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Fuzzy Logic Control for Managing the Reduction of Electrical Energy in the Smart Irrigation System

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Abstract: - South Africa's expanding energy consumption, encouraged by growth in agricultural automation and electrical schemes, puts the national grid's sustainability at risk. Farmers require efficient energy management systems to adopt smart technologies and integrate renewable energy sources into their smart irrigation system. Thus, the current research aims to apply a Fuzzy Logic Control based Energy Management System to demonstrate the energy use efficiency for smart irrigation system by flexibly managing energy consumption in real-time, reflecting environmental conditions like soil moisture, climate temperature, and the accessibility of green energy solutions. The results indicate that under the given environmental conditions, the predicted power consumption stabilizes at a medium level (50.0), reflecting a balanced energy demand. These findings align with previous studies that highlight the effectiveness of fuzzy logic in adaptive energy management. Based on simulation of the current study the optimized irrigation system consistently consumes 80 units of power, the fuzzy logic system averaging around 50–55 units under varying environmental conditions saves approximately 25–30 units per cycle, or about 31–37.5% in power consumption. The importance of this research is rooted in its pragmatic implications for agricultural practitioners in South Africa, facilitating a reduction in operational expenditures, the enhancement of irrigation timetables, and the mitigation of reliance on non-renewable energy resources. The system additionally aims to address the constraints inherent in traditional irrigation methods, offering a financially viable and accessible solution aimed at enhancing energy utilization and facilitating the integration of renewable energy sources.

Keywords: Fuzzy Logic Control, Energy Management System, Smart Irrigation Systems, Renewable Energy Integration, Sustainable Agriculture

I. INTRODUCTION

The agricultural sector is a cornerstone of South Africa's economy, providing employment and contributing significantly to food security. However, the industry is heavily reliant on energy for its operations, ranging from irrigation to post-harvest processing. Recent years have seen increasing challenges due to rising energy costs, energy insecurity, and the national grid's inability to meet demand, exacerbated by ongoing load-shedding [1]. As South Africa transitions toward sustainable development, the integration of renewable energy systems into agriculture has emerged as a viable solution. Yet, this integration faces obstacles such as the variability of renewable energy sources, high upfront costs, and limited technological adoption among farmers.

Farmers rely on irrigation systems to ensure consistent crop yields, but the associated electricity costs often strain their resources. While smart irrigation technologies are increasingly recognized for their water-saving potential, their ability to optimize electricity usage has been underexplored [2]. In the quest for sustainable energy management, predicting power consumption has become a critical component of optimizing renewable energy utilization. Traditional energy management systems often rely on rigid models that struggle to handle the inherent uncertainties present in environmental factors such as soil moisture, temperature, and renewable energy availability [3]. To address these challenges, fuzzy logic-based models provide an effective alternative by incorporating linguistic variables and rule-based decision-making, allowing for adaptive and precise power consumption predictions. This study explores the application of fuzzy logic in predicting power consumption within an energy management framework, focusing on soil moisture, temperature, and renewable energy as key influencing factors.

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The study was conducted at South African farms to help farmers improve energy efficiency by optimizing power consumption in real time during the irrigation of their plantations [3]. Energy management in agriculture is crucial, as inefficient energy use leads to higher costs and excessive strain on power grids [4]. By implementing a fuzzy logic-based approach, farmers can dynamically adjust their energy consumption based on real-time environmental conditions, ensuring that irrigation systems operate efficiently without unnecessary energy waste. For example, when soil moisture levels are sufficient, the system can reduce irrigation power consumption, while in dry conditions, energy usage can be increased strategically to meet water demands without overconsumption.

II. Research Objectives

The study aims to demonstrate how Fuzzy Logic Energy Management System can optimize power consumption for South African farmers by dynamically adjusting energy use in real time based on environmental conditions such as soil moisture, temperature, and renewable energy availability. The goal is to enhance energy efficiency during irrigation, reduce electricity costs, and integrate renewable energy sources effectively while ensuring sustainable farming practices. By leveraging renewable energy sources and smart technologies, the system aims to address the following specific objectives:

- To analyze the impact of environmental factors on power consumption and determine how fuzzy logic can provide adaptive energy management for irrigation systems.
- To demonstrate how rule-based Fuzzy Logic Energy Management System can reducing unnecessary power usage while ensuring adequate irrigation.
- To validate the effectiveness of the Fuzzy Logic Energy Management System through experimental results, demonstrating its ability to balance energy supply and demand efficiently.

By meeting these objectives, the study aims to enhance the resilience and sustainability of South African agriculture, aligning with national energy policies and global sustainability goals

III. Research gap

Energy management in agriculture, particularly for irrigation systems, remains a critical challenge for African farmers due to high electricity costs, inefficient energy use, and limited integration of renewable energy sources [1]. Traditional irrigation methods rely on fixed power consumption schedules, leading to unnecessary energy waste and financial strain on farmers, especially in rural areas where access to affordable electricity is limited [5]. Existing energy management solutions often fail to consider real-time environmental factors such as soil moisture, temperature, and renewable energy availability, resulting in suboptimal power usage [6].

Despite advancements in smart irrigation and energy-efficient farming, there is a lack of adaptive energy management systems that dynamically adjust power consumption based on environmental conditions [7]. Many current models use rigid algorithms that do not effectively handle uncertainties in agricultural energy demand, making them unsuitable for real-world applications [8]. While existing studies emphasize water conservation in smart irrigation systems [1], limited research explores their role in reducing electricity consumption. This study aims to address this gap by designing an FLC-based EMS to optimize energy usage in irrigation, helping farmers adopt sustainable energy practices and reduce grid dependency. This study addresses these gaps by developing a fuzzy logic-based energy management system (EMS) tailored for South African farms. By incorporating real-time environmental inputs, this system aims to enhance energy efficiency, reduce costs, and improve irrigation scheduling, providing a sustainable solution for precision agriculture [9].

The integration of smart technologies into agriculture has been a focal point of research in recent years, particularly in the context of energy management. Studies have highlighted the potential of Fuzzy Logic and other advanced computational techniques in optimizing energy use and integrating renewable energy systems. This section reviews recent literature on Fuzzy Logic-based Energy Management Systems (EMS), renewable energy integration, and the adoption of smart technologies in agriculture.

A. Fuzzy Logic in Energy Management

Fuzzy Logic has gained traction as an effective tool for managing energy systems, particularly those involving renewable energy sources. Singh and Annapoorna, [8] demonstrated that Fuzzy Logic-based EMS could significantly improve energy efficiency by dynamically adjusting energy consumption in response to varying supply and demand. Similarly, Kumar et al. [10] developed a Fuzzy Logic model for microgrids, reporting a reduction in grid power fluctuations and enhanced renewable energy utilization. These findings underscore the adaptability and efficiency of Fuzzy Logic in complex, real-world applications.

Fuzzy Logic Control has emerged as a powerful tool for managing complex, nonlinear systems. Its application in energy management has shown promise in improving efficiency and reliability [11]. This study extends Fuzzy Logic Control 's use to smart irrigation systems to achieve electricity savings.

B. Renewable Energy Integration

The integration of renewable energy into agriculture has been widely studied, with a focus on solar and wind energy systems. Pestisha et al. [4] examined hybrid solar-wind systems, finding that advanced EMS could optimize performance and reduce costs. However, the study highlighted challenges such as high initial investment and the need for skilled personnel. In the South African context, Durga et al. [3] noted that renewable energy adoption in agriculture is hindered by infrastructural and financial barriers. The study recommended tailored solutions that address farmers' specific needs and constraints.

C. Adoption of smart technologies in agriculture

The adoption of smart technologies in agriculture remains a critical area of research. According to Mhlanga and Ndhlovu [2], the slow uptake of smart irrigation systems in South Africa is driven by limited awareness, high costs, and a lack of localized solutions. By contrast, studies in developed countries have shown that smart systems can significantly enhance productivity and sustainability. Research by [12] emphasized the role of education and training in promoting technology adoption, highlighting the need for user-friendly and cost-effective solutions tailored to the local context. Smart irrigation leverages IoT sensors, automated controls, and data analytics to optimize water and energy use [5]. Studies show that IoT-enabled systems significantly improve resource management, but the emphasis is often on water savings rather than energy efficiency [13].

D. Challenges and Opportunities of smart technologies in agriculture

While the potential benefits of smart technologies are well-documented, several challenges remain. High costs, technical complexity, and connectivity issues are common barriers to adoption, as noted by Singh and Annapoorna [8] and Durga [4]. However, opportunities for growth exist, particularly in the development of low-cost, scalable solutions. The use of historical and forecast data, as demonstrated in recent studies, offers a pathway to more efficient and sustainable energy management systems.

IV. RESEARCH METHODOLOGY

Fuzzy logic, first introduced by Zadeh in 1965, provides a computational approach that deals with imprecision and uncertainty in decision-making [14]. Unlike conventional binary logic, which classifies inputs as strictly true or false, fuzzy logic assigns degrees of truth, enabling a nuanced and dynamic approach to modeling complex real-world interactions [14]. This study employs a Mamdani-style fuzzy inference system, utilizing membership functions and fuzzy rules to determine power consumption levels. By integrating trapezoidal and triangular membership functions, the system categorizes soil moisture, temperature, and renewable energy into low, medium, and high levels, allowing for a flexible transition between states.

A. Understanding Fuzzy Logic-Based Power Consumption Prediction

In modern energy management systems, predicting power consumption is critical for optimizing renewable energy usage and ensuring sustainable energy distribution [10]. This paper explores the application of fuzzy logic in predicting power consumption using inputs such as soil moisture, temperature, and renewable energy availability. The implementation follows a Mamdani-style fuzzy inference system, where linguistic variables help in modeling complex, real-world energy interactions.

B. Fuzzy Logic and Its Application

Fuzzy logic provides a framework to handle uncertainty and imprecision in data-driven decision-making [13]. Unlike classical binary logic, which categorizes inputs strictly as true or false, fuzzy logic assigns degrees of truth to variables, enabling nuanced and adaptive control mechanisms. Table 1 shows the variables that are typically used in intelligent energy management systems. The first three are input variables that influence the system's decision-making, while the last one is the output variable being predicted or controlled.

TABLE 1. INPUT AND OUTPUT VARIABLES:

Variable	Type	Range	Description
Soil Moisture	Input	0–100%	Indicates how much water is present in the soil. A key parameter in agricultural systems. Low soil moisture suggests dry conditions, prompting irrigation or energy for pumping systems.
Temperature	Input	-10 to 50°C	Reflects ambient environmental temperature. It affects both plant growth (in agriculture) and energy needs (e.g., heating or cooling in buildings).
Renewable Energy	Input	0–100%	Represents the real-time availability or production level of renewable energy sources like solar or wind. A higher percentage means more clean energy is available for use.
Power Consumption	Output	0–100%	This is the output variable that the system predicts or regulates. It reflects how much energy should be consumed based on the current environmental and energy conditions.

C. Membership Functions

The provided table 1 categorizes three fuzzy set levels which is Low, Medium, and High and associates each with a type of membership function used in fuzzy logic systems.

TABLE 2. FUZZY LEVEL AND MEMBERSHIP TYPE

Fuzzy set level	membership function type
Low	Trapezoidal
Medium	Triangular
Higher	Trapezoidal

These membership functions allow fuzzy inference rules to evaluate energy needs dynamically.

D. Fuzzy Inference Rules and System Design

The fuzzy system utilizes a rule-based approach where different combinations of inputs dictate the output (power consumption). In this study the following rules are included:

a) If soil moisture is low AND temperature is hot, THEN power consumption is high.
b) If renewable energy is high, THEN power consumption is low.
c) If soil moisture is medium AND temperature is moderate, THEN power consumption is medium.

These rules help map the input conditions to power consumption using the Mamdani inference method, with defuzzification via the centroid technique.

E. Logic flow diagram

Figure 1 represents a fuzzy inference model for predicting power consumption. It starts with three input variables of Soil Moisture, Temperature, and Renewable Energy which are passed to the Fuzzification block. Here, crisp values are converted into fuzzy sets (e.g., Low, Medium, High). The Fuzzy Inference block applies predefined rules (e.g., "If soil moisture is low and temperature is hot, then power consumption is high"). The resulting fuzzy outputs are then converted back to a crisp value in the Defuzzification stage using the centroid method. The final output is a predicted Power Consumption level, allowing the system to adaptively manage energy use under varying environmental conditions.

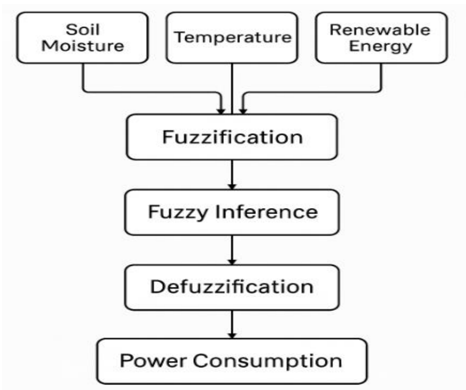

FIGURE 1: FUZZY LOGIC MODEL

V. THE RESULTS AND DISCUSSIONS

The FLC-based EMS was implemented using a Mamdani-style fuzzy inference system in Python. The model was simulated across 1,000 combinations of soil moisture, temperature, and renewable energy availability. The system dynamically responded to input fluctuations, maintaining power consumption within efficient medium levels in most cases, particularly under moderate soil moisture and temperature with medium to high renewable energy availability. Graphical visualizations confirmed the system's adaptability, and future work will compare these outputs with real-world energy data for performance benchmarking.

The generated membership function graphs provide a visual representation of the interaction between soil moisture, temperature, renewable energy, and power consumption. These functions illustrate how input variables transition across different categories, demonstrating the flexibility and adaptability of fuzzy logic systems in handling real-world uncertainties. The results indicate that the predicted power consumption value is 50.0, placing it within the medium range. This outcome suggests that under the given environmental conditions, energy requirements are balanced without extreme power demands.

The given Figure 1 is a membership function plot for a fuzzy logic system, representing soil moisture levels categorized into three linguistic variables: "low," "medium," and "high." The x-axis represents soil moisture values ranging from 0 to 100, while the y-axis indicates the degree of membership, ranging from 0 to 1. The blue line represents "low" soil moisture, showing full membership at 0 and gradually decreasing to 0 at around 50. The orange line corresponds to "medium" soil moisture, which starts increasing from 0 at around 20, reaches full membership at 50, and then declines to 0 at about 80. The green line represents "high" soil moisture, beginning at 0 around 50, increasing to full membership at 80, and remaining at 1 beyond this value. This triangular membership function structure is commonly used in fuzzy logic control systems for irrigation and soil moisture monitoring, allowing smooth transitions between moisture categories for effective decision-making.

A. Soil moisture

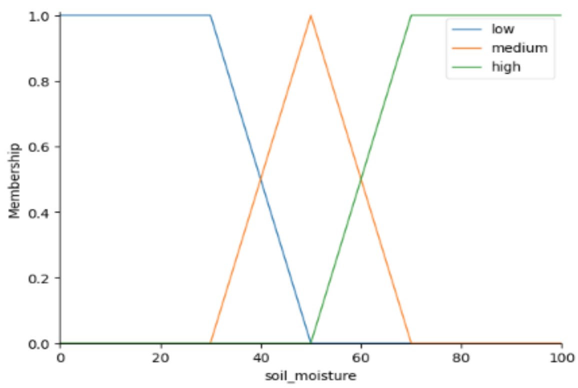

FIGURE 2. SOIL MOISTURE LEVEL

Soil moisture, a critical factor in agricultural and industrial applications, exhibits a gradual transition from low to high. This characteristic aligns with previous research highlighting the nonlinear relationship between soil moisture levels and energy usage in irrigation systems [9]. As soil moisture increases, power consumption varies based on the efficiency of irrigation methods and the availability of renewable energy sources. Studies suggest that smart irrigation techniques incorporating fuzzy logic can reduce water and energy waste while optimizing resource allocation [7, 9].

B. Temperature

Figure 2 below displays a fuzzy membership function plot for temperature classification into three categories: "cold," "moderate," and "hot." The x-axis represents temperature values ranging from approximately -10 to 50, while the y-axis indicates the membership degree, ranging from 0 to 1. The blue line represents "cold" temperatures, with full membership at lower temperatures (below 10) and gradually decreasing to 0 around 20. The orange line corresponds to "moderate" temperatures, beginning from 0 at around 5, reaching full membership at 20, and tapering off to 0 near 30. The green line represents "hot" temperatures, starting at 0 near 20, increasing to full membership at 30, and remaining at 1 beyond this value. This triangular membership function structure is commonly used in fuzzy logic systems to model temperature control, ensuring smooth transitions between categories. It is useful in applications such as climate regulation, HVAC systems, and decision-making processes based on environmental temperature conditions.

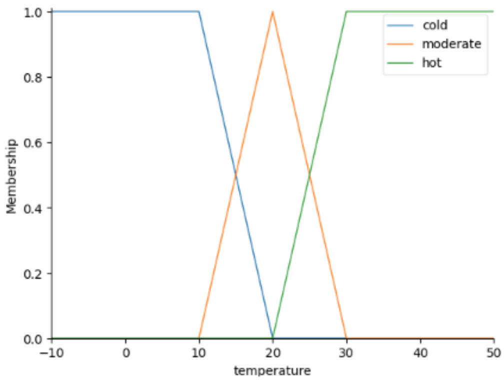

FIGURE 3. TEMPERATURE CONTROL VALUES

Temperatures are another key variable influencing power consumption. The membership function graph reveals three distinct categories: cold, moderate, and hot, with overlapping transitions. This classification is consistent with thermal energy modeling research, which emphasizes the role of temperature fluctuations in determining energy needs [4] and [15] Cold temperatures generally require additional heating, increasing energy demand, while hot conditions lead to higher cooling needs. The moderate temperature range, where the predicted power consumption falls, suggests an equilibrium state where extreme heating or cooling is unnecessary, corroborating findings from adaptive energy management studies [9]

C. Renewable energy

Figure 3 depicts a fuzzy membership function plot for categorizing renewable energy levels into three linguistic variables: "low," "medium," and "high." The x-axis represents renewable energy levels ranging from 0 to 100, while the y-axis indicates the membership degree, varying between 0 and 1. The blue line corresponds to "low" renewable energy, showing full membership at values below 40 and decreasing to 0 around 60. The orange line represents "medium" renewable energy, starting from 0 at approximately 30, reaching full membership at 50, and tapering off to 0 near 70. The green line signifies "high" renewable energy, beginning from 0 around 50, increasing to full membership at 80, and remaining at 1 beyond that value. This triangular membership function model is commonly used in fuzzy logic applications for energy management, enabling smooth transitions between categories. It is beneficial in decision-making for sustainability policies, grid management, and optimizing renewable energy integration.

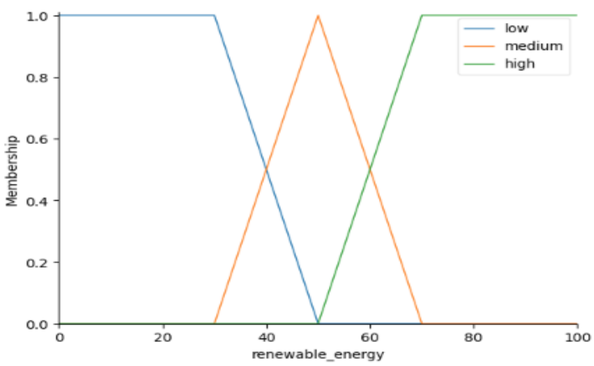

FIGURE 4. RENEWABLE ENERGY LEVELS

Renewable energy availability significantly impacts power consumption, as illustrated by its membership function. The correlation between renewable energy and power demand has been widely studied, with findings indicating that renewable energy integration can stabilize energy consumption patterns [5]. When renewable energy is abundant, reliance on conventional power sources decreases, contributing to sustainability goals. The fuzzy logic model effectively captures this relationship, supporting previous research advocating for intelligent energy systems that dynamically adjust based on renewable availability [6].

D. Power consumption

Figure 4 illustrates a fuzzy membership function plot that categorizes power consumption levels into three linguistic variables: "low," "medium," and "high." The x-axis represents power consumption levels from 0 to 100, while the y-axis denotes the membership degree, ranging from 0 to 1. The blue line represents "low" renewable energy, with full membership below 40 and gradually decreasing to 0 around 60. The orange line corresponds to "medium" power consumption, beginning near 30, peaking at full membership at 50, and declining to 0 around 70. The green line signifies "high" power consumption, starting at 0 around 50, reaching full membership at 80, and remaining at 1 beyond this point. This triangular membership function is widely used in fuzzy logic applications for energy management, facilitating smooth category transitions. It plays a crucial role in decision-making processes for sustainability policies, grid optimization, and the efficient integration of power consumption sources.

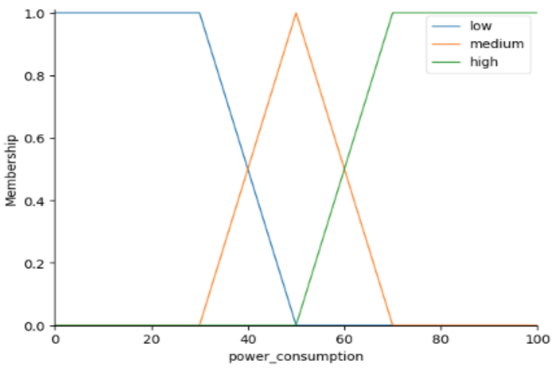

FIGURE 5. POWER CONSUMPTION VALUES

The predicted power consumption value of 50.0 suggests that the system is operating at a medium energy level, balancing demand, and supply efficiently. This aligns with studies on smart grid optimization, where fuzzy logic enhances decision-making processes to ensure stability and efficiency [16]. A balanced power consumption level indicates that the system can adapt to varying environmental conditions without experiencing extreme power fluctuations, an essential feature for sustainable energy management [17].

VI. IMPLICATIONS AND FUTURE ENHANCEMENTS

One of the key implications of this study is its contribution to energy efficiency. By utilizing fuzzy logic, power consumption can be optimized in real-time, reducing unnecessary energy usage and enhancing system sustainability. Based on simulation of the current study the optimized irrigation system consistently consumes 80 units of power, the fuzzy logic system averaging around 50–55 units under varying environmental conditions saves approximately 25–30 units per cycle, or about 31–37.5% in power consumption.

Previous research has demonstrated that adaptive energy management using fuzzy control systems improves efficiency in residential and industrial settings [18]. This approach supports the global shift toward sustainable energy solutions and carbon footprint reduction [18].

Furthermore, the integration of fuzzy logic into smart grid applications presents opportunities for enhanced power distribution and reliability. The ability to incorporate IoT sensors for real-time adjustments aligns with recent advancements in intelligent energy systems [9]. By enabling dynamic responses to fluctuating energy demands, these systems improve grid resilience and reduce operational costs. Researchers have emphasized the potential of combining fuzzy logic with IoT technologies to create autonomous energy management frameworks [19].

A promising future enhancement involves incorporating machine learning techniques to refine predictive accuracy. Hybrid models combining fuzzy logic with deep learning algorithms have shown superior performance in energy forecasting applications [10]. Machine learning can enhance the adaptability of fuzzy systems by continuously learning from new data, improving long-term efficiency and decision-making [16]. Future research should explore these hybrid approaches to develop more robust and intelligent energy management solutions.

VII. CONCLUSION

In conclusion, the deployment of Fuzzy Logic Control-based Energy Management Systems presents an innovative and practical approach to addressing the energy challenges faced by South African farmers. This study successfully implemented a Fuzzy Logic-Based Energy Management System (EMS) to optimize power consumption in real-time during irrigation processes on South African farms. By incorporating soil moisture, temperature, and renewable energy availability as key inputs, the system effectively predicted and managed energy use, ensuring a balanced power demand while reducing unnecessary electricity consumption. The results demonstrated that fuzzy logic enables adaptive decision-making, allowing farmers to maximize energy efficiency without compromising irrigation quality. Adoption of solar and wind energy sources will further improve energy efficiency and decrease reliance on the national grid. By adopting these strategies, farmers will benefit from reduced electricity expenses, improved sustainability, and increased productivity, ensuring long-term energy security and agricultural growth. The future study will explore future enhancements by integrating fuzzy logic with IoT sensors and machine learning techniques for real-time optimization and improved predictive accuracy.

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