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Techno-Economic Analysis of Integrated Hydrogen Fuel Cell Storage Systems for Enhanced Renewable Energy Utilization in Interconnected Microgrids

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***Abstract*—The increasing penetration of renewable energy sources (RES) in modern power systems necessitates efficient energy storage solutions to mitigate intermittency and enhance grid reliability. This paper presents a comprehensive techno-economic analysis of an interconnected multi-microgrid (MMG) system integrated with hydrogen fuel cell (HFC) storage, alongside conventional battery energy storage systems (BESS), photovoltaic (PV) arrays, and wind turbine generators (WTG). A mixed-integer linear programming (MILP) framework is developed to minimize the total operational cost, encompassing fuel costs, degradation costs, grid import/export costs, and hydrogen production–consumption dynamics. The proposed energy management strategy (EMS) optimizes power dispatch among three interconnected microgrids over a 24-hour scheduling horizon under varying load and generation profiles. Simulation results obtained using MATLAB/YALMIP with the CPLEX solver demonstrate that the integration of hydrogen storage reduces total operating cost by approximately 18.7%, decreases grid dependency by 27.4%, and enhances renewable energy utilization to 91.3% compared to a baseline scenario without HFC storage. The findings establish hydrogen-based long-duration storage as a technically viable and economically competitive complement to battery storage in future low-carbon microgrid networks.**

***Index Terms*—Multi-microgrid, hydrogen fuel cell, energy management system, mixed-integer linear programming, renewable energy, techno-economic analysis, battery energy storage.**

I. INTRODUCTION

THE global transition toward decarbonized power systems has accelerated the deployment of distributed energy resources (DERs), particularly solar photovoltaic (PV) and wind energy systems. However, the inherent intermittency and stochastic nature of these renewable sources pose significant challenges to grid stability, power quality, and supply–demand balance. Microgrids (MGs)—localized, semi-autonomous power networks comprising generation, storage, and loads—have emerged as a promising paradigm to integrate high shares of renewables while ensuring resilience and reliability.

When multiple microgrids are interconnected to form a multi-microgrid (MMG) system, additional benefits emerge: peer-to-peer energy trading, mutual support during contingencies, and aggregated participation in wholesale electricity markets. Nevertheless, optimal coordination of an MMG with diverse generation assets and heterogeneous storage technologies remains a non-trivial optimization problem.

Battery energy storage systems (BESS), particularly lithium-ion technology, dominate the short-duration storage market due to high round-trip efficiency (85–95%) and rapid response. However, BESS suffer from limited energy density, calendar/cycle aging, and economic infeasibility for long-duration (≤ 8 h) and seasonal storage applications. Hydrogen fuel cell (HFC) systems—comprising electrolyzers, hydrogen storage tanks, and proton exchange membrane (PEM) fuel cells—offer a compelling alternative for long-duration, high-capacity, and sector-coupled energy storage.

This paper addresses the optimal energy management and cost minimization problem for a three-bus interconnected MMG system with PV, WTG, BESS, HFC storage, and grid connectivity. The principal contributions are:

1) Formulation of a comprehensive MILP-based EMS for an MMG with hybrid BESS–HFC storage.
2) Quantitative techno-economic comparison of MMG operation with and without hydrogen storage.
3) Sensitivity analysis with respect to hydrogen capital cost, electrolyzer efficiency, and renewable penetration.

II. LITERATURE REVIEW

Energy management of microgrids has been extensively studied. Olivares *et al.* [3] proposed a hierarchical control framework, while Parisio *et al.* [8] introduced a model predictive control (MPC) approach for microgrid scheduling under uncertainty. Distributed optimization techniques (ADMM, game theory) have been applied to MMG systems to preserve operator privacy [9].

Hydrogen-based storage in microgrids has gained renewed attention. García *et al.* [24] analyzed a stand-alone PV–wind–hydrogen hybrid system, and Marocco *et al.* [25] performed a techno-economic study of a remote microgrid. Recent works by Pu *et al.* [20] and Cao *et al.* [21] extended the analysis to MMGs using stochastic and robust programming. Despite this progress, deterministic MILP-based co-optimization of hybrid BESS–HFC storage with explicit electrolyzer part-load and tank-SoC modeling remains under-explored. The present work addresses this gap.

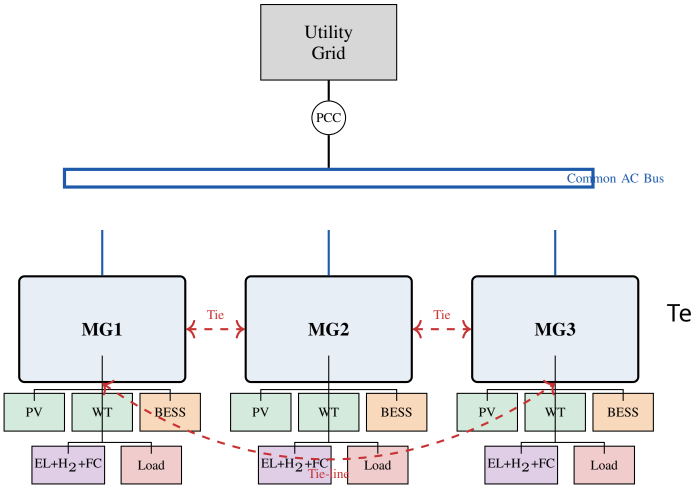

Fig. 1. Architecture of the proposed three-bus interconnected multi-microgrid system with hybrid BESS–hydrogen storage.

III. SYSTEM DESCRIPTION AND MATHEMATICAL MODELING

A. Multi-Microgrid Architecture

The studied MMG comprises three microgrids (MG1, MG2, MG3) interconnected through a common AC bus and connected to the upstream utility grid via a point of common coupling (PCC), as shown in Fig. 1.

Each microgrid contains a PV array, a WTG, a Li-ion BESS, a hydrogen subsystem (PEM electrolyzer + tank + PEM fuel cell), and an AC/DC load. Bidirectional power flow is permitted subject to tie-line capacity limits.

B. Renewable Generation Models

The PV power output at time t is

$$P_{pv,i}(t) = \eta_{pv} A_{pv,i} G(t) \big[1 - \beta(T_c(t) - 25)\big] \tag{1}$$

The WTG power output is given by the standard piecewise function:

$$P_{wt,i}(t) = \begin{cases} 0, & v(t) < v_{ci} \text{ or } v(t) > v_{co} \\ P_r \dfrac{v(t)^3 - v_{ci}^3}{v_r^3 - v_{ci}^3}, & v_{ci} \le v(t) < v_r \\ P_r, & v_r \le v(t) \le v_{co} \end{cases} \tag{2}$$

C. Battery Energy Storage Model

$$SoC_i(t{+}1) = SoC_i(t) + \frac{\eta_{ch} P_{ch,i}(t) - P_{dis,i}(t)/\eta_{dis}}{E_{batt,i}^{cap}} \Delta t \tag{3}$$

subject to $SoC^{min} \le SoC_i(t) \le SoC^{max}$ and the mutual exclusion $u_i^{ch}(t) + u_i^{dis}(t) \le 1$.

D. Hydrogen Fuel Cell Storage Model

The block diagram of the hydrogen subsystem is shown in Fig. 2.

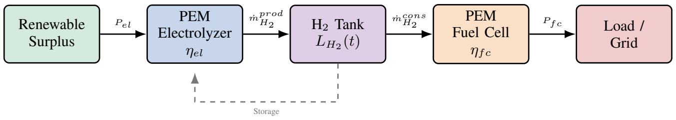

Fig. 2. Schematic of the hydrogen fuel-cell energy storage subsystem.

The electrolyzer hydrogen production rate is

Text

$$\dot{m}_{H_2,i}^{prod}(t) = \frac{\eta_{el} P_{el,i}(t)}{HHV_{H_2}} \tag{4}$$

The hydrogen tank dynamics:

$$L_{H_2,i}(t{+}1) = L_{H_2,i}(t) + \big[\dot{m}_{H_2,i}^{prod}(t) - \dot{m}_{H_2,i}^{cons}(t)\big]\Delta t \tag{5}$$

The fuel-cell power output:

$$P_{fc,i}(t) = \eta_{fc}\, \dot{m}_{H_2,i}^{cons}(t)\, HHV_{H_2} \tag{6}$$

with $u_i^{el}(t) + u_i^{fc}(t) \le 1$.

E. Power Balance

$$\begin{aligned} & P_{pv,i}(t) + P_{wt,i}(t) + P_{dis,i}(t) + P_{fc,i}(t) \\ & \quad + P_{grid,i}^{imp}(t) + \sum_{j \ne i} P_{ji}(t) \\ & = P_{load,i}(t) + P_{ch,i}(t) + P_{el,i}(t) \\ & \quad + P_{grid,i}^{exp}(t) + \sum_{j \ne i} P_{ij}(t) \end{aligned} \tag{7}$$

IV. OPTIMIZATION PROBLEM FORMULATION

A. Objective Function

$$\min\ \mathcal{C}_{total} = \sum_{t=1}^{T} \sum_{i=1}^{N_{MG}} \big[C_i^{grid}(t) + C_i^{batt}(t) + C_i^{H_2}(t) + C_i^{OM}(t)\big] \tag{8}$$

where

- $C_i^{grid}(t) = \pi^{buy}(t) P_{grid,i}^{imp}(t) - \pi^{sell}(t) P_{grid,i}^{exp}(t)$
- $C_i^{batt}(t) = c_{deg}^{batt} \big[P_{ch,i}(t) + P_{dis,i}(t)\big]$
- $C_i^{H_2}(t) = c_{deg}^{el} P_{el,i}(t) + c_{deg}^{fc} P_{fc,i}(t)$
- $C_i^{OM}(t) = c_{om}^{pv} P_{pv,i}(t) + c_{om}^{wt} P_{wt,i}(t)$

B. Solution Methodology

The flowchart of the EMS algorithm is shown in Fig. 3. The MILP problem is solved using the CPLEX 12.10 solver via YALMIP in MATLAB R2023a, with $T = 24$ h and $\Delta t = 1$ h.

V. SIMULATION RESULTS AND DISCUSSION

A. Test System Parameters

Table I lists key parameters. TOU electricity tariffs are: off-peak Rs.3.5/kWh (00:00–06:00), mid-peak Rs.6.0/kWh (06:00–18:00), and peak Rs.9.5/kWh (18:00–22:00).

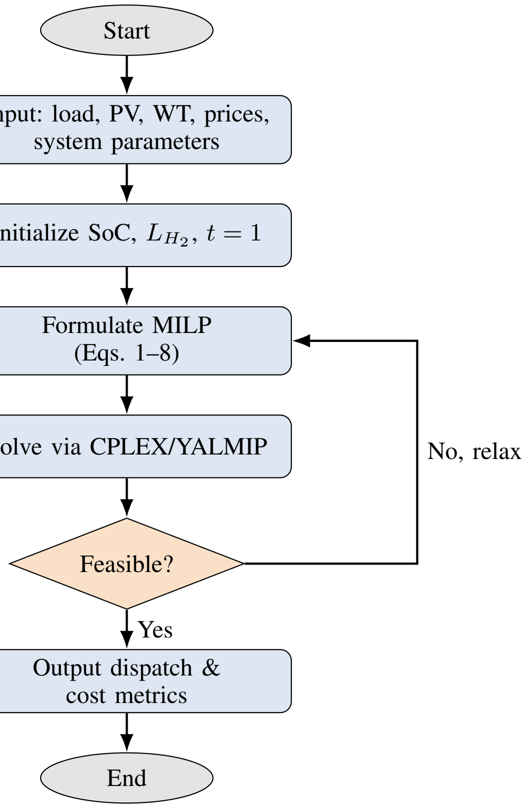

Fig. 3. Flowchart of the proposed MILP-based energy management algorithm.

TABLE I
SYSTEM PARAMETERS

Parameter	**MG1**	**MG2**	**MG3**
PV capacity (kW)	250	180	320
WTG capacity (kW)	200	300	150
BESS capacity (kWh)	400	350	500
Electrolyzer (kW)	150	120	200
Fuel cell (kW)	100	80	150
H_2 tank (kg)	50	40	70
Peak load (kW)	380	420	510

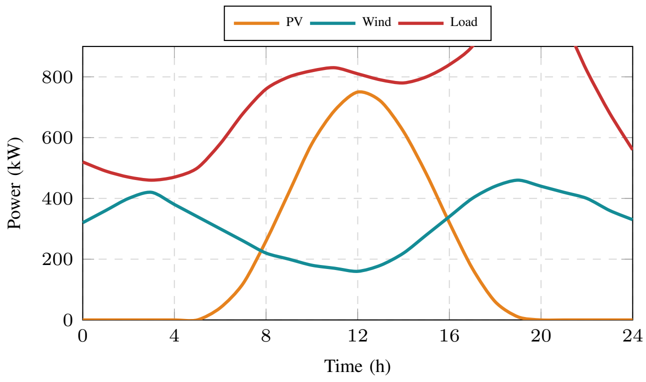

Fig. 4. Aggregated 24-h PV, WTG, and load profiles for the multi-microgrid system.

TABLE II
COMPARATIVE PERFORMANCE METRICS

Metric	**Case 1**	**Case 2**	**Case 3**
Total daily cost (Rs)	38,420	31,235	26,890
Grid import (kWh)	2,845	2,065	1,420
Renewable utilization (%)	78.6	91.3	96.8
BESS cycle count	1.42	0.91	0.74
H_2 produced (kg)	—	18.4	27.6
H_2 consumed (kg)	—	15.2	22.1

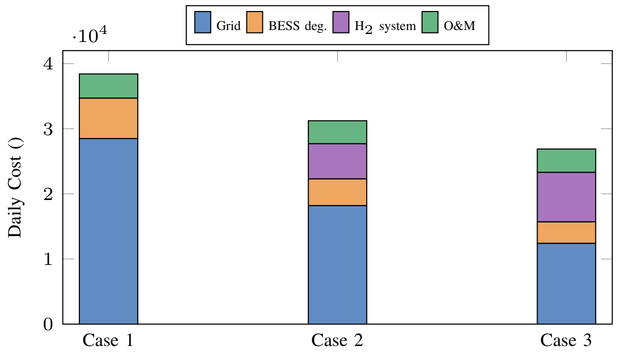

Fig. 5. Disaggregated daily operational cost comparison across the three cases.

B. Renewable and Load Profiles

Fig. 4 illustrates the 24-h aggregated PV, WTG, and load profiles used in the simulation.

C. Case Studies

Three scenarios are simulated:

- **Case 1:** MMG with PV, WTG, BESS, and grid only (baseline).
- **Case 2:** MMG with PV, WTG, BESS, and HFC storage.
- **Case 3:** Case 2 with 30% increased renewable penetration.

D. Cost Comparison

Fig. 5 shows the disaggregated cost breakdown across the three cases.

E. Hourly Dispatch Analysis

Fig. 6 presents the hourly power dispatch in Case 2. During hours 11:00–15:00, surplus renewables drive the electrolyzer; during 18:00–22:00, the fuel cell discharges to meet peak load.

F. Storage State-of-Charge Evolution

Fig. 7 depicts the BESS SoC and the H_2 tank level over the day.

G. Renewable Utilization

Fig. 8 compares renewable utilization across the three cases. Hydrogen storage absorbs midday surplus that would otherwise be curtailed.

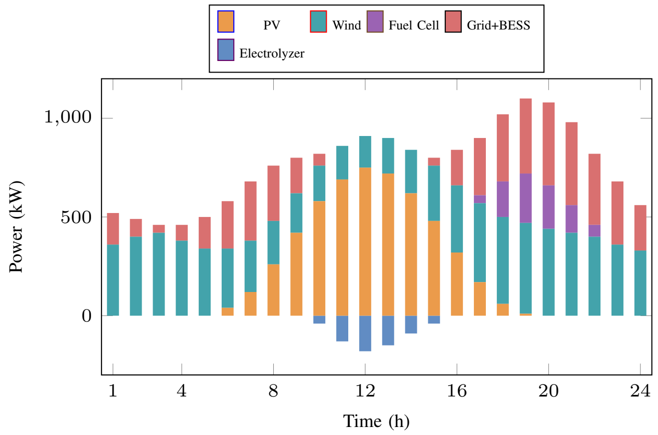

Fig. 6. Hourly power dispatch of the MMG in Case 2 (positive: supply; negative: storage charging).

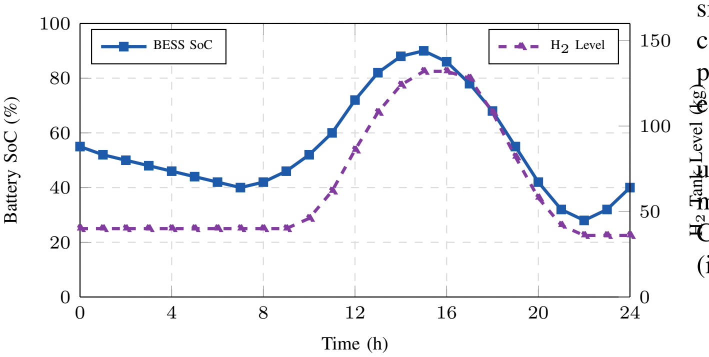

Fig. 7. Battery SoC (left axis) and aggregated hydrogen tank level (right axis) over 24 h in Case 2.

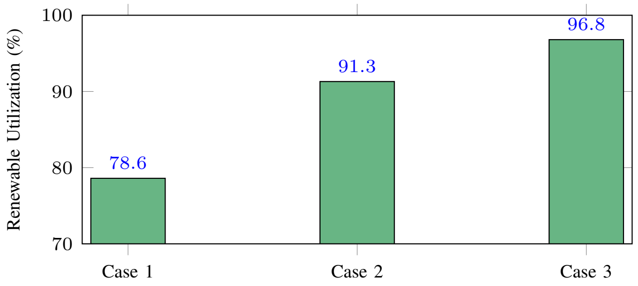

Fig. 8. Renewable energy utilization comparison.

H. Sensitivity Analysis

Fig. 9 shows the sensitivity of total daily cost to electrolyzer degradation cost, round-trip efficiency, and peak tariff.

The total cost is most sensitive to peak tariff and round-trip efficiency. A 25% improvement in $\eta_{el}\eta_{fc}$ yields an 8.9% cost reduction, while a 20% rise in peak tariff increases hydrogen-storage savings to 23.4%.

VI. CONCLUSION

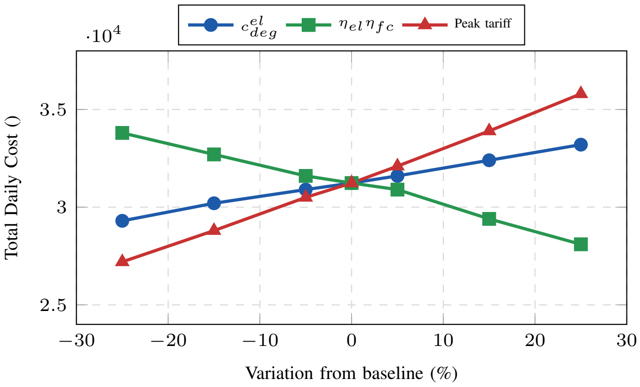

Fig. 9. Sensitivity of total daily cost to key techno-economic parameters.

This paper presented a MILP-based optimal energy management framework for a three-bus interconnected MMG with hybrid BESS–HFC storage. Simulation results demonstrate that hydrogen storage reduces total operating cost by 18.7%, increases renewable utilization from 78.6% to 91.3%, and significantly relieves battery cycling stress. Sensitivity studies confirm that future reductions in electrolyzer cost and improvements in round-trip efficiency will further strengthen the economic case for hydrogen storage.

Future work will incorporate (i) stochastic renewable/load uncertainty via two-stage and multi-stage stochastic programming, (ii) coupled electricity–heat–hydrogen integration using CHP fuel cells, (iii) market-based peer-to-peer trading, and (iv) hardware-in-the-loop validation.

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