PROPOSED JOURNAL PUBLICATION

Design, Optimization and Performance Analysis of a Photovoltaic (PV) Hybrid Welding Machine

Abstract

This study presents the design and development of a fuzzy logic–controlled hybrid welding machine powered by photovoltaic (PV), battery storage, and utility grid sources. A multi-objective optimization framework was implemented using fuzzy rule–based allocation to minimize grid dependency, reduce operating costs, and maximize energy savings. Simulation results demonstrated reliable inverter performance, with the rectified welding output voltage stabilizing at approximately 50 V and the welding current reaching about 70 A. The system delivered up to 3 kW output power with arc power near 2.5 kW, ensuring stable arc operation. Efficiency was maintained at around 63–64%, while energy savings of 38.8% was obtained. Guided by the simulation outcomes, a prototype hybrid welding machine was constructed with a microcontroller-based fuzzy logic control unit and tested under varying operating conditions. The prototype validated the simulation by exhibiting smooth source switching, effective prioritization of solar input, and stable welding arc performance. Cost analysis, based on a proposed grid tariff of ₦1.16kWh, indicated savings of ₦255.20 per hour, ₦2,041.60 for a projected 8-hour period. The results confirm that fuzzy logic optimization enhances energy efficiency, lowers welding costs, and provides a practical solution for sustainable welding operations, particularly in regions with unreliable grid supply.
.

Keywords: Hybrid welding machine, Fuzzy logic control, Energy optimization, Photovoltaic integration, Battery storage, System efficiency, Renewable energy welding.

1. Introduction

Photovoltaic systems have witnessed substantial advancements in efficiency and cost reduction, making them a viable alternative for industrial applications. Recent studies highlight the potential of PV systems to supplement or even replace grid power in various industrial processes, leading to significant energy savings and environmental benefits [1]. However, the intermittent nature of solar energy necessitates a reliable control strategy to ensure consistent power supply and optimal system performance.

Hybrid systems that combine PV solar energy with grid electricity offer a balanced solution, leveraging the strengths of both sources. The key to an effective hybrid system lies in the management and distribution of power between the PV array and the utility grid. Traditional control methods often fall short in dynamically adapting to varying solar irradiance and load demands. This is where advanced control strategies, such as fuzzy logic control, come into play. Fuzzy logic control is particularly well-suited for managing hybrid energy systems due to its ability to handle uncertainties and non-linearity in system behavior. Unlike conventional controllers, fuzzy logic controllers do not require precise mathematical models of the system. Instead, they use linguistic variables and a set of heuristic rules to make control decisions, providing a robust and flexible approach to power management [2].

In this paper, the design, optimization, and performance analysis of a hybrid PV and utility-powered welding machine using fuzzy logic control is presented. The proposed system aims to maximize the utilization of solar energy while ensuring the reliability and efficiency of the welding process. The integration of a fuzzy logic controller allows for dynamic power distribution based on real-time solar irradiance, battery state of charge, and welding machine power demand [2].

This study builds on the existing body of research in hybrid energy systems and fuzzy logic control. Previous work has demonstrated the feasibility of hybrid PV-grid systems in various applications, including residential and commercial buildings, but their application in industrial processes, particularly welding, remains underexplored [3]. This research seeks to fill this gap by providing a comprehensive analysis of the hybrid system's performance in a real-world welding application.

2. Literature Review

Hybrid energy systems that combine PV solar power with utility grid electricity offer a balanced approach to leveraging renewable energy while ensuring reliability. Numerous studies have demonstrated the feasibility and benefits of such systems across various applications. Ammari *et al.* [4] reviewed hybrid renewable energy systems, emphasizing their potential to enhance energy security and reduce greenhouse gas emissions. The review underscored the importance of optimal control strategies to manage the power distribution between PV and grid sources effectively. Liao *et al.* [5] explored the economic benefits of PV systems in industrial applications, demonstrating significant cost savings and a reduction in carbon footprint.

Fuzzy logic control has gained traction as an effective method for managing hybrid energy systems due to its ability to handle uncertainties and non-linearities. Unlike traditional control methods that require precise mathematical models, fuzzy logic controllers use linguistic variables and heuristic rules to make control decisions. The advantages of fuzzy logic control in hybrid renewable energy systems, highlighting its robustness and flexibility in managing power distribution was presented in [6]. Several studies have successfully applied fuzzy logic control to hybrid energy systems. For instance, Rawat *et al.* [7] developed a frequency control scheme for a hybrid isolated power system using a type-2 fuzzy PID controller. The system, modeled with two topologies. First combining a wind turbine generator (WTG) with a diesel engine generator (DEG), and the second comprising photovoltaic (PV) and micro-hydro power (MHP) sources with a DEG. Simulation results showed reduced frequency deviations and improved transient response compared to conventional PID and fuzzy PI+D controllers.

While the integration of hybrid energy systems in residential and commercial buildings is well-documented, their application in industrial processes, particularly welding, remains underexplored. Welding operations are energy-intensive and traditionally rely on grid electricity, which incurs high operational costs and contributes to carbon emissions. The potential for PV systems to supplement or replace grid power in welding processes has been recognized, but comprehensive studies focusing on this application are limited. Recent advancements in PV technology and control strategies present an opportunity to address this gap. By integrating PV systems with grid power and employing fuzzy logic control, it is possible to enhance the energy efficiency and sustainability of welding operations. This research aims to build on the existing literature by designing, optimizing, and analyzing the performance of a hybrid PV and utility-powered welding machine using fuzzy logic control.

3. Design Methodology

3.1. System Architecture

The hybrid welding machine is designed to provide a reliable and sustainable welding power source by integrating three distinct energy inputs: a solar photovoltaic (PV) source, battery storage and a conventional alternating current (AC) grid supply. The combination of renewable and conventional power ensures uninterrupted operation, particularly in environments where grid reliability is limited or solar availability fluctuates. At the core of the system is a dynamic controller, which functions as the central supervisory unit. The controller continuously monitors load demand and source availability, while coordinating energy flow across the subsystems. It generates four distinct control outputs: AC control, solar/inverter control, AC/DC power flow control and Shut down control. These outputs ensure that power is efficiently managed between the PV source, grid supply, battery bank, inverter, and welding transformer.

Through the **AC** control pathway, the grid supply is directly energize the transformer for welding and also provide the required charging current for the battery bank. The charger control optimizes the charging process, ensuring that the battery is replenished either from PV energy under high solar irradiance conditions or from the grid when solar input is insufficient. DC control regulates the direct current contribution from the PV source, while inverter control governs the conversion of stored DC energy into AC, guaranteeing that welding operations can continue seamlessly in the absence of direct AC supply. The battery bank serves as an intermediate energy storage unit, bridging the gap between fluctuating energy input and continuous welding demand. During periods of excess solar generation, the battery is charged and subsequently utilized during nighttime operation or cloudy conditions. The inverter plays a crucial role in this process, converting the stored DC power into AC with characteristics suitable for welding applications.

The transformer steps down the AC voltage, whether sourced from the grid or the inverter, to the required level for arc welding. Finally, at the electrode arc ignition and workpiece interface, the system sustains a stable electric arc, providing the thermal energy required for metal fusion and joint formation. Figure 1.1illustrate represents the block description of the hybrid welding machine The hybrid operation follows a power prioritization strategy designed to maximize efficiency and reduce dependence on the grid. Under sufficient solar irradiance, the PV source is prioritized for both welding and battery charging. When solar availability declines, the AC grid supplements the demand. In cases of complete source unavailability, the battery bank ensures continuity of operation, thereby eliminating downtime.

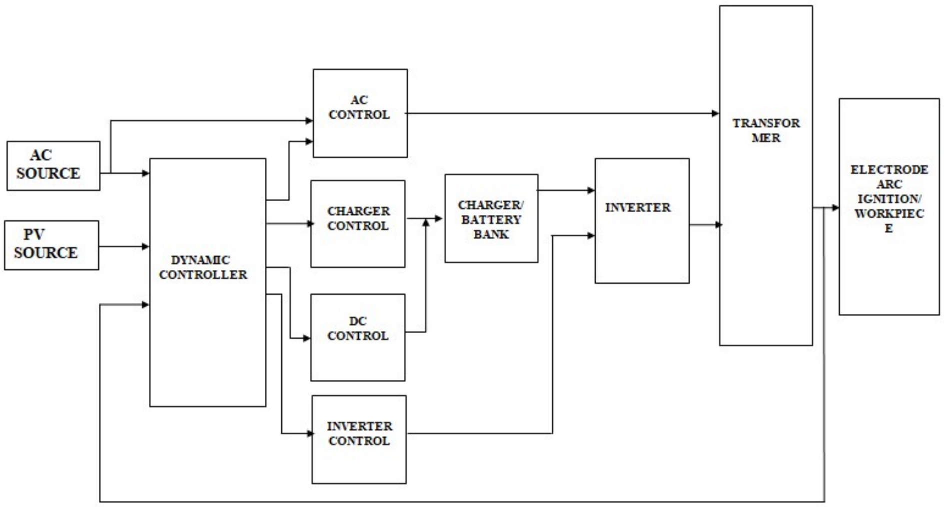

Figure 1: Block Diagram of a PV Hybrid Welding Machine

3.2. System Modeling

3.2.1. PVS and Utility power source

A photovoltaic system (PVS) converts solar energy into electrical energy using solar cells. The cells are composed of a p-n junction fabricated by differently doped semiconductor materials [2]. The output of a PV cell is influenced by factors such as temperature, irradiance, and the characteristics of the materials used in the cell. The current-voltage (I-V) characteristic of a PV cell is given by equation 1 [2].

$$I = I_{PH} - I_S.\left(\exp\left(\frac{q.(V+R_S.I)}{\alpha.k.T}\right) - 1\right) - \frac{V+R_S.I}{R_{SH}} \quad \textbf{1.1]}$$

Where;

I is the Solar cell current (A),

V is the Solar cell output voltage (V),

I_{PH} is the photocurrent, which is proportional to the solar irradiance (A),

I_S is the Diode saturation current (A),

R_S is the Solar cell series resistance (Ω),

R_{SH} is the Solar cell shunts resistance (Ω),

A is the Ideality factor (between 1 and 2),

K is the Boltzmann constant (1.38×10^{-23} J/K),

T is the Cell temperature in Kelvin (K).

The relationship between the output current and voltage is given in equation 2.0, where Np stands for the cells connected in parallel and Ns for the cells connected in series.

$$I = N_p \times I_{ph} - N_p \times I_0 \times \left[exp\left(\frac{V/N_s + I\times R_s/N_p}{n\times V_t}\right)\right] - I_{sh} \quad (2)$$

3.2.2. Modeling of the battery

Battery is an electrical generator formed by a combination of several cells constituted of positive and negative electrodes joined by an electrolyte; these cells use the electrochemical properties of an oxidant-reluctant pair and convert chemical energy into electrical energy [2]. The storage modeling is based on equivalent circuit model (ECM). The ECM is widely used due to its simplicity and ability to provide accurate predictions for many applications. It is comprises a voltage source (V_{oc}) (open-circuit voltage) in series with an internal resistance (R_b), the Battery current (I_b) and the state of charge (SOC), The terminal voltage (V_t) is given by [2]

$$\boldsymbol{V_t = V_{oc} - \left(K\frac{\int I_b dt}{Q_0}\right) - R_b I_b} \qquad \textbf{(3)}$$

Where: K is a constant , Q_O = Capacity of the battery (Ah),

$$\text{SOC} = 100 \times \left(1 + \frac{\int I_b dt}{Q_0}\right) \qquad (4)$$

3.2.3. Modeling of the Inverter Block

An inverter is a DC–AC power electronic converter that synthesizes an AC voltage from a DC link using semiconductor switches (MOSFETs/IGBTs) driven by sinusoidal pulse-width modulation (SPWM) [8][9].The output voltage and current of a single phase full bridge inverter can be expressed as[10][11]:

$$V_o(t) = M.\frac{V_{dc}}{2}.\sin(wt) \qquad (5)$$

$$I_o(t) = \frac{V_o(t)}{Z_L} \qquad (6)$$

Where:

$V_o(t) ==$ instantaneous AC output voltage
V_{dc} = input DC voltage from the battery or DC source
M= modulation index ($0 \le M \le 1$)
ω = angular frequency of the output waveform
$I_o(t)$= output current
Z_L= Load impedance

3.2.4. Modeling of the Transformer

A transformer is a magnetic coupling device primarily composed of windings wound around a shared core. Its operation is governed by electromagnetic induction, where varying current through one winding (the primary) induces voltage in other (the secondary) via mutual flux linkage [8].For real transformers; an equivalent circuit model is commonly used due to its clarity and ability to predict performance in power system simulations. For an ideal multi-winding transformer, the voltage-to-turns ratio and the ampere-to- turn ratio are constant across all windings and given as[12][13]:

$$\frac{V_P}{N_P} = \frac{V_S}{N_S} \;, \qquad \frac{I_P}{I_S} = \frac{N_S}{N_P} \qquad (7)$$

Vp,Vs are primary and secondary voltage, I_p, I_S are the primary and secondary current, Ns, Np are the primary and secondary number of turns of the transformer.

3.2.5. Modeling of the electrode Arc ignition

Modeling of electrode arc ignition in DC welding machines focuses on the dynamics of arc initiation and the stability of the welding arc. Recent studies have explored nonlinear models that simulate the arc characteristics by considering factors such as welding current, voltage, electrode movement, electrical and thermal phenomena during ignition [14]. The arc voltage (Va) is a function of the Dc voltage (Va=Vt), while the welding current (I) is directly dependent on the DC current (Ib). This is because the battery provides the electrical energy that drives the welding process. The welding current is the amount of current that flows through the electrode and the work piece, creating the arc necessary for welding. While the battery current represents the flow of charge from the battery supplying the power, equation 3 can be expressed as;

$$\boldsymbol{V_a = V_{oc} - \left(K\frac{\int I_b dt}{Q_0}\right) - R_b I_b} \quad \textbf{(8)}$$

The welding current (I) is expressed as;

$$\boldsymbol{I = \frac{V_a}{R_a}} \quad (9)$$

Where, R_a is the arc Resistance and it is given as;

$$\boldsymbol{R_a = \frac{l_a}{A_c . \sigma_a}} \quad (10)$$

Where:

$\boldsymbol{l_a}$ is the arc length (m) (distance between the electrode and the workpiece).

$\boldsymbol{A_c}$ is the cross-sectional area of the arc (m^2)

$\boldsymbol{\sigma_a}$ is the electrical conductivity of the plasma (S/m).

The heat generated by the arc is transferred to the work piece, causing melting and fusion. The heat input (Q) into the work piece can be described as:

$$Q = \eta . P_a = \eta . V_a . I \quad (11)$$

Where:

η is the thermal efficiency of the welding process (typically around 0.7 to 0.9 for DC welding).

P_a is the arc power (W)

The heat conduction in the workpiece can be modeled by the heat diffusion equation:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p}\nabla^2 T + \frac{Q}{\rho c_p} \quad (12)$$

Where:

T is the temperature (K)

t is the time (s)

k is the thermal conductivity (W/m·K)

ρ is the density of the material (kg/m^3)

c_p is the specific heat capacity (J/kg·K)

$\nabla^2 T$ is the Laplacian of the temperature, representing heat diffusion.

3.2.6. Modeling of the controller

The fuzzy logic controller is designed to manage the power distribution dynamically, ensuring optimal utilization of solar energy while maintaining seamless operation. The fuzzy logic controller uses linguistic variables and a set of rules to determine the power distribution strategy. Key inputs include:

1. Solar Irradiance (G) : Indicates the available solar power.
2. Utility power supply
3. Battery State of Charge (SOC): Reflects the energy stored in the battery.(Use terminal voltage (Vt)

Figure 2 represent the fuzzy inference system for the inputs and output of the fuzzy controller.

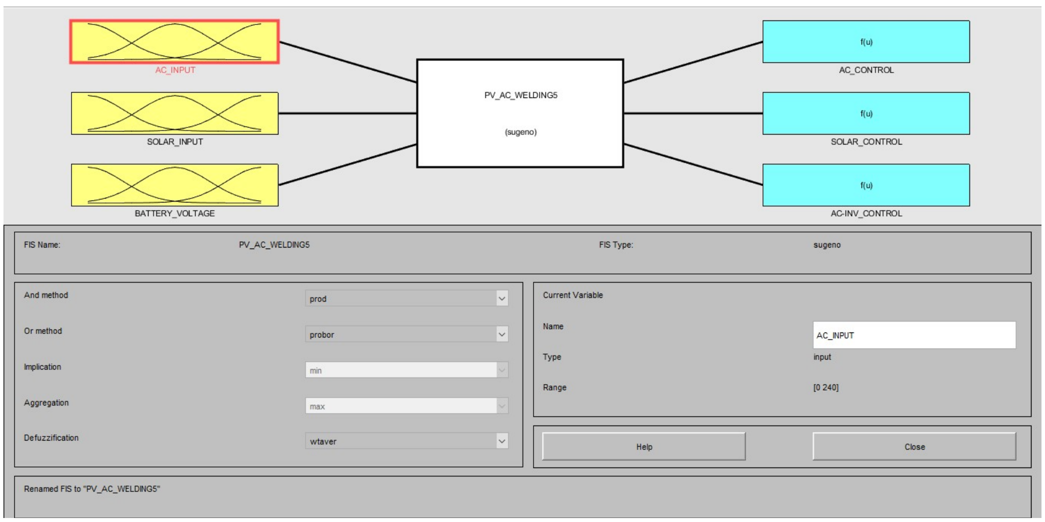

Figure 2: Fuzzy logic Energy optimization and control

The rule base consists of a set of five (5) if-then rules that define the control strategy. The inference mechanism processes the inputs and applies the rules to determine the outputs actions, such as:

i. Prioritizing PV power usage when solar irradiance is high.
ii. Utilizing battery power during peak demand periods.
iii. Switching to grid power when PV is insufficient and battery bank is low
iv. Shutting down of the system when the two power sources are not available and the battery voltage is drained below the threshold.

The fuzzy rules for the system optimization are:

1. If (AC_INPUT is HIGH) and (SOLAR_INPUT is HIGH) then (AC_CONTROL is LOW)(SOLAR_CONTROL is HIGH)(AC-INV_CONTROL is LOW) (1)
2. If (AC_INPUT is HIGH) and (SOLAR_INPUT is LOW) then (AC_CONTROL is HIGH)(SOLAR_CONTROL is LOW)(AC-INV_CONTROL is HIGH) (1)
3. If (AC_INPUT is LOW) and (SOLAR_INPUT is HIGH) then (AC_CONTROL is LOW)(SOLAR_CONTROL is HIGH)(AC-INV_CONTROL is LOW) (1)

4. If (AC_INPUT is LOW) and (SOLAR_INPUT is LOW) and (BATTERY_VOLTAGE is HIGH) then (AC_CONTROL is LOW)(SOLAR_CONTROL is HIGH)(AC-INV_CONTROL is LOW) (1)

5. If (AC_INPUT is HIGH) and (SOLAR_INPUT is LOW) and (BATTERY_VOLTAGE is LOW) then (AC_CONTROL is LOW)(SOLAR_CONTROL is LOW)(AC-INV_CONTROL is LOW) (1)

Figure 3 represent the fuzzy rule base

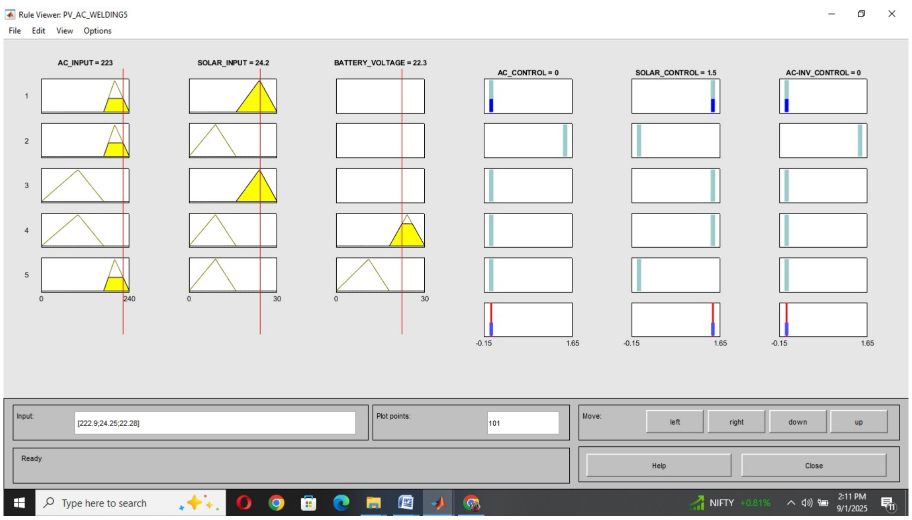

Figure 3: Fuzzy logic rule base

MATLAB/Simulink is used for simulating the power flows and control strategies. Figure 4 represent the simulink model developed from equation 1 to equation 12 that will provide analysis on the system's behavior under various operating conditions.

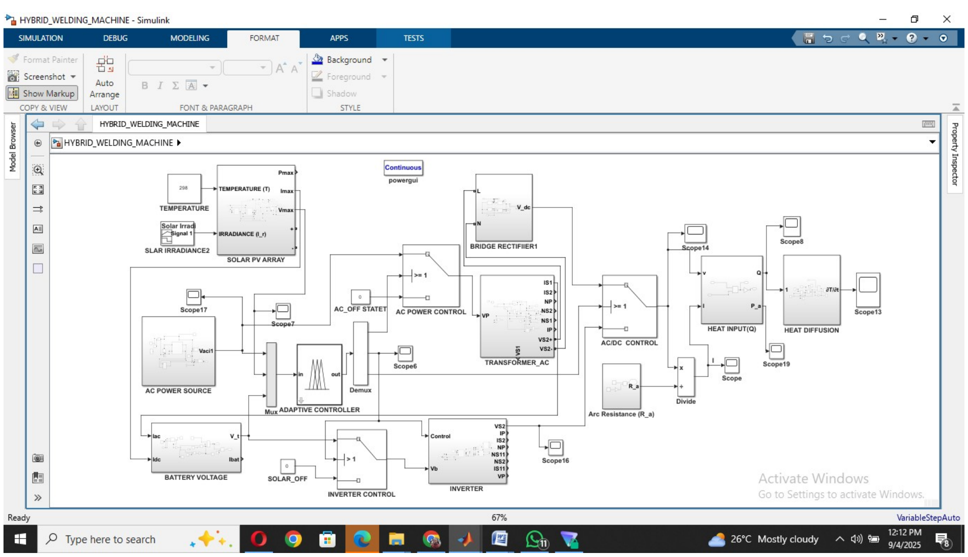

Figure 4: Simulink Model for Hybrid Solar Welding Machine

4.0. System Optimization

The hybrid system is optimized through simulation and experimental validation. Key optimization goals include maximizing solar energy utilization, minimizing grid power consumption, and ensuring stable welding performance.

4.1. Optimization Framework

In a hybrid energy system for welding machines, one of the key issues is how to allocate the available energy sources (solar PV, battery bank, and AC utility) adaptively in order to optimize the system performance under practical constraints. The system uses fuzzy logic control to optimize energy use by applying rule-based allocation among the three energy sources. The rule-based decision framework governs the allocation among the three energy sources, thereby formulating a multi-objective optimization problem.

Decision Variables

i. Utilization of Solar PV (kWh)
ii. Utilization of Battery Bank (kWh)
iii. Utilization of AC Utility (kWh)

Constraints

i. Solar irradiance availability (G, W/m²)
ii. Battery State of Charge (SOC, %)
iii. AC supply availability (binary ON/OFF)
iv. Load demand (P_{load}, kW)

Objective Functions

1. **Objective Function 1 (Maximize Energy Savings)**

Energy savings are defined in terms of reduced grid (AC utility) usage relative to a baseline system powered entirely by grid electricity:

$$F_1(\mathrm{E_{savings}}) = Max\left(\frac{E_{\mathrm{grid,baseline}} - E_{\mathrm{grid,hybrid}}}{E_{\mathrm{grid,baseline}}} \times 100\right) \qquad (13)$$

Where:

$E_{\mathrm{grid,baseline}}$ = Energy consumption from grid in the baseline system (kWh)
$E_{\mathrm{grid,hybrid}}$ = Energy consumption from grid in the hybrid system (kWh)

Subject to:

$$\begin{Bmatrix} \mathrm{SOC}, & \mathrm{SOC}_{min} \leq \mathrm{SOC} \leq \mathrm{SOC}_{min} \\ \mathrm{G}, & \mathrm{G} \geq \mathrm{G}_{min} \\ \mathrm{P}_{Load}, & \mathrm{P}_{Load} \leq \mathrm{P}_{max} \end{Bmatrix}$$

Objective Function 2 (Minimize Cost of Energy Use)

$$F_2 = \text{Min}(\text{Cgrid} \times \text{E}_{\text{savings}}) \tag{14}$$

C_{grid} = cost per kWh of utility power
$\text{E}_{\text{savings}}$ = Energy Saved

The system efficiency metric is given as:

$$\boldsymbol{\eta_{sys}}(t) = \frac{\boldsymbol{P_a(t)}}{\boldsymbol{P_{PV}(t)+P_{grid}(t)+P_{bat}(t)}} \times 100 \tag{15}$$

Where: $P_{PV}(t)$ *is the* power generated from then solar panels,
$P_{grid}(t)$ *is the Ac supply power*, $P_{bat}(t)$ *is the battery power*

5. Experimental Setup

Based on the simulation studies, a prototype hybrid welding machine was developed and constructed. The system integrates a photovoltaic (PV) array, utility grid supply, and battery storage, all coordinated through a microcontroller-based fuzzy logic control unit. The prototype was built to validate the simulation outcomes and assess the performance of the proposed optimization strategy. The developed prototype was successfully tested under different operating conditions, demonstrating the feasibility of the hybrid configuration. Figure 5 illustrates the experimental setup.

6. Results

The simulation results are presented in Figure 6. The AC input voltage (Figure 1) shows a stable sinusoidal waveform of about ±200 V, which is effectively rectified to produce a steady welding output voltage of approximately 50 V (Figure 3). The solar PV input (Figure 2) maintains a nearly constant DC level around 25.6 V with a slight rise, confirming its contribution as a supplementary source. The welding output current (Figure 4) rapidly rises and stabilizes at about 70 A, demonstrating the system's ability to supply sufficient and stable current for welding. Overall, the results validate that the hybrid system delivers reliable voltage and current outputs suitable for welding operations.

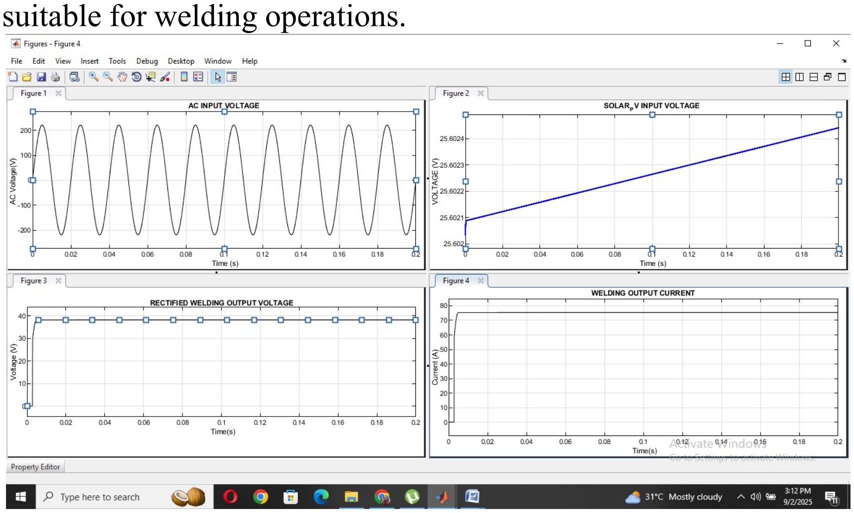

Figure 6: Simulation results

The simulation outputs in Figure 7 illustrate the inverter and welding arc performance. The inverter AC voltage (Figure 1) shows a stable sinusoidal waveform, confirming proper inverter operation. The arc power (Figure 2) rapidly increases and stabilizes at approximately 2500 W, ensuring sufficient power delivery for welding. Similarly, the output power (Figure 4) rises quickly and remains steady at about 3000 W, reflecting the system's capacity to sustain the welding load. The total arc heat energy (Figure 3) also stabilizes at around 2000 J, indicating consistent thermal energy supplied to the weld zone. These results validate the inverter's efficiency and the hybrid system's ability to provide stable power and heat energy required for reliable welding performance.

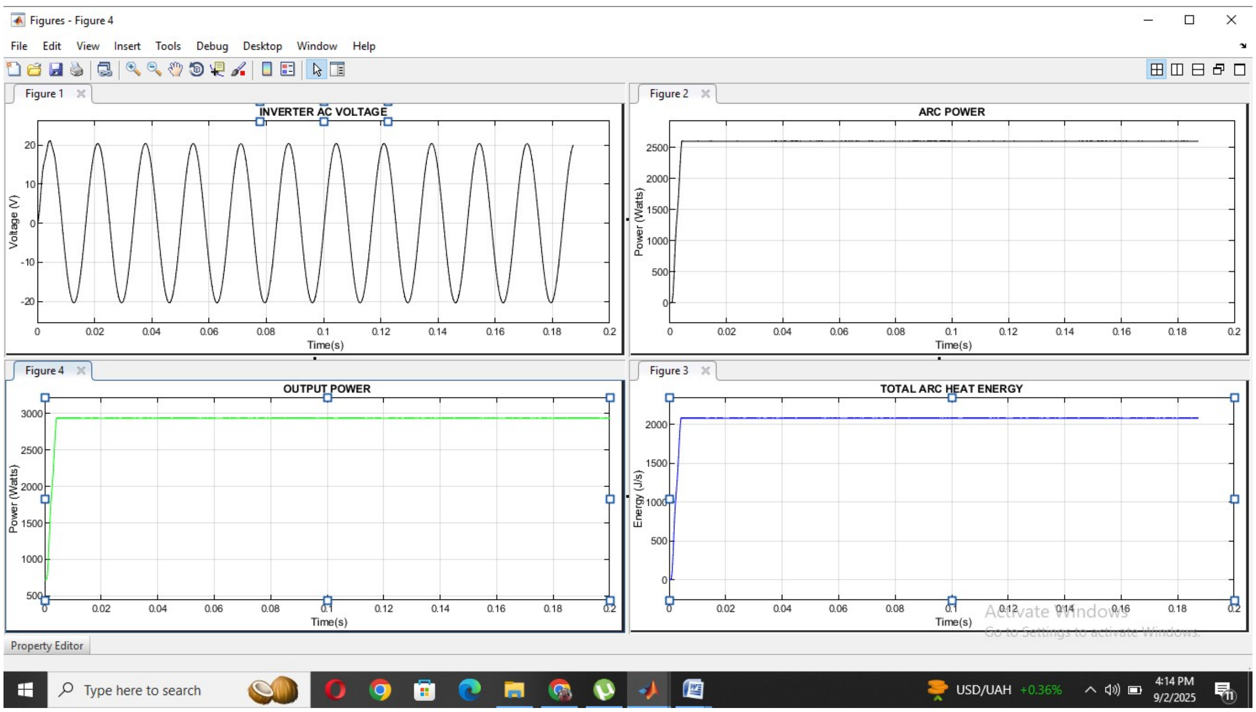

Figure 7: Simulated Output parameters

The simulation result in Figure 8 illustrates the System efficiency and the energy saving performance. The System efficiency quickly settles around **≈63–64%** , indicating stable conversion under load. The Energy-Savings curve (right plot) steps from ~0% to a peak near **≈50%**, then settles **≈40–38.8%**, showing the fuzzy-rule controller is reducing grid supply drawn by roughly by 40% once PV/battery support the load.

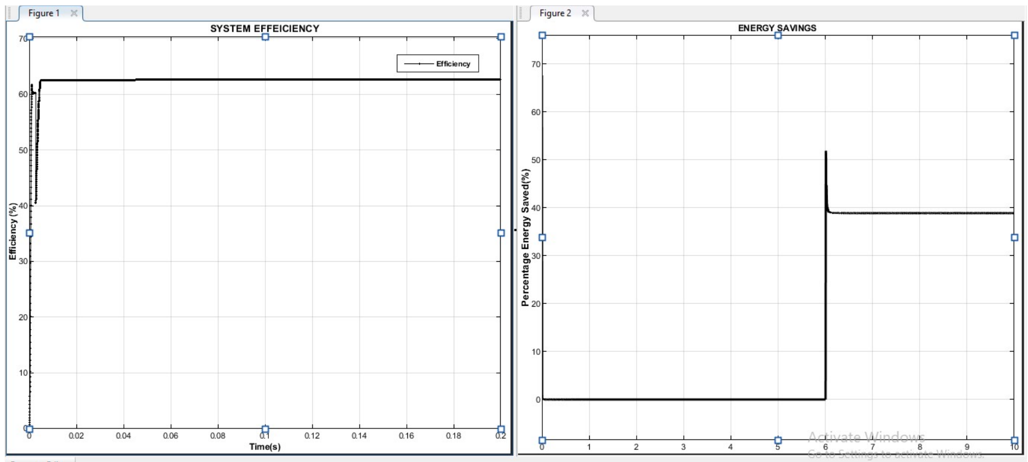

Figure 8: Simulation Results of output Performance Test

The cost-saving potential of the hybrid welding system was evaluated from figure 8, using equation 14: $\text{Cost Saving} = \text{Cgrid} \times E_{\text{savings}}$, where Cgrid is assumed to be =₦220kWh and $E_{savings}$ is the energy saved through reduced grid consumption. From the simulation, the welding load demand was approximately 3 kW, corresponding to 3 kWh of energy per hour. With the average energy savings at 38.8% as indicated in the simulation results, the system saved 1.16kWh per hour ($E_{savings}$= 0.385×3). This translates to cost savings of approximately ₦255.20 savings (₦220×1.16) at 38.8%. For over an 8-hour working shift, this amount will be ₦2,041.60, demonstrating significant economic benefits of the proposed hybrid configuration.

The experimental prototype was subjected to different operating scenarios to evaluate its performance. Tests were conducted under varying solar irradiance, battery state-of-charge levels, and availability of grid supply. The results showed that the fuzzy logic control effectively prioritized solar power utilization, ensured smooth switching between sources, and maintained welding stability. Energy savings were achieved by reducing dependence on utility supply whenever sufficient solar and battery energy were available. The system also demonstrated reliable response to sudden load changes, with the microcontroller-based control ensuring minimal welding arc interruption. Furthermore, the prototype validated the accuracy of the simulation results, confirming that the optimization strategy based on fuzzy logic rules is both practical and efficient for real-world operation.

7. Conclusion

The hybrid PV and utility-powered welding machine, managed by a fuzzy logic controller, offers a promising solution for enhancing energy efficiency and reliability in welding operations. This study demonstrates the feasibility and advantages of a PV Hybrid Welding Machine in industrial applications. The integration of PV technology not only reduces energy consumption but also promotes the use of renewable energy sources in manufacturing. Future work will focus on scaling the system for larger applications and exploring other renewable energy integrations.

References

[1] R. Ahshan, A. M. Al-Hanshi, M. A. Al-Naabi, H. A. Al-Hashmi, and A. H. Al-Badi, "Design and economic analysis of a grid-connected rooftop solar PV system for typical home applications in Oman," *Electrical Science & Engineering*, vol. 2, no. 2, pp. 15–23, 2020.

[2] F. E. Tahiri, K. Chikh, and M. Khafallah, "Optimal management energy system and control strategies for isolated hybrid solar-wind-battery-diesel power system," *Emerging Science Journal*, vol. 5, no. 2, pp. 1–12, Apr. 2021.

[3] J. C. León Gómez, S. E. De León Aldaco, and J. A. Alquicira, "A review of hybrid renewable energy systems: architectures, battery systems, and optimization techniques," *Eng.*, vol. 4, no. 2, pp. 1446–1467, 2023.

[4] C. Ammari, D. Belatrache, B. Touhami, and S. Makhloufi, "Sizing, optimization, control and energy management of hybrid renewable energy system—A review," *Energy and Built Environment*, vol. 3, no. 4, pp. 399–411, 2022.

[5] Q. Liao, Y. Zhang, Y. Tao, J. Ye, and C. Li, "Economic analysis of an industrial photovoltaic system coupling with battery storage," *Int. J. Energy Res.*, vol. 43, no. 12, pp. 6461–6474, 2019.

[6] M. B. Smida and A. Sakly, "Fuzzy logic control of a hybrid renewable energy system: A comparative study," *Wind Eng.*, vol. 45, no. 4, pp. 793–806, 2021.

[7] S. Rawat, B. Jha, and M. K. Panda, "Operation and control of a hybrid isolated power system with type-2 fuzzy PID controller," *Iranian J. Sci. Technol., Trans. Electr. Eng.*, vol. 42, no. 4, pp. 403–417, 2018.

[8] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*. Hoboken, NJ, USA: Wiley, 2003.

[9] R. Musona and I. Serban, "Differential single-phase inverters with active power decoupling: A survey," *IEEE Access*, vol. 11, pp. 53654–53670, 2023.

[10] S. Jayalath, "Design of LCL-filters for grid-connected voltage source inverters," *Electronics*, vol. 5, no. 4, pp. 1–12, 2016.

[11] R. L. Maurya and M. Rajeev, "Implementation of multilevel DC-link inverter for standalone application," in *Proc. Int. Conf. Nascent Technol. Eng. (ICNTE)*, 2017, pp. 1–6.

[12] J. D. Glover, T. Overbye, and M. Sarma, *Power System Analysis and Design*, 6th ed. Boston, MA, USA: Cengage Learning, 2011.

[13] R. W. Erickson and D. Maksimović, *Fundamentals of Power Electronics*, 3rd ed. Cham, Switzerland: Springer, 2020.

[14] J. Zhang, S. Chen, H. Zhao, Y. Yu, and M. Liu, "Designing a multi-output power supply for multi-electrode arc welding," *Electronics*, vol. 12, no. 7, p. 1702, 2023.

.