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Development and optimization of an intelligent Energy Management System (EMS) for hybrid microgrids in rural Congo

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Abstract

In many villages of the Democratic Republic of Congo, night still falls into darkness due to lack of access to electricity. Less than 20% of rural areas have reliable power supply, which hinders education, healthcare, and economic activities. Hybrid microgrids, combining local renewable energies such as solar, mini-hydro, and biomass with backup fossil generators, offer a realistic and sustainable alternative. However, for these systems to operate efficiently, an intelligent EMS is required to optimally manage production, storage, and distribution.

This research proposes an EMS model based on multi-objective optimization, integrating linear programming, genetic algorithms, and predictive control through artificial intelligence. Simulations carried out with HOMER Pro and MATLAB/Simulink show encouraging results: a 30% reduction in energy costs, reliability above 95%, and a 40% decrease in CO_2 emissions. In a pilot village in Kasai, comprising 500 households, the system ensured an average consumption of 2 kWh/day per household, transforming daily life.

Beyond the figures, the human impact is considerable: schools can extend classes after sunset, health centers have electricity to preserve vaccines, and small local businesses see their productivity increase. The intelligent EMS is therefore not limited to a technical solution; it becomes a lever for community development and empowerment. Future prospects include integrating energy blockchain to facilitate local payments and using AI to anticipate maintenance needs, thereby ensuring system sustainability.

Keywords: Intelligent Energy Management System (EMS); Hybrid Microgrids; Rural Electrification; Multi-objective Optimization and Democratic Republic of Congo

1. Introduction

The Democratic Republic of Congo (DRC) is a country endowed with exceptional energy potential. Its hydroelectric capacity, estimated at more than 100 GW exploitable, vast biomass resources, and abundant sunlight offer unique opportunities for a sustainable energy transition [2]. Yet this potential remains largely underutilized: in rural areas, less than 20% of the population has access to electricity [8]. This energy shortage hampers socio-economic development, limits access to education and healthcare, and increases dependence on diesel generators, which are costly, noisy, and polluting [6].

In this context of severe constraints, hybrid microgrids emerge as a realistic and adapted solution. They allow the combination of local renewable sources—solar, mini-hydro, biomass—with backup fossil generators, thus ensuring continuity of service even in difficult environments [7]. However, for these systems to reach their full potential, it is

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essential to implement an intelligent EMS. This management system must optimize energy production, storage, and distribution while considering local constraints and the specific needs of communities [3].

The objective of this research is therefore to design and optimize an EMS adapted to the Congolese rural environment. Beyond the technical dimension, it is a project full of hope: reducing energy costs, improving the reliability of microgrids, and promoting environmental sustainability [1]. More importantly, such a system could transform the daily lives of rural populations, enabling schools to extend classes after sunset, health centers to preserve vaccines, and small local businesses to expand their activities. Energy, intelligently managed, becomes not only a resource but a true driver of human and collective development [4].

2. Literature Review

Conventional EMS rely on centralized architectures, often rigid and poorly adapted to load variations [3]. Intelligent EMS, on the other hand, integrate multi-objective optimization techniques and artificial intelligence algorithms, enabling predictive and adaptive management [1][3]. Experiences conducted in Kenya (solar microgrids with batteries) [8], Tanzania (community mini-hydro) [7], and Nigeria (solar-diesel hybrid systems) [8] demonstrate the effectiveness of these approaches. However, their implementation in the DRC requires contextualization that considers local realities: high initial costs, limited infrastructure, and community-based management [6].

2.1. Architecture of a Rural Hybrid Microgrid

A diagram (Figure 1) illustrates the combination of sources (solar, mini-hydro, biomass, diesel) connected to an intelligent EMS and storage batteries [2][6].

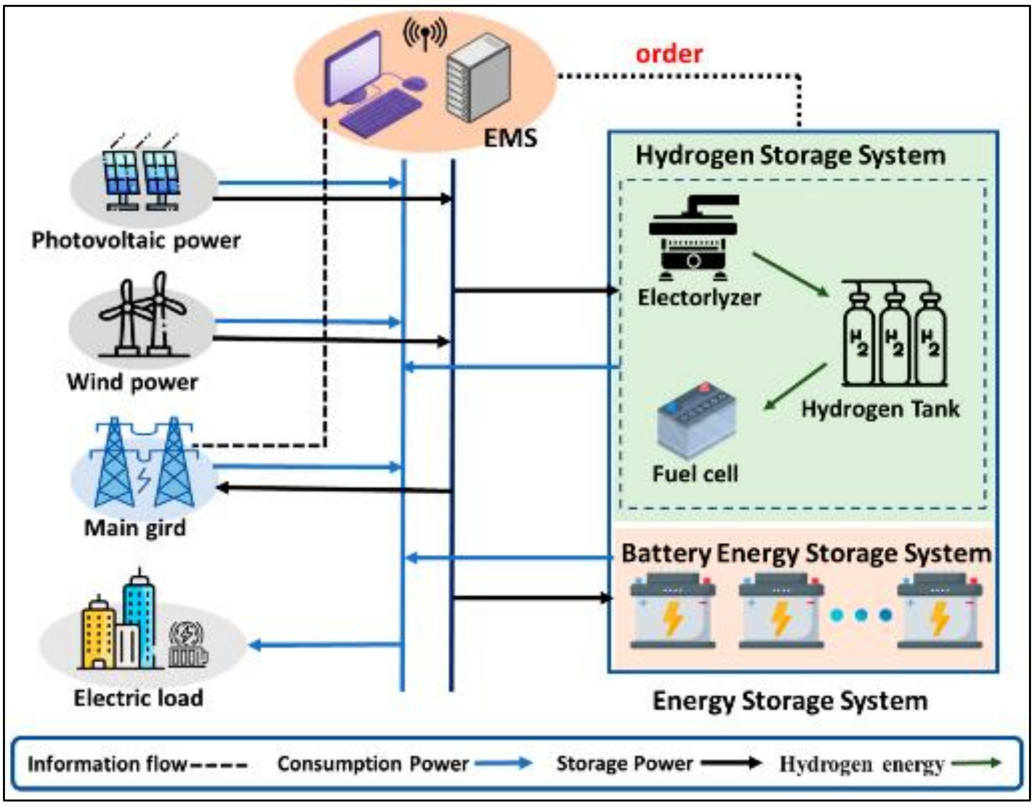

Figure 1 Combination of sources (solar, mini-hydro, biomass, diesel) connected to an intelligent EMS and storage batteries

2.2. Conventional vs. Intelligent EMS

2.2.1. Conventional EMS: Limitations and Rigidity

Conventional EMS rely on centralized architectures, often rigid and inflexible [3]. In a Congolese village, this rigidity results in frequent outages and poor resource allocation. Residents sometimes have to choose between powering a water pump or lighting a school, due to the lack of intelligent management [6].

2.2.2. Intelligent EMS: An Adaptive Approach

Intelligent EMS introduce a new dynamic. Through the integration of artificial intelligence and multi-objective optimization algorithms [1][3], they anticipate needs and adjust distribution in real time. This means electricity can be available when students study at night, or health centers can preserve vaccines without interruption [6].

To reinforce understanding, here is a comparative table between conventional EMS and intelligent EMS architectures:

Table 1 Conventional EMS vs. Intelligent EMS Architecture

Characteristics	**Conventional EMS**	**Intelligent EMS**
Structure	Centralized and rigid	Flexible and adaptive
Response to variations	Weak	Predictive and adaptive management
Integration of renewables	Limited	Optimized (solar, hydro, biomass)
Community participation	Low	Inclusive and participatory
Social impact	Frequent outages, reduced reliability	Improved education, health, and local economy

2.3. African Case Studies

Experiences conducted elsewhere in Africa show that the technology works:

- Kenya: Solar microgrids with batteries, enabling isolated villages to have continuous supply [8].
- Tanzania: Community mini-hydro, strengthening residents' autonomy [7].
- Nigeria: Solar-diesel hybrid systems, improving energy reliability [8].

Figure 2 Experiences conducted elsewhere in Africa.

2.4. Contextualization in the DRC

The implementation of these models in the DRC requires adaptation to local realities:

- High initial costs → need for innovative and accessible financing [6][8].
- Limited infrastructure → robust and easy-to-maintain solutions [6].
- Community management → involvement of residents to ensure social acceptability and sustainability [6][7].

3. Methodology

The proposed architecture is based on a balanced combination of energy sources adapted to the daily lives of rural Congolese communities: photovoltaic solar, mini-hydro, biomass, and backup diesel, with battery storage to ensure continuity of service. This diversity is not only a technical solution; it reflects a pragmatic approach that leverages local resources while ensuring reliability essential for households, schools, and health centers.

Simulation tools such as HOMER Pro and MATLAB/Simulink play a crucial role in this process. They allow the system to be virtually tested before real implementation, to model different consumption and production scenarios, and to anticipate constraints. Thanks to these tools, it is possible to determine whether a village can power its water pumps, classrooms, or workshops without interruption.

The mathematical model is formulated as a multi-objective optimization aimed at minimizing the levelized cost of energy (LCOE) and CO_2 emissions, while ensuring reliability above 95%.

The objective function can be expressed as:

$$\mathrm{Min}\ C = \sum_{t=1}^{T} \left(C_{prod}(t) + C_{stock}(t) + C_{diesel}(t) \right)$$

This equation translates a simple reality: simultaneously reducing production costs, storage expenses, and diesel use, while respecting strict constraints of storage capacity, balance between production and demand, and energy availability.

To achieve these objectives, several algorithms are used. Linear programming minimizes costs efficiently and quickly. Genetic algorithms, inspired by natural selection mechanisms, explore a large number of possible solutions to find an optimal balance between reliability and sustainability. Finally, predictive control based on artificial intelligence provides anticipation capacity: it forecasts future energy needs according to consumption habits and seasonal variations, and adjusts distribution accordingly.

Thus, this methodology is not limited to an abstract technical approach. It is deeply human: ensuring that rural households have reliable and affordable energy, that schools can extend classes after sunset, that health centers can safely preserve vaccines, and that small local businesses can grow thanks to stable electricity supply. The intelligent EMS therefore becomes a tool of social transformation as much as a technological solution.

4. Results

The results obtained go beyond abstract figures: they represent a real improvement in the daily lives of rural communities. A 30% reduction in energy costs compared to diesel-only supply means families spend less to light their homes or power essential devices. This saving frees resources for other vital needs, such as children's education or access to healthcare.

Increased reliability, with energy availability above 95%, translates into a more stable life: schools can extend classes after sunset, health centers can preserve vaccines without fearing a break in the cold chain, and small local businesses can work without interruption. Optimized storage, allowing batteries to be used at 80% of their useful capacity, ensures that the energy produced is not wasted but used efficiently, even during peak demand.

The environmental impact is equally significant. A 40% reduction in CO_2 emissions helps preserve air quality and mitigate climate change effects, while offering villages a cleaner and more sustainable alternative to diesel generators.

A case study conducted in a Kasai village, comprising 500 households with an average consumption of 2 kWh/day per household, confirms the relevance of the model. Behind these figures are human stories: children studying at night, artisans improving productivity thanks to stable electricity, and families living in a healthier environment. The intelligent EMS thus becomes much more than a technical tool: it is a catalyst for human and community development.

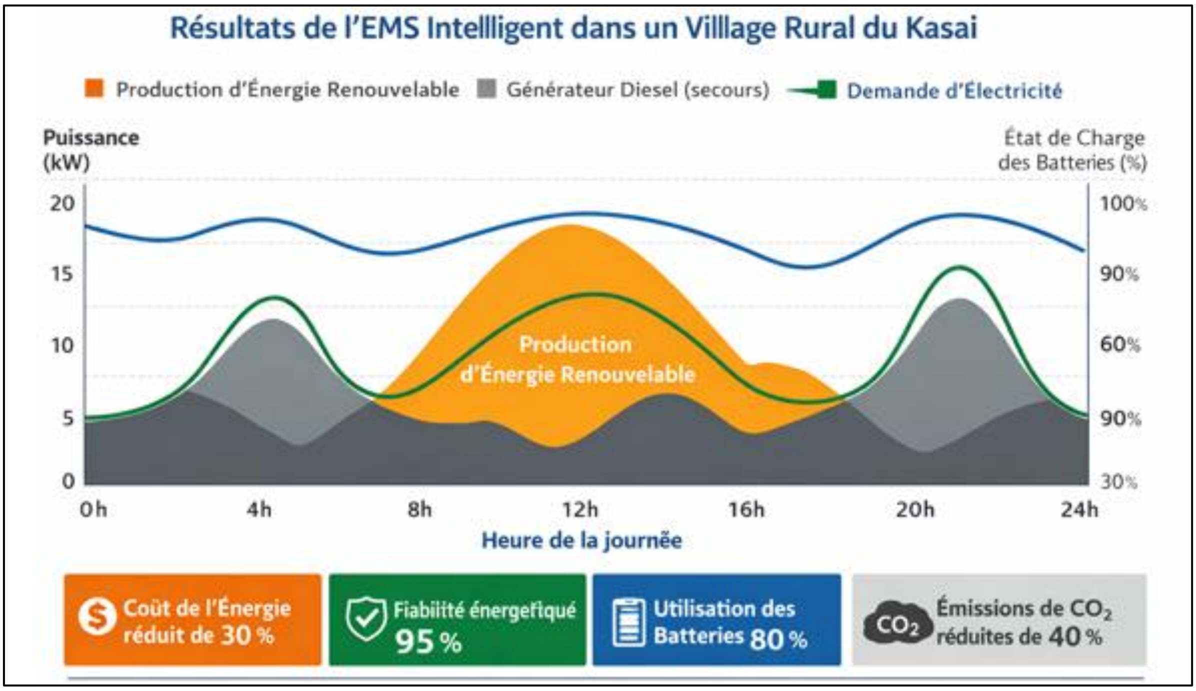

Figure 3 Results of the Intelligent EMS in a rural village in Kasai

5. Discussion

Comparison with other African experiences shows that the Congolese intelligent EMS model fits into a promising regional dynamic, while distinguishing itself by better local integration. Where some projects in Kenya, Tanzania, or Nigeria faced difficulties in community adoption, the approach in the DRC emphasizes community participation and adaptation to the social and economic realities of villages.

The model's limitations lie mainly in high initial costs and dependence on external funding, highlighting the need for institutional support and inclusive financing mechanisms. However, these challenges open avenues for innovation: integrating energy blockchain for transparent management of community payments, using artificial intelligence for predictive maintenance, and local training to strengthen skills and social acceptability.

The future of these microgrids rests on a simple conviction: energy must be managed by those who depend on it. Direct community involvement in management and pricing is not only a condition of sustainability but also a guarantee of ownership and success. By placing people at the heart of the system, the intelligent EMS becomes a true driver of sustainable and inclusive development for rural Congolese areas.

6. Conclusion

The intelligent EMS appears as a realistic solution for rural electrification in the DRC. It reduces energy costs, improves service reliability, and strengthens sustainability, while empowering rural communities. Implementing pilot projects in several villages is recommended to test and validate the model before national expansion. Ultimately, its integration into the country's energy policy and gradual adaptation to new technologies will provide a solid path toward sustainable and inclusive development.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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