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Efficient energy management for hybrid power systems using Fuzzy Logic Controller

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Abstract

Energy management is critical for the efficient utilization of power resources, particularly in hybrid energy systems that integrate multiple energy sources. This study presents a Fuzzy Logic-based Energy Management System (FLEMS) designed to optimize power distribution and enhance overall system efficiency. The proposed system leverages fuzzy logic to enable real-time decision-making by dynamically adjusting power flow based on key parameters such as load demand, renewable energy availability, and battery storage capacity. The hybrid system integrates solar photovoltaic (PV), a diesel generator, and battery storage to ensure a stable and reliable power supply while minimizing energy wastage. Two operational modes are evaluated through simulation: grid-connected and islanded. In the grid-connected mode, surplus energy generated by the PV system is either exported to the grid or used to charge the battery. In islanded mode, excess energy charges the battery, and the diesel generator is activated only when necessary to meet demand. Simulation results demonstrate that FLEMS improves system performance, reduces operational costs, and enhances energy sustainability compared to conventional rule-based control methods. This research underscores the potential of intelligent control strategies in advancing the efficiency, flexibility, and reliability of modern hybrid energy management systems.

1.0 Introduction

Utility grids often struggle to meet growing energy demands, leading to issues such as load shedding and poor power quality. As a result, implementing effective energy management systems has become increasingly crucial. Energy management plays a vital role not only in distribution networks but also in generation systems. For a country to achieve economic growth, it must support and expand its industrial sector. However, as the number of industrial facilities rises, so does the demand for and consumption of energy. The industrial sector accounts for the highest consumption of commercially generated electrical energy. To address the widening gap between energy demand and supply, either additional industrial energy must be produced or current energy usage must be reduced without affecting the quality or quantity of production.

Currently, energy consumption in the residential sector is increasing at a faster pace than in the industrial sector. However, during power shortages, priority is given to the industrial sector, leaving households to face the most frequent and prolonged outages (Jamal et al., 2021). An effective power management system is proposed by (Angalaeswari et al., 2017), utilizing a Fuzzy Logic Controller (FLC) to regulate the controller's duty cycle in the Maximum Power Point Tracking (MPPT) method. The fuzzy rules are developed based on the error and its rate of change, derived from the slope of the solar cell's PV characteristics. To validate the results, the irradiation levels are varied, and the FLC effectively maintains the appropriate voltage and current levels at the grid. A wind and solar-based microgrid system is proposed by (Fouad et al., 2017), focusing on operational, control, and stability challenges. The system is modeled and simulated in MATLAB/Simulink to analyze key technical issues associated with the operation of renewable energy-based microgrids. Numerous researchers have conducted studies on energy management in hybrid energy systems; a selection of these studies is reviewed and discussed below: (Olaleye et al., 2023) presents the development of a fuzzy logic-based energy management system for a hybrid energy setup, aimed at controlling various energy sources and operational modes. The results demonstrate the efficiency and effectiveness of the proposed method in managing energy demand and load distribution.

The use of fuzzy logic techniques offers flexibility and ease of modification, enabling adjustments to enhance the controller's performance. In (Ferahtia et al., 2022) an optimal energy management strategy was proposed for a DC microgrid in this study. The researchers focused on a commercial building power system comprising a solar array, fuel cell, battery storage system, a bidirectional DC/AC grid converter, and employed the Salp Swarm Algorithm (SSA) to develop the energy management system (EMS). (Nivolianiti et al., 2024) presents a comparative analysis of five distinct energy management strategies—namely control-based, optimization-based, deterministic rule-based, and FL rule-based—evaluating their performance in terms of total hydrogen consumption. The analysis is conducted within the context of a small hydrogen-powered passenger vessel operating under a river trip scenario, aiming to identify the most efficient approach for minimizing hydrogen usage while maintaining reliable operation. Simulation results revealed that the EMS provided effective power management and performance, with the SSA-based approach ensuring high power quality and safe operational conditions. Additionally, the proposed strategy enabled the local generation units to reliably meet load demands.

The main contribution of this work is the design of an FLC to intelligently manage power flow between multiple energy sources, such as solar PV, battery storage, and grid, and various loads, ensuring optimal operation under different conditions.

This paper is organized as follows: section 1 gives a brief introduction on energy management and related literature, sections 2 describe the system modeling, while section 3 describes the techniques used in carrying out the work, in section 4, results and discussions were presented and finally section 5 gives the conclusion of the work.

2.0 Brief Literature Review

This section briefly introduces the components relevant to the implementation of this research.

2.1 PV module

Solar cells are electronic devices that convert photon energy into clean, pollution-free electricity. When interconnected in series and parallel arrangements, these cells form photovoltaic (PV) modules, which can be further combined to create PV arrays capable of generating environmentally friendly electricity (Vinod et al., 2018)This process of capturing and converting sunlight into electrical energy is commonly known as photovoltaic conversion (Belkassmi et al., 2018).

An ideal solar PV device can be modeled as a solar cell with a current source (Iph) connected in parallel to a diode as shown in Figure 1. Using Kirchhoff's first law, the output current of this ideal solar cell can be expressed mathematically as given in (1). The I-V characteristics of PV solar cells are fundamentally described by Shockley's diode current equation given in (2) (Vinod et al., 2018).

By substituting the diode current equation into Kirchhoff's law equation, we can derive a comprehensive expression for the output current of an ideal solar cell as given in (3)

$$I = I_{ph} - I_d \quad (1)$$

$$I_d = I_s \left[exp\left(\frac{qV_{oc}}{N_s KAT_o} \right) - 1 \right] \quad (2)$$

$$I = I_{ph} - I_s \left[exp\left(\frac{qV_{oc}}{N_s KAT_o} \right) - 1 \right] \quad (3)$$

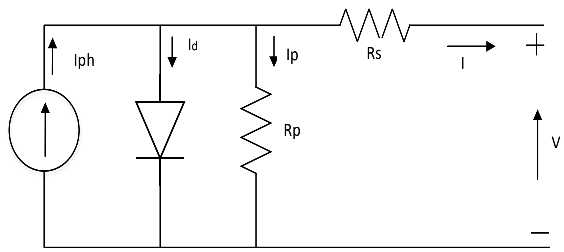

Figure 1: Single diode model of a PV module (Mendalek & Al-Haddad, 2017)

In reality, a more accurate circuit model includes both series resistance (Rs) and parallel resistance (Rp) as shown in Figure 1. These parameters significantly affect the efficiency of PV solar cells (Vinod et al., 2018). Though ideally these resistances might be ignored, practical applications require their consideration. When R_s is taken into account and R_p is considered finite, the diode current in (2) requires modification as given in (4).

$$I_d = I_s\left[exp\left(\frac{q(V+IR_s)}{N_sKAT_o}\right)-1\right] \quad (4)$$

Equation (3) can also be modified taken R_s into account

$$I = I_{ph} - I_s\left[exp\left(\frac{q(V+IR_s)}{N_sKAT_o}\right)-1\right] \quad (5)$$

For PV cells arranged in series-parallel configurations, the output current in (5) must be further adapted to reflect this arrangement as given in (6).

$$I = N_p * I_{ph} - N_p * I_s\left[exp\left(\frac{q(V+IR_s)}{N_sKAT_o}\right)-1\right] \quad (6)$$

Additionally, (7) shows that the photocurrent (I_{ph}) is proportional to incident flux and independent of voltage or series resistance. However, it maintains a linear relationship with solar radiation and is influenced by temperature variations.

$$I_{ph} = [I_{sc} + K_i(T_o - T_r)] * \frac{G}{G_{ref}} \quad (7)$$

This mathematical modeling provides the foundation for understanding PV system behavior under various operating conditions, which is essential for designing effective energy management systems that optimize power generation from solar resources in hybrid power systems.

2.2 Battery Energy Management using fuzzy logic control

Lithium-ion batteries have emerged as a prominent solution for hybrid energy storage systems, owing to their high energy density, efficiency, compact design, and extended lifecycle (Aranya et al., 2015). These attributes make them particularly suited for applications requiring reliable energy management. A simplified model of a lithium-ion battery is utilized in this context, where the state of charge (SOC) serves as a critical indicator of the available energy reserve. As defined by (8), SOC is calculated as (Jadhav & Nair, 2019):

$$SOC = 100\left(1 - \frac{\int_0^t idt}{Q}\right) \quad (8)$$

Here, Q represents the battery total capacity (in ampere-hours and i denotes its current (in amperes). The charging and discharging dynamics of the battery are further characterized by (9) and (10), which model the voltage behavior during these processes:

$$f_1(iti^*i) = E_o - \left(k + \left(\frac{Q}{Q-it}\right) + it\right) + it + A + \exp(-B + it) \quad (9)$$

$$f_2(iti^*i) = E_o - \left(k + \left(\frac{Q}{Q-0.iQ}\right) + it\right) + it + A + \exp(-B + it) \quad (10)$$

In these equations, K signifies polarization resistance E_o is the initial voltage, and A and B represent exponential voltage and capacity coefficients, respectively.

The battery operates in two distinct modes: charging (when current is positive) and discharging (when current is negative). To regulate its SOC effectively, a FLC is implemented. This controller dynamically adjusts the battery's current based on two inputs: photovoltaic (PV) power and the rate of change in SOC (ΔSOC). By processing these inputs, the FLC determines the optimal current to maintain the desired SOC, ensuring efficient energy allocation.

The FLC employs a rule-based system with five membership functions for both inputs and outputs: Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB), as illustrated in Figures 2–4. These functions map the relationship between PV power fluctuations, SOC trends, and the required current adjustments. For instance, when PV power is insufficient (negative value), the system evaluates the battery's SOC. If SOC exceeds a predefined threshold, the battery discharges to meet the load demand. Conversely, if SOC is low, the FLC prioritizes charging to replenish the stored energy. The controller's output current is derived by scaling these membership functions, enabling precise control over charge and discharge rates.

This integrated approach ensures seamless energy management by balancing renewable generation with storage capabilities. By utilizing the lithium-ion battery's rapid response and the FLC's adaptability, the system maintains stability even under variable energy conditions, highlighting the synergy between advanced battery technology and intelligent control strategies.

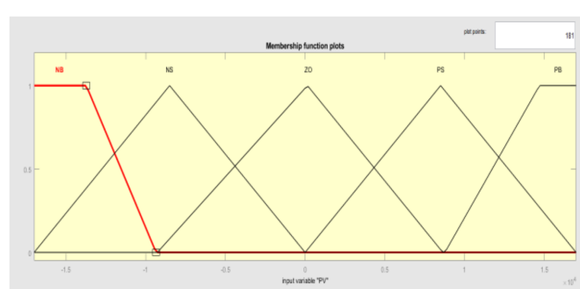

Figure 2: Input membership function of variable ΔPV

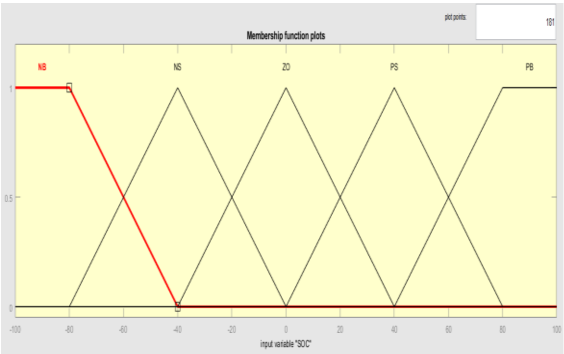

Figure 3: Input membership function of variable ΔSOC

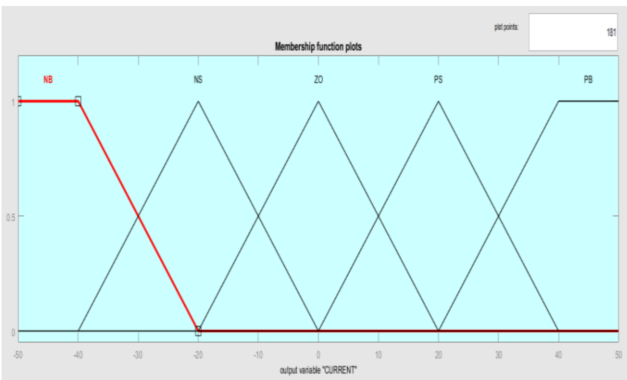

Figure 4: Output membership function ΔI

Table 1 outlines the fuzzy logic rules governing the proposed energy management system, which determine the battery's current adjustments (ΔI) based on two input variables: the deviation in photovoltaic power (ΔP) and the rate of change in the state of charge (ΔSOC). For instance, when both ΔP and ΔSOC are classified as Negative Big (NB)—indicating a significant deficit in PV power and a rapid decline in SOC—the controller assigns the output current (ΔI) as Positive Big (PB). This rule prioritizes charging the battery to counteract energy shortages and stabilize the system. Conversely, scenarios where ΔP and ΔSOC are Positive Big (PB) would trigger discharging to optimize energy utilization.

A critical parameter in this setup is the SOC threshold, set at 50%, which dictates the battery's operational mode. If the SOC falls below this threshold, the fuzzy controller prioritizes charging to replenish the energy reserve. Conversely, when SOC exceeds 50%, the system enables discharging to support load demands. This binary threshold simplifies mode transitions while aligning with the fuzzy rules to maintain operational efficiency. For example, during periods of low PV generation (negative ΔP), the controller evaluates the SOC. If SOC is above 50%, the battery discharges to compensate for the energy deficit. If SOC drops below 50%, charging is initiated to prevent over-depletion, ensuring sustained availability of stored energy.

The fuzzy rules in Table 1 systematically translate input combinations into actionable outputs, balancing energy supply and demand. Each rule correlates specific membership grades (NB, NS, Z, PS, PB) of ΔP and ΔSOC to a corresponding ΔI value. This structured approach allows the controller to adapt dynamically to fluctuating conditions. For instance, moderate PV deficits (ΔP = NS) coupled with a gradual SOC decline (ΔSOC = NS) might yield a smaller charging current (PS), whereas extreme imbalances trigger proportional responses (PB or NB). By scaling these outputs through predefined factors, the system fine-tunes the charge/discharge rates, ensuring precise control over the battery's energy flow.

This integration of threshold-based mode switching and rule-based fuzzy logic enhances the system's robustness. The 50% SOC threshold acts as a safeguard, preventing deep discharges that could compromise battery longevity. Meanwhile, the fuzzy rules enable nuanced adjustments, accommodating transient variations in renewable generation and load requirements. Together, these mechanisms optimize energy distribution, highlighting the synergy between threshold-driven mode selection and adaptive fuzzy logic in hybrid storage systems. Such a design ensures reliability across diverse operating conditions, from prolonged renewable shortages to sudden load spikes, while preserving the battery's health and efficiency.

Table 1: Fuzzy Rules of the Proposed System

ΔI		ΔPV				
		NB	NS	Z	PS	PB
ΔSOC	NB	PB	PB	PB	PB	PB
	NS	PB	PB	PS	PS	PB
	Z	Z	Z	Z	PS	PB
	PS	NS	NS	NS	NS	PB
	PB	NB	NB	NB	NB	PB

2.3 Hybrid Control Switch Unit

The hybrid system operates in grid-connected and off-grid modes, with a FLC circuit implemented in MATLAB/Simulink, as illustrated in Figure 5. In grid-connected mode, when the PV output exceeds the load demand, the surplus power is exported to the grid. Conversely, if the PV output is insufficient, power is drawn from the grid. In off-grid mode, excess PV power is stored in the batteries when generation exceeds demand. If the PV output falls short of the load requirement, a diesel generator is activated to supply the deficit.

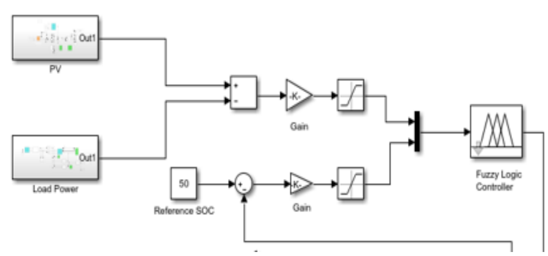

Figure 5: Hybrid system Control Model in On/Off Mode (MATLAB/SIMULINK)

3.0 Methodology

In order to archive the goal of hybridizing these Energy supplies, the following steps were taken:

3.1 Problem formulation

An efficient power system is requiring to satisfied power balance equation at all the time:

$$\sum P_{gen}(t) = \sum\big(P_{load}(t) + P_{loss}(t)\big) \qquad (11)$$

If this balance is not established, then the system is not efficient.

With priority to PV power as the grid is not always available, this gives rise to equation (12)

$$\sum P_{gen} = P_{pv} \pm P_{grid} + P_{DG} \qquad (12)$$

With priority to PV, we can either sell to the grid or purchase from the grid as depicted in equation (13), this is only applicable when the hybrid system is on grid mode.

$$P_{grid} = \begin{cases} 0, for\ P_{pv} = P_{load} \\ < 0\ for\ P_{pv} > P_{load} \\ > 0\ for\ P_{pv} < P_{load} \end{cases} \qquad (13)$$

On the condition when the system is on the off-grid mode, then we have equation (14)

$$P_{gen} = P_{pv} + P_{DG} \qquad (14)$$

Where:

$$P_{DG} = 0, for\ P_{pv} \geq P_{load} \qquad (15)$$

and,

$$P_{DG} > 0, for P_{pv} < P_{load} \qquad (16)$$

While if $P_{pv} = P_{grid} = 0,\ then$

$$P_{gen} = P_{DG} \qquad (17)$$

These operations are implemented in if rule.

4.0 Results and Discussions

The battery management system using fuzzy logic technique is implemented in the MATLAB/SIMULINK environment. The complete system is as shown in Figure 6. The fuzzy state of charge control system is designed to maintain the battery SOC at a minimum threshold level of 50% or a maximum threshold level of 100% to avoid battery damage as a result of overcharging or extreme low charging state. if initial value of SOC is low or high. Reference SOC given to the fuzzy controller is 50%, hence the SOC of battery is maintained at 50%.

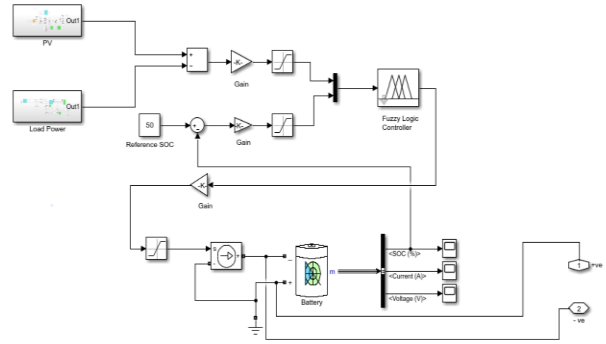

Figure 6: Battery Management Using FLC (MATLAB/SIMULINK

4.1 Hybrid System on Islanding mode

In this mode, the hybrid microgrid is been operated in an islanding mode. In this mode, the hybrid system does not either sell to the grid or purchase from the grid. In this scenario, a dynamic load of 5 kW is used as the load demand. In the islanding mode, whenever power output from the PV is greater than the load power demand, the excess power charges the battery and whenever the PV output power is less than the load demand, the diesel generator comes up to compensate the power shortage as shown in Figure 7.

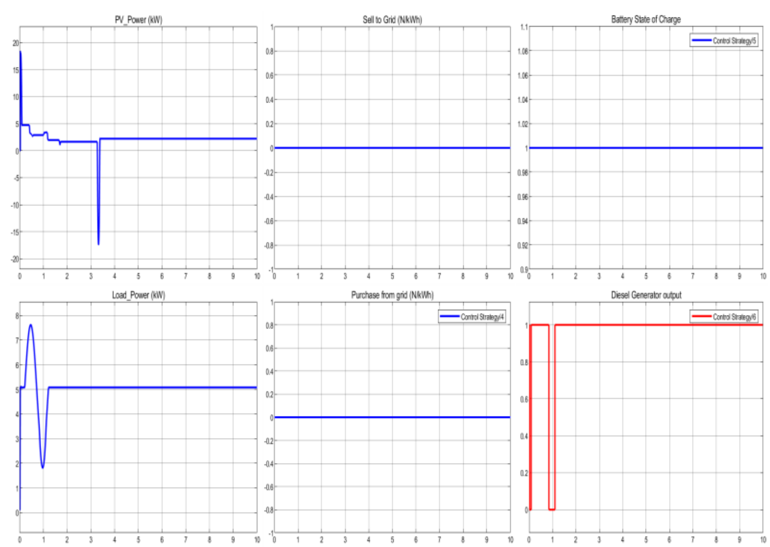

Figure 7: Islanding mode

4.2 Hybrid System in grid-connected mode

In the grid-connected mode, whenever power output from the PV is greater than the load power demand, the excess power is sold out to the grid as well charges the battery. In the event that the PV output power is less than the load demand, energy is purchased from the grid as shown in Figure 8.

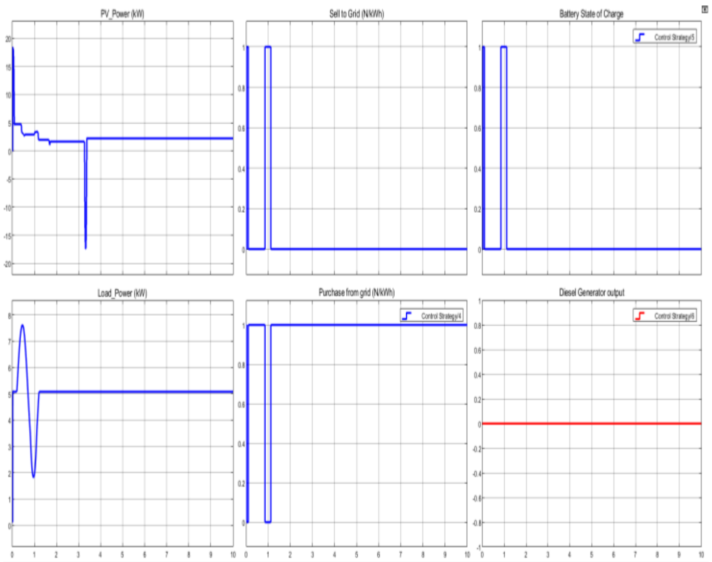

Figure 8: Grid-connected mode.

5.0 Conclusion and Recommendation

A hybrid system is implemented based on PV power generation. The various subsystems that make up the system are model separately and their performances are evaluated. The system is design to operate in two modes; islanded mode and grid connected. The performance of the system is investigated using a simulation based on MATLAB/SIMULINK. The fuzzy logic controller manages the hybrid power system to ensure an uninterrupted power supply, reduce reliance on the diesel generator, optimize the use of available energy sources, and extend battery lifespan. By minimizing diesel usage, the emission of harmful gases is significantly reduced, making the system an eco-friendly and sustainable green energy solution suitable for deployment in any location or country. The proposed system can be implemented in real power system to ensure efficient power supply where supply interruption will not be tolerated such as clinic, hospital etc. In future we shall analyze the economic aspect of the work and compare with various options so that the work will be both technically and economically viable.

References

Angalaeswari, S., Swathika, O. V. G., Ananthakrishnan, V., Daya, J. L. F., & Jamuna, K. (2017). Efficient Power Management of Grid operated MicroGrid Using Fuzzy Logic Controller (FLC). *Energy Procedia*, *117*, 268–274. https://doi.org/10.1016/j.egypro.2017.05.131

Aranya, S. D. S., Sathyamoorthi, S., & Gandhiraj, R. (2015). A fuzzy logic based energy management system for a microgrid. *ARPN Journal of Engineering and Applied Sciences*, *10*(6), 2663–2669.

Belkassmi, Y., Rafiki, A., Gueraoui, K., Elmaimouni, L., Tata, O., & Hassanain, N. (2018). Modeling and simulation of photovoltaic module based on one diode model using Matlab/Simulink. *Proceedings - 2017 International Conference on Engineering and MIS, ICEMIS 2017*, *2018-Janua*, 1–6. https://doi.org/10.1109/ICEMIS.2017.8272965

Ferahtia, S., Djeroui, A., Rezk, H., Houari, A., Zeghlache, S., & Machmoum, M. (2022). Optimal control and implementation of energy management strategy for a DC microgrid. *Energy*, *238*, 121777. https://doi.org/10.1016/j.energy.2021.121777

Fouad, M. A., Badr, M. A., & Ibrahim, M. M. (2017). Modeling of Micro-grid System Components using Matlab/Simulink. *Global Scientific Journals*, *5*(5), 163–177.

Jadhav, A. D., & Nair, S. (2019). Battery Management using Fuzzy Logic Controller. *Journal of Physics: Conference Series*, *1172*(1). https://doi.org/10.1088/1742-6596/1172/1/012093

Jamal, H., Ali, H., Zakir Baig, M., Hussain, S., Zeeshan Tariq, M., Butt, Y., Rafay Minhas, R. A., Zia, Z., & Manan, A. (2021). An Efficient Energy Management System for Hybrid Power Sources. *2021 4th International Conference on Energy Conservation and Efficiency, ICECE 2021 - Proceedings*, *8*. https://doi.org/10.1109/ICECE51984.2021.9406310

Mendalek, N., & Al-Haddad, K. (2017). Photovoltaic system modeling and simulation. *Proceedings of the IEEE International Conference on Industrial Technology*, 1522–1527. https://doi.org/10.1109/ICIT.2017.7915592

Nivolianiti, E., Karnavas, Y. L., & Charpentier, J. F. (2024). Fuzzy Logic-Based Energy Management Strategy for Hybrid Fuel Cell Electric Ship Power and Propulsion System. *Journal of Marine Science and Engineering*, *12*(10). https://doi.org/10.3390/jmse12101813

Olaleye, T. A., Olatomiwa, L., Longe, O. M., & Jack, K. E. (2023). An Energy Management Scheme for Hybrid Energy System Using Fuzzy Logic Controller. *Nigerian Journal of Technological Development*, *20*(1), 66–78. https://doi.org/10.4314/njtd.v20i1.1292

Vinod, Kumar, R., & Singh, S. K. (2018). Solar photovoltaic modeling and simulation: As a renewable energy solution. *Energy Reports*, *4*, 701–712. https://doi.org/10.1016/j.egyr.2018.09.008