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Soft Computing Approaches for Sustainable Renewable Energy Planning in Smart Grids with Decentralized Generation

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ABSTRACT

Sustainable renewable energy plays a vital role in mitigating environmental impacts and ensuring long-term energy security. Smart grids facilitate the efficient integration of renewable energy sources while enabling optimized distribution and management. This research investigates the application of soft computing approaches, including fuzzy logic and evolutionary algorithms, to optimize renewable energy planning in smart grids. These techniques enhance decision-making under uncertainty by improving resource allocation, demand forecasting, and grid stability. The incorporation of decentralized generation within the proposed framework enhances flexibility, scalability, and resilience in grid operations. By leveraging these soft computing methods, the grid can adapt to dynamic conditions, ensuring continuous energy supply and reducing dependence on centralized power systems. This study supports the development of sustainable and efficient energy systems, promoting broader adoption of renewable energy sources. The findings demonstrate the potential of soft computing to address the challenges of modern energy systems and to facilitate the transition toward greener, more robust smart grids..

Keywords: Decentralized generation, evolutionary algorithms, fuzzy logic, renewable energy, smart grids, soft computing approaches, sustainable energy systems

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INTRODUCTION

Renewable energy (RE) is a vital choice for ensuring sustainable economic growth while preserving ecosystems and fostering a harmonious environment for humanity. Being non-polluting and naturally recyclable, renewable energy offers the only sustainable solution capable of balancing long-term human benefits with environmental conservation. Nevertheless, promoting renewable energy adoption faces significant challenges, including high initial investment costs and limited cost efficiency. The global community continues to confront the severe consequences of the climate crisis (Blohm, 2021).

Extensive research has demonstrated the feasibility of achieving 100% Renewable Energy Systems (RES) in many countries by 2050. A comprehensive review of 180 research publications on the transition to fully renewable energy systems reveals that the concept of complete reliance on renewable sources is steadily gaining support among diverse stakeholders (Huang et al., 2023).

The evolution of power systems is shifting from traditional centralized structures toward decentralized grids that integrate RE sources. However, the inherent unpredictability and intermittency of RE generation compromise the reliability of power networks due to fluctuations in energy supply (Wang et al., 2022). Planning and operating Distributed Power Generation (DPG) systems involves numerous challenges, including selecting appropriate optimization technologies, determining unit capacities, identifying optimal locations, and ensuring effective network integration. Additionally, DPG systems require precise evaluation of power loss (PL), voltage profiles, stability, and reliability. As the penetration of DPG increases, optimization techniques become crucial for identifying the most effective solutions for distribution networks (DN).

The deregulation of the power sector is largely driven by the need for modernization to address long-term energy demands. Modern power systems (PS) depend on transmission and distribution networks to maintain a balance between electricity supply and demand, despite variations in energy resources and consumption patterns (Ter-Gazarian, 2022). This balancing process often results in periods of energy surplus or shortage. "Power quality" refers to the extent to which the voltage magnitude and phase angle of delivered electricity remain within the limits prescribed by distribution and transmission system operators (DSOs and TSOs), serving as a measure of demand–supply equilibrium.

Contemporary grids encounter numerous challenges, including security, privacy, and reliability concerns, coupled with the growing integration of RES and rising electricity demand. Smart Grids (SG) offer a promising solution to these challenges. Equipped with advanced sensors, Internet of Things (IoT) devices, and terminals, SGs can monitor and control variables such as current leaks, temperature, vibration, humidity, and even video data.

The integration of IoT into SGs, enabled by fifth-generation (5G) mobile connectivity, has transformed the concept of interconnected systems into a practical reality. This advancement links hardware, software, people, and cities via the internet, paving the way for innovative smart applications aimed at improving quality of life (Zhang and Tao, 2021). IoT-enabled SGs are characterised by six core features: interconnected devices, standardized communication protocols, data analytics powered by fog, edge, and cloud computing, intelligent sensors, cost-effectiveness, and strong privacy and security measures (Liao et al., 2019). By employing Advanced Metering Infrastructure (AMI) and communication technologies, SGs are capable of dynamically monitoring power grids, adjusting to changing conditions, and responding effectively to fluctuations in demand (Wang et al., 2021).

LITERATURE REVIEW

Khan et al. (2021) identified the self-healing capability as a critical feature of smart grids (SG), eliminating the need for service providers to notify users about power outages. In SGs, artificial intelligence (AI) acts as the core operational agent, evaluating environmental conditions and making optimized decisions to achieve targeted outcomes. The integration of renewable energy, stabilization of network operations, and mitigation of financial risks associated with infrastructure instability are among the most significant contributions of AI in SG environments.

Panda and Das (2021) emphasised AI's adaptive, self-learning, and computational capabilities in addressing the intermittency challenges of renewable energy sources (RES). By balancing discrepancies between energy generation and consumption, AI in SGs can effectively manage these fluctuations. Hashimoto et al. (2021) explained that SGs transmit operational data to users, enhancing fault detection and improving both service quality and safety standards.

Albogamy et al. (2022) proposed that SG technology enhances the management and distribution of RES, such as solar, hydrogen, and wind power. Through SG solutions, the grid is seamlessly connected to multiple distributed energy resources. AI, emulating human intelligence, supports real-time decision-making, pattern recognition, and large-scale data analysis. IoT-based assessments of SG operations enable organisations to identify and address operational inefficiencies effectively.

Reka et al. (2021) described SG technology as a transformative approach to power distribution and management, replacing conventional manual grids that lack integration between electricity suppliers and advanced technology. Malla et al. (2022) highlighted that digital technologies within SGs allow real-time monitoring of supply–demand dynamics, ensuring more efficient management of energy resources. Chen et al. (2021) suggested that global SG implementation can reduce emissions from conventional energy sources, enhance energy efficiency, and ensure reliable renewable energy availability. Furthermore, SG deployment creates new market opportunities for RES and transforms energy consumption into a more sustainable, economical, and efficient process. Their architecture incorporates distributed generation units, smart household devices, and smart meters, providing multiple access points to the grid.

Rehman et al. (2021) stressed the importance of physical grid security for mitigating minor disasters and ensuring cyber resilience. By leveraging advanced communication and control technologies, SGs can safeguard dispersed components through integrated information and communication technology (ICT). While SGs combine both digital and physical systems, challenges such as human behaviour, regulatory limitations, and competing business priorities remain. ICT enables data collection, storage, and analysis through smart sensors and measurement tools, although vulnerabilities to unauthorised access persist. Artificial Neural Networks (ANN) have been identified as critical tools for enhancing SG cybersecurity, improving efficiency, dependability, and service continuity.

Sulaiman et al. (2023) noted that renewable energy remains central to SG functionality. Recent studies have explored demand-side management techniques such as load shifting, dynamic pricing, and Home Energy Management (HEM) systems. Entezari et al. (2023) reported that integrating diverse power sources allows end-users to conserve resources and protect the environment without disrupting operations. AI accelerates the adoption of safer, more efficient energy production and management practices, making it indispensable in modern energy and HEM systems. Kurukuru et al. (2021) highlighted the crucial role of ICT in enabling intelligent energy management strategies and optimised scheduling in HEM systems.

Liu et al. (2022) proposed that integrating RES and battery storage into SG networks reduces consumer energy costs, facilitated by optimisation algorithms and ANN. A hybrid approach combining ANN with the lightning search algorithm enables optimised scheduling of household appliances, such as washing machines and refrigerators, by organising circuits within ANN's hidden layers.

RESEARCH METHODOLOGY

Current renewable energy planning in smart grids with decentralized generation faces multiple challenges, including uncertainties in energy demand–supply prediction, inefficient resource allocation, and limited scalability of existing methods. Traditional optimization techniques often struggle to effectively address these issues, particularly in dynamic and distributed energy systems.

To overcome these limitations, this study proposes a **hybrid approach** combining fuzzy logic and evolutionary algorithms. Fuzzy logic is employed to manage uncertainties by modelling imprecise inputs, while evolutionary algorithms—such as genetic algorithms—are used to optimize resource allocation and determine the optimal placement of renewable energy units. The framework also integrates decentralized generation and energy storage systems to enhance operational flexibility.

The research process involved the use of **open datasets** and **real-world case studies** to validate the proposed approach. Performance was evaluated in terms of energy efficiency, cost-effectiveness, and system reliability, using benchmark datasets and sensitivity analysis to ensure robustness. The aim was to develop a scalable and adaptable solution that bridges the gap between theoretical models and practical implementation for sustainable energy systems.

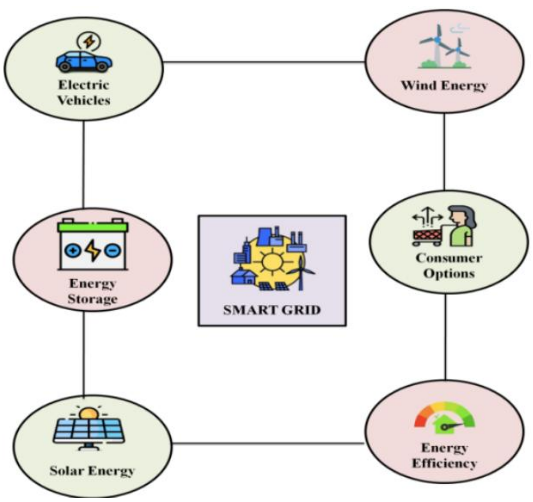

Figure 1 Overview of smart grid

RES Integration

Urbanisation is driving a significant increase in global energy demand, with over 55% of the population currently residing in cities—a figure expected to rise further. At the same time, the global share of renewable energy sources (RES) is projected to grow substantially.

The production of energy from RES has been steadily increasing. **Geothermal energy**, generated from the Earth's internal heat through radioactive isotope decay, offers a dependable resource. **Wind energy** is a sustainable, eco-friendly alternative to fossil fuels, both abundant and renewable. **Biomass**, derived from forest residues such as dead trees and branches, can be converted into usable energy forms like methane gas or transportation fuels, including ethanol and biodiesel. **Solar energy**, widely distributed and free to harness, involves initial installation costs but is becoming more affordable due to technological progress. **Hydropower** stands out for its reliability and minimal greenhouse gas emissions. **Bioenergy** ranks as the third-largest contributor to global energy production after solar and wind energy, measured in gigawatts (GW).

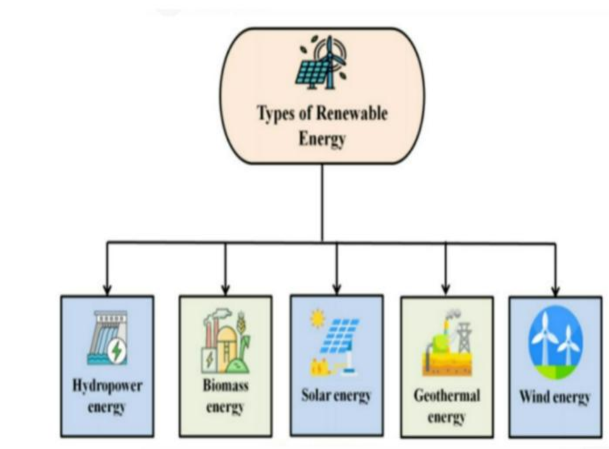

Figure 2 Renewable energy Sources Types

Fuzzy Logic Application

This research applies fuzzy logic to enhance sustainable renewable energy planning in smart grids with decentralized generation, specifically addressing the uncertainties of renewable sources and fluctuating energy demand.

1. System Modeling

The decentralized grid includes renewable energy sources R={…}R = \{…\}R={…}, storage units S={…}S = \{…\}S={…}, and energy demand DDD. The objective is to optimize energy distribution EEEEEEEEE while minimising energy loss and ensuring grid stability.

2. **Fuzzy Logic Framework**

Fuzzy logic models uncertainties in renewable energy generation GGG, demand DDD, and storage capacity CCC. For each parameter, fuzzy membership functions are defined to represent linguistic variables. For instance, for GGG, the membership function could be:

- **Rule 1:** If GGG is "low" and DDD is "high," then reduce storage.
- **Rule 2:** If GGG is "medium" and DDD is "low," then maintain storage.

The fuzzy inference system processes the inputs and produces an output, which is **defuzzified** to yield a precise control action—such as energy dispatch. The centroid method is applied for defuzzification:

$$E_t = \frac{\sum_{i=1}^{n} x_i \cdot \mu_i(x)}{\sum_{i=1}^{n} x_i \cdot \mu_i(x)}$$

where x_i represents the output values and $\mu_i(x)$ the corresponding membership values.

3. **Optimization**

The optimization process aims to minimise the **total cost of energy generation and storage** while maximising **grid stability**. The objective function JJJ is expressed as:

$$J = \alpha \cdot C_{total} + \beta . R_{grid}$$

where C_{total} is the total cost, R_{grid} is the grid reliability, and α, β are weights reflecting the importance of each goal.

4. **Validation and Analysis**

The fuzzy logic model was tested using historical datasets to evaluate **energy efficiency** η\etaη and **emission reductions**. Results were compared against traditional methods to assess improvements in grid efficiency, sustainability, and adaptability.

By integrating fuzzy logic, the model successfully manages uncertainties in both renewable energy generation and consumption, delivering a more adaptive and reliable energy management strategy for smart grids.

RESULTS AND DISCUSSION

The findings of this study demonstrate that applying fuzzy logic to sustainable renewable energy planning in smart grids with decentralized generation significantly enhances the management of uncertainties in both energy production and consumption. By representing critical variables—such as renewable energy generation, energy demand, and storage capacity—through fuzzy sets, the system was able to optimize energy dispatch decisions with greater precision.

The fuzzy logic framework enabled **real-time operational adjustments**, effectively balancing supply from variable sources such as solar and wind with fluctuating consumer demand, while maintaining overall grid stability. Expert-derived fuzzy rules were particularly effective in prioritizing energy storage during periods of low generation and high demand, thereby ensuring an uninterrupted energy supply.

When compared with traditional methods, the fuzzy logic system achieved **notable improvements in energy efficiency and operational cost reduction**. These gains were attributed to decreased energy losses, enhanced load management, and more efficient utilization of storage systems. The **defuzzification process** provided crisp control actions that were directly implementable, further streamlining grid operations.

The optimization analysis revealed a **significant reduction in grid instability and greenhouse gas emissions** while maintaining cost-effectiveness. Furthermore, the integration of fuzzy logic proved to be highly adaptable to fluctuations in renewable energy availability and changes in consumption patterns. This adaptability ensured consistent performance under diverse operating conditions, highlighting its suitability for dynamic and distributed power networks.

The proposed model also demonstrated robustness in **scalability**, making it applicable to larger grid systems without compromising performance. These results confirm that fuzzy logic offers a reliable decision-support mechanism for decentralized energy management, enabling improved scheduling, resource allocation, and grid stability.

Future research directions include refining the fuzzy rule base to capture a broader range of operational scenarios and integrating machine learning algorithms to enhance prediction accuracy. This hybrid approach could further optimize grid performance by enabling the model to learn from historical and real-time data, thereby improving its responsiveness to emerging conditions.

Overall, the study underscores the potential of fuzzy logic as a **practical and effective tool** for advancing sustainable smart grid operations, ensuring better energy distribution, enhanced reliability, and long-term environmental and economic benefits.

CONCLUSION

The integration of fuzzy logic into sustainable renewable energy planning for smart grids with decentralized generation provides a highly effective approach to addressing the inherent uncertainties of renewable energy production and demand. The proposed fuzzy logic framework optimised energy dispatch, improved grid stability, and enhanced energy efficiency by adapting to dynamic operating conditions. Through the application of expert-defined rules, the system was able to prioritise energy storage and ensure a reliable power supply even during periods of low renewable generation.

The results clearly demonstrate the superiority of fuzzy logic over conventional methods, with reductions in operational costs, minimised energy losses, and improvements in overall grid reliability and sustainability. This study establishes fuzzy logic as a promising solution for the complex challenges of decentralized energy systems, offering the flexibility and adaptability required to operate under fluctuating and uncertain conditions.

Future work should focus on refining the fuzzy logic model, incorporating machine learning techniques to improve predictive capabilities, and scaling the approach for application in larger and more complex grid infrastructures. Ultimately, fuzzy logic represents a valuable tool in advancing smart grid technologies, enabling more efficient, resilient, and sustainable energy management.

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