National Centre for Energy and Environment, Energy Commission of Nigeria, University of Benin:
ISSN 2504-9593
DOI: 10.5281/zenodo.19384760
https://ijree.com/index.php/publications/article/view/53
Int. J. Renew. Energ & Environ Vol.4 (1), pp 435-464(2026)

FUZZY LOGIC-BASED ENERGY MANAGEMENT SYSTEM FOR HYBRID RENEWABLE ENERGY SOURCES

***[1]Adedeji, W. O., [2]Adetayo, O. O., Ojerinde, B.J.,[3]Ajiboye, A.G., [3]Yekeen, A.I., [4]Pelemo, J., [5]Molokwu, I.M., [6]Okpara I.N., [7]Fanifosi J.O.**
[1]Department of Mechatronics Engineering, Osun State University.
[2]Department of Mechanical Engineering, Osun State University.
[3]Department of Mechatronics Engineering, Federal University of Technology, Minna
[4]Department of Weldering and Fabrication Engineering, Yaba College of Technology, Yaba.
[5]Department of Weldering and Fabrication Engineering, Nigerian Naval Institute of Technology, Sapele.
[6]Mechanical Engineering Technology, Federal Polytechnic Nekede, Owerri.
[7]Mechanical Engineering Technology, Federal Polytechnic Ede Osun State.
*Corresponding author email: wasiu.adedeji@uniosun.edu.ng

Abstract
This study reviews the applications of fuzzy logic in energy management systems (EMS) for hybrid renewable energy systems (HRES). Hybrid Renewable Energy Systems (HRES) constitute a collection of renewable sources, including solar, wind or hydropower to provide energy reliably and sustainably, however their performance is highly influenced by the intermittent and unpredictable characteristics of green energy generation. Thanks to its capacity to work in the shaded overall vision, fuzzy logic is an excellent fit for this obstacle in spite of uncertainty, undeniable and deficient information. The key components of the fuzzy logic-based EMS are (fuzzification, rule base, inference mechanism and defuzzification) which demonstrate how these components support an adaptive and intelligent energy management. This contributes to the flexibility, efficiency and reliability of HRES by dynamically responding to fluctuations in energy generation and demand. As per the paper, using fuzzy logic together with artificial intelligence and machine learning can also help improve forecasting and decision-making. All in all, fuzzy logic shows itself as a useful mechanism for sustainable energy optimization.
Keywords: Fuzzy logic; Energy management systems; Hybrid renewable energy systems; Smart grids; Fuzzification; Renewable energy integration

1.0 INTRODUCTION

Energy Management Systems (EMS) are crucial in today's energy systems, particularly due to the increased penetration of renewable energy sources. The EMS performs monitoring, controlling and optimisation for energy generation and consumption, and doing this to be efficient while guaranteeing an overall stability of the energy grid. Gellings (2009) states that EMS is focused on controlling the generation, storage and consumption of energy in a real time fashion – a crucial requirement when dealing with an energy system which involves intermittent

renewable energy sources. To a related issue, an EMS when implemented guarantees low energy costs, is sustainable and fosters environmental protection (Fikru, 2019). EMS penetration rates are increasing due largely to a worldwide quest for clean energy resources and energy utilization optimization within sectors such as residential through to industrial (Benson & Magee, 2014).
Similarly, the importance of EMS can be seen with regards to the incorporation of

renewable energy sources like solar, wind and hydro into an energy grid. The inherent variability and intermittency of these energy sources make it challenging to integrate such sources into the grid. According to Espín-Sarzosa et al. (2020), the energy curve of RE is adjusted to meet the demand and in this way the EMS system smoothen the energy curve. In this way, EMS not only guarantees the stability of the energy grid, but also simplifies the embedded hybrid energy systems integrating comprising more renewable energy sources with a variety of primary sources in power generation.

1.1 Hybrid Renewable Energy Systems (HRES)

Hybrid Renewable Energy Systems (HRES) are designed to combine multiple renewable energy sources, such as solar, wind, and hydropower, to reduce dependence on a single source of power. Compared with single-source renewable systems, HRES can provide greater reliability, improved resource utilization, and lower energy cost because the strengths of one source can compensate for the limitations of another (Hassan et al., 2023; León Gómez et al., 2023; Sawle et al., 2018). It can generate power from solar in the daytime it is a period of strong sun (Hirsch et al, 2018) and use wind to produce electricity at the same time to maintain reliable power supply. According to Arcos-Aviles et al. (2016) advancements in HRES can provide a sound solution to places where power from the electric grids are unreliable or not available.

There are many advantages in utilizing HRES and among them are included; helping to the energy security, decrease of carbon emissions from environment, Electricity supply for remote areas. Apart from the above advantages, the multiparametric utilization of various energy resources in HRESs will result in decreasing electricity generation costs as well as enhancing the efficiency of the energy systems. But the harmonization of energy from distinct sources within HRES, such as in all systems, is very challenging especially due to the demand-supply dynamics of energy (Hassan et al., 2023; Maghami et al., 2023; Taghizad-Tavana et al., 2025). This is by Arcos-Aviles et al. (2021), which is complexity of the diverse sources for the power utilized in the scheme. This, in turn, needs a proper EMS to optimally control the various power sources presented in such systems.

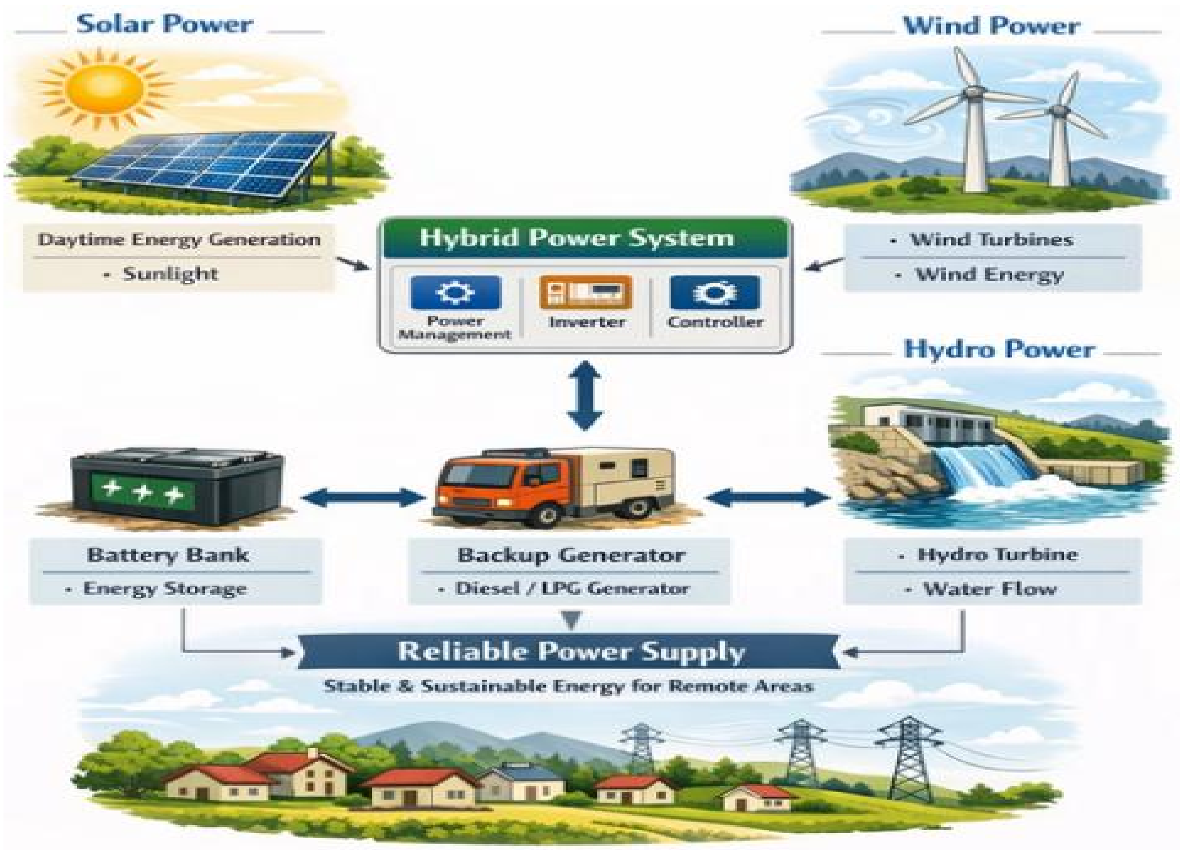

Figure 1: Hybrid RENEWABLE Energy Systems

1.2 Fuzzy Logic in EMS

Fuzzy logic: A sophisticated computerized algorithm for energy systems control Fuzzy logic is a new generation computer-based algorithm that provides an adaptive and dynamic operation of energy systems. Fuzzy logic can be a good choice when things are uncertain and data is vague. While the conventional energy control systems rely on mathematical models and need precise data and modelling, (Tang et al., 2024).

The fuzzy logic uses an approximate reasoning approach which is consistent with applications involving nonlinear systems such as hybrid renewable energy systems (Boza& Evgeniou, 2021). For EMS's used in an HRES, the fuzzy logic theory can be suitably implemented to overcome the imprecision of renewable sources and execute timely decisions on energy management (Aguila-Leon et al., 2021).

Fuzzy logic's greatest virtue is its ability to effectively control complex systems without requiring precise input data. As per Arcos-Aviles et al. (2017), indicated that to monitors the operation of energy storage systems, it is important to find an optimal cycle between charging and discharging so that deterioration can be avoided making more energy still available. Fuzzy controllers are adopted by energy management systems for decision making under weather, energy availability and system circumstances while deterministic models can do so as proposed by Jafari et al. (2018). Because of this capability, fuzzy logic is also highly effective in the control of hybrid systems with renewable and other energy sources.

Moreover the fuzzy logic's capability to operate under no certainty has also rendered it as the most suitable method to be used while dealing with power distribution system in microgrid and decentralized energy system (Jafari et al., 2018). As an example, fuzzy logic system could be incorporated in a hybrid to regulate energy flow from solar, wind and hydro systems, so that the required amount of power is provided with minimum costs as well as losses. Thus, dealing with challenging tasks under uncertainty makes it a competent approach in the context of next energy systems (Boza & Evgeniou, 2021). Figure 2 shows a simple structure of the fuzzy logic controller for energy management in hybrid renewable energy systems. It illustrates how the input variables are renewable energy generation, essential load demand, and weather conditions that process through fuzzification followed by inference and defuzzyfication to control actions (battery management, grid interaction, power distribution); all of these operating under uncertain and variable operation.

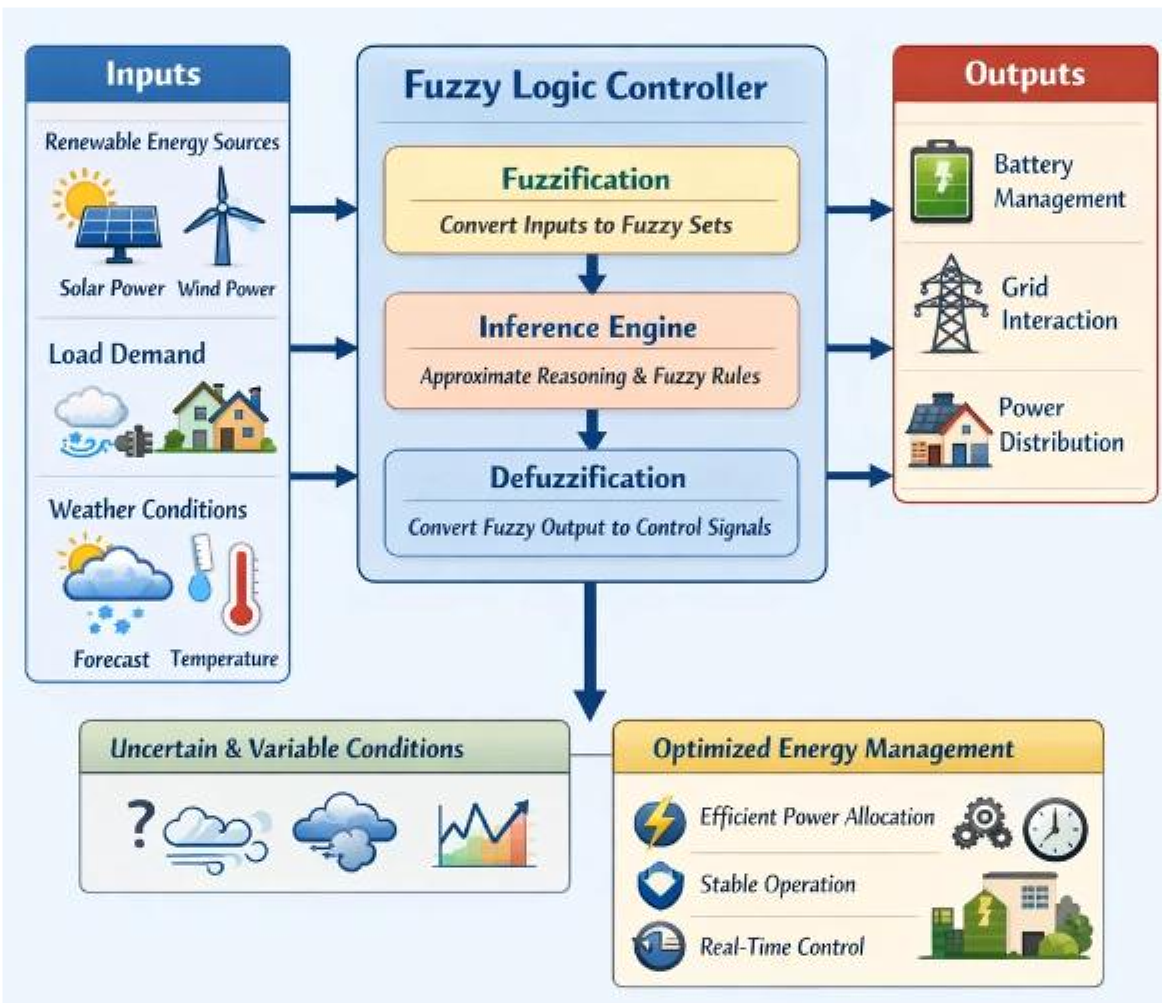

Figure 2: Fuzzy Logic in EMS

The aim of this review would be to highlight the application of fuzzy logic in the advancement of EMS for hybridized HRES and integration of control systems utilizing fuzzy logic and result into an optimal management of energy in different forms. According to Arcos-Aviles et al. (2017), the principal objective of these reviews is to ascertain the application of fuzzy logic with uncertainty handling RE management and at the same time to enhance system performance on a global scale.

In this review article, we provide an in-depth analysis of the advantages and limitations of employing fuzzy logic for EMS, specifically for HRES systems. This will involve case studies to illustrate good the EMS by applying fuzzy logic can control energy storage, predictions and consumption in hybrid systems. We will also present how that can address the growing complexity of power (in particular, the increasing penetration of renewable energy sources) systems. Finally, to provide trends that can be developed in the use of fuzzy systems in energy management system will be provided by this paper

2.0 Fundamentals of Hybrid Renewable Energy Systems

2.1 Types of Renewable Energy Sources

Hybrid renewable energy system is the combination of multiple renewable sources to create more secure and sustainable solutions of energy. Solar and wind energy, and hydropower are usually acknowledged as mainstream renewable sources of HRES. They each have different benefits and challenges, which when combined work to offset the variability of renewable generation (Hassan et al., 2023; Giedraityte et al., 2025; Samala et al., 2025).

Solar is one of the widely used renewable energy sources in HRES. It produces energy from the sun using photovoltaic cells that convert sunlight to electricity. Primary solar resources are enormous, renewable and available in most regions of the world. As a result, it is one of the most suggested system in many areas around the globe. It is a volatile resource, because its availability is affected by the presence of sunlight, which may not be available when it is dark or cloudy and so must be supplemented for steady supply. (Benson & Magee, 2014)

A second important renewable source of energy is Wind Energy in the HRES. Mechanical power is produced by wind turbines, taking advantage of the kinetic power of the wind and changing that into electrical energy. Wind power is a clean, renewable source of energy that can be harnessed where there is consistent wind. Like solar, wind energy is also intermittent because it relies on the blowing of the wind, which changes according to time of day and season. But wind power is a good complement to solar power also when there is wind, but no sunlight (U.S. Department of Energy, 2013; Murphy et al., 2023).

Hydropower refers to the generation of electricity from flowing water, typically through dams or turbines installed in rivers and other water bodies. It is one of the oldest and most dependable forms of renewable energy and can provide continuous and stable power, making it an important component of hybrid renewable energy systems (IEA, 2025). The feasibility of hydropower is strongly bound to geographic prerequisites, specifically the presence of waterbodies, and large-scale hydropower facilities can cause significant environmental damages with impacts on ecosystem and local people (Hirsch et al., 2018).

Biomass energy essentially converts carbonaceous organic substances, including agricultural and forestry materials and municipal waste, into electricity, heat and transportation fuels. There are some distinct advantages of biomass in HRES over other sources, and these include the provision of base-load and dispatchable power by burning dry bagasse. Biomass power is not intercepted by the weather in the way that solar or wind biomass is. Hence, it also functions as a backup or emergencies power supplier. Bio mass production is dependent on land, water and others that may give rise with large-scale bio mass plans to sus tainability problems due to availability of raw materials and emission factors.

2.2 Integration of Multiple Renewable Sources

The addition of several renewable energy sources in HRES compensates for issues such as intermittency and variation associated with reliance on a single energy source. This power mix's intermittency is mitigated by the combination of solar, wind, hydro and biomass, which complement one another as power sources. Each renewable energy source has its own generation pattern, and when they are combined, the system can provide a more constant stream of power despite fluctuations in any individual source. Reliability and stability of energy supply are key benefits of integrating various forms of renewables (Hassan et al., 2023; Alhijazi et al., 2023; Giedraityte et al., 2025). For example, if in a period with no solar energy during the night, wind may be able to support this lack as it is still able to generate at this time of day and therefore balancing the incapacity of sunshine physically appearing in the atmosphere from sunrise certainty to the sunset one (Arcos-Aviles et al., 2016). Additionally, hydropower can be reliable continuous power generation if water is easily available. Such a hybrid can be used for the purpose of in spite of such periodic fluctuations during energy production from these sources, at least to average energy input over long term so that the consumer must not face with lack of electrical power.

Variability and intermittency of each energy sources are the key challenge encountered in HRES with multiple renewable resources. Between the weather, time of day and season, solar and wind systems can vary greatly in output. This requires a sophisticated EMS capable of accurately forecasting energy generation and being able to match it with demand. Storage, whether in batteries or flywheels, stores surplus during a period when production is greater than needed and lets it go at the time demand exceeds supply.

A more general problem is the competition in time between different sources of energy. Each power source has varying features and can be operated at different voltages, frequencies, so that they must be well organized for each other for their cooperation. Therefore, a system should be able to control each energy flow from every source and integrate in an efficient manner this coupling to contribute stability and reliability for the grid (Hassan et al., 2023; Onsomu et al., 2024; IEA, 2025).

2.3 Components of Key Hybrid Renewable Systems

Hybrid renewable energy systems need some key parts for their proper operation. These include energy source converters, energy storage systems, inverters, and controllers. All of these components are essential for the control, production, storage, and distribution of power (Hassan et al., 2023; Elalfy et al., 2024).

Usually, HRES combine different renewable energy sources such as solar and wind. Their hybrid arrangement helps provide a more reliable energy supply by reducing the effect of adverse weather conditions on any single source. Each source is connected to the system through an energy conversion device, such as photovoltaic panels or wind turbine generators, which contribute to the total generated power (Hassan et al., 2023; León Gómez et al., 2023).

Energy storage systems, including batteries and flywheels, are necessary for matching energy supply with demand. They store excess energy produced during peak generation periods and release it when demand exceeds production. In HRES, batteries are among the most widely used storage devices because of their relatively high efficiency for electrical energy storage and discharge, while flywheels store energy in the form of rotational kinetic energy. Energy storage is therefore important for addressing the intermittency of renewable sources such as solar and wind (Elalfy et al., 2024; IEA, 2025).

Inverters are also key components because they convert the DC output from photovoltaic panels or some wind energy systems into the AC electricity used by most appliances and power networks. They also help regulate voltage and frequency to meet power quality requirements. In hybrid systems with multiple energy inputs, inverter synchronization is necessary for proper operation (Elalfy et al., 2024; Hassan et al., 2023).

Controllers direct the overall operation of the system by managing energy generation from different sources and coordinating the charging and discharging of storage systems. Advanced controllers can operate in real time by considering weather conditions, demand level, and storage availability, using methods such as fuzzy logic and other intelligent algorithms. This allows the system to function efficiently and respond optimally under changing operating conditions (Elalfy et al., 2024; León Gómez et al., 2023). Figure 3 illustrates the major components of a hybrid renewable energy system. It shows how multiple renewable energy sources, including solar panels, wind turbines, hydropower, and biomass generators, are connected through energy converters, power control units, and energy storage devices such as battery banks and flywheel storage to supply electrical load.

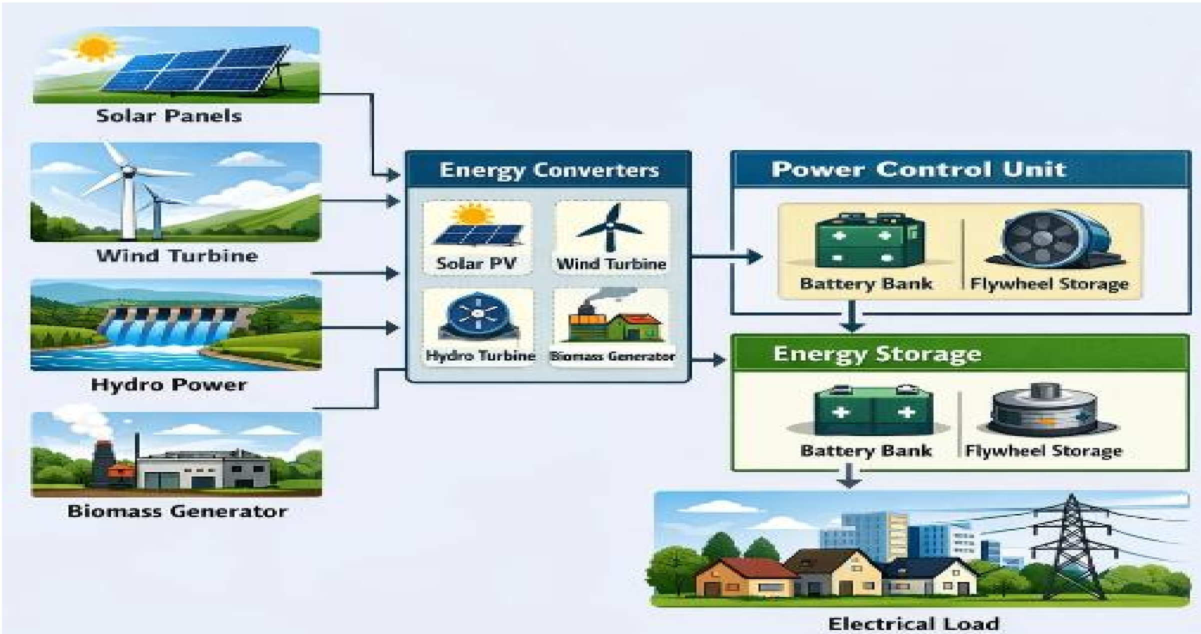

Figure 3: Components of a Hybrid Renewable Energy Systems

2.4 Power Conversion and Control Mechanisms

Power conversion and control strategies are very important n a hybrid renewable system in order to operate efficiently. These are to control the power flow of the hybrid renewable energy system as generation and storage form, among others.

Converters are used to convert the energy that has been generated by utilisation of RE to usable form. In any case, solar energy creates DC power while everything from the devices we charge to the grid that sends electricity to your home and industry uses AC. However, the power generated by solar power must be converted to usable AC energy for homes and industries, and also for grid use (Arcos-Aviles et al., 2016). This is just like wind and hydro power, both generate DC/variable AC that must be converted to stable AC.

The energy flow is controled by the controllers in the system, to guarantee an optimal distribution of energy and combine the produced energy from different sources with a good load match. Based on Arcos-Aviles et al. (2017), these controllers play a crucial roles in the operation of a system and they are being responsible of operations monitoring and of making decisions about which energy resources to use, such as transitioning between different types of energy sources when some becomes available, and transition from charging to discharging an ESS. Sophisticated control strategies like fuzzy logic and model predictive controls can be effective means toward increasing the efficiency of energy management.

The HRES network communication enables interconnected elements of a network to exchange data. This will enable the orchestration of different sources and storage systems. Communication will facilitate controllers to receive the data required in the decision-making related to energy storage and balancing (Hirsch et al., 2018). Communication networks can also be used to remotely monitor and control the network.

3.0 Energy Management Systems (EMS)

3.1 Traditional EMS vs. Fuzzy Logic-Based EMS

Classical Energy Management Systems, shortened EMS, also play an important role for the maximization of production, transportation and consuming processes of electricity on power grids. These networks adopt determinist control process, which apply the precise mathematical model and historical experience to accurately forecast supply and demand of energy (Benson & Magee, 2014). For instance the conventional EMS usually rely on optimization procedures which assume that supply or demand is both innately variable and also predictable, something well-suited to managing classical energy sources but less so for renewable ones whose erratic nature has become increasingly clear (Gellings, 2009; Fikru, 2019)

In contrast, fuzzy logic-based EMS offer greater support in the operation of Hybrid Renewable Energy Systems (HRES) because they can manage imprecise and uncertain data (Boza & Evgeniou, 2021). Fuzzy logic EMS are not like classic EMS which decide in a strict manner with the measured true values. Instead, it makes "fuzzy" logic decisions based on in-between values (Arcos-Aviles et al., 2016). This allows the fuzzy logic EMS system to adequately address the dynamic and uncertain characteristics of renewable energy sources that typically generate fluctuating outputs, which are difficult for conventional EMS system to solve (Arcos-Aviles et al., 2016). The nature of fuzzy logic makes it more suitable for energy management in HRES on a dynamic basis as the scenario is constantly changing with uncertain and incomplete data (Boglou et al., 2020).

In addition, fuzzy-logic systems have the ability to improve the energy-commodity management because of its adaptive rules and self-learning depending from evolving conditions such as weather patterns and energy demand (Jafari et al., 2018). This flexibility has the tendency of making HRES perform better, in that energy storage devices like battery or flywheel can work under ideal charging and discharging situations as a function of moment. In contrast, the fixed-based EMS system have difficulty in getting things right in such adaptive and dynamic environments (Benson & Magee, 2014). Thus, the adaptive and uncertainty handling capacities of fuzzy logic make it a highly efficient approach for energy management of hybrid renewable systems as energy management systems are not able to perform quite well in such situations (Arcos-Aviles et al., 2017).

3.2 Components of EMS

Energy Management Systems (EMS) has several key components, operating in the combined mode for optimised energy generation, distribution and consumption. Energy forecast is an indispensable component in the system of renewable energy, which includes predicting renewable energy resource (energy potential) that will be obtained from renewable resources (Benson & Magee, 2014). Such energy forecasting is usually achieved using historical and weather information. However, infinite variability is applicable for renewable energy sources like wind and Sun since predict model does not yield enough reliability as well for predictions to assume that they are accurate (Fikru, 2019). In this context, to improve such estimations, a fuzzy-logic EMS can take into account current weather conditions for adapting estimates dynamically (Jafari et al., 2018).

A second essential point in hybrid renewable energy systems is load prediction, which aims to estimate the power demand at an arbitrary moment (Arcos-Aviles et al., 2016). This is relevant, particularly in hybrid renewable sources since power demand varies across different times of day. Common models aggregating load forecasting may be based on past consumption form, which does not account for abrupt consumption changes or technology advances of power consuming equipment (Boza & Evgeniou, 2021). Nevertheless, where applications such as load forecasting are concerned, fuzzy logic optimization can handle uncertain data input (eg. ambiguous consumer activities) to produce better- adaptable forecasts (Jafari et al., 2018).

System optimization, another important part of EMS, can also make effective production, storage and dispatch of energy (Arcos-Aviles et al., 2017). In conventional EMS steady-state conditions are considered for system optimization, which may not be effective in alternative power systems having renewable resources with the variable power generations (Boza & Evgeniou, 2021). The strong point of the EMS in the thesis is working based on fuzzy logic, which makes it possible to online optimize for power production usage by storing generated power when there is more than demand and supplying stored energy to demand when was more than dynamic (Boglou et al., 2020). Real-time power distribution optimization as such is impossible in conventional EMS that may not be able to perform real-time optimization (Fikru, 2019).

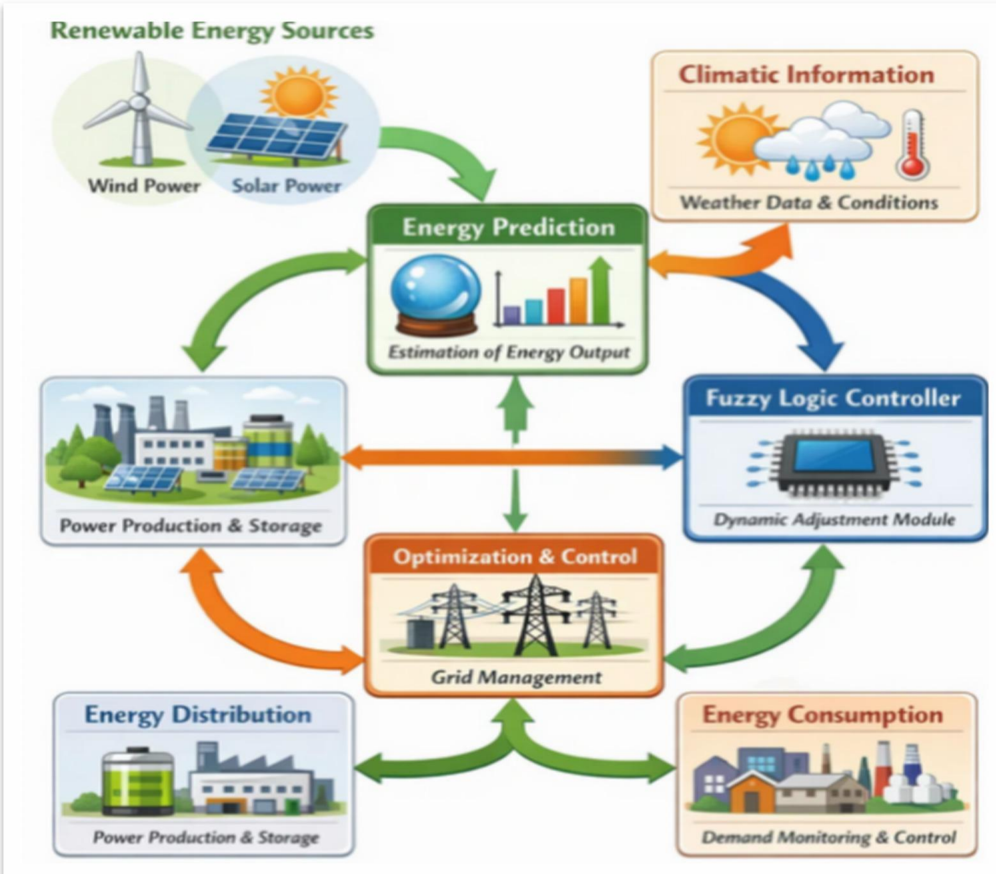

Figure 4: Components of EMS

3.3 Objectives of EMS in Hybrid Systems

The primary objective of an EMS in HRES is EEmax. Gellings (2009) adds that it is to maximize energy generation and distribution and attempting to minimize the energy waste. But in a HRES scenario, the importance of achieving energy efficiency is seriously taken into account due to its intermittency and vagaries of the renewables such as solar and wind that results in over generation sometimes while under the full capacity some other times. Utilization of modern EMS control strategies such as fuzzy logic provides maximization of the overall system efficiency and at the same time stores excess energy for later use in peak hours (Arcos-Aviles et al., 2021). Instead, the use of fuzzy logic in this case contributes to optimizing energy exchange between diverse renewable sources, which could allow the entire system to operate at its capacity even under changing conditions (Arcos-Aviles et al., 2017).

Cost reduction is also an important goal of EMS. The cost of installation and hybrid renewable energy systems can be high in the early stages. Further, managing the uncertainties associated with renewable sources can increase the operational costs (Fikru, 2019). EMS has the potential to address this through an optimized control of both, energy production and energy consumption. Traditional EMS can take in consideration fixed schedules and forecasts to predict the required energy amount, while Fuzzy Logic-Based EMS may put into use real-time solutions to avoid costly closes power supplies from the Grid or formed by Generators (Boza & Evgeniou, 2021). By achieving more predictive predictions of required energy, less reliance will be placed on expensive Grid supplied electricity or Fossil-Fuel-Based Generators to generate excess electricity when demand is high (Jafari et al., 2018).

Reliability is one of the important missions of EMS in hybrid vehicles to be achieved. The irregularity of the power produced by renewable sources does not allow to guarantee a secure supply of energy. In order to circumvent this problem, the EMS always has the duty of supervision and control over energy flow from different sources ensuring that there is a continuous demand for energy (Arcos-Aviles et al., 2016). Use of fuzzy logic base EMS design will improve the reliability in HRES because we can take better decision based on load and generation variations at any instant of time (Boza & Evgeniou, 2021). Leveraging on the power of fuzzy logic in addressing uncertainties, these systems play a role in guaranteeing that the energy supply is maintained convenient also when little renewable power is generated (Fikru, 2019).

3.4 Design Considerations for Fuzzy EMS

Memberships functions, rule base and inference engine are the main components of fuzzy logic based EMS system. These elements are crucial, in order to be able to take decisions based on the approximate knowledge frequently encountered in renewable energy systems.

The membership functions serve as instruments to describe how input variables are correlated with fuzzy sets. The latter functions are of particular importance in fuzzy logic, since their purpose is to underline that the system must be able to operate on imprecise inputs, which can be roughly associated with „low", „medium"° and „high" (Boza & Evgeniou, 2021). Membership functions can be applied on the variables of energy generation, wind speed and solar intensity in the EMS to adopt fuzzy logic so that the system performs real-time decision making. According to Arcos-Aviles et al. (2016) that in order for a fuzzy logic system to make good decisions quickly and accurately despite the existence of uncertainty or vagueness, its membership functions should be well-formed.

The rule base consists of a set of IF-THEN rules, which define the relationship between input variables and consequent's state (Jafari et al., 2018). For example, if there is not much solar PV generation, the EMS can play around with wind and storing surplus. Consequently, the rule base must be carefully designed in order to filter out possible system responses that are not valid or pertinent given the state of the environment at any time (Arcos-Aviles et al., 2017). The responsive behavior of the system to taking right decisions, anytime, can be enhanced by optimizing the rule base as suggested by Fikru (2019).

Thirdly, inference mechanisms process input information that is fuzzy, generating an outcome or output (Boza & Evgeniou, 2021). Inference mechanisms involve fuzzy information aggregation, rule base implementation, and the selection of the most appropriate action. In fuzzy EMS, inference mechanisms such as Mamdani or Sugeno method aid in deciding the best energy-management strategy through fuzzy input values (Arcos-Aviles et al., 2017). With the participation of reasoning mechanisms, fuzzy

EMS can make adaptive decisions, thus efficiently and effectively driving hybrid power generation based on better performance of hybrid power generation technologies.

4.0 Fuzzy Logic in Energy Management

It is a method of processing vague or incomplete data like humans by performing mathematical operations. It was conceived by Lotfi Zadeh in 1965 as a generalization of the traditional two-valued logic system which deals with exact and absolute true and false (Zadeh, 1965). In traditional logic systems, the values are only binary (0 or 1) whereas in fuzzy logic systems truth values may be any number between 0 and 1. This has encouraged the extended use of fuzzy logic systems in energy systems which are characterized by non-smooth renewable sources like solar wind (Boza and Evgeniou, 2021).

The key thanks that we discuss in fuzzy logic are the process of taking inputs and converting them into something playable. Fuzzification So Fuzzification is really the process of converting a number into a set or category such as low, medium and high (i.e., fuzzy set or category). For example, at 25°C it could be categorized as being 'warm' or 'medium' in a fuzzy logic system (Jafari et al., 2018). This is a necessary feature of any fuzzy logic system, as it allows for real-world uncertain inputs (eg weather or energy demand forecasts).

The second part of FML is the rulebase, a set of if-then rules that are used to represent system s knowledge. This rulebase allows a fuzzy logic system to infer the information from an imprecise input. For instance, in energy storage system with adoption of fuzzy logic this could be translated into a rule: "IF there is low generation of solar power and high storage THEN reduce the usage". It is developed by human experts or an ML algorithm and the essence of the system's decision-making on energy, storage, as well as the load (Arcos-Aviles, Li, & Zhang, 2021).

Finally, the fuzzy output is defuzzified to convert its decision with crisp system. the fuzzy output, derived from the rules applied has to be transformed into a formable control action (like power set point or load sharing) needed for application in the system. The other well-known techniques for defuzzification are also related to the centroid. It establishes the center of that fuzzy set by calculating the centre of gravity to produce a decision with an optimal output (Arcos-Aviles et al., 2016).

With such three ingredients, fuzzy logic can provide a kind of extremely important tool to deal with the highly complicated nonlinear systems, especially for those system; that suffer from uncertainties and imprecise variables. It is especially valuable for energy systems that are subject to uncertain variations due to energy productions and loads (Fikru, 2019). In addition to its ability for modelling human-like decision-making, one of the main advantages of fuzzy logic in decision making related to energy systems is that many renewable and sustainable systems such as wind energy (which cannot be linearly modelled) can be modeled using fuzzy-logic improving their performance.

4.1 Application of Fuzzy Logic in Energy Systems

Fuzzy regression has been also used successfully in energy-related fields. Interest is primarily in the variability of produced energy for renewables. A solar panel generates power only when the sun is out. The same issue arises for wind turbines in that they can only generate power in sufficient winds. Thus, the interconnection issues of energy supply and demand are relative complex where flow energy management under fuzziness approach can be considered (Boglou et al., 2020).

Fuzzy logic has also been very useful for this goal in several applications to energy systems, such as in controlling energy flow. Where HRES exists, multiple sources of energy is available through solar, wind and hydro. This is where fuzzy logic comes in handy, as a key factor in providing smoother and efficient energy flow from those sources to meet society's demand for power. For instance, during the cases where wind power energy generation is reducing, and solar power source is increasing; use FLC to control the capacity of wind power and make it corresponds with solar source or optimize storage system so that any electric extra that is generated from this solar source be saved in history for desired future (Arcos-Aviles et al., 2017).

An additional area where fuzzy logic can play an important role is the control of energy storage systems in HRES. In times of reduced production, such as at night or on overcast days, there is not enough energy produced to power the load, and the system receives energy from stored energy (batteries/flywheels in HRES) that was previously stored. Older control systems may have even relied on on/off thresholds to tell them whether they're charging their battery or feeding power back to the grid. Fuzzy logic control systems can also give rise to more scientifically sound results regarding multiple parameters such as the current state of the art on energy production, anticipated demand and a charge status at a battery. Fuzzy logic may decide to reduce the battery charging rate if it has some reasonable solar productions or, following lack of power from wind outside community at a bid to improve whole system efficiency level (Fikru, 2019).

Fuzzy logic is employed for load management of energy systems apart from generation and storage. Demand side management (DSM) has been an essential strategy to match the demand for energy with that available in the systems, especially under high penetration of renewable sources. Fuzzy logic is effectively used to optimal the energy supplied in a sharing a distribution to different users on the prevailed conditions. For instance, fuzzy logic could be employed in smart grid applications to determine how energy can flow between homes and devices (HVAC and water heaters) under low generation of power from renewable sources (Boza & Evgeniou, 2021). The usage of fuzzy logic in energy management is shown as a hybrid renewable energy system (HRES) in figure 5. The figure highlights the performance of such Variable Renewable Energy Generation inputs, especially Solar and Wind power processed through a fuzzy inference system made with some input parameters like sunlight, wind speed, demand for energy to increase energy storage capacity giving support to grid integration as well as load balance.

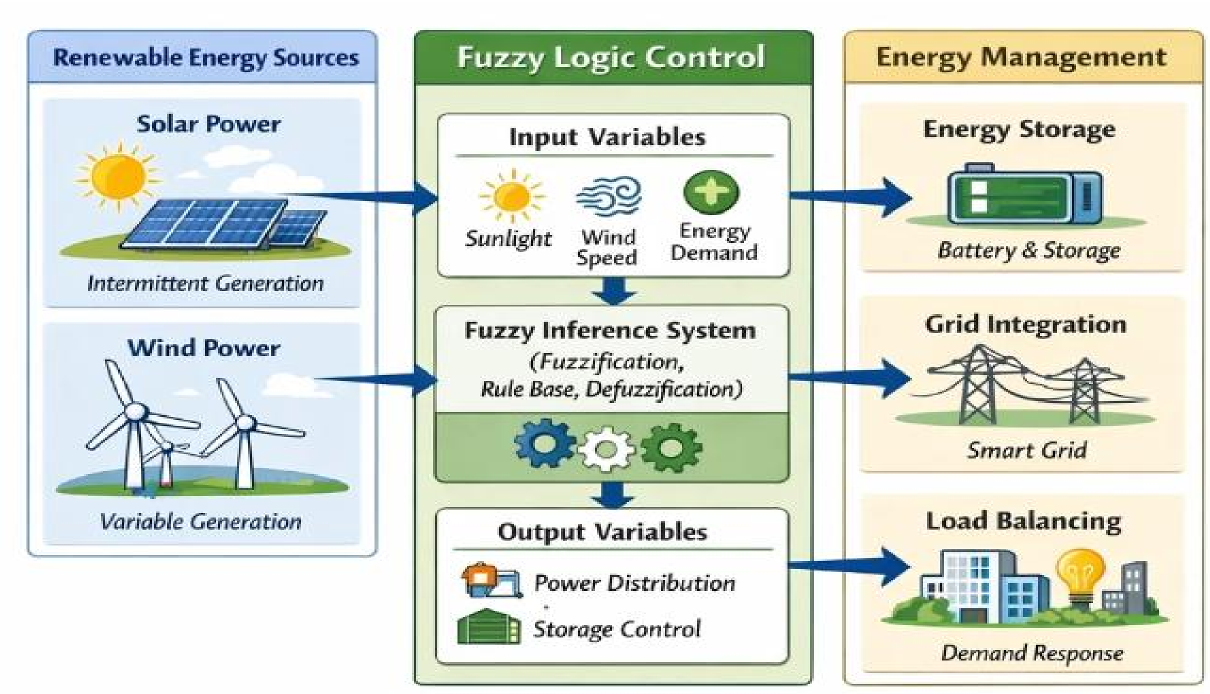

Figure 5: Application of Fuzzy Logic in Energy Systems

4.2 Fuzzy Logic for Energy Forecasting & Load Prediction

It is also crucial for the control of energy systems, especially while incorporating renewable energies. This enables EMS to predict when peak and off-peak energy will be generated, alter storage plans, and ultimately control the flow of energy efficiently. Standard forecasting methods, which rely on statistical techniques and historical data, are less adequate when it comes to the inherent variability and uncertainty of renewable energy generation. This is where the use of fuzzy logic comes in energy demand forecasting.

In terms of energy predictions, a fuzzy logic system can process the input variables with some uncertainty (as weather patterns, temperature and cloudiness), to predict productions of solar or wind energy (Benson & Magee, 2014). As an example, a fuzzy pattern-based system could assimilate several inputs variables simultaneously and employ fuzzy logic to forecast solar production potential given the weather whose forecast may not be known precisely.

Another location where the use of fuzzy logic is crucial, is in predicting the loads. It is crucial to accurately predict the loads in order for power usage to be controlled especially when considering very high penetration of renewables into power grids. Fuzzy logic-based prediction of the loads can accommodate the inconsistent behaviour of loads with respect to load consumer behavior, the project activity behaviour, and load consumption pattern in terms of daily and seasons (repeated) variations (Arcos-Aviles et al. There are few studies with case examples where it has been demonstrated that the fuzzy systems are also important in energy forecasting and load management. For instance, Jafari et al. in 2018 investigated the energy demand prediction in solar and wind based micro-grid not only for fuzzy logic, but it was considered to have improved accuracy as compared to traditional techniques with better flexibility particularly; where weather conditions are unpredictable. In another study, by Arcos-Aviles et al. in 2016 have employed fuzzy logic in prediction of wind power generation in a hybrid power system and thus improved the ability to predict the availability of energy and change dispatch plan.

4.3 Advantages of Using Fuzzy Logic in EMS

Fuzzy based techniques in EMS There are several advantages of using fuzzy logic in Energy Management System (EMS) when dealing with Hybrid Renewable Energy Systems (HRES). The first benefit concerns the matter of decision flexibility. The truth is that a system can indeed make decisions based on this sort of fuzzy logic - it's typically used where information is uncertain or incomplete. This is particularly crucial in a system like Energy Management where the source of renewable energy may fluctuate unpredictably, as in wind and solar power (Boza & Evgeniou, 2021). The system does not require ``perfect" information (as for other systems that are based on conventional decision-making techniques).

The advantages of fuzzy logic used in EMS is that its ability to handle uncertainties effectively. This is because renewable energy sources have uncertain nature in the aspect of weather variability, generation capacity and demand. This is in stark contrast to conventional control systems, which cannot appropriately handle uncertainty since they rely on deterministic models under steady conditions (Arcos-Aviles et al., 2017). That is, fuzzy logic can effectively handle the uncertainties in power generation as it considers decision-making based on the input fuzzy variables. This is a step in the direction of ensuring that energy generated, stored, and later distributed will be maximized (Fikru, 2019).

In the end utilization of fuzzy logic improves EMS decision making. This, as noted, is because the control systems have traditionally been focused on simpler algorithms that entail decisions like switch generation on/switch generation off. But the fuzzy logic, which is of a hybrid renewable system, can allow a decision to be taken on the amount of energy that should be stored (storing), when it has to be supplied from storages and power being fed into various power sources (Arcos-Aviles et al., 2017).

5.0 Fuzzy Logic-Based EMS for Hybrid Renewable Energy Sources

5.1 Fuzzy Logic-Controlled Energy

Fuzzy logic has also been found to be a successful method in the area of energy management for HRES. There are several reasons why fuzzy logic can be considered for energy management, first of all because it is able to correctly handle imprecise, uncertain and dynamic information. The application of fuzzy logic for energy management offers several methods and one well-established method is the fuzzy rule based controllers. Specifically, they act on the premise that a fuzzy rule set can be represented as IF-THEN statements describing an optimal action in relation to system state information (Benson & Magee, 2014) Thus in an energy system with incorporated solar and wind renewable energy resources, for instance, a fuzzy rule-based controller can serve to determine whether the surplus energy generated by solar PV units is storable and/or transferrable for meeting subsequent energy demands according to local weather conditions and its available storage capacity (Arcos-Aviles et al., 2017).

The adaptive fuzzy control is another approach to enhance the fuzzy logic based EMS. For Traditional systems, the rule base and membership functions are consistent to improve their performance (Fikru, 2019). On the deapatative type, fuzzy control systems adjust their rule base and membership functions in relation to the changes of system conditions in real time (Fikru, 2019). In energy systems, renewable power generation may fluctuate on a seasonal or day-to-day basis due to environmental conditions (Boza & Evgeniou, 2021), and making predictions from this data is useful. In all-of-the-above energy systems, you need to harness sun power and wind power and everything else to maintain consistent flow of energy (Boza & Evgeniou, 2021).

It is worth mentioning that the fuzzy based EMS has a signature influence on energy flow and storage management of the hybrid system. It is able to determine the operation of the different energy sources and their variability during generation (Arcos-Aviles et al., 2017). On top of that, the EMS system might be able to make the system less reliant on the backup generators. It does so by favoring the renewable energy and storage resources. This could enhance the sustainability and efficiency of the system (Boglou et al., 2020).

5.2 Energy Flow Optimization in Hybrid Systems Using Fuzzy Logic

Optimizing energy flow is one of the main objectives of Energy Management Systems (EMS) in the context of Hybrid Renewable Energy Systems (HRES). Optimizing energy flow is important in cases where various energy sources, such as solar energy, wind energy, and hydropower, are connected. These sources of energy usually generate energy at different times of the day depending on the weather. Fuzzy logic is very important in optimally handling energy flow in HRES. The generation, storage, and distribution of energy are controlled through variations in fuzzy logic (Arcos-Aviles et al., 2016).

Methods for optimizing energy flow using fuzzy logic include energy forecasting, load forecasting, and storage. For example, using fuzzy logic, the amount of energy to store in batteries or any other storage system can be optimized with respect to real-time solar or wind energy generation (Boza & Evgeniou, 2021). During high solar energy generation, yet with near-capacity storage, fuzzy logic can help in deciding on the best time to store this excess energy, at the same time ensuring that the required amount of energy is also available. During low solar energy generation, fuzzy logic helps in using more energy from the storage system, hence creating a link between supply and demand (Fikru, 2019). Additionally, fuzzy logic can be applied to the balancing of different energy resources in a hybrid system to identify the best contribution of each energy resource to the total energy supply. For instance, for a hybrid system that consists of solar energy and wind energy, fuzzy logic can be applied to identify when to utilize solar energy and when to change to wind energy based on the availability of the energy resources and the demand for energy (Arcos-Aviles et al., 2016). The application of fuzzy logic ensures a smooth supply of energy between the different energy resources in the system. Optimization of energy flow through the use of fuzzy logic also considers real-time decision-making. Energy distribution in a smart grid environment can be optimized through the use of fuzzy logic. According to Beglou et al. (2020), fuzzy logic can be applied in the smart grid energy area to adjust the energy output level of the various sources with regard to energy demand predictions and the level of renewable energy (Boglou et al., 2020).

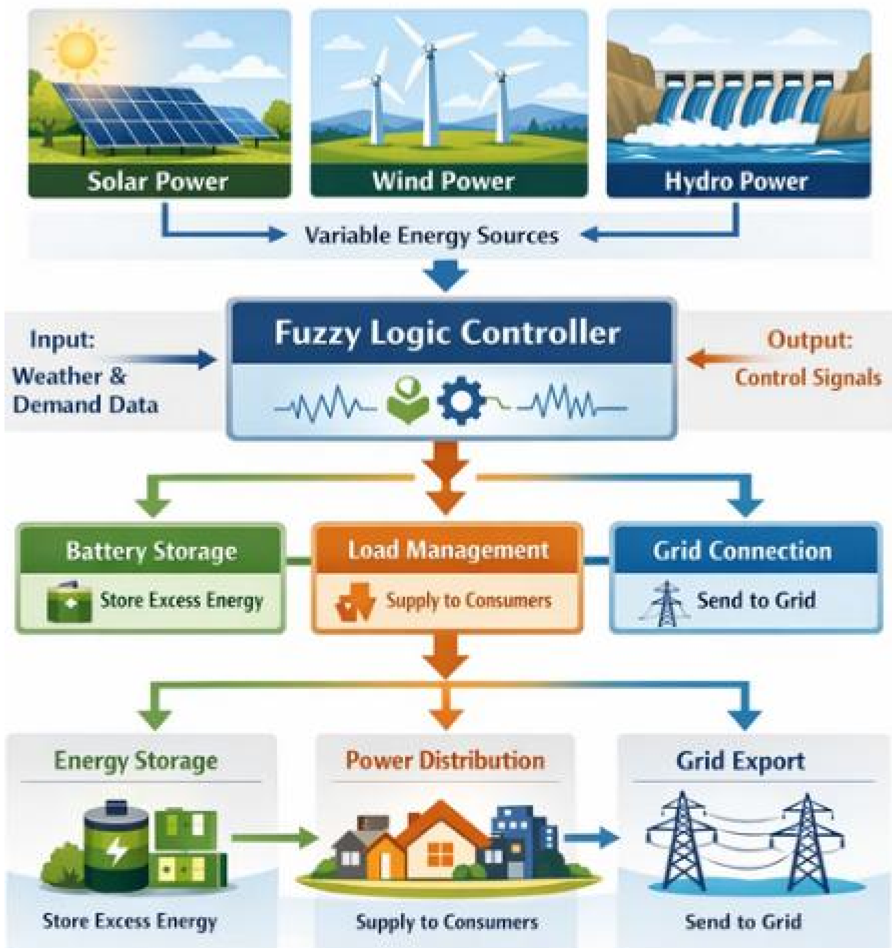

Figure 6: Energy Flow Optimization in Hybrid Systems Using Fuzzy Logic

5.3 Storage Management and Fuzzy Logic

Energy storage systems are vital components of hybrid renewable energy systems, as they accommodate energies surplus generated during times when production is high to be used later in times when production is low. Storing energy in batteries: Handling with care is a necessity for a stable future energy system. Fuzzy logic is used in electric vehicle battery management systems for efficient use of energies of batteries to prevent loss (Fikru, 2019). Fuzzy logic can be used to control battery charge and discharge in a typical energy storage system based on demand required generation of energy, and also depending on battery state of charge other parameters (Arcos-Aviles et al., 2021). For instance, if the amount of solar energy generated is high but the power demand is low, then fuzzy logic may be used to determine when it makes the most sense to charge batteries, as a function of battery state and capacity, for example. However, if the energy demand is greater than the renewable one, the fuzzy logic can be used to better manage which is the best solution during the batteries' dispersions in order to satisfy a certain amount of reducing power.

Fuzzy logic has potential to handle the intricacy of compounding multiple energy storages in hybrid system. There are systems that utilize batteries and also flywheels as energy stores. With fuzzy logic, the charging and discharging modes of two energy storages may be managed according to their system's requirement, therefore both energystorages are fully employed. Fuzzy logic' is, therefore, a key aspect to ensure the sustainability and improve the performance of hybrid renewable energy systems (Boza & Evgeniou, 2021).

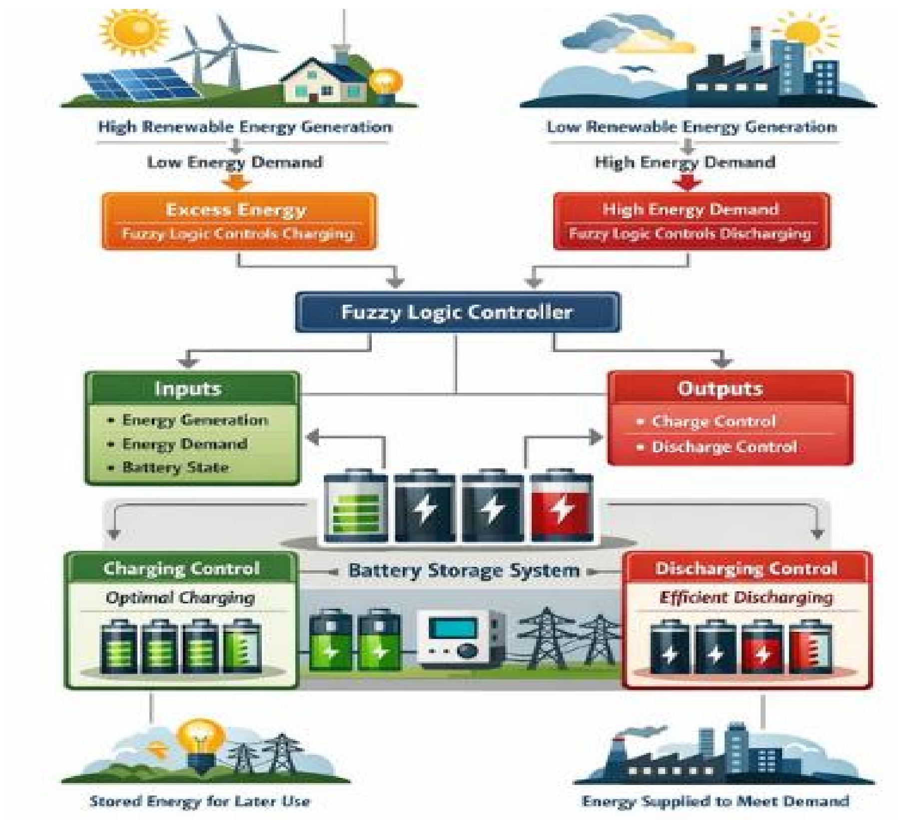

Figure 7: Storage Management and Fuzzy Logic in Battery Systems

5.4 Load Forecasting and Demand Response Using Fuzzy Logic

So, load forecasting and demand response become the key part of any EMS in the hybrid RES. accurate load prediction is important in predicting the energy demand which is needed for optimization of energy generation and storage. But, energy needs cannot be predicted easily because consumption patterns fluctuate on a daily (adaystic) basis in response to many external factors – including weather changes -, within the day, or seasonally. Arcos-Aviles et al. (2017) Offline input data processing for uncertain and incomplete information is done to design a better load forecast using fuzzy logic than typical techniques.

Fuzzy logic is an effective tool in demand response that can maximize the energy usage during peak and low generation period. Thus, Fuzzy logic aids on DSR in hybrid systems that energy consumption behav- iours monitor and may instantly adjust appliances or systems by using fuzzy rules. It can therefore also modify HVACs, water heaters or other industrial equipment during peak periods or when renewable generation is minimal. It's a way to balance supply and demand at the grid and rely less on backup generation from fossil fuels.

Studies carried out have shown the efficiency of fuzzy logic in load forecasting and demand response. Jafari et al. used fuzzy logic to predict energy requirement of a system which is hybrid including both solar and wind sources. The FL model provided a superior performance compared to other classical methodologies in terms of accuracy, and when the predicted load dropped on a period of high renewable generation, it yielded better behavior. Similarly, Boglou et al. applied fuzzy logic to optimize demand response in smart grid for energy efficiency and peak demand reduction. Both case studies are clear demonstrations on the possibility of using FL for improving load forecasting and DSM in HRES systems.

5.5 Case Studies and Implementations

It has been seen in various literature reviews that several case studies are being shown for successful application of Fuzzy Logic to EMS(HRES). A very recent paper by Arcos-Aviles et al. (2016) employed fuzzy logic for energy management of a hybrid solar-wind microgrid. This paper evidences how fuzzy rule based controllers can modulate the energy flow between a solar cells system, wind turbine generators and an energy storage device into the power network for efficiency enhancement and less dependence from backup fossil fuels generation. The above case study demonstrates that the fuzzy logic based control of a multi-source energy system is indeed successful in maintaining real-time power production and consumption.

A second case was reported by Arcos-Aviles et al. (2017) on a hybrid renewable system installed at an off-grid remote community. Fuzzy logic controllers had been employed in the system to maximize the use of solar, wind & hydropower and energy storage batteries. The fuzzy logic system minimized energy cost and enhanced the reliability of the energy supply to ensure that the village could obtain a stable and unlimited supply of power, regardless of low renewable resource penetration. This case-study highlights the promising applications of fuzzy logic to improve operation of HRES at remote and/or off-grid sites.

Boglou et al. (2020) also utilized fuzzy logic based demand side management to a smart grid network including renewable and unfading energy types. The charging/discharge operations of batteries for peak demand reduction and system energy efficiency have been conveniently controlled by using fuzzy logic. This case study should clarify the extent to which demand response is increased by fuzzy logic, particularly in combination with those plants where a significant amount of energy conversion originated from renewable sources. Fuzzy logic can therefore provide a better load shifting as well as energy storage and remove dependency on the electricity grid directly fuelled by fossil using fuel oil tanks to increase sustainable system.

6.0 Challenges and Limitations of Fuzzy Logic in Hybrid Systems

6.1 Computational Complexity

One of the biggest obstacles to using fuzzy logic in HRES is the complexity and computational overheads associated with decision-making. By their very nature, FLSs contain large number of variables as well as fuzzy rules and they must be all processed at the same time implying more often difficult computational load. Modelling of each system includes real time energy generation, demand, storage level and climate parameter (e.g. data described from the weather) monitoring. The real-time processing of big data from one system source may cause a lot of computational burden, and if the number of independent power sources and energy storage systems are more than single, it may produce many kinds of good paths with different lengths while one input demand appears.

For instance, the HRES includes continual activities in interpreting energy movement and storage. It continually has to decide when to charge or discharge a battery, how to move energy between sources and ensure that grid stability is always maintained in real-time (Fikru, 2019). Those choices demand high processing speed and efficient algorithms that ensure the stability and reliability of energy management. Arcos-Aviles et al. describe how Fuzzy Logic, while more flexible and adaptive than conventional control systems, imposes an even larger burden on processing power -- particularly for complex systems. This is more pronounced when scaling up and for real-time systems that implement fuzzy logic. The number of such variables and fuzzy rules grows significantly, exponentially with growing number of the renewable sources being considered, energy storage systems and receivers. What emerges as the key issue is how to handle such computational work so as to achieve rapid response times, and specifically prevent system slowdowns which could lead to an inefficient use of energy (what is called an "operational vulnerability"). This issue becomes even more evident when considering a set of different energy sources-combining solar, wind and hydro power-from which the power generation should be continuously monitored and controlled.

Consequently, fuzzy logic adds the adaptability and flexibility of HRES as downside imposes considerable computational complexity which causes decision -making hard in real time and particularly for complex and dynamical systems. A such requirement for great computational power and optimal algorithms of calculations can make an application of fuzzy logic in different hybrid systems not always realizable, especially at the presence of limitations in resources.

6.2 Tuning Fuzzy Logic Parameters

One of the difficulties in using FL for HRES systems is how to define and optimize the parameters employed in fuzzy logic, including membership functions, rules, and inference. These membership functions are defined as defining the categorisation of input information into fuzzy sets in terms of ‘low’, ‘medium ‘or ’high’° (Arcos-Aviles etal, 2017). This setting the membership functions would be needed in order to make the system working properly, since performance on interpreting and processing information by the system mostly depend on these parameters. Such procedure would demand expertize and time if there are several input variables (Fikru, 2019).

Tuning of fuzzy logic controller is also a cumbersome task, where the parameters like the number of fuzzy rules, membership functions and inference engines etc. The development of a fuzzy logic controller is a trial and error process where experts tune up the parameters manually to ensure that operational inputs are well combined (Benson & Magee, 2014). Furthermore, this can become more complicated in hybrid systems with multi renewable and storage sources “in such cases they may require different membership functions and rules” (Benson et al., 2014). Additionally, when renewable energy resources are applied, there is an added complication due to the fact that parameters of a fuzzy logic controller must be adjusted based on season and demand in this case (Boza & Evgeniou, 2021).

The parameter optimization problem of FL can influence the efficiency and performance of the whole system. If the parameter optimization is not good, FL controller may make wrong decisions. Inefficient power distribution, battery overcharging/undercharging and load forecasting errors can be introduced by the FL controller (Arcos-Aviles et al., 2017A.). Moreover, if the optimization of FL parameters is suboptimal, response time might be slow as well. All these issues need to be tackled through specialization and the development of FL systems tailored to hybrid RES.

6.3 Integration with Other Techniques

Combination of fuzzy logic Fuzzy logic when combined with models such as artificial neural networks and genetic algorithms becomes one of the most interesting new areas, within application of FL method in HRES. Use of fuzzy logic in conjunction with these models enhances the systems ability to handle complex conditions including nonlinear relationships, which optimize the energy management system (Benson & Magee, 2014). For example, the employment of neural networks provides the system with models to deal with intricate relationships in energy generation and consumption patterns that cannot be faced directly by isolated fuzzy logic systems. By using neural networks on the basis of fuzzy sets, there is a potential to predict energy generation and consumption that already occurred (Gure, 2014).

Genetic algorithms are also a technique that can be combined with fuzzy logic to improve the optimum energy management of hybrid systems. Genetic algorithms are schemes used in locating the optimal values, and often they are ideal to use for solving complex optimisation problems using simulated procedure of evolution on nature. Genetic algorithms can integrate together with fuzzy logic to improve the decision-making system as these genetic techniques also creates, modifies or enhances the rules of fuzzy logic based on real-time data from how these given systems performs (Boza & Evgeniou, 2021). For instance, in an HRES, the control process between solar power generation and wind speed generation may apply fuzzy logic, where optimization of developing of the fuzzy logic rules is performed by the genetic algorithms with respect to HRES performance.

However, there are several problems related to fusion of fuzzy logic with other techniques. This is because combining fuzzy logic with a neural network and/or genetic algorithms will result in the system being more complex to compute, which mandates higher processing power –and hence memory- (Boglou et al., 2020). The intervention to integrate different technologies will also probably need complex processing, since it is necessary to continuously adapt this system in order for it still works well within a dynamic context of our energy system.

6.4 Scalability and Implementation Issues

Scalability is one of the problems faced with fuzzy logic when used in large HRES. This is because for larger systems, the number of fuzzy logic operations to be carried out grows exponentially. Thus, the performance of fuzzy logic systems may be observed to decrease for large size systems where multitask management of several energy source and consumers are needed (Fikru, 2019). This may delay the response of the fuzzy logic systems in real-time energy optimization.

There are also implementation issues which must be addressed during the scaling up of fuzzy logic EMS. For instance, it will be a challenge to model accurately the influences between various energy producers and consumers, particularly in places where insufficient power is generated under uncertainty conditions within massive EMS systems. Moreover, the necessity of adjusting fuzzy logic EMS dynamically to changes in the system (such as, for example weather variation and the introduction of new energy generation technologies) could be also a source of implementation difficulty in large EMS [23], as described previously by Arcos-Aviles et al. (2021). The other issue there is of course - worrying about integration collision with other infrastructure that's been implemented. And this is because, the fuzzy logic EMSs must be integrated in the existing technologies in place in power industry so that the same can serve its purpose. Examples of such legacy infrastructures are SCADA systems and other utility management programs. Fuzzy logic application can be expensive to carry out in the presence of power manageability with current facilities (Boza & Evgeniou, 2021).

7.0 Future Trends and Emerging Research in Fuzzy Logic-Based EMS for HRES

7.1 Advancements in Fuzzy Logic Control Algorithms

The area of fuzzy logic-based energy management systems (EMS) in the context of Hybrid Renewable Energy Systems (HRES) has seen significant developments over the years; and it is believed that the next generation of fuzzy logic-based systems will be equipped with even greater capabilities. The next generation of fuzzy logic-based control algorithms is increasingly incorporating advanced concepts of artificial intelligence (AI) and advanced optimization methodologies to enhance decision-making and real-time adaptation in the area of energy management (Boza & Evgeniou, 2021). AI-based fuzzy logic systems that utilize machine learning concepts along with fuzzy logic are an area that has great potential.

Fuzzy logic utilizing AI has great potential for HRES, as it involves the processing of large-scale data coming from varied renewable energy resources, which requires instantaneous analysis (Fikru, 2019). The application of machine learning techniques, such as reinforcement learning and deep learning, would be useful for adjusting the parameters of fuzzy logic automatically, thereby making the system more adaptable to varied operating conditions. Machine learning would be helpful in optimizing the adaptive fuzzy control of energy storage systems, making them capable of learning the knowledge of past energy production and consumption behaviors (Arcos-Aviles et al., 2021).

In addition, the next-generation fuzzy logic system may incorporate multi-objective optimization, which takes into account various Conflicting goals, including low cost, optimal energy efficiency, and reliability, all within the framework provided by fuzzy logic. This will empower the energy management system to make more informed decisions, based on real-time information, to ensure that hybrid systems are always optimized to work at their optimum levels (Boza & Evgeniou, 2021). The further integration of fuzzy logic systems and various next-generation AI technologies is expected to improve the efficiency, reliability, and sustainability of HRES.

7.2 Integration of IoT, Machine Learning, and Big Data with Fuzzy Logic

The combination of Internet of Things (IoT), machine learning, and big data technology with fuzzy logic-based EMS stands as one of the most encouraging areas in the coming decades in hybrid renewable energy management (Jafari et al., 2018). The IoT technology has the capability to provide real-time data in significant amounts from different parts of the energy system like energy production sources, energy storage systems, and energy consumers. This data can be utilized to analyze in real time the functioning of HRES. The data was not available in the past. Machine learning applications can support the efficiency of fuzzy logic systems by learning from large data sets, thereby enabling the decision-making process to be optimized. For example, machine learning models can be employed to forecast the energy production that can be derived from solar and wind energy, as the energy produced depends on the prevailing environment (Boza & Evgeniou, 2021). This data can be used to improve the fuzzy logic process of electricity distribution and storage to ensure efficiency and accuracy in the process of electricity distribution and loading forecast (Arcos-Aviles et al., 2021).

Further, big data expands the capabilities of fuzzy logic in EMS by offering a vast amount of data that can be leveraged by EMS to enable trend analysis and enhance the decision-making capability of the system. For example, with big data, fuzzy logic is able to analyze multiple variables simultaneously, including data on weather patterns, energy use trends, and economic trends. For instance, Fikru (2019) argues that through big data analytics and fuzzy logic analysis, energy management system decisions can be made even more accurately. This integration of IoT technology, machine learning algorithms, and big data with fuzzy logic helps EMS become smarter. With the integration of IoT technology, machine learning technology, and big data into fuzzy logic-based EMS systems, the future of HRES systems becomes increasingly automated and adaptive, ensuring more efficient management of energy to meet the increasing levels of energy demand and varying trends in the production outputs from renewable energy sources (Jafari et al., 2018). By the integration of modern technologies, the EMS system will be capable of making more precise forecasts and adjusting its responses to system changes more quickly.

7.3 Smart Grid and Smart City Integration

Integration of fuzzy logic-based EMS in smart grids and smart cities is a prominent area for future research and development. A smart grid can be defined as a component of a smart city, referring to electrical grids integrated with advanced communication and control systems to monitor and control electricity generation, distribution, and consumption. Hence, fuzzy logic can be considered extremely useful in such applications for efficient energy flow, forecasting, and demand-side management (Boglou et al., 2020).

In smart grids, fuzzy logic could be applied for optimizing energy distribution amid real-time inputs from renewable energy sources, energy storage, and energy demands. Fuzzy logic, for instance, could be applied for managing energy supply and demands by automatically adjusting the energy generated from different energy sources such as solar, wind, or hydraulic energy amid variables such as weather conditions, energy demands, and energy stability (Arcos-Aviles et al., 2016). Moreover, fuzzy logic could also be applied for optimizing the utilization of DERs in smart grids, thereby increasing the stability of smart grids and decreasing energy losses. Moreover, fuzzy logic could also be applied for managing interactions between renewable energy sources and the conventional energy supply chain, thereby decreasing energy waste by storing or redirecting excess energy whenever necessary (Fikru, 2019).

In smart cities, EMS using FL can aid in optimizing energy usage in different sectors, such as transport, buildings, and infrastructure, among others. For example, EMS using FL can aid in optimizing energy usage in smart cities by harnessing renewable energy sources and storing them through energy storage systems and managing demand response, thus optimizing energy usage in a city (Boza & Evgeniou, 2021). For example, EMS using FL can aid in optimizing energy usage in smart buildings by managing heating, cooling, and lighting systems according to the availability of energy in a smart city. Likewise, in smart transport, EMS using FL can aid in optimizing EV charge according to renewable energy availability, hence ensuring that there is energy efficiency in the transport system in a smart city (Benson & Magee, 2014).

Fuzzy logic in the smart grid and smart city environments has a critical part to play in the realization of the full potential of sustainable urban energy management. With an increasing number of urban areas exploring the smart grid and smart city concepts, the need for dynamic and flexible approaches to managing the use of energy in the form of fuzzy logic concepts will always be on the rise. Fuzzy logic concepts in the management of urban energy have the potential to promote efficiency in the use of energy.

Figure 8: Fuzzy Logic-Based Energy Management in Smart Grids and Smart Cities

7.4 Sustainability and Environmental Impact

Sustainability and environment have relevance to the core of Hybrid Renewable Energy Systems (HRES), and the EMS using Fuzzy Logic can make a significant contribution to the sustainability requirements of HRES. Sustainability in the context of energy management means the ability to satisfy the current needs without compromising the capacity of the current and future generations to satisfy their requirements (Arcos-Aviles et al., 2021). By making effective utilization of renewable resources of energy while curtailing the usage of fossil fuel, Fuzzy Logic EMS can make HRES sustainable.

The major role of fuzzy logic in achieving the principles of sustainability is the promotion of energy efficiency. Fuzzy logic optimizes the production, storage, and supply of energy with the aim of ensuring that renewable resources of energy are harnessed in the most energy-efficient manner (Boza & Evgeniou, 2021). Fuzzy logic can be applied for the regulation of the charge and discharge of batteries with the objective of maximizing energy conservation and maximizing the life of the storage system. This will significantly improve the energy efficiency of HRES as well as the environmental impacts, considering the minimized requirement for energy generation, particularly that of fossil fuels.

Fuzzy logic systems in EMS can, therefore, cut down carbon emissions through optimal use of clean energy resources. In the case of HRES, the employment of solar, wind, and hydro energy can greatly reduce carbon emissions associated with energy production. Fuzzy logic systems can, therefore, reduce reliance on non-renewable energy as a source of backup power, which, as mentioned, is normally carbon-emitting in nature (Fikru, 2019). In addition, through proper balancing of energy supply and demand through energy storage systems and demand management, fuzzy logic systems ensure that energy production, use, and disposal are done without carbon-emitting peaking power stations.

In conclusion, fuzzy logic ensures the financial viability of HRES systems in terms of lowered costs in energy storage, production, and management. In its effect on energy storage and supply, fuzzy logic ensures a lowered dependency on expensive backup power, hence a reduced cost burden in energy production and consumption (Boza & Evgeniou, 2021). Financial viability through efficient energy management in conjunction with the environmental aspect created through increased usage in environmental conservation initiatives makes fuzzy logic-based EMS essential in managing the transition to sustainable and eco-friendly energy infrastructure.

8.0 Conclusion

Fuzzy logic has been a successful tool in optimizing HRES in terms of increasing its efficiency. This is because, through fuzzy logic, decision-making is made possible using imprecise, uncertain, or incomplete information, which can increase HRES output by optimizing energy generation, storage, and distribution in a smart way. HRES is composed of different renewable energy sources that include solar, wind, and hydropower, among others, which make HRES a system that needs something like fuzzy logic in order to optimize and ensure that HRES functions in a proper way that can rely on renewable energy from different sources, like solar, wind, and hydropower, among others, in a more efficient way.

Looking into the future, the applications of fuzzy logic in the coming energy systems are tremendous. Among the long-term advantages of applying fuzzy logic EMS in the hybrid renewable energy system, there is enhanced adaptability and sustainability. As the energy systems become more complex with the integration of DG sources and energy storage systems, fuzzy logic shall play an important role in matching the supply and demand. Its capacity to process multiple inputs and generate real-time responses ensures that the energy systems can respond to different circumstances while allowing higher access to the renewable energy sources to be included in the energy systems. Advances in the AI-powered fuzzy systems shall improve the predictive techniques, thereby further optimizing the energy systems.

From the perspective of future research directions, there are a few prominent areas that have to be focused on. Improving the computational complexity of fuzzy logic-based systems, especially in the context of large-scale systems, should be a significant area to be explored. Developing more sophisticated hybrid systems that combine fuzzy logic and machine learning and/or optimization techniques would help enhance the flexibility and efficiency of HRE systems. Finally, the role and potential application area of fuzzy logic in next-generation technologies such as Smart Grid and Smart City should be very important to develop efficient and sustainable energy systems.

References

Aguila-Leon, J., Vargas-Salgado, C., Chiñas-Palacios, C., & Díaz-Bello, D. (2022). Energy management model for a standalone hybrid microgrid through a particle swarm optimization and artificial neural networks approach. *Energy Conversion and Management, 267*, 115920. https://doi.org/10.1016/j.enconman.2022.115920

Arcos-Aviles, D., Pascual, J., Guinjoan, F., Marroyo, L., Garcia-Gutierrez, G., Gordillo-Orquera, R., ... Marietta, M. P. (2021). An energy management system design using fuzzy logic control: Smoothing the grid power profile of a residential electro-thermal microgrid. *IEEE Access, 9*, 25172–25188. https://doi.org/10.1109/ACCESS.2021.3061886

Arcos-Aviles, D., Pascual, J., Guinjoan, F., Marroyo, L., Sanchis, P., & Marietta, M. P. (2017). Low complexity energy management strategy for grid profile smoothing of a residential grid-connected microgrid using generation and demand forecasting. *Applied Energy, 205*, 69–84. https://doi.org/10.1016/j.apenergy.2017.06.062

Arcos-Aviles, D., Pascual, J., Marroyo, L., Sanchis, P., & Guinjoan, F. (2016). Fuzzy logic-based energy management system design for residential grid-connected microgrids. *IEEE Transactions on Smart Grid, 9*(2), 530–543. https://doi.org/10.1109/TSG.2016.2519514

Balijepalli, V. M., Pradhan, V., Khaparde, S. A., & Shereef, R. M. (2011). Review of demand response under smart grid paradigm. In *2011 IEEE PES Innovative Smart Grid Technologies-India* (pp. 57–62). IEEE.

Benson, C. L., & Magee, C. L. (2014). On improvement rates for renewable energy technologies: Solar PV, wind turbines, capacitors, and batteries. *Renewable Energy, 68*, 745–751. https://doi.org/10.1016/j.renene.2014.02.013

Boglou, V., Karavas, C.-S., Arvanitis, K., & Karlis, A. (2020). A fuzzy energy management strategy for the coordination of electric vehicle charging in low voltage distribution grids. *Energies, 13*(14), 3709. https://doi.org/10.3390/en13143709

Boglou, V., Karavas, C. S., Karlis, A., & Arvanitis, K. (2022). An intelligent decentralized energy management strategy for the optimal electric vehicles' charging in low-voltage islanded microgrids. *International Journal of Energy Research, 46*(3), 2988–3016. https://doi.org/10.1002/er.6753

Boza, P., & Evgeniou, T. (2021). Artificial intelligence to support the integration of variable renewable energy sources to the power system. *Applied Energy, 290*, 116754. https://doi.org/10.1016/j.apenergy.2021.116754

Brown, D. P., & Sappington, D. E. M. (2018). On the role of maximum demand charges in the presence of distributed generation resources. *Energy Economics, 69*, 237–249. https://doi.org/10.1016/j.eneco.2017.12.004

Darghouth, N. R., Barbose, G., Zuboy, J., Gagnon, P. J., Mills, A. D., & Bird, L. (2020). Demand charge savings from solar PV and energy storage. *Energy Policy, 146*, 111766. https://doi.org/10.1016/j.enpol.2020.111766

Dimitroulis, P., & Alamaniotis, M. (2022). Multimodal energy management system for residential building prosumers utilizing various lifestyles. *Electric Power Systems Research, 213*, 108732. https://doi.org/10.1016/j.epsr.2022.108732

Espín-Sarzosa, D., Palma-Behnke, R., & Núñez-Mata, O. (2020). Energy management systems for microgrids: Main existing trends in centralized control architectures. *Energies, 13*(3), 547. https://doi.org/10.3390/en13030547

Fikru, M. G. (2019). Electricity bill savings and the role of energy efficiency improvements: A case study of residential solar adopters in the USA. *Renewable and Sustainable Energy Reviews, 106*, 124–132. https://doi.org/10.1016/j.rser.2019.02.011

Gellings, C. W. (2009). *The smart grid: Enabling energy efficiency and demand response*. Fairmont Press.

Georgitsioti, T., Pearsall, N., & Forbes, I. (2014). Simplified levelised cost of the domestic photovoltaic energy in the UK: The importance of the feed-in tariff scheme. *IET Renewable Power Generation, 8*(5), 451–458. https://doi.org/10.1049/iet-rpg.2013.0227

García Vera, Y. E., Dufo-López, R., & Bernal-Agustín, J. L. (2019). Energy management in microgrids with renewable energy sources: A literature review. *Applied Sciences, 9*(18), 3854. https://doi.org/10.3390/app9183854

Hirsch, A., Parag, Y., & Guerrero, J. (2018). Microgrids: A review of technologies, key drivers, and outstanding issues. *Renewable and Sustainable Energy Reviews, 90*, 402–411. https://doi.org/10.1016/j.rser.2018.03.012

Hocaoğlu, F. O., Gerek, Ö. N., & Kurban, M. (2009). A novel hybrid (wind-photovoltaic) system sizing procedure. *Solar Energy, 83*(11), 2019–2028. https://doi.org/10.1016/j.solener.2009.06.013

Ibrahim, O., Owonikoko, W. O., Abdulkarim, A., Otuoze, A. O., Afolayan, M. A., Madugu, I. S., ... Lawal, M. A. (2021). Performance evaluation of different membership function in fuzzy logic-based short-term load forecasting. *Pertanika Journal of Science & Technology, 29*(2), 1329–1351.

International Renewable Energy Agency. (2019). *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*. https://www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future

Jafari, M., Malekjamshidi, Z., Lu, D.-D.-C., & Zhu, J. (2018). Development of a fuzzy-logic-based energy management system for a multiport multioperation mode residential smart microgrid. *IEEE Transactions on Power Electronics, 34*(4), 3283–3301. https://doi.org/10.1109/TPEL.2018.2831162

Javaid, N., Ahmed, F., Ullah, I., Abid, S., Abdul, W., Alamri, A., ... Khan, A. (2017). Towards cost and comfort based hybrid optimization for residential load scheduling in a smart grid. *Energies, 10*(10), 1546. https://doi.org/10.3390/en10101546

Javanmard, M. E., Ghaderi, S. F., & Hoseinzadeh, M. (2021). Data mining with 12 machine learning algorithms for predicting costs and carbon dioxide emission in an integrated energy-water optimization model in buildings. *Energy Conversion and Management, 238*, 114153. https://doi.org/10.1016/j.enconman.2021.114153

Kanakadhurga, D., & Prabaharan, N. (2022). Demand side management in microgrid: A critical review of key issues and recent trends. *Renewable and Sustainable Energy Reviews, 156*, 111915. https://doi.org/10.1016/j.rser.2022.111915

Karavas, C.-S., Arvanitis, K., & Papadakis, G. (2017). A game theory approach to multi-agent decentralized energy management of autonomous polygeneration microgrids. *Energies, 10*(11), 1756. https://doi.org/10.3390/en10111756

Khatib, H. (2016). A review of the IEA/NEA projected costs of electricity–2015 edition. *Energy Policy, 88*, 229–233. https://doi.org/10.1016/j.enpol.2015.10.010

Lai, C. S., & McCulloch, M. D. (2017). Levelized cost of electricity for solar photovoltaic and electrical energy storage. *Applied Energy, 190*, 191–203. https://doi.org/10.1016/j.apenergy.2016.12.018

Lazard. (2019). *Lazard's levelized cost of energy analysis—Version 13.0*. https://www.lazard.com/research-insights/levelized-cost-of-energy-and-levelized-cost-of-storage-2019/

LBS. (2020). *12V 200Ah lithium battery LBS-12200-SP* [Data sheet]. Shenzhen Polinovel Technology Co., Ltd. https://www.lithiumbatterysystems.com.au/wp-content/uploads/2020/01/DS_LBS-12200-SP_V1.pdf

And this one should replace the malformed "Cost, I., & Indicators, C. (2017) …" entry:

International Renewable Energy Agency. (2018). *Renewable power generation costs in 2017*. https://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017