VidyutAI: AI-Driven Smart Energy Management System for Net-Zero Cities

Empowering India's transition towards intelligent, sustainable, and resilient urban ecosystems.

Integrated System Configuration for Optimal Energy Flow

Our energy management system integrates several key components to create a resilient and efficient power infrastructure. Each element plays a crucial role in ensuring uninterrupted energy supply and optimizing resource utilization.

Solar PV

Harnessing renewable energy from the sun.

Battery Storage

Storing excess energy for later use.

Hydrogen Storage

Long-term energy storage and clean fuel.

The Grid

Connecting to the main power supply for stability.

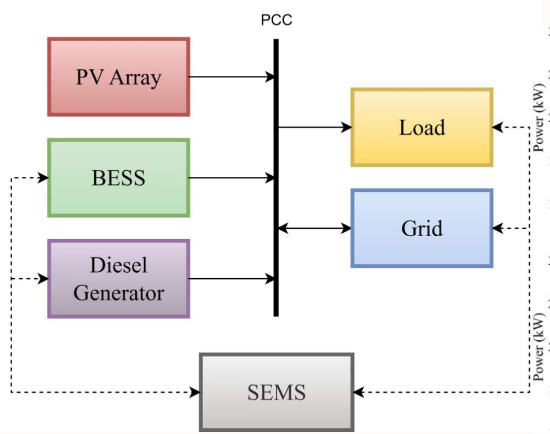
Diesel Generator

Backup power for critical situations.

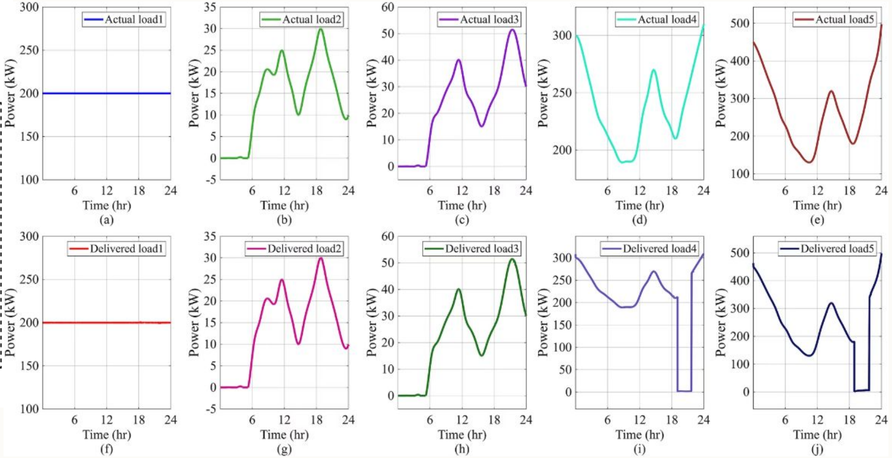
Load Control

Meeting the energy demands of connected consumers optimally.

1. Microgrid Load Generation Optimization



Critical load 1 | Critical load 2 | Flexible Load High priority | Flexible Load Medium priority | Flexible Load Low priority



Objectives

Minimize Cost

Optimization algorithm prioritize reducing operational expenses through intelligent resource allocation and demand-side management.

Minimize Emission

We aim to decrease the environmental impact by optimizing the use of renewable energy sources and reducing reliance on fossil fuels.

Improve Performance & Reliability

The system enhances grid stability and ensures continuous power supply, even during peak demand or system disturbances.

Coordinated Generation Optimization

Proposed for grid-connected and islanded modes to balance load, minimize import costs, and ensure reliable supply.

Priority Load Management

Ensures continuous supply for critical loads and optimizes shedding based on importance.

Balancing Demand & Generation

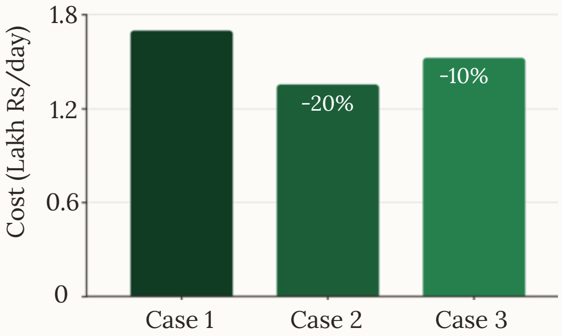
Addressing the unpredictability of RES for reliable power supply.

Impact Analysis: Cost & Carbon Reduction

Our analysis demonstrates significant cost and carbon emission reductions across various test cases through strategic load management.

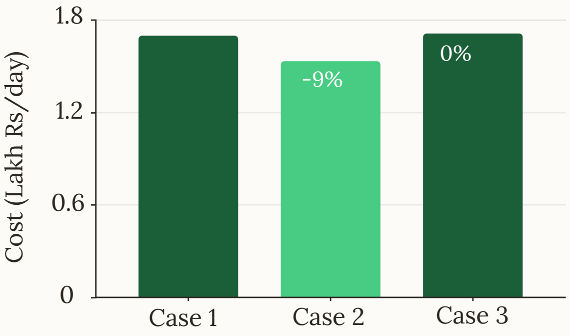
Cost Reduction: Demand-side Response

Optimizing energy consumption during high grid charges.



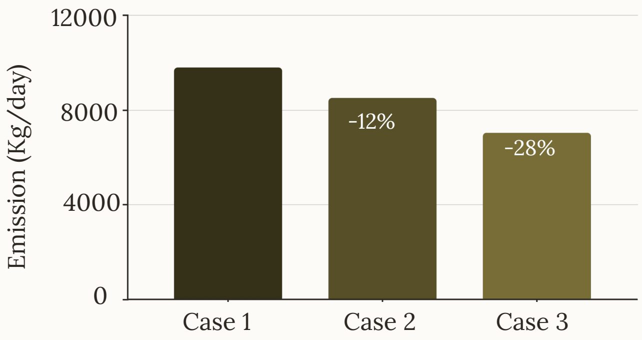
Cost Reduction: Load Shifting

Distributing energy usage to hours of low charges for savings.



Carbon Emission Reduction

Decreasing environmental footprint through efficient energy use.



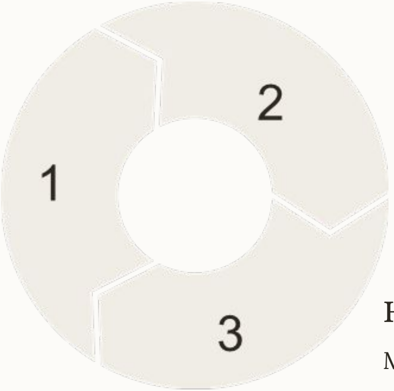
Case 1 – Conventional EMS

Case 2 - EMS with demand management

Case 3 – EMS with demand management and DG disabled

2. Smart Energy Management System: Integrating Diverse Storage Devices

This project explores a comprehensive smart energy management system (SEMS) that seamlessly integrates various energy storage technologies. Our goal is to create a resilient and economically viable microgrid solution.



Battery Storage

High-efficiency, quick-response battery energy storage systems (BESS).

Pumped Hydro Storage

Large-scale, long-duration pumped hydro energy storage (PHES) for robust backup.

Hydrogen fuel cell

Maximizing renewable energy utilization through intelligent solar photovoltaic (PV) integration.

The SEMS leverages a sophisticated control algorithm to manage these diverse assets, ensuring optimal performance and reliability.

I. Optimization with Hydrogen Fuel Cell as an Energy Storage System

Why Hydrogen Fuel Cells?

- Pivotal technology in global transition to **clean and sustainable energy**
- Highly efficient **zero-emission** alternative to traditional fossil fuels
- Produces only water and heat as byproducts

Why Energy Management Systems?

- Maximizes **efficiency** of hydrogen fuel cell operations
- Ensures **reliability** through optimal system control
- Enhances **economic viability** through resource optimization

System Configuration

Solar Photovoltaic

Primary renewable energy generation from solar PV arrays

Battery Storage

Short-term energy storage for load balancing and peak shaving

Hydrogen Storage

Long-duration energy storage through hydrogen fuel cells

Grid Connection

Bidirectional interface with main utility grid

Diesel Generator

Backup power source for critical resilience

Load Management

Real-time monitoring and distribution of electrical demand

Optimization with Hydrogen Fuel Cell

The financial impact of advanced energy management strategies reveals substantial cost savings and improved efficiency.

4.85

Cost: Rule based

Ruled based optimization results in 4.85 INR/kWh.

3.73

Cost: System without hydrogen fuel cell

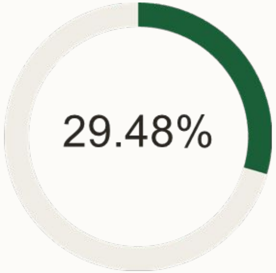
3.73 INR/kWh during the simulated month of operation for system with only battery energy storage.

3.42

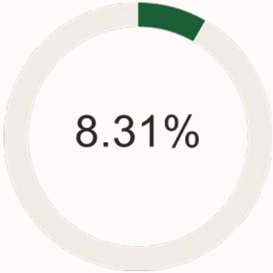
Cost with hydrogen fuel cell

Computed 3.42 INR/kWh, indicating lesser operational expenses.

The optimized approach, especially with hydrogen fuel cells, leads to a significant reduction in total operating costs and cost per kWh, demonstrating superior economic performance compared to rule-based dispatch.



Cost savings
Compared to rule based optimization



Additional savings
With hydrogen fuel cell integration

II. Comparative Cost Analysis: PHES vs. BESS

Understanding the cost implications of different energy storage systems is crucial for long-term project viability. We conducted a detailed cost analysis comparing Pumped Hydro Energy Storage (PHES) and Battery Energy Storage Systems (BESS).

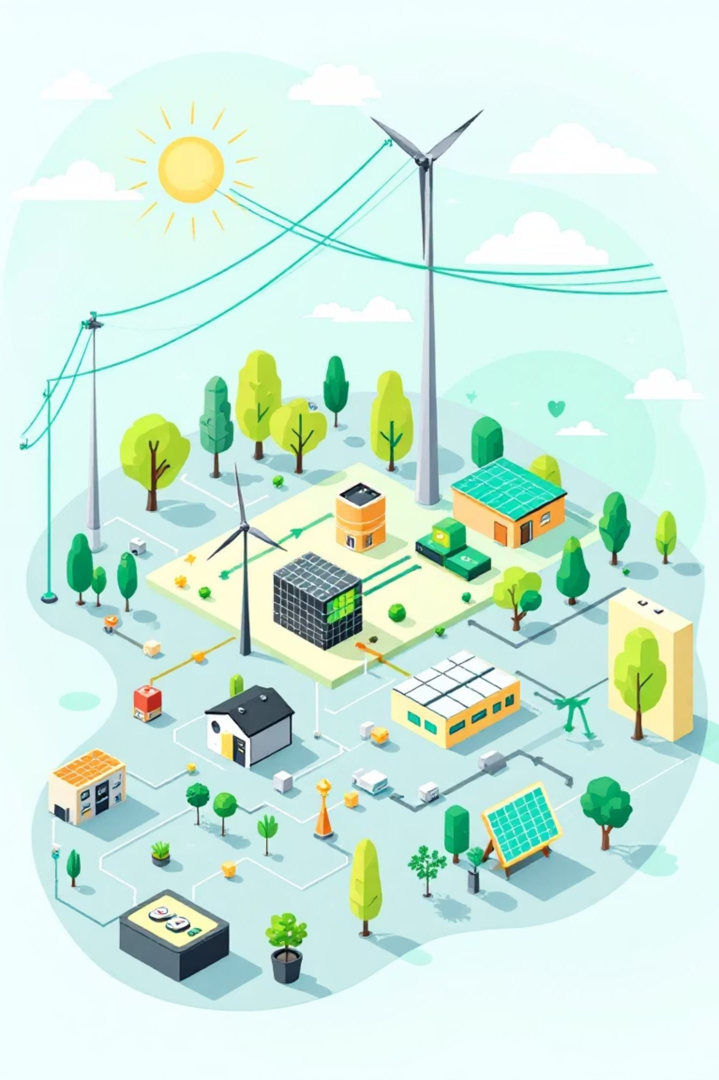
Capital Expenditure (CAPEX)

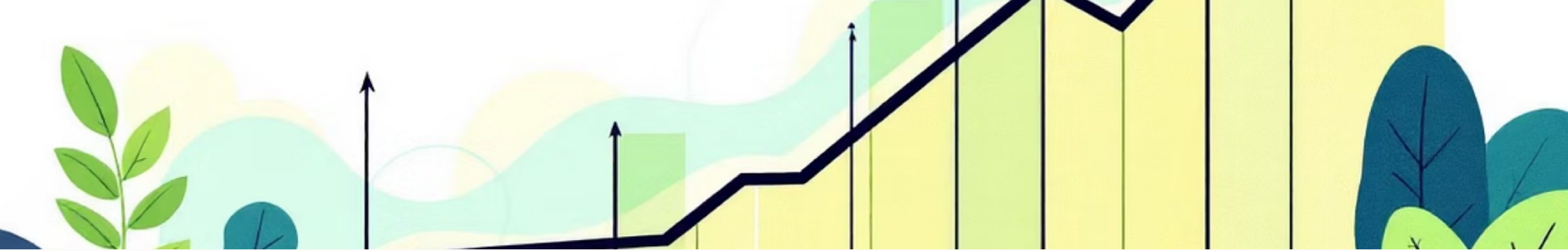
- Initial investment costs for PHES and BESS infrastructure.
- Installation and commissioning expenses.

Operational Expenditure (OPEX)

- Daily running costs, maintenance, and energy losses.
- Long-term operational efficiency differences.

This analysis, particularly for a one-month operation, provides critical insights into the economic advantages of each technology.





Economic Impact: Cost Savings Achieved

The implementation of the smart energy management system, particularly with optimal storage selection, yielded significant economic benefits. This section details the measurable cost reductions and operational efficiencies.

3.83

PHES Cost

Achieved at 3.83 INR/kWh during the simulated month of operation.

4.31

BESS Cost

Computed at 4.31 INR/kWh, indicating higher operational expenses.

12.53%

Cost Reduction

PHES demonstrated a 12.53% lower operational cost compared to BESS.

These figures underscore the importance of selecting the appropriate energy storage technology based on economic factors rather than solely on efficiency metrics.

Efficiency vs. Cost

BESS offers superior efficiency but carries a higher operational cost (4.31 INR/kWh).

Strategic Selection

Storage selection should prioritize techno-economic factors over mere efficiency figures for long-success.

3. CO_2 emission minimization using energy management systems

A comprehensive solution for optimizing energy management systems, enabling real-time CO_2 emission reduction and cost-effective energy distribution across hybrid renewable systems.

CO_2 Emission

Comparative Environmental Impact Analysis

Our CO_2-optimized backend achieves a **9.87% reduction** in overall emissions compared to traditional rule-based control strategies, demonstrating the power of intelligent optimization.

Component	Rule-Based (kg)	CO_2 Optimization (kg)	Difference
Grid	6,272.74	5,615.74	−657.0
Diesel	0	0	0
Battery	88.16	106.16	+18.0
PV	725.00	725.00	0
Fuel Cell	39.96	39.96	0
Electrolyzer	0	0	0
Total Emissions	**7,125.86**	**6,486.86**	**−639.0**
Emission Intensity (kg/kWh)	**0.2839**	**0.2584**	−0.0255 (−9.87%)

Price

Economic Impact Comparison

While the primary focus is emission reduction, our optimization maintains near-equivalent cost performance, demonstrating that environmental responsibility doesn't require economic sacrifice.

Component	CO_2 Optimization (INR)	Rule-Based (INR)	Difference
Grid Energy Cost	45,978.00	51,078.84	+5,100.84
Solar Energy Cost	41,325.00	41,325.00	0
Battery O&M Cost	32,299.18	26,822.68	−5,476.50
Fuel Cell O&M Cost	1,198.80	1,198.80	0
Electrolyzer O&M	0	0	0
TOTAL COST	**120,800.98**	**120,425.32**	**−375.66**
Cost per kWh	**4.81**	**4.80**	**~same**

The optimization achieves significant emission reductions with virtually no cost penalty (less than 0.3% difference), proving the viability of sustainable energy management at scale.

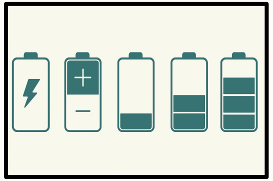
Need for Battery Digital Twins

Motivation

Usage optimization is necessary for safe, reliable, and long-term operation

1

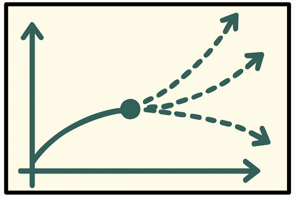
Initial state



Initial state of a battery includes age, temperature and initial voltage

2

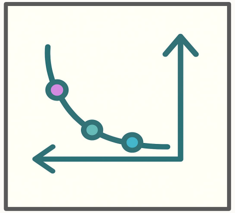
Digital twin based forecasting



We can forecast future usage from an initial state

3

Optimized action



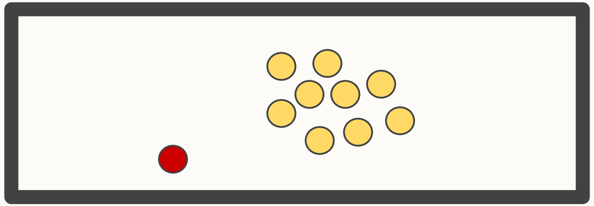
The forecasted states are then used to take an optimized action

4.Fast and Accurate Adaptation of Battery Digital Twin

Unseen conditions always arise when a modelled system is deployed in the real world.

Beneficial usage when the digital twin adapts itself quickly

Slow adaptation or inaccurate forecasting could lead to unsafe and suboptimal usage



1 % MAPE Threshold Coverage for Voltage	87.13 % -> 95.11 % | 9% Improvement for 1% threshold coverage
1% Voltage threshold recovery time	258.97 s -> 5.85 s | 44x faster average adaptation
Temperature Predictions	Prediction error went from being below 2 ℃ to below 1.75 ℃

Improvement in Decoder transformer based architecture + continual learning

Improvement in voltage and temperature predictions

44x faster average adaptation time.

High coverage for voltage predictions

Accurate temperature predictions

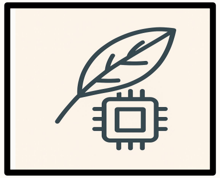
Fast adaptation

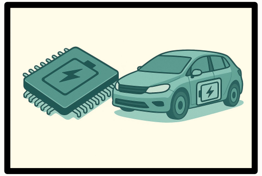
Current methods use simple transfer learning and do not take into account a deployed system

5. Lightweight Battery Digital Twin

Computationally heavy digital twins impede deployability.

Solution





0.965 MB MLP based model architecture

MAPE-scaled loss penalising higher loss terms.

Edge deployable light model

Pre-training gets completed after seeing all the data just once

Initial Voltage, Temperature and Age

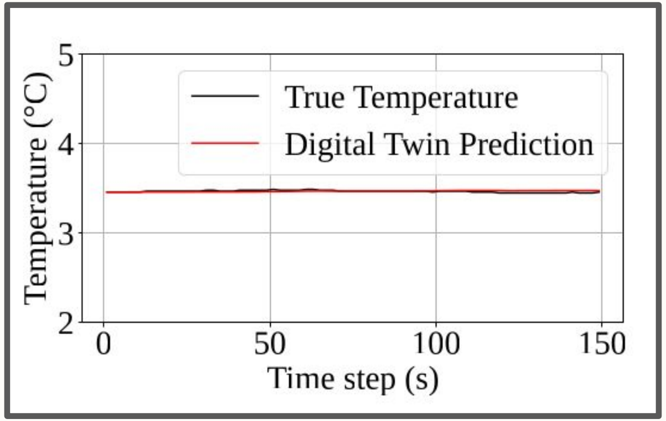
Input Current

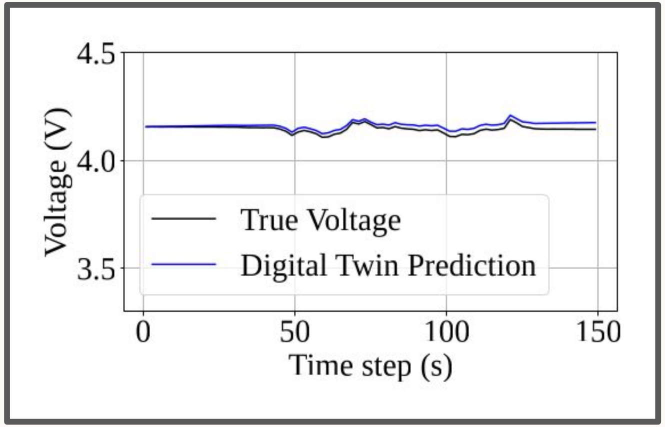
Future Voltage & Temperature Prediction

Performance assessment

< 1.5%	< 0.12℃
Voltage MAPE	Temperature MAE

Robustness testing (in unseen conditions) with or without fine tuning yields high accuracy results.
With or without fine tuning we get <1.5 % Voltage MAPE and <0.12 ℃ Temperature MAE.



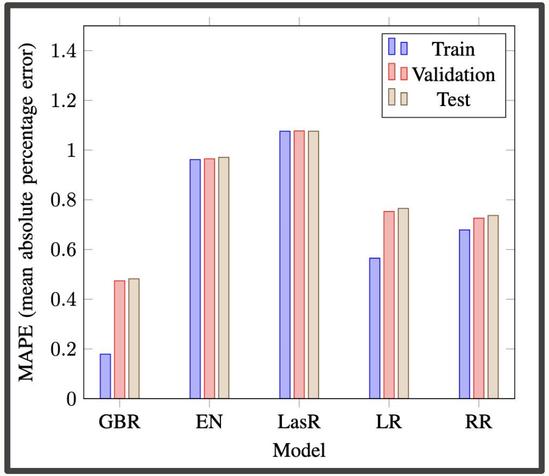


6. Fast Capacity Estimation for Swapping Enablement

Critical issue with battery swapping

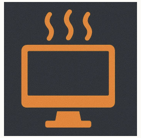
Requires trust from both the sides about the quality of batteries being exchanged.

Capacity prediction using only 2 seconds of battery characteristics



Current methods

- Require data storage
- Resource intensive models
- Time consuming



Capacity prediction results

0.482 %	0.011
MAPE	MAE

No expensive instrumentation required

Increased swapping throughput benefits EV user and swapping operator

Trust in battery swapping because it can be done in front of the owner.

Present capacity estimation methods have poorer accuracy or require a lot of time.

Quarterly Deliverable for Year 1 : **Energy**

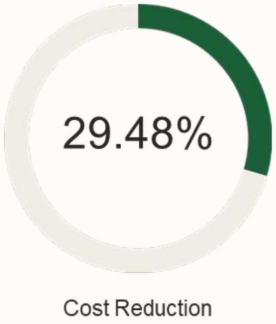
	2025-26											
	Q1			Q2			Q3			Q4		
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Smart Energy Management System for Renewable Energy Microgrid	Setup of data monitoring system for distributed generation and load demand: at high power using IIT Gandhinagar campus loads and PV source along with battery energy storage system.											
				Data collection for Indian Green Energy Microgrid with Energy Storage: operating in varying ambient conditions impacting renewable energy output along with seasonal load variations								
							Develop high-fidelity electro-thermal aging model (ETAM) for PV & EV: Solar PV under dust and shading conditions, and EV batteries operating under varying temperature and humidity using above collected and open source datasets					
										Design and customization of energy management system (EMS) algorithms for three use cases: with VidyutAI web interface: residential, industrial and commercial at power level of 2kW, 20kW and 200 kW respectively.		

Optimization with hydrogen fuel cell

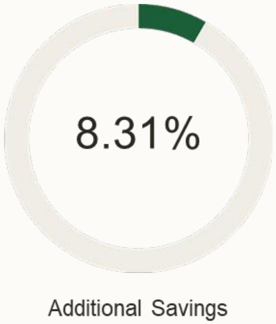
The financial impact of advanced energy management strategies reveals substantial cost savings and improved efficiency.

Grid Cost	53468.60	33723.79	22646.72
Diesel Fuel Cost	0	0	0
Solar Cost	41325.00	41325.00	41325.00
Battery O&M	26822.68	18498.40	18498.40
Fuel Cell O&M	0	0	2397.60
Electrolyzer O&M	0	0	869.15
Total Operating Cost	121616.28	93547.19	85736.88
Cost per kWh (INR/kWh)	4.85	3.73	3.42

The optimized approach, especially with hydrogen fuel cells, leads to a significant reduction in total operating costs and cost per kWh, demonstrating superior economic performance compared to rule-based dispatch.



Compared to rule based optimization



With hydrogen fuel cell integration