



ADAPTIVE FUZZY-LOGIC ENERGY MANAGEMENT FOR HYBRID SOLAR–WIND MICROGRIDS: A SIMULATION-ORIENTED STUDY

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ABSTRACT :

Hybrid solar–wind microgrids can improve the availability of renewable electricity because solar photovoltaic (PV) generation and wind generation respond differently to changing weather conditions. Their output, however, is variable, and the mismatch between generation and load can cause energy shortages, unnecessary battery cycling, or renewable-energy curtailment. This paper proposes a simulation-oriented fuzzy-logic energy-management framework for a hybrid solar–wind microgrid with battery storage. The controller uses solar power, wind power, load demand, and battery state of charge (SOC) as decision inputs and determines a suitable power-allocation action. The proposed workflow includes input scaling, linguistic membership functions, an interpretable IF–THEN rule base, fuzzy inference, defuzzification, and evaluation of power balance. Unlike controllers that depend on a precise mathematical model, fuzzy logic can represent operational knowledge through understandable rules. The paper establishes a reproducible evaluation plan using MATLAB/Simulink or an equivalent simulation environment. Since the project simulation and measured outputs are not supplied in the source material, numerical performance improvements are not claimed; they are identified as quantities to be tested in future work. The framework is intended to support systematic comparison of solar-only, wind-supported, and combined solar–wind–battery operation.

Keywords—*hybrid microgrid, solar photovoltaic, wind energy, fuzzy logic controller, energy management, battery state of charge, power balancing.*

1. Introduction

The growth of electricity demand and the need to reduce emissions have encouraged the integration of renewable energy sources into distribution-level power systems. Solar PV systems convert sunlight into electrical energy, while wind energy conversion systems use the kinetic energy of moving air. Combining the two sources can reduce dependence on a single weather resource and may improve the availability of local generation. A microgrid coordinates distributed generation, storage, converters, and loads within a defined electrical system.

The main operational difficulty is that renewable generation is not constant. PV output changes with irradiance, temperature, shading, and time of day. Wind-turbine output depends on wind speed and turbine operating limits. Load demand also varies. When renewable generation exceeds demand, excess energy may be stored or curtailed. When generation is insufficient, storage can supply the deficit, provided that the battery has adequate energy and remains within its operating limits.

An energy-management controller therefore needs to make decisions from several changing variables. Fuzzy logic control (FLC) is a useful candidate because it represents control knowledge using linguistic terms such as Low, Medium, and High. Instead of requiring a complete analytical model of every component, a fuzzy controller maps measured or simulated inputs to a control decision through membership functions and IF–THEN rules. Previous research has applied fuzzy logic to renewable-energy management and solar–wind systems [1]–[3].

This paper develops a structured proposal for fuzzy-logic-based power management in a hybrid solar–wind microgrid. The focus is the controller design and the method for evaluating it, rather than claiming results that have not yet been generated by simulation.

2. Related Work

Alfred et al. presented a fuzzy-logic energy-management model for a standalone solar PV–wind system with battery storage. Their work illustrates how rule-based control can coordinate renewable sources and storage in response to demand and battery condition [1]. The study provides a relevant example of using linguistic rules for practical energy allocation.

Shezan et al. examined optimization and control approaches for an islanded hybrid microgrid, including fuzzy logic and other optimization methods [2]. Their work places fuzzy control within a wider set of strategies for improving the operation of renewable microgrids. The choice of controller should

nevertheless be assessed against the system model, objectives, and constraints used in each study.

Jemaa et al. reported hardware implementation of a fuzzy logic controller for a hybrid wind–solar system at an isolated site [3]. This is relevant to the practical implementation of fuzzy control beyond purely theoretical discussion. A broader review of maximum power point tracking (MPPT) methods for hybrid wind and solar systems compares approaches including perturb-and-observe, incremental conductance, fuzzy logic, neural networks, and neuro-fuzzy methods [4].

These studies support the use of fuzzy methods as a practical control option, but their reported results cannot automatically be transferred to a different microgrid. Performance depends on component ratings, membership-function ranges, rule design, weather profiles, battery constraints, converter models, and load patterns. The present work therefore defines a transparent evaluation procedure and leaves quantitative conclusions to be established from the project's own simulation.

3. Problem Statement and Research Gap

A hybrid solar–wind microgrid must continuously balance renewable generation, load demand, and battery operation despite changing environmental conditions. A controller that reacts to only one source may not make effective use of complementary solar and wind availability. A fixed switching strategy can also fail to represent the combined effects of renewable power, load level, and battery SOC.

The project addresses the design of a simple, interpretable fuzzy-logic energy-management layer that considers these variables together. The intended contribution is a clearly specified controller structure and a repeatable simulation plan for examining power balance, battery behaviour, renewable-energy utilization, and unmet load. It is not claimed that fuzzy logic is universally superior to all alternative controllers.

4. Objectives

- To model the main functional blocks of a hybrid solar PV–wind microgrid with battery storage.
- To design a fuzzy-logic controller using renewable generation, load demand, and battery SOC as inputs.
- To define linguistic membership functions and a rule base for power-allocation decisions.
- To evaluate the controller under changing solar, wind, and load profiles using simulation.
- To compare key indicators such as unmet load, renewable-energy utilization, battery SOC limits, and power-balance error with a clearly defined baseline.

5. Proposed System Architecture

The proposed architecture contains a solar PV subsystem, a wind-energy conversion subsystem, power-conditioning converters, a common DC link or suitable AC coupling arrangement, a battery energy-storage system, an inverter where required, the load, and a supervisory fuzzy controller. The exact electrical topology should be selected to match the simulation model and the available component data.

The PV subsystem produces DC power. A DC–DC converter may be used to regulate the PV operating point and implement MPPT. The wind subsystem converts mechanical energy into electrical power; its output is conditioned using the appropriate rectifier and converter arrangement. The battery absorbs surplus energy or supplies energy during a generation shortfall, subject to SOC, current, and voltage limits. The inverter supplies AC loads when the system uses a DC link.

The fuzzy controller acts as an energy-management layer. It should not be confused with the low-level MPPT controller: MPPT aims to extract available power from a renewable source, whereas energy management decides how generated power, storage, and demand should be coordinated. These functions may exchange signals but have different objectives.

6. Proposed Fuzzy-Logic Controller

6.1 Input and output variables

The initial design uses four inputs: solar PV power (P_{pv}), wind power (P_{wind}), load demand (P_{load}), and battery state of charge (SOC). Each variable is scaled to a defined range before fuzzification. For example, a normalized power input may be calculated as $x_{norm} = (x - x_{min}) / (x_{max} - x_{min})$, where x_{min} and x_{max} are the selected lower and upper bounds. These bounds must be taken from the actual model ratings or an explicitly stated operating range. Values should be clipped or otherwise handled consistently when they fall outside the selected range.

Each normalized input may be described by three linguistic sets—Low, Medium, and High—using triangular or trapezoidal membership functions. SOC limits should be chosen according to the battery specification and the project's operating policy; they should not be assumed to be universal values. The output can represent a normalized battery power command, a source-priority index, or a power-allocation command. The selected output definition must remain consistent throughout the model and paper.

6.2 Fuzzification and inference

Fuzzification converts a crisp input into degrees of membership in linguistic sets. A value may belong partly to two neighbouring sets, which allows smooth transitions rather than abrupt switching at a single threshold. The inference engine evaluates the applicable IF–THEN rules. For a Mamdani-type controller, rule outputs are commonly combined using a defined aggregation method and converted to a crisp output using defuzzification, such as

the centroid method [5].

A conceptual rule example is: IF solar power is High AND wind power is Medium AND load demand is Low AND battery SOC is High, THEN use renewable generation to supply the load and direct permissible surplus power toward battery charging. This is an illustrative rule, not a validated command for every operating condition. Its final action must respect converter ratings, battery charge limits, and the system's power-flow convention.

6.3 Illustrative rule logic

Input condition (illustrative)	Possible management action
Solar High, Wind High, Load Low, SOC Low/Medium	Supply the load from renewable generation and charge the battery if charging limits permit.
Solar Low, Wind Low, Load High, SOC High	Use available renewable generation and discharge the battery within its permitted limits.
Solar Low, Wind Low, Load High, SOC Low	Protect the battery; consider non-critical load reduction or an available backup source.
Solar Medium, Wind High, Load Medium, SOC High	Prioritize renewable supply and assess whether surplus energy can be stored.
Solar High, Wind Low, Load High, SOC Medium	Use solar generation first and let storage cover only the remaining deficit, if feasible.

A complete controller needs a rule for every relevant combination or a documented method for handling uncovered combinations. Four inputs with three linguistic sets each can produce up to $3^4 = 81$ combinations. A smaller rule base is possible if rules are structured carefully, but coverage and conflicts must be checked. The project presentation mentions a 27-rule design; that count corresponds to three variables with three sets each, so it should only be used if the implemented controller actually has three fuzzy inputs. If SOC is also an input, the rule count and design need to be reconciled with the actual model.

7. Mathematical Formulation and Performance Measures

At each simulation step, the instantaneous power balance can be written conceptually as:

$$P_{pv}(t) + P_{wind}(t) + P_{batt,dis}(t) + P_{backup}(t) = P_{load}(t) + P_{batt,ch}(t) + P_{loss}(t) + P_{curt}(t)$$

Here, $P_{batt,dis}$ is battery discharge power, $P_{batt,ch}$ is battery charging power, P_{backup} is backup-source power if included, P_{loss} represents conversion and distribution losses, and P_{curt} is curtailed renewable power. The sign convention must be stated clearly in the simulation. Battery charging and discharging should not occur simultaneously unless the model specifically justifies that behaviour.

The following indicators are proposed for evaluation:

- Unmet energy (kWh): the time-integral or sum of load demand that is not served.
- Renewable-energy utilization (%): renewable energy used by the load and/or storage divided by available renewable energy, with the definition stated explicitly.
- Power-balance error: the difference between total power entering and leaving the modeled system at each time step.
- Battery SOC range (%): minimum and maximum SOC observed during the simulation, checked against permitted limits.
- Curtailment (kWh): renewable energy available but not used or stored.
- Controller response: settling behaviour, switching activity, and response to changes in generation or demand.

If a baseline comparison is performed, both the baseline and fuzzy controller should use the same component ratings, weather inputs, load profile, simulation time step, and initial SOC. Only then can observed differences be meaningfully attributed to the control strategy.

8. Simulation Methodology

1. Define the microgrid topology and enter verified component ratings for PV, wind turbine, converters, battery, and load.
2. Select or construct time-series profiles for solar irradiance, wind speed, and load demand. Record the source and time resolution of each dataset.
3. Implement PV and wind power conversion models, including converter limits and any MPPT blocks that are part of the project.
4. Define the battery model, initial SOC, charging/discharging limits, and lower and upper SOC protection thresholds.
5. Normalize controller inputs using documented ranges and design the Low, Medium, and High membership functions.
6. Build the fuzzy rule base, inference method, aggregation method, and defuzzification method; test all rule combinations for coverage.
7. Run representative cases, including high solar/low wind, low solar/high wind, low renewable generation/high load, and surplus renewable generation.
8. Export time-series plots for PV power, wind power, load demand, battery power, SOC, controller output, and power-balance error.
9. Calculate the performance indicators and compare the fuzzy controller with a stated baseline, if the baseline is implemented.

9. Results and Discussion: Reporting Plan

The project presentation identifies simulation and result sections, but the supplied material does not provide readable numerical datasets, plotted values,

controller settings, or a verified quantitative comparison. For that reason, this paper does not invent performance figures or state that a particular percentage improvement has already been achieved.

After simulation, the results section should report (i) whether the power balance is maintained, (ii) how SOC changes during surplus and deficit periods, (iii) the extent of unmet load and curtailment, (iv) whether SOC and converter constraints are respected, and (v) how the fuzzy controller compares with the selected baseline. Each figure should identify units, time interval, and case conditions. If results do not improve every metric, that should be reported transparently and explained in relation to the chosen objective.

The expected technical benefit is a controller that expresses power-allocation decisions in a transparent rule base and responds to changing renewable supply and load. This is a design expectation to be tested, not a measured finding. The final paper should replace this section with actual graphs, parameter tables, and calculations from the completed simulation.

10. Limitations

The controller's behaviour depends on the selected membership functions, rule coverage, input scaling, and defuzzification method. A poorly designed rule base may produce conflicting decisions or unnecessary switching. Simulation results may also differ from field behaviour because of sensor noise, communication delay, converter losses, battery ageing, thermal effects, and imperfect weather forecasts. The proposed framework should therefore be tested over multiple profiles and, if feasible, validated using hardware-in-the-loop or a physical prototype. No claim of experimental validation is made in this paper.

11. Conclusion and Future Scope

This paper has outlined an interpretable fuzzy-logic energy-management framework for a hybrid solar–wind microgrid with battery storage. The proposed controller considers solar generation, wind generation, load demand, and battery SOC to determine suitable energy-allocation actions. The paper distinguishes energy management from MPPT, describes input normalization and linguistic membership functions, gives illustrative operating rules, and defines performance measures for simulation.

The next stage is to implement and validate the controller using the project's actual component specifications and time-series inputs. Future work can compare alternative membership functions, tune the rule base, include electricity cost or battery ageing as additional objectives, and compare fuzzy control against a conventional rule-based strategy or another optimization method. Quantitative conclusions should only be added after the simulation outputs have been checked and documented.

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