



ANALYSIS OF ENERGY EFFICIENCY PERFORMANCE USING THE MEMBERSHIP FUNCTION (MF) METHOD IN A FUZZY LOGIC CONTROL SYSTEM FOR RESIDENTIAL SPLIT AIR CONDITIONERS (AC)

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Abstract

A fuzzy logic-based control system in household split-type air conditioners (AC) offers an alternative approach to reducing excess energy consumption without compromising thermal comfort. This study aims to test the effectiveness of three types of membership functions (MF), namely triangular, trapezoidal, and Gaussian, in improving energy efficiency and the stability of room temperature and humidity control. Simulations were performed using MATLAB software with the Mamdani fuzzy inference method and centroid defuzzification technique. The three MF were tested using 30 sets of temperature and humidity data to analyze their effect on fan speed and power consumption. The simulation results show that the trapezoidal MF provides the highest energy efficiency of 57.24%, followed by the Gaussian MF at 56.80% and the triangular MF at 53.71%. These findings indicate that fuzzy systems can significantly reduce energy consumption compared to conventional air conditioner controllers. This research is expected to serve as a reference in the development of more energy-efficient intelligent control systems.

Keywords: Fuzzy System, Membership Function, Temperature Control, Energy Saving, MATLAB, Household Air Conditioner

Abstract

Fuzzy logic-based control systems in household air conditioning units provide an effective alternative for reducing excessive energy consumption while preserving indoor thermal comfort. This study investigates the performance of three types of Membership Functions (MF) – triangular, trapezoidal, and gaussian – in enhancing energy efficiency and maintaining stable control over room temperature and humidity. The experiment was conducted via MATLAB simulation, employing the Mamdani fuzzy inference model and centroid defuzzification technique. A total of 30 temperature and humidity data samples were analyzed to assess their impact on fan speed output and power consumption. The findings indicate that the trapezoidal MF achieved the highest energy savings at 57.24%, followed by Gaussian at 56.80%, and triangular at 53.71%. These results confirm that fuzzy systems are considerably more energy-efficient than traditional AC control methods. The research contributes a valuable reference for future development of intelligent and energy-saving control technologies.

Keywords: Fuzzy Control System, Membership Function, Temperature Regulation, Energy Saving, MATLAB, Household AC



1. INTRODUCTION

Population growth and global activities have significantly increased energy demand. Energy is divided into two main categories, namely renewable and non-renewable energy. Non-renewable energy has limited availability due to its geological formation process, while renewable energy can be naturally and sustainably replenished [1]. The availability of electrical energy plays an important role in the quality of life and economic progress of a country [2].

According to the International Energy Agency (IEA), global energy demand is expected to increase by 55% during the period 2005–2030, posing challenges in maintaining a balance between energy generation and demand [3]. One energy efficiency measure in HVAC systems is radiant cooling, which offers better thermal efficiency than conventional systems, but its application in tropical regions such as Indonesia is still limited [6].

Another developing approach is the use of intelligent control systems to efficiently regulate temperature and humidity in order to reduce energy consumption in air conditioners. Various methods have been used, such as PID, PI, PD, LQR, and fuzzy logic [6]. Although PID is widely used in industry due to its reliability, with around 95% of closed-loop systems using it [7], this method relies on mathematical models that are often not optimal for complex systems [8].

In contrast, Fuzzy Logic Controllers (FLC) are capable of handling nonlinear systems and dynamic parameters by relying on linguistic rules based on expert knowledge [9]. In air conditioner control, FLC utilizes linguistic variables such as Cold, Medium, Fast, and Slow to produce flexible and adaptive control [8]. The main component of FLC is the membership function (MF), which converts linguistic data into numerical form. Triangular MF is widely used due to its simplicity, while trapezoidal and Gaussian forms are used for flexibility and smoother representation [17]. Previous studies have shown that the application of fuzzy logic in multivariable AC systems can improve stability and efficiency.

Various studies have demonstrated the effectiveness of fuzzy logic control in improving AC system efficiency. Shah et al. [6] successfully reduced annual energy consumption by up to 25% using fuzzy controllers compared to LQR and other nonlinear methods. Berouine et al.

found that fuzzy control was able to reduce energy consumption more significantly than ON/OFF, PID, and state-feedback methods, with efficiency advantages of 11%, 9%, and 4%, respectively. Meanwhile, Waheed et al. [9] demonstrated the adaptive capability of FLC to temperature, humidity, and oxygen levels, which also increased energy efficiency. Parameshwaran et al. [10] combined fuzzy logic with genetic algorithms and showed that this approach can maintain thermal comfort without sacrificing energy efficiency. Attia et al. [12] proved that fuzzy systems provide smaller steady-state errors and better responses to thermal load changes than conventional systems, both in summer and winter.

Based on several previous studies, it is known that the main focus of most studies related to air conditioning system control is on comparing fuzzy logic methods with conventional control techniques, such as PID (Proportional-Integral-Derivative), PI, PD, and steady-state-based approaches. Generally, these studies assess the effectiveness of fuzzy logic in



maintaining temperature and humidity stability as well as energy efficiency compared to other methods. However, to date, there has been relatively little research specifically examining the influence and effectiveness of MF shapes and configurations in fuzzy control systems. In fact, MF is an important component in the fuzzification process, which determines how input data is converted into fuzzy values and affects the accuracy of the system's response to changing conditions.

The limitations of research in this area indicate significant opportunities for further exploration, particularly in order to improve the performance and efficiency of AC systems with fuzzy logic. Thus, studying the performance of various types of MF can be an important foundation in developing control systems that are more efficient, precise, economical, and optimal in power consumption. By conducting this research, it is hoped that optimal results will be found

In reducing power consumption in air conditioners by evaluating the performance of membership functions as a comparison, as well as temperature and humidity as parameters. This research is also expected to serve as a reference in the development of fuzzy logic control methods to create a control system capable of reducing power consumption in household electronic appliances.

The objectives of this research are:

1. To design and simulate a fuzzy logic control system in household split air conditioners based on temperature and humidity using MATLAB software.
2. Evaluating the effect of various types of MF on the performance of fuzzy control systems in regulating room temperature and humidity.
3. To determine the most optimal type of MF () in improving energy efficiency and maintaining thermal comfort in the use of household air conditioners.

A. Fuzzy Logic Toolbox

The Fuzzy Logic Toolbox in MATLAB is a powerful tool for designing and implementing fuzzy logic systems. Fuzzy Logic Toolbox Features:

1. Fuzzy inference systems (FIS): Design and implement Mamdani and Sugeno fuzzy systems.
2. Fuzzy membership functions: Define custom membership functions or use built-in functions.
3. Fuzzy rules: Define rules using linguistic variables and fuzzy operators.
4. Defuzzification methods: Choose from various defuzzification methods, such as centroid or bisector.
5. MATLAB Integration: The Fuzzy Logic Toolbox integrates seamlessly with MATLAB, allowing you to use fuzzy logic with other MATLAB tools and functions.

Some common uses of the Fuzzy Logic Toolbox include design fuzzy logic controllers for complex systems, use fuzzy logic for image segmentation, edge detection and also implement fuzzy logic for decision-making in applications like expert systems or recommender systems.

B. Fuzzy Logic

Fuzzy logic is a mathematical approach to deal with uncertainty and imprecision. It's based on fuzzy sets, which allow for degrees of membership rather than binary true or false values.

Fuzzy logic is widely used in control systems, image processing, decision-making, and more. In its implementation, a fuzzy system consists of stages such as fuzzification, fuzzy inference, and defuzzification.

B. Membership Function (MF)

Membership Function (MF) is a key component in fuzzy systems that determines the membership level of a value in a fuzzy set. This function converts numerical data into linguistic representations, enabling rule-based inference. The accuracy and performance of fuzzy systems are greatly influenced by the form and characteristics of the MF used.

MF has specific characteristics such as a continuous domain [0–1], normal properties (has peak maximum membership), and convexity that affects the transition



shape between membership levels. Proper MF design can improve the stability and response of fuzzy systems.

There are several types of MF that are commonly used:

- 1) Triangular MF: triangular in shape, simple, and easy to implement.

Mathematically, triangular MF can be expressed as

$$\mu(x) = \max \left\{ \min \left(\frac{x-a}{b-a}, \frac{c-x}{c-b} \right), 0 \right\}$$

$$\begin{array}{ll} 0, & x \leq a; x \geq c \\ \frac{x-a}{b-a}, & a < x \leq b \\ \frac{c-x}{c-b}, & b < x < c \end{array}$$

Dimana,

a = titik kiri dimana fungsi mulai naik dari 0

b = titik puncak dimana fungsi mencapai nilai maksimum 1

c = titik kanan dimana fungsi kembali ke 0

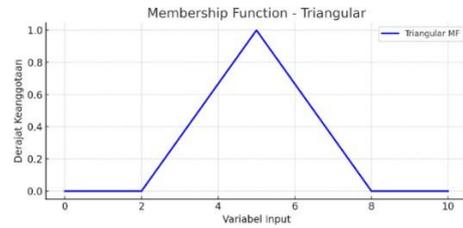


Figure 1. Triangular MF Graph Plot

2) Trapezoidal MF: has a flat area that allows stability in a certain range of values.

Mathematically, the trapezoidal MF function is defined as:

$$\mu(x) = \max\left\{\min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right\}$$

$$\begin{aligned} 0, & \quad x \leq a; x \geq d \\ \frac{x-a}{b-a}, & \quad a < x \leq b \\ 1, & \quad b < x \leq c \\ \frac{d-x}{d-c}, & \quad c < x < d \end{aligned}$$

Dimana,

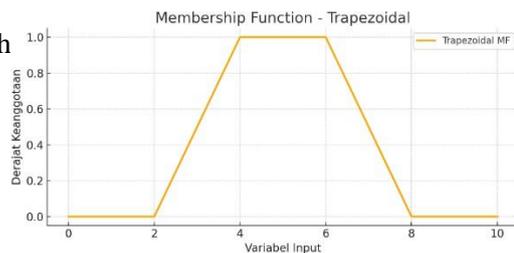
a = titik kiri dimana fungsi mulai naik dari 0

b = titik dimana fungsi mencapai nilai maksimum 1 (awal daerah datar)

c = titik dimana fungsi masih bernilai 1 (akhir daerah datar)

d = titik kanan dimana fungsi kembali 0

Figure 2. Trapezoidal MF Graph Plot
Gaussian MF: has a bell-shaped curve, offering smooth transitions and high precision.





Mathematically

mathematically, gaussian MF is defined as:

$$\mu(x) = \frac{-(x - c)^2}{2\sigma^2}$$

Dimana,

c = pusat dari fungsi gaussian

σ = standar deviasi yang menjadi penentu dalam lebar kurva

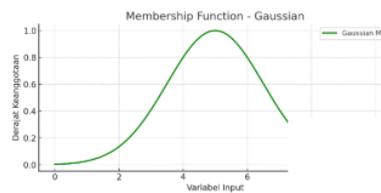


Figure 3 Gaussian MF Graph Plot

E. Fuzzy Logic Control System in Split AC

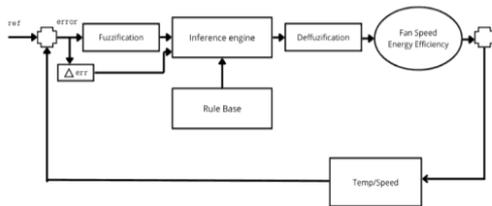


Figure 4 Block Diagram of the Fuzzy Logic Control System Flow for AC

Figure 4 shows the block diagram of the fuzzy logic control system for regulating fan speed and energy efficiency in air conditioners. The error signal is obtained from the difference between the reference temperature and the actual temperature, then together with the error change (Δ error) it enters the fuzzification process to be converted into linguistic values.

This value is processed by the inference engine using rules in the rule base, producing a fuzzy output which is then converted to a definite value through defuzzification. The final result in the form of fan speed is used to control the system, while also forming feedback through measurement of the actual temperature and speed for continuous adjustment.

2. RESEARCH METHOD

A. Research Type and Approach

This research uses a simulation-based experimental approach, which focuses on evaluating the performance of various Membership Function (MF) forms in fuzzy logic control systems for household air conditioners. The simulation was performed using MATLAB software with the Fuzzy Logic Toolbox. The research process began with a literature study, fuzzy system design, simulation, and performance evaluation.

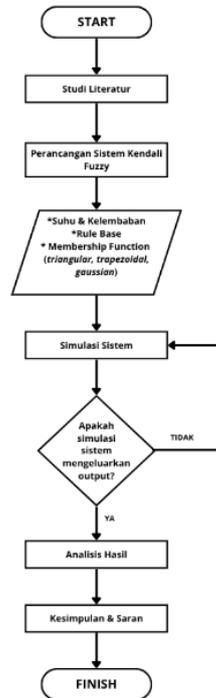


Figure 5 Research Flow Diagram

B. Research Location and Time

The research was conducted at the Control Engineering Laboratory, Faculty of Engineering, Indonesian Christian University, during the period from April to June 2025.

C. Problem Identification

The main problem lies in the inefficiency of conventional AC control systems and the lack of in-depth studies on the effect of MF shape on fuzzy system performance. Therefore, this study highlights the evaluation of three types of MF: triangular, trapezoidal, and Gaussian.

D. Fuzzy Control System Design

The fuzzy system is designed with two inputs: temperature error and humidity error, and one output in the form of fan speed. These three variables are modeled in fuzzy form, each with several linguistic categories. The Mamdani fuzzy inference system is used for the decision-making process based on IF-THEN rules.

E. Rule Base

The fuzzy system in this study uses 49 rules that combine 7 linguistic categories for each input. Example of a rule: IF temperature error is NB AND humidity error is Z THEN fan speed is Fast. The rules are determined heuristically to reflect real conditions and energy efficiency.

F. Simulation and MATLAB Implementation The simulation was conducted in the environment MATLAB, uses GUI that allows the user to directly input temperature and humidity values. The system was tested with 30 sets of temperature and humidity data to evaluate the fan speed response based on each MF shape.

G. Defuzzification Method



The defuzzification method used is centroid, as it is considered the most representative in producing stable outputs that reflect the overall fuzzy distribution. This process converts fuzzy outputs into crisp values for fan speed settings.

3. RESULTS AND DISCUSSION

A. Research Data

The research data was obtained from the results of fuzzy logic control system simulations using MATLAB Fuzzy Logic Toolbox and a designed GUI interface. The simulation was conducted for 30 variations of temperature and humidity input combinations, with a temperature range of 16–33 °C and relative humidity between 35–80%. The assumption is that the household air conditioning system operates for 12 hours a day, with observation intervals of every 0.4 hours. This data is used to test the performance of the fuzzy system in regulating fan speed based on different Membership Function (MF) shapes, namely triangular, trapezoidal, and Gaussian.

Table 1 Research Data Test Sample

No	Temperature (°C)	Air Humidity (%)	Time Range (Hours)
1	28	36	0.4
2	21.5	45.7	0.4
3	30	65	0.4
4	33	38	0.4
5	24.6	36.9	0.4
6	20.3	57	0.4
7	21.2	43.5	0.4
8	28	59	0.4
9	20.1	61.7	0.4
10	31.7	35.8	0.4
11	22.3	48.6	0.4
12	26.1	59.4	0.4
13	29.8	40.3	0.4
14	31.2	55.1	0.4
15	25.4	61.9	0.4
16	19.9	47.2	0.4
17	27.6	66.4	0.4
18	23.7	52.8	0.4
19	21.5	39	0.4
20	20	55	0.4
21	17.3	44.6	0.4
22	30.6	58.2	0.4
23	32.1	49.7	0.4
24	28.9	72.3	0.4
25	18.5	38.5	0.4



26	24.4	69.8	0.4
27	22.8	43.2	0.4
28	27.1	75.6	0.4
29	25	62	0.4
30	19	41.5	0.4

In this simulation, the reference temperature and humidity are set at a constant 25 °C and 55%, respectively, in accordance with SNI standards and thermal comfort recommendations in Indonesia. These values were chosen as ideal references for frequently used air-conditioned rooms. The system output, in the form of fan speed, is obtained from a combination of temperature and humidity inputs using the centroid defuzzification method. The data is used to evaluate the consistency of the fuzzy system against input variations and to identify the most optimal Membership Function (MF) shape in improving energy efficiency and thermal comfort.

The use of a GUI also makes it easier for users to use the application with a simple display without having to execute the code manually.

Figure 5 GUI Display of Fuzzy Logic Control System in Air Conditioners

Through this GUI, the simulation process becomes more interactive and intuitive. Users can easily modify input parameters and compare the results obtained from each defuzzification method. Thus, the GUI not only facilitates system testing but also serves as an important tool in the overall evaluation of fuzzy system performance.

B. System Testing with 3 Types of MF

In the first test, the triangular membership function was used. The system was simulated with various combinations of temperature and humidity inputs, and testing was carried out using the centroid defuzzification method. In this study, two variables were used, namely Temperature Error and Humidity Error, as well as one output variable in the form of Fan Speed. These three variables were designed using the triangular membership function because it is simple and efficient for calculations.

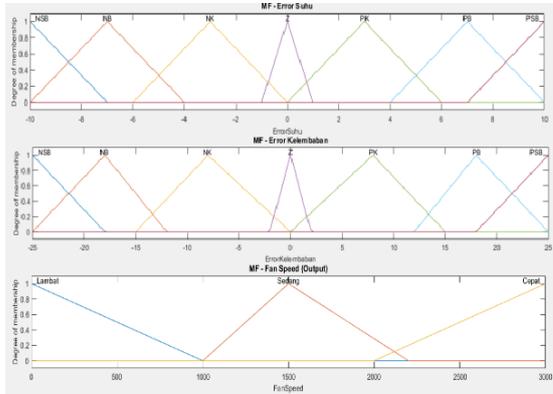


Figure 6 MF display for Temperature Error, Humidity Error, and fan speed

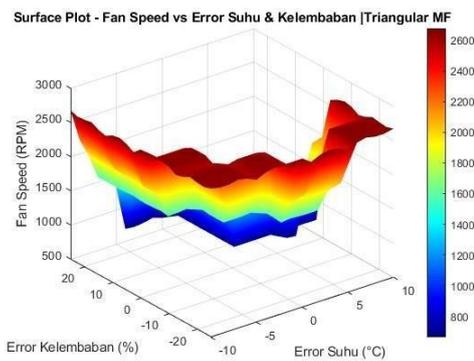


Figure 7 Surface View Display in System Testing with Triangular MF

From the Surface View results, it can be seen that the fan speed increases significantly when the temperature error is large and negative (the actual temperature is much higher than the target temperature) and the humidity error also shows a large deviation, and tends to be moderate when the temperature and humidity errors approach zero. Then the fan speed decreases when the actual temperature is too low compared to the target temperature or humidity is too high.

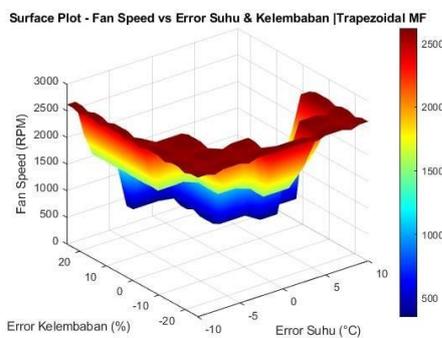


Figure 8 Surface View Display in System Testing with MF Trapezoidal

From the graph, it can be observed that the fan speed value increases proportionally as the temperature and humidity errors increase. The plot surface shows a blue area at the bottom of the graph,



which indicates a low fan speed value (around 500 RPM), and a red area, which indicates a high fan speed (close to 3000 RPM), corresponding to extreme error conditions.

The surface shape in the graph appears quite smooth but with a tendency toward linear transitions. This is due to the characteristics of the trapezoidal membership function, which has a flat top, providing a stable system response within a certain range of values. This response makes the system control more tolerant to small fluctuations in error values, while still providing proportional output changes to input changes.

In other words, fuzzy systems with trapezoidal MF produce responsive but not overly sensitive control, making them suitable for use in automatic air conditioning settings that require efficiency without sacrificing comfort. This is also consistent with test results showing that the MF type provides the highest energy efficiency among the three types of membership functions tested.

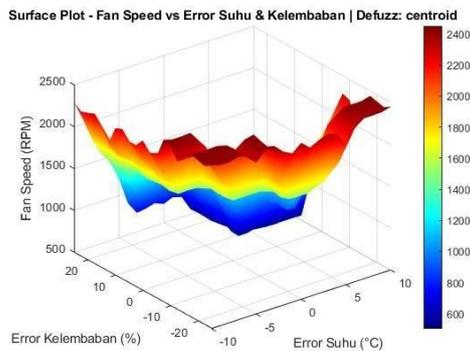


Figure 10 Surface View Display in System Testing with Gaussian MF

From this visualization, it can be seen that changes in fan speed respond smoothly and continuously to variations in both input parameters. The blue color on the surface represents low fan speed (around 600 RPM), while the red color indicates high speed (up to 2400 RPM). The smooth color gradient pattern is a characteristic of the Gaussian MF, which has a symmetrical curved shape without sharp edges. This produces a smoother output compared to other membership functions such as triangular or trapezoidal.

Surface that formed shows that the system is capable of gradually adjusting fan speed to changes in environmental conditions. Thus, the Gaussian function provides more adaptive and precise control transitions to small fluctuations in temperature and humidity error values. This advantage makes Gaussian MF very suitable for use in systems that require smooth control responses, such as rooms with dynamic temperature and humidity changes.

Overall, this visualization shows that the use of Gaussian MF provides control results that are



responsive and stable control results, although its energy consumption is slightly higher compared to other MF.

C. Comparison Analysis of Results

In this estimation, a calculation approach based on the ratio of speed to maximum speed was used to estimate motor power consumption. The assumption is that the fan motor consumes a maximum power of 90 watts when operating at full capacity at 3000 RPM. Therefore, power consumption is calculated using the formula:

$$\text{Daya (W)} = \left(\frac{\text{Fan Speed}}{3000} \right) \times 90$$

Therefore, the energy consumed by the AC based on each MF for 12 hours is

Table 5 Power Consumption of Each MF Over 12 Hours

No	Type of MF	Output (RPM)	Power (W)
1	Triangular	41639	1249.7
2	Trapezoidal	38487	1154.61
3	Gaussian	38884	1166.52

In the simulation conducted, it was assumed that a conventional AC fan operated at a full speed of 3000 RPM with an electrical power of 90 watts for 12 hours per day. Based on this assumption, the daily energy consumption of the conventional system can be calculated as follows:

$$W_{total} = 90W \times 12 \text{ Jam} = 1,08 \text{ kWh}$$

In contrast, the fuzzy system is able to adjust the fan speed proportionally to the temperature and humidity error values. Testing was conducted on three types of membership functions (MF), namely triangular, trapezoidal, and Gaussian. Results. The estimated daily energy consumption of each type of MF can be seen in the following table:

Table 6 Estimated Energy Efficiency of Each MF

System Type	Average RPM	Power (W)	Power Consumption / Day (Wh)	Energy Savings (%)
AC Conventional	3000	90	2700	-
Fuzzy MF Triangulation	1796.5	53.90	1249.7	53.71



Fuzzy MF Trapezoidal	177 7.9	53. 34	1154.6 1	57.24
Fuzzy MF Gaussian	180 6.4	54. 19	1166.5 2	56.8

The simulation results show that trapezoidal MF is a viable primary option when power consumption efficiency is a priority for the system. Meanwhile, Gaussian MF offers more responsive and smooth control capabilities, making it more suitable for environments with high or unstable temperature and humidity fluctuations.

4. CONCLUSION

This study has successfully designed and simulated a fuzzy logic control system for household split air conditioners, with the aim of improving energy efficiency through fan speed control based on temperature and humidity error values. Three types of MF triangular, trapezoidal, and Gaussian MF types were tested to evaluate their effect on system performance. Simulation results on 30 data sets show that all MF types are capable of producing adaptive fan speed control that is more efficient than the conventional ON-OFF approach. Among the three, trapezoidal MF shows the best performance with the highest energy efficiency reaching 57.24%, followed by Gaussian (56.80%) and triangular (53.71%). Overall, the MF-based fuzzy system, particularly with trapezoidal MF, is recommended as an energy-efficient alternative for residential air conditioning systems without compromising thermal comfort.

5. REFERENCES

- Alnavis, N. B., Wirawan, R., Solihah, K. I., Nugroho, V. H. (2024). Sustainable electricity: The potential and challenges of electricity supply in Indonesia. *Journal of Innovation Materials, Energy, and Sustainable Engineering*, 1(2).
- Alhamid, M. I., Daud, Y., Surachman, A., Sugiyono, A., Aditya, H. B., & Mahlia, T. M. I. (2016). Potential of geothermal energy for electricity generation in Indonesia: A review. *Renewable and Sustainable Energy Reviews*, 53, 733-740.
- Garrab, A., Bouallegue, A., & Bouallegue, R. (2017). An agent-based fuzzy control for smart home energy management in a smart grid environment. *International Journal of Renewable Energy Research*, 7(2), 599-612.
- Miyamoto, K., Pratiwi, S. N., Nishiiri, S., Takaguchi, H., & Kubota, T. (2024). Relationship between Cooling Methods and Energy Consumption for the Development of Low-Carbon Collective Housing in Indonesia. *Sustainability*, 16(4), 1635.
- Chandrakasan, A., Somasundaram, K., Sivakumaran, N. (2009). Design and implementation of fuzzy logic controller for an air conditioner with energy saving. 57-62.
- Shah, Z. A., Sindi, H. F., Ul-Haq, A., & Ali, M. A. (2020). Fuzzy Logic-based direct load control scheme for air conditioning load to reduce energy consumption. *IEEE access*, 8, 117413-117427.
- Joyo, M. K., Ahmed, S. F., Hazry, D., Tanveer, M. H., & Warsi, F. A. (2013). Position controller design for quad-rotor under perturbed condition. *Wulfenia Journal*, 20(7), 178-189.



- Berouine, A., Akssas, E., Naitmalek, Y., Lachhab, F., Bakhouya, M., Ouladsine, R., & Essaaidi, M. (2019, April). A fuzzy logic-based approach for HVAC systems control. In 2019 6th International Conference on Control, Decision and Information Technologies (CoDIT) (pp. 1510-1515). IEEE.
- Waheed, S. R., Adnan, M. M., Suaib, N. M., & Rahim, M. S. M. (2020, April). Fuzzy logic controller for classroom air conditioner. In *Journal of Physics: Conference Series* (Vol. 1484, No. 1, p. 012018). IOP Publishing.
- Parameshwaran, R., Karunakaran, R., Kumar, C. V. R., & Iniyar, S. (2010). Energy conservative building air conditioning system controlled and optimized using fuzzygenetic algorithm. *Energy and Buildings*, 42(5), 745-762.
- Attia, A. H., Rezek, S. F., & Saleh, A. M. (2015). Fuzzy logic control of air conditioning system in residential buildings. *Alexandria Engineering Journal*, 54(3), 395-403.
- Zadeh, L. A. (1965). Fuzzy sets. *Information and Control*, 8(3), 338–353.
- MathWorks. (2021). *Fuzzy Logic Toolbox User's Guide*. The MathWorks, Inc.
- Ross, T. J. (2017). *Fuzzy Logic with Engineering Applications* (4th ed.). John Wiley & Sons.
- Klir, G., & Yuan, B. (1995). *Fuzzy Sets and Fuzzy Logic: Theory and Applications*. Prentice Hall.
- Zhao, J., & Bose, B. K. (2002, November). Evaluation of membership functions for fuzzy logic controlled induction motor drive. In *IEEE Conference of the Industrial Electronics Society. IECON 02* (Vol. 1, pp. 229-234). IEEE. E 2002 28th Annual Conferences.