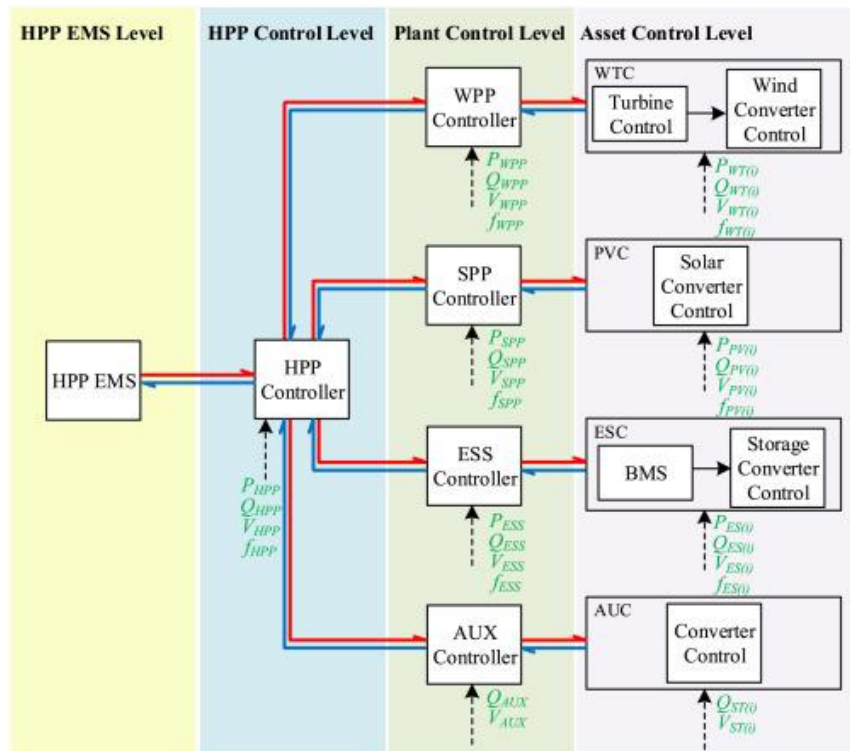

Fig. 2. Hierarchical Control Architecture for Hybrid Power Systems (Long et al., 2022)

4. PERFORMANCE METRICS

Evaluating the performance of EMS for hybrid power systems involves assessing various metrics, including fuel efficiency, emissions reduction, and system reliability (Ammar, 2018).
4.1 Fuel Efficiency

One of the primary benefits of hybrid power systems is improved fuel efficiency. By optimizing the use of renewable energy sources and energy storage systems, EMS can significantly reduce the amount of fuel consumed by ships (X. Chen & Guo, 2022) This not only lowers operational costs but also contributes to environmental sustainability (Tang et al., 2019).

4.2 Emissions Reduction

Reducing emissions is a key objective for the maritime industry, and hybrid power systems play a crucial role in achieving this goal. EMS enables ships to minimize their reliance on fossil fuels by integrating renewable energy sources and improving energy efficiency (Roslan et al., 2022). This results in lower emissions of greenhouse gases and other pollutants (Sletten & Zadeh, 2022).

4.3 System Reliability

Reliability is a critical factor for any maritime power system, given the harsh operating conditions and the need for continuous operation. Hybrid power systems enhance reliability by providing multiple power sources and ensuring redundancy (Daya & Lazakis, 2023). EMS plays a vital role in maintaining this reliability by monitoring system performance and making real-time adjustments as needed (Shafique et al., 2021).

Table 2 Performance Metrics of Hybrid Power Systems(Ammar, 2018)

Metric	Description	Significance
Fuel Efficiency	Measure of fuel consumption per unit of energy	Reduces operational costs and emissions
Emissions Reduction	Reduction in greenhouse gases and pollutants	Enhances environmental sustainability
System Reliability	Ability to maintain continuous operation	Ensures safe and reliable maritime transport

Table 2 is performance metrics of hybrid power systems. Fuel Efficiency measures fuel consumption per unit of energy produced. It reduces operational costs and emissions, making maritime operations more economical and environmentally friendly. Emissions Reduction involves decreasing greenhouse gases and pollutants. This enhances environmental sustainability and ensures compliance with international maritime regulations. System Reliability is the ability to maintain continuous operation. It ensures safe and reliable maritime transport by minimizing the risk of power outages and operational disruptions. These metrics help optimize hybrid power systems for better efficiency, sustainability, and reliability in maritime operations.

4.4 Economic Viability

The economic viability of hybrid power systems depends on factors such as initial investment, operational costs, and potential savings from reduced fuel consumption and maintenance (Iqbar et al., 2022).While the initial cost of hybrid systems can be high, the long-term benefits often outweigh these costs, making them a financially attractive option for ship operators (Cha et al., 2023). Figure 3 shows economic analysis of hybrid power systems. The hybrid system economic evaluation starts by defining objectives, such as cost reduction or increased reliability. Next, the system design and configuration are determined, identifying components like solar panels and batteries, and their capacities. Data on resource availability and load demand is collected. Cost analysis follows, calculating initial investment, operation, maintenance, and replacement costs. Economic parameters like discount rate and project lifespan are set. Energy production is simulated to estimate performance under various conditions.

Financial analysis includes calculating Net Present Value (NPV), Levelized Cost of Energy (LCOE), payback period, and Internal Rate of Return (IRR). Sensitivity analysis assesses the impact of changing parameters, while risk assessment identifies potential risks. Environmental impact is evaluated for benefits like carbon savings. Decision-making compares different configurations based on economic and environmental analyses. Implementation planning and monitoring are then established to track performance and adjust. This process ensures a comprehensive evaluation of the hybrid system's economic viability.

CONCLUSION

Energy management systems are critical for the effective operation of hybrid power systems in ships. The integration of advanced control strategies, power electronics, and communication systems has significantly enhanced the performance and reliability of these systems. Hybrid power systems offer substantial benefits in terms of fuel efficiency, emissions reduction, and economic viability. However, further research is needed to address challenges such as system complexity and integration. Future work should focus on developing more sophisticated control algorithms, improving the efficiency of power electronics, and enhancing communication systems. Additionally, real-world trials and pilot projects are essential for validating theoretical models and demonstrating the practical benefits of hybrid power systems in maritime applications.

REFERENCES

Abo-Alela, S. (2018). Design And Performance Of Hybrid Wind-Solar Energy Generation System For Efficiency Improvement. *Journal of Al-Azhar University Engineering Sector*, *13*(48). https://doi.org/10.21608/auej.2018.18981

Ait Allal, A., El Amrani, L., Haidine, A., Mansouri, K., & Youssfi, M. (2020). Implementation of 5G communication network for a safe operation of autonomous and conventional ships. *International Journal of Engineering Research in Africa*, *51*. https://doi.org/10.4028/www.scientific.net/JERA.51.229

Alam, F., Haider Zaidi, S. S., Rehmat, A., Mutarraf, M. U., Nasir, M., & Guerrero, J. M. (2023). Robust Hierarchical Control Design for the Power Sharing in Hybrid Shipboard Microgrids. *Inventions*, *8*(1). https://doi.org/10.3390/inventions8010007

Al-Rawashdeh, H., Al-Khashman, O. A., Al Bdour, J. T., Gomaa, M. R., Rezk, H., Marashli, A., Arrfou, L. M., & Louzazni, M. (2023). Performance Analysis of a Hybrid Renewable-Energy System for Green Buildings to Improve Efficiency and Reduce GHG Emissions with Multiple Scenarios. *Sustainability (Switzerland)*, *15*(9). https://doi.org/10.3390/su15097529

Alves, F., Badikyan, H., Antonio Moreira, H. J., Azevedo, J., Moreira, P. M., Romero, L., & Leitao, P. (2020). Deployment of a Smart and Predictive Maintenance System in an Industrial Case Study. *IEEE International Symposium on Industrial Electronics*, *2020-June*. https://doi.org/10.1109/ISIE45063.2020.9152441

Amir, M., Zaheeruddin, & Haque, A. (2022). Intelligent based hybrid renewable energy resources forecasting and real time power demand management system for resilient energy systems. *Science Progress*, *105*(4). https://doi.org/10.1177/00368504221132144

Ammar, N. R. (2018). Energy- and cost-efficiency analysis of greenhouse gas emission reduction using slow steaming of ships: case study RO-RO cargo vessel. *Ships and Offshore Structures*, *13*(8). https://doi.org/10.1080/17445302.2018.1470920

Bandla, K. C., & Padhy, N. P. (2020). Decentralized Control for Coordinated Power Management among Multiple HESS in DC Microgrid. *2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy, PESGRE 2020*. https://doi.org/10.1109/PESGRE45664.2020.9070769

Bizon, N., Oproescu, M., & Raceanu, M. (2015). Efficient energy control strategies for a standalone Renewable/Fuel Cell Hybrid Power Source. *Energy Conversion and Management*, *90*. https://doi.org/10.1016/j.enconman.2014.11.002

Byrne, R. H., Nguyen, T. A., Copp, D. A., Chalamala, B. R., & Gyuk, I. (2017). Energy Management and Optimization Methods for Grid Energy Storage Systems. *IEEE Access*, *6*. https://doi.org/10.1109/ACCESS.2017.2741578

Cha, M., Enshaei, H., Nguyen, H., & Jayasinghe, S. G. (2023). Towards a future electric ferry using optimisation-based power management strategy in fuel cell and battery vehicle application — A review. In *Renewable and Sustainable Energy Reviews* (Vol. 183). https://doi.org/10.1016/j.rser.2023.113470

Chen, W., Tai, K., Lau, M. W. S., Abdelhakim, A., Chan, R. R., Adnanes, A. K., & Tjahjowidodo, T. (2023). Robust Real-Time Shipboard Energy Management System With Improved Adaptive Model Predictive Control. *IEEE Access*, *11*. https://doi.org/10.1109/ACCESS.2023.3321692

Chen, X., & Guo, Y. (2022). *Research on energy management strategy of fuel cell-battery hybrid power ship*. https://doi.org/10.1117/12.2628503

Daya, A. A., & Lazakis, I. (2023). Component Criticality Analysis for Improved Ship Machinery Reliability. *Machines*, *11*(7). https://doi.org/10.3390/machines11070737

Department of Energy, U. (2015). Wide Bandgap Semiconductors for Power Electronics Technology Assessment. *Quadrennial Technology Review*.

Ebrahimi, J., & Eren, S. (2022). A Multi-Source DC/AC Converter for Integrated Hybrid Energy Storage Systems. *IEEE Transactions on Energy Conversion*, *37*(4). https://doi.org/10.1109/TEC.2022.3174518

Esobinenwu, C. S. (2023). Optimization of Hybrid Solar PV and Diesel Generator System for an Efficient Electricity Supply. *International Journal of Electrical and Electronics Engineering Studies*, *9*(1). https://doi.org/10.37745/ijeees.13/vol9n13746

Geertsma, R. D., Negenborn, R. R., Visser, K., & Hopman, J. J. (2017). Design and control of hybrid power and propulsion systems for smart ships: A review of developments. In *Applied Energy* (Vol. 194). https://doi.org/10.1016/j.apenergy.2017.02.060

German-Galkin, S., & Tarnapowicz, D. (2023). Energy Optimization of a Series Hybrid Electric Ship Propulsion System. *Nase More*, *70*(1). https://doi.org/10.17818/NM/2023/1.2

Hou, J., Song, Z., Hofmann, H., & Sun, J. (2019). Adaptive model predictive control for hybrid energy storage energy management in all-electric ship microgrids. *Energy Conversion and Management*, *198*. https://doi.org/10.1016/j.enconman.2019.111929

Iqbar, I. M., Muhammad, M., Gilani, S. I. U. H., & Adam, F. (2022). Feasibility Study of Harnessing Low Wind Speed Turbine as Hybrid Power Source for Offshore Platforms. *Journal of Marine Science and Engineering*, *10*(7). https://doi.org/10.3390/jmse10070963

Jayachandran, M., & Ravi, G. (2019). Predictive power management strategy for PV/battery hybrid unit based islanded AC microgrid. *International Journal of Electrical Power and Energy Systems*, *110*. https://doi.org/10.1016/j.ijepes.2019.03.033

Li, H., Liu, Z., Yang, Y., Yang, H., Shu, B., & Liu, W. (2024). A proactive energy management strategy for battery-powered autonomous systems. *Applied Energy*, *363*. https://doi.org/10.1016/j.apenergy.2024.122995

Liu, F., & Ruan, X. (2020). Series-Parallel Conversion Systems Exhibiting the Characteristic of Natural Power Balance with Unmatched Constituent Modules. *2020 IEEE 9th International Power Electronics and Motion Control Conference, IPEMC 2020 ECCE Asia*. https://doi.org/10.1109/IPEMC-ECCEAsia48364.2020.9368040

Long, Q., Das, K., Pombo, D. V., & Sørensen, P. E. (2022). Hierarchical control architecture of co-located hybrid power plants. *International Journal of Electrical Power and Energy Systems*, *143*. https://doi.org/10.1016/j.ijepes.2022.108407

Mahfuz-Ur-Rahman, A. M., Islam, M. R., Muttaqi, K. M., & Sutanto, D. (2021). An Effective Energy Management with Advanced Converter and Control for a PV-Battery Storage Based Microgrid to Improve Energy Resiliency. *IEEE Transactions on Industry Applications*, *57*(6). https://doi.org/10.1109/TIA.2021.3115085

Mokhtar, M., Marei, M. I., Sameh, M. A., & Attia, M. A. (2022). An Adaptive Load Frequency Control for Power Systems with Renewable Energy Sources. *Energies*, *15*(2). https://doi.org/10.3390/en15020573

Moretti, L., Meraldi, L., Niccolai, A., Manzolini, G., & Leva, S. (2021). An innovative tunable rule-based strategy for the predictive management of hybrid microgrids. *Electronics (Switzerland)*, *10*(10). https://doi.org/10.3390/electronics10101162

Naji, N., Abid, M. R., Benhaddou, D., & Krami, N. (2020). Context-aware wireless sensor networks for smart building energy management system. *Information (Switzerland)*, *11*(11). https://doi.org/10.3390/info11110530

Oladigbolu, J. O., Ramli, M. A. M., & Al-Turki, Y. A. (2020). Optimal design of a hybrid pv solar/micro-hydro/diesel/battery energy system for a remote rural village under tropical climate conditions. *Electronics (Switzerland)*, *9*(9). https://doi.org/10.3390/electronics9091491

Othman, M., Anvari-Moghaddam, A., Ahamad, N., Chun-Lien, S., & Guerrero, J. M. (2018). Scheduling of Power Generation in Hybrid Shipboard Microgrids with Energy Storage Systems. *Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018*. https://doi.org/10.1109/EEEIC.2018.8494363

Paduraru, R., Craciun, C., Munteanu, T., & Burlibasa, A. (2023). EMC Aspects in Power Conversion Systems for Marine Applications. *2023 8th International Symposium on Electrical and Electronics Engineering, ISEEE 2023 - Proceedings*. https://doi.org/10.1109/ISEEE58596.2023.10310650

Papadopoulos, K. I., Nasoulis, C. P., Ntouvelos, E. G., Gkoutzamanis, V. G., & Kalfas, A. I. (2022). Power Flow Optimization for a Hybrid-Electric Propulsion System. *Journal of Engineering for Gas Turbines and Power*, *144*(11). https://doi.org/10.1115/1.4055478

Rahman, M. A., Islam, M. R., Muttaqi, K. M., & Sutanto, D. (2020). Modeling and Control of SiC-Based High-Frequency Magnetic Linked Converter for Next Generation Solid State Transformers. *IEEE Transactions on Energy Conversion*, *35*(1). https://doi.org/10.1109/TEC.2019.2940042

Roslan, S. B., Konovessis, D., & Tay, Z. Y. (2022). Sustainable Hybrid Marine Power Systems for Power Management Optimisation: A Review. In *Energies* (Vol. 15, Issue 24). https://doi.org/10.3390/en15249622

Sadeghi, M., Roghanian, E., Shahriari, H., & Sadeghi, H. (2021). Reliability optimization for non-repairable series-parallel systems with a choice of redundancy strategies and heterogeneous components: Erlang time-to-failure distribution. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *235*(3). https://doi.org/10.1177/1748006X20952575

Scarabaggio, P., Grammatico, S., Carli, R., & Dotoli, M. (2022). Distributed Demand Side Management with Stochastic Wind Power Forecasting. *IEEE Transactions on Control Systems Technology*, *30*(1). https://doi.org/10.1109/TCST.2021.3056751

Sedhom, B. E., El-Saadawi, M. M., Hatata, A. Y., & Alsayyari, A. S. (2020). Hierarchical control technique-based harmony search optimization algorithm versus model predictive control for autonomous smart microgrids. *International Journal of Electrical Power and Energy Systems*, *115*. https://doi.org/10.1016/j.ijepes.2019.105511

Shafique, H., Tjernberg, L. B., Archer, D. E., & Wingstedt, S. (2021). Energy Management System (EMS) of Battery Energy Storage System (BESS) - Providing Ancillary Services. *2021 IEEE Madrid PowerTech, PowerTech 2021 - Conference Proceedings*. https://doi.org/10.1109/PowerTech46648.2021.9494781

Sletten, P. S., & Zadeh, M. (2022). Comparative study of energy efficiency and cost optimization in low-emission marine power systems with alternative fuels. *2022 IEEE Transportation Electrification Conference and Expo, ITEC 2022*. https://doi.org/10.1109/ITEC53557.2022.9813749

Tang, R., Wu, Z., & Li, X. (2019). Optimal power flow dispatching of maritime hybrid energy system using model predictive control. *Energy Procedia*, *158*. https://doi.org/10.1016/j.egypro.2019.01.490

Xie, P., Asgharian, H., Guerrero, J. M., Vasquez, J. C., Araya, S. S., & Liso, V. (2024). A two-layer energy management system for a hybrid electrical passenger ship with multi-PEM fuel cell stack. *International Journal of Hydrogen Energy*, *50*. https://doi.org/10.1016/j.ijhydene.2023.09.297

Yuan, Y., Zhang, T., Shen, B., Yan, X., & Long, T. (2018). A fuzzy logic energy management strategy for a photovoltaic/diesel/battery hybrid ship based on experimental database. *Energies*, *11*(9). https://doi.org/10.3390/en11092211