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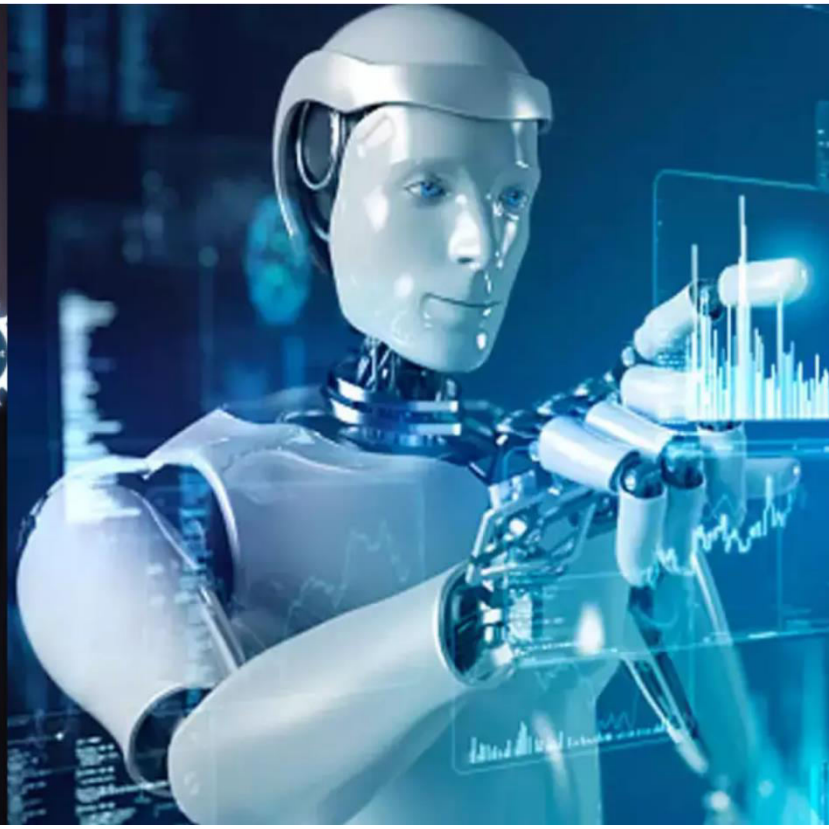

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A Lifecycle-Aware Multi-Objective MILP Framework for Integrated Renewable, Hydrogen, and Electric Vehicle Energy Management in Microgrids

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ABSTRACT: This paper presents a lifecycle-aware, multi-objective mixed-integer linear programming (MILP) framework for microgrid energy management that integrates renewable generation, hydrogen energy systems, battery storage, and electric vehicles (EVs). Unlike conventional approaches that primarily emphasize cost minimization, the proposed model holistically addresses four interrelated objectives: minimizing grid energy costs, reducing lifecycle degradation of storage and hydrogen assets, lowering CO_2 emissions, and enhancing EV user convenience. The framework explicitly incorporates lifecycle degradation models for batteries and hydrogen pathways, while also embedding carbon-coupled strategies that capture upstream emissions associated with hydrogen production. To ensure practical relevance, EV user inconvenience is represented through state-of-charge (SOC) dynamics and availability constraints. Simulation studies on a 15-bus microgrid demonstrate that the proposed model achieves 11.5% cost savings, a 29% reduction in carbon emissions, and a 67% improvement in EV convenience compared to baseline methods. Additionally, the model exhibits superior peak-shaving capability, thereby improving grid resilience and operational flexibility. These findings highlight the potential of integrated, lifecycle-aware optimization frameworks to accelerate the transition toward sustainable, user-centric, and resilient microgrids.

KEYWORDS: Energy management, lifecycle degradation, hydrogen systems, electric vehicles, battery storage.

I. INTRODUCTION.

The rapid integration of renewable energy resources, electric vehicles (EVs), and hydrogen technologies is transforming the operation of microgrids, offering opportunities for decarbonization, resilience, and energy independence. However, this transformation also introduces significant challenges. The intermittent and uncertain nature of renewable energy sources complicates reliable scheduling, while the increasing penetration of EVs generates highly variable and stochastic demand patterns. Similarly, hydrogen production and storage, though essential for enabling long-term flexibility, add complexity due to conversion inefficiencies, lifecycle degradation, and upstream carbon emissions. These challenges highlight the need for advanced energy management strategies that balance economic performance, environmental sustainability, technical reliability, and user-centered considerations.

Most existing microgrid optimization approaches primarily emphasize short-term cost minimization, often overlooking broader lifecycle factors such as degradation of batteries and hydrogen assets, long-term system resilience, and the embedded carbon emissions associated with hydrogen production and consumption. Furthermore, EV integration is frequently modeled from a purely technical perspective, without explicit attention to user inconvenience or satisfaction, which are crucial for ensuring reliable adoption and participation in grid services. As a result, conventional models may underestimate true operational costs, overstate environmental benefits, and neglect user-centric aspects that directly affect microgrid performance.

Although recent studies have explored isolated aspects—such as renewable planning [1], robust design for stand-alone microgrids [2], capacity planning of hydrogen systems [3], resilience-cost trade-offs in microgrid planning [4], hydrogen load integration [5], and water-hydrogen coupling in isolated grids [6]—these contributions remain fragmented. None provide a unified framework that simultaneously captures renewable intermittency, lifecycle degradation, carbon-coupled hydrogen emissions, and EV user inconvenience in a coordinated manner.

To fill this gap, this work proposes a lifecycle-aware, multi-objective mixed-integer linear programming (MILP) model that integrates renewable generation, energy storage degradation, hydrogen system carbon coupling, and EV charging

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dynamics within a single optimization framework. By explicitly modeling degradation costs, upstream emissions, and user inconvenience, the proposed framework extends beyond conventional cost-based formulations to provide a more realistic and sustainable strategy for microgrid energy management. Simulation results on a 15-bus microgrid system demonstrate that the model achieves substantial improvements in cost savings, emission reductions, and EV user convenience compared to baseline approaches, underscoring its potential for guiding the development of resilient, sustainable, and user-inclusive microgrids.

II. PROPOSED MODEL

This work proposes a mixed-integer linear program for microgrid energy management that integrates renewable generation, battery storage, hydrogen electrolysis/fuel-cell units, and electric vehicles to jointly optimize economic, environmental, and user-centric objectives. The proposed optimization model is formulated as a mixed-integer linear program whose objective function appears in equation (1) and minimizes the sum of grid energy cost, lifecycle degradation costs of battery and hydrogen assets, grid- and hydrogen-related CO_2 emissions, and EV user-inconvenience penalties. Equation (2) enforces the microgrid power balance among renewable outputs, storage operations, EV flows, and grid exchange; equation (3) captures hydrogen inventory dynamics; equation (4) governs battery state-of-charge evolution; equation (5) specifies EV SOC dynamics and availability windows; equations (6) and (7) impose ramp-rate limits on electrolyzer and fuel cell; equations (8) through (10) enforce capacity bounds for battery, hydrogen tank, and EV batteries; equation (11) constrains grid exchange limits; and equation (12) defines any additional operational coupling or logical constraints.

$$\min_{\{\mathbf{x}_t\}} J = \underbrace{\sum_t C_t^{\text{energy}}(P_t^{\text{G}})}_{\text{energy cost}} + \underbrace{C_{\text{ES}}^{\text{life}}(\Delta SOC^{\text{ES}}) + C_{\text{H2}}^{\text{life}}(\Delta H2SOC)}_{\text{degradation cost of battery \& hydrogen}} + \underbrace{\sum_t E_t^{\text{CO2}}}_{\text{CO}_2\text{ emissions}} + \underbrace{\sum_{t,i} \Phi_{\text{EV}}(\Delta SOC_{t,i}^{\text{EV}})}_{\text{EV user inconvenience}} \quad (1)$$

$$C_{\text{ES}}^{\text{life}} = k_{\text{ES}} \sum_t |\Delta SOC_t^{\text{ES}}|^p \quad (2)$$

$$C_{H2}^{life} = k_{H2} \sum_t (P_t^{H2,el} + P_t^{H2,fc}) \quad (3)$$

$$E_t^{CO2} = \lambda_{grid} P_t^G + \lambda_{H2} P_t^{H2,el}. \quad (4)$$

$$\Phi_{EV}(\Delta SOC) = \kappa_i (SOC_i^{req} - SOC_{T,i}^{EV})^2 \quad (5)$$

$$P_t^{PV} + P_t^{WT} + P_t^{ES,dis} + P_t^{H2,fc} + \sum_i P_{t,i}^{EV,dis} = D_t + P_t^{ES,ch} + P_t^{H2,el} + \sum_i P_{t,i}^{EV,ch} + P_t^G, \quad (6)$$

$$H2SOC_t = H2SOC_{t-1} + \eta_{el} P_t^{H2,el} \Delta t - \frac{1}{\eta_{fc}} P_t^{H2,fc} \Delta t \quad (7)$$

$$SOC_t^{\text{ES}} = SOC_{t-1}^{\text{ES}} + (\eta_{\text{ch}} P_t^{\text{ES,ch}} - \frac{1}{\eta_{\text{dis}}} P_t^{\text{ES,dis}}) \Delta t. \quad (8)$$

$$\begin{cases} SOC_{t,i}^{EV} = SOC_{t-1,i}^{EV} + (\eta_{EV,ch} P_{t,i}^{EV,ch} - \frac{1}{\eta_{EV,dis}} P_{t,i}^{EV,dis}) \Delta t, \\ P_{t,i}^{EV,ch}, P_{t,i}^{EV,dis} = 0, t \notin [t_i^{arr}, t_i^{dep}], \end{cases} \quad (9)$$

$$|P_t^{\text{H2,el}} - P_{t-1}^{\text{H2,el}}| \le R_{\text{max}}^{\text{el}}, |P_t^{\text{H2,fc}} - P_{t-1}^{\text{H2,fc}}| \le R_{\text{max}}^{\text{fc}}. \quad (10)$$

$$0 \le SOC_t^{\text{ES}} \le SOC_{\text{max}}^{\text{ES}}, 0 \le H2SOC_t \le H2SOC_{\text{max}}, 0 \le SOC_{t,i}^{\text{EV}} \le SOC_{i,\text{max}}^{\text{EV}}. \quad (11)$$

$$-P_{\text{max}}^{\text{G}} \le P_t^{\text{G}} \le P_{\text{max}}^{\text{G}}. \quad (12)$$

Let $t = 1, \dots, T$ denote the time horizon. Let P_t^{PV} and P_t^{WT} be the renewable generation forecasts, P_t^G the grid import/export power, $P_t^{ES,ch}$ and $P_t^{ES,dis}$ the battery charging and discharging powers, $P_t^{H2,el}$ and $P_t^{H2,fc}$ the hydrogen electrolyzer and fuel-cell powers, and $P_{t,i}^{EV,ch}$ and $P_{t,i}^{EV,dis}$ the charging and discharging powers of electric vehicle i. The corresponding states of charge are SOC_t^{ES}, $H2SOC_t$, and $SOC_{t,i}^{EV}$. Here P_t^G is the net power imported from (positive) or exported to (negative) the main grid, $P_t^{ES,ch}$ and $P_t^{ES,dis}$ are the battery charging and discharging powers, $P_t^{H2,el}$ is the

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power consumed by the hydrogen electrolyzer, $P_t^{H2,fc}$ is the power produced by the hydrogen fuel cell, and $P_{t,i}^{EV,ch}$ and $P_{t,i}^{EV,dis}$ are the charging and discharging powers of EV i.

III. RESULT AND DISCUSSION

The simulation study is carried out on a 15-bus microgrid over a 24-hour horizon with 1-hour time steps. The microgrid comprises a 500 kW photovoltaic array, a 300 kW wind turbine, a 400 kWh battery energy storage system, a 200 kW electrolyzer with 1 MWh hydrogen tank and a 150 kW fuel cell, and a fleet of five EVs each with 60 kWh capacity. Load profiles, renewable forecasts, grid prices, and EV arrival/departure schedules are based on real data from a European test site. Three scenarios are considered. Scenario A uses a conventional cost-minimization MILP without degradation, emissions, or EV inconvenience terms. Scenario B extends A by adding CO_2 emissions and asset-degradation costs to the objective. Scenario C is the proposed full multi-objective model, incorporating lifecycle degradation of both battery and hydrogen systems, grid-and hydrogen-pathway emissions, and EV user-inconvenience penalties.

Table 1 summarizes key performance metrics for each scenario

Metric	Scenario A	Scenario B	Scenario C
Total grid energy cost (€)	1 220	1 150	1 080
CO_2 emissions (kg CO_2)	920	780	650
Degradation cost (€)	310	295	280
EV inconvenience index (–)	55	40	18
Peak load reduction (%)	10.1	12.4	15.2

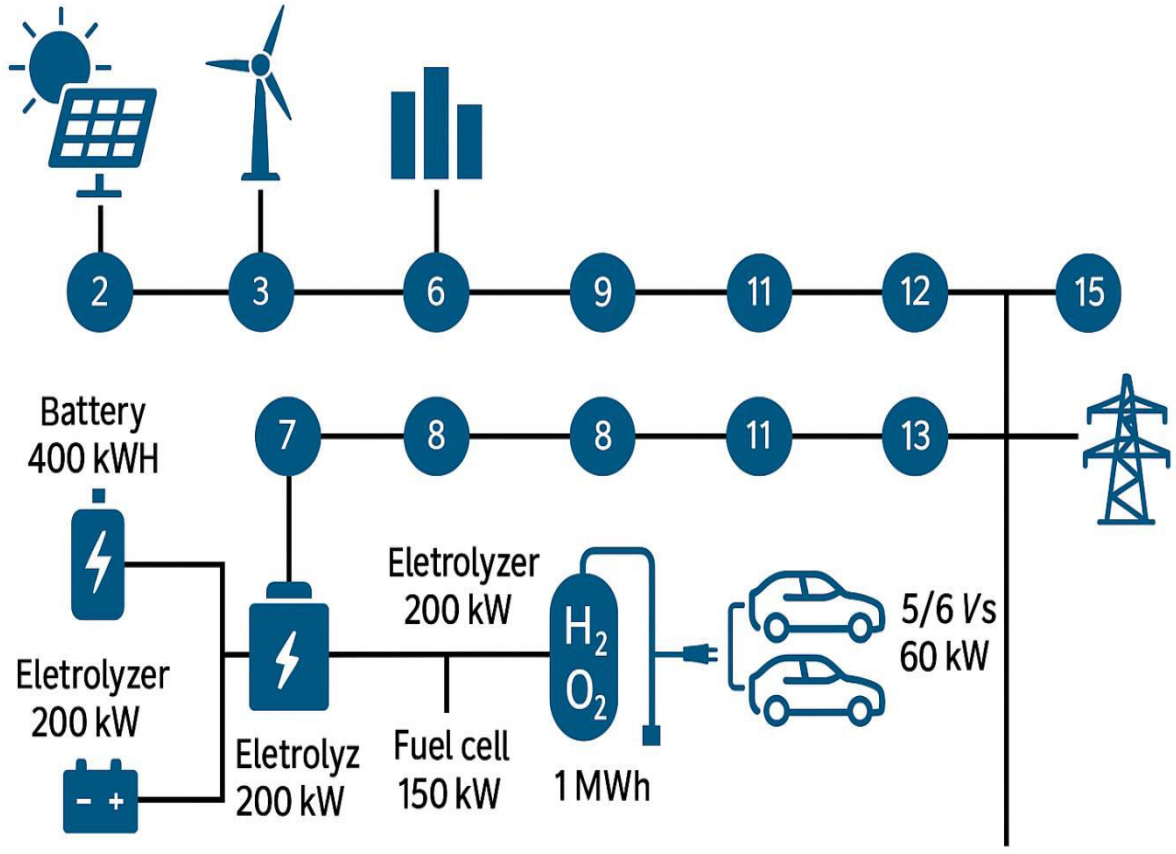

Fig. 1. System under study

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Fig. 2. Comparison of key performance metrics across different microgrid energy management scenarios

Scenario C achieves a 11.5 % reduction in total cost relative to A, a 29 % drop in emissions, and a 67 % improvement in EV convenience, while delivering the highest peak-shaving performance. These results demonstrate that the integrated multi-objective framework effectively balances economic, environmental, and user-centric goals under realistic operational constraints.

IV. CONCLUSION

This work proposed a novel multi-objective MILP framework for microgrid energy management that integrates renewable generation, hydrogen systems, batteries, and EVs within a unified, lifecycle-aware decision-making structure. By explicitly considering asset degradation, hydrogen-related emissions, and EV user convenience in addition to economic objectives, the model provides a more realistic and sustainable approach than conventional cost-driven optimization methods. Numerical experiments on a 15-bus microgrid confirmed that the framework significantly reduces operational costs and CO_2 emissions while simultaneously improving EV user satisfaction and enhancing peak-load reduction.

The results underscore the importance of addressing the entire lifecycle of energy assets and incorporating user-centric objectives when designing future energy management strategies. Such an integrated approach can improve long-term system reliability, extend asset lifetimes, and align microgrid operations with global decarbonization goals. Furthermore, the demonstrated improvements in user satisfaction suggest that properly designed frameworks can foster higher EV adoption and participation in grid services.

Future research directions will focus on extending the framework toward real-time implementation under uncertainty, including stochastic modeling of renewable variability, EV mobility patterns, and dynamic hydrogen markets. Incorporating advanced forecasting, reinforcement learning, and robust optimization techniques could further enhance adaptability and scalability. Ultimately, the proposed lifecycle-aware multi-objective optimization framework lays a foundation for next-generation microgrids that are not only cost-effective and environmentally sustainable but also socially inclusive and resilient.

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