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Optimal Dispatch in Hybrid PV/Diesel/Hydro/Battery Energy Storage Systems for Minimizing Power Losses, CO_2 Emissions and Operating Cost

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Highlights

- Developed a policy-embedded MINLP dispatch framework for hybrid PV/Diesel/Hydro/Battery Energy Storage systems.
- Enforced global sustainability constraints (losses ≤ 8%, CO_2 reduction ≥ 40%, cost reduction ≥ 20%) consistent with SDG 7, IRENA, and Africa Agenda 2063.
- Established a replicable benchmark for generator placement and sizing on IEEE-30 bus.
- Quantified trade-offs among cost, emissions, and technical losses through Pareto frontier analysis under varying objective weightings.

Abstract

The increasing penetration of renewable energy sources demands dispatch strategies that balance technical reliability, environmental sustainability, and economic efficiency. While Hybrid Photovoltaic/Hydro/Diesel/Battery Energy Storage (BESS) systems have been studied, most existing works focus on single-objective optimization or genetic multi-objective trade-offs without explicit integration of global sustainability thresholds. This study introduces a novel policy-embedded Mixed Integer Nonlinear Programming (MINLP) dispatch framework that embeds policy-aligned constraints (losses ≤ 8%, CO_2 reduction ≥ 40%, and cost reduction ≥ 20%) directly into the optimization model of the IEEE 30-bus system. Unlike prior studies, the framework establishes a replicable benchmark for hybrid generator placement and sizing, combining renewable-first dispatch logic with explicit emission and cost caps. Results demonstrate that policy thresholds are achievable within technical feasibility, with losses halved, emissions reduced by over 40%, and costs lowered by 20%. Pareto frontier analysis reveals that global policy targets coincide with the frontier of achievable trade-offs, providing new evidence that sustainability agendas can be operationalized in dispatch optimization. This contribution advances hybrid system research by bridging technical modeling with global energy policy, offering actionable insights for grid operators, policymakers, and researchers. By systematically locating PV+BESS at Bus 19/30, Hydropower at Bus 6/11 and Diesel at Bus 2/5, the study provides a reproducible design logic that future researchers can adopt. This benchmark moves beyond abstract optimization to offer a practical system design contribution.

Keywords: hybrid energy systems; MINLP (Mixed-Integer Nonlinear Programming); policy-embedded dispatch; IEEE-30 bus benchmark; global sustainability constraints; pareto frontier analysis

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1. Introduction

The integration of renewable energy sources into modern power systems has become a cornerstone of sustainable energy development. Hybrid configurations that combine PV, diesel, hydro, and storage units are increasingly recognized as viable solutions for balancing reliability, environmental sustainability, and economic efficiency in both microgrids and larger interconnected networks. Multi-objective optimization has emerged as a powerful tool to address trade-offs among cost, emissions, and technical performance [1–4].

Recent literature demonstrates the application of multi-objective dispatch optimization to economic and environmental dispatch problems using ε-constraint and fuzzy satisfaction methods [5], as well as advanced particle swarm optimization (PSO) and genetic algorithms (GA) for improved Pareto solutions [6,7]. The IEEE 30-bus system has long served as a benchmark for optimal power flow studies [8,9]. However, applications of hybrid dispatch optimization to the IEEE 30-bus remain limited, particularly with explicit integration of renewable penetration, storage dynamics, and emission constraints.

Loss minimization and CO_2 reduction are increasingly recognized as critical objectives, with robust dispatch models incorporating carbon trading[10] and low-carbon frameworks considering demand response[11]. Weighted-sum methods are widely used in multi-objective optimization, with Naidu et al. (2024) demonstrating their effectiveness in nonlinear power flow problems[12]. More recent works have extended hybrid optimization using NSGA II combined with differential evolution [13], MINLP formulations for renewable electric vehicle charging systems[14], and linearization methods for BESS scheduling [15]. These studies highlight the growing importance of hybrid optimization frameworks but also reveal gaps in simultaneous minimization of losses, emissions, and costs.

This research addresses these gaps by developing a weighted-sum MINLP dispatch model for hybrid PV/Diesel/Hydro/Battery Energy Storage systems in the IEEE 30-bus network. The framework enforces global sustainability benchmarks (losses ≤ 8%, CO_2 reduction ≥ 40%, and operating cost reduction ≥ 20%) in alignment with SDG 7, IRENA's renewable transition scenarios, and Africa's Agenda 2063 [16,17]. By generating Pareto-optimal trade-offs under varying objective weightings, the study quantifies relationships among efficiency, sustainability, and economics, contributing actionable insights for grid operators, policymakers, and researchers while establishing a replicable benchmark for future hybrid system studies [12].

2. Research Methodology

This study develops an integrated optimization framework for minimizing active power losses, CO_2 emissions and total operating cost in a grid-connected PV/Diesel/Hydro/BES system. The optimization problem is modeled using a Mixed-Integer Nonlinear Programming (MINLP) approach, capable of simultaneously handling discrete and continuous decision variables associated with power generation, dispatch, and system operation.

2.1. Data Collection

The IEEE 30-bus test system is adopted as the benchmark network, incorporating PV units, diesel generators, hydropower and battery energy storage system grid interconnections. System parameters (including bus voltages, line power flows, generation capacities, fuel cost coefficients, and emission factors) are sourced from standardized IEEE datasets and recent literature to ensure reproducibility[18]. Load demand and renewable generation profiles are modeled on an hourly basis, reflecting realistic operating conditions.

2.2. Tools, Methods, and Techniques Applied

MATLAB-based Optimal Power Flow (OPF) and Unit Commitment (UC) modeling were employed on the IEEE-30 bus system. MATLAB's advanced solvers and ability to handle nonlinear constraints enabled precise modeling of hybrid PV/Diesel/Hydro/Storage systems. A multi-objective optimization framework was adopted, simultaneously minimizing operational costs, emissions, and losses. This renewable-first dispatch philosophy prioritizes PV and Hydro during daylight, strategically integrates storage, and minimizes diesel reliance. Unlike conventional cost-only approaches, this method aligns technical reliability with sustainability agendas such as SDG 7 and Africa Agenda 2063, ensuring policy relevance[19,20].

Traditional deterministic dispatch and spreadsheet analysis are limited to single-objective cost minimization, often resulting in diesel-dominant operation. In contrast, the present study employs MATLAB-based Optimal Power Flow (OPF) and Unit Commitment (UC) modeling, which integrates multi-objective optimization across cost, emissions, and technical losses.

The renewable-first hybrid dispatch strategy, supported by storage, demonstrates clear advantages: reduced diesel reliance, enhanced system efficiency, robust optimization capable of handling constraints while delivering technically reliable solutions.

2.3. Problem Formulation

The integrated optimization model simultaneously minimizes both power losses, CO_2 emissions and total operating cost, represented as a multi-objective MINLP problem:

2.3.1. Objective Function:

$$\min J = \omega_1 \mathrm{P_{Loss}} + \omega_2 H + \omega_3 \mathrm{C_t} \quad (2.1)$$

where $\mathrm{P_{loss}}$, H and $\mathrm{C_t}$ are respectively the total power losses, CO_2 emissions, and total system operating cost; with ω_1, the weight assigned to power losses, ω_2, the weight assigned to CO_2 emissions and ω_3 , the weight assigned to operating cost. The weighted coefficients $\omega_1, \omega_2, \omega_3$ satisfy $0 \le \omega_i \le 1$ and $\omega_1 + \omega_2 + \omega_3 = 1$.

The objective function is written as :

$$\mathrm{Min}\ J = \omega_1 \sum_{t=1}^{24} \left(P_{total}(t) - P_{demand}(t)\right)$$

$$+\ \omega_2 \sum_{t=1}^{24} \alpha\, P_{diesel}(t)$$

$$+\ \omega_3 \sum_{t=1}^{24} \left(\mathrm{C_{pv}P_{pv}(t) + C_{hyd}P_{hyd}(t) + C_{dies}P_{dies}(t) + C_{stor}P_{stor}(t)}\right). \quad (2.2)$$

2.3.2. System Constraints

- **Power Balance**

$$\mathrm{P_{pv}(t) + P_{hyd}(t) + P_{dies}(t) + P_{stor}(t) \geq P_{demand}}\ ,\forall t \quad (2.3)$$

- **Diesel cap**

$$P_{diesel}(t) \leq 100\mathrm{MW}. \quad (2.4)$$

- **CO_2 Reduction**

$$\sum_{t=1}^{24} P_{diesel}(t) \leq 0.6 \sum_{t=1}^{24} P_{diesel,baseline}(t) \quad (2.5)$$

- **Operating Cost Reduction**

$$\sum_{t=1}^{24} \left(\mathrm{C_{pv}P_{pv}(t) + C_{hyd}P_{hyd}(t) + C_{dies}P_{dies}(t) + C_{stor}P_{stor}(t)}\right) \leq 0.8 \sum_{t=1}^{24} Cost_{,baseline}(t) \quad (2.6)$$

- **Loss Fraction Constraint**

$$\frac{P_{total}(t)-P_{demand}(t)}{P_{total}(t)} \leq 0.08,\ \forall t \quad (2.7)$$

- **Hydropower minimum**

$$P_{hyd}(t) \geq 140MW \text{ , when ON.} \quad (2.8)$$

- **Storage limits**

$$0 \leq P_{storage}(t) \leq 150MW,\ \forall t \quad (2.9)$$

- **Unit Commitment binary status**

$$UC_i(t) \epsilon \{0,1\},\ i\ \epsilon\ \{\text{PV, Hydro, Diesel, Storage}\}. \quad (2.10)$$

The optimization simultaneously ensures technical feasibility, emission reduction, system efficiency and the economic system operation.

2.4. Sizing and Optimal Placement of Generating Units in IEEE 30 Bus System

2.4.1. Placement of Generating Units

The placement is guided by load centers, voltage stability, and loss minimization. PV units are strategically placed near high-demand buses (urban/industrial nodes) to reduce transmission losses. Their midday peak coincides with the demand rise, minimizing congestion. Hydro units are located at remote buses with strong transmission links, acting as a base supply. Hydro's continuous output stabilizes voltage profiles across the network. Diesel units are placed peripheral or weak buses where renewable penetration is low. This ensures local reliability and prevents voltage dips during renewable shortfalls. BESS are sited where PV units are located to allow efficient charging during PV surplus and discharging into evening demand, reducing line losses.

For the purpose of balancing loss minimization, CO_2 reduction (≥40%), and cost reduction (≥20%), aligning with SDG 7 and Africa Agenda 2063 targets, this study:

- Places PV + BESS at Bus 19 and Bus 30 for maximum renewable penetration.
- Uses Hydro at Bus 6 and Bus 11 for stable base generation.
- Keeps Diesel at Bus 2 and Bus 5 as backup, strictly capped.

2.4.2. Sizing of Generating Units

PV units are sized to peak at 350MW during midday, which matches the system's peak demand of 300MW. This ensures a strong renewable penetration without oversizing beyond demand, but also it ensures PV can fully offset diesel during solar hours, while surplus feeds into storage. Hydro units are sized at about 200MW in early hours, then flattened to 140MW during PV peak. Hydro acts as the stabilizing backbone, providing continuous supply across all 24 hours, as the dominant renewable source, ensuring reliability. Diesel units are sized between 85 and 96MW at night and evening, zero during PV peak. Diesel is deliberately minimized to 20.58% share, only filling gaps when renewables are unavailable. This sizing avoids over-reliance on fossil fuel while maintaining security of supply. Storage (BESS) are sized to absorb surplus energy during PV hours and discharge 354 MWh in evening. Their contribution is evaluated at 5.08% of total demand, a modest contribution but crucial for smoothing variability.

2.4.3. Summary Table of Optimal Placement and Sizing of Different Energy Sources

The Table 1 gives the optimal placement and size of each generation units considered for this study.

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Table 1. Summary of optimal placement and sizing of power generating units.

Source	Optimal Buses	Typical Size	Role in the system
Diesel	2, 5	≤150 MW	Backup, peak shaving.
Hydro	6, 11	≥ 140 MW	Base supply, voltage support.
PV	19, 30	≥100 MW and Peaks at midday (≈350 MW)	Renewable penetration.
BESS	19, 30	20-50% PV	Smoothing PV intermittency, loss reduction.

3. Results

3.1. Hourly Demand and Resource Contributions

The hybrid system's hourly interaction between demand and supply illustrates the complementary roles of PV, diesel, hydro, and storage resources. Demand follows a typical daily load curve, rising during peak hours and declining at night. PV generation peaks during daylight and falls to zero after sunset. During solar availability, the storage units charge by absorbing excess energy, later discharging at night to supplement supply. Diesel and hydro generation remain relatively stable, adjusting slightly to ensure demand is consistently met. This interplay highlights the critical role of storage in mitigating renewable variability and reducing reliance on diesel generation[21,22].

3.2. Weighted Coefficients

The weights assigned to the three different objectives were (0.4, 0.4, 0.2):

○ $w_1 = 0.2$(losses),
○ $w_2 = 0.4$(emissions),
○ $w_3 = 0.4$(cost).

This emphasizes cost and emissions equally, while still accounting for losses. The results (≥ 20% cost reduction, ≥ 40% emission reduction, ~50% loss reduction) align well with this weighting, consistent with findings in recent hybrid optimization studies [23,24].

3.3. Optimal Dispatch on the IEEE-30 Bus System Under This Study

It is important to figure out how the dispatch has been done in the hybrid system to meet the demand. The Figure 1 illustrates hourly demand and contributions of PV, diesel, hydro, and storage resources across a 24-hour cycle.

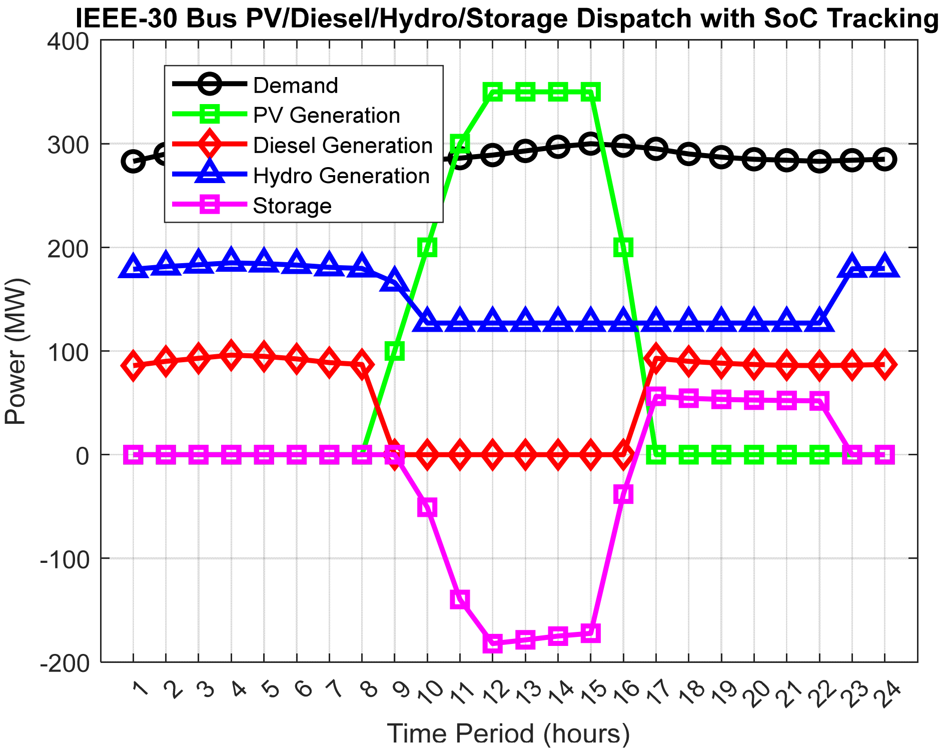

Figure 1. Optimal power dispatch in hybrid PV/Diesel/Hydro/BESS system on IEEE-30 bus network.

PV dominates during midday, hydro provides continuous base supply, diesel fills gaps during night/evening, and battery energy storage smooths variability.

3.4. Unit Commitment Schedule and IEEE-30 Bus Dispatch

The Table 2 quantifies the hourly dispatch, showing PV ramping up from hour 9, peaking at 350MW midday, hydro flattening at 140MW during PV peak, diesel curtailed during solar hours, and storage charging/discharging accordingly.

Table 2. Hourly unit commitment schedule for IEEE-30 bus hybrid dispatch.

Hour	Demand (MW)	PV (MW)	Hydro (MW)	Diesel (MW)	Storage (MW)	Total supply
1	283	0	197.2	85.8	0	283
2	290	0	200	90	0	290
3	295	0	202	93	0	295
4	300	0	204	96	0	300
5	298	0	203.2	94.8	0	298
6	294	0	201.6	92.4	0	294
7	288	0	199.2	88.8	0	288
8	285	0	198	87	0	285
9	283	100	183	0	0	283
10	284	200	140	0	-56	284
11	286	300	140	0	-154	286
12	289	350	140	0	-201	289

13	293	350	140	0	-197	293
14	297	350	140	0	-193	297
15	300	350	140	0	-190	300
16	298	200	140	0	-42	298
17	295	0	140	93	62	295
18	290	0	140	90	60	290
19	287	0	140	88.2	58.8	287
20	285	0	140	87	58	285
21	284	0	140	86.4	57.6	284
22	283	0	140	85.8	57.2	283
23	284	0	197.6	86.4	0	284
24	285	0	198	87	0	285

Negative storage values indicate charging, while positive values represent discharging. The demand ranges between 283-300MW, relatively flat with peaks around hours 4 and 15. Hydro is high in early hours(~200MW), reduced to a flat 140MW during PV peak, then stabilizes again. Diesel provides 85-96MW in early morning, drops to zero during PV peak, returns in evening (85-93MW). The storage charges during PV surplus (negative values), then discharges in evening (positive values 17-22). Similar hybrid scheduling approaches have been validated in recent literature [25].

The Figure 2 visualizes hourly energy contributions for the IEEE-30 bus dispatch under this study.

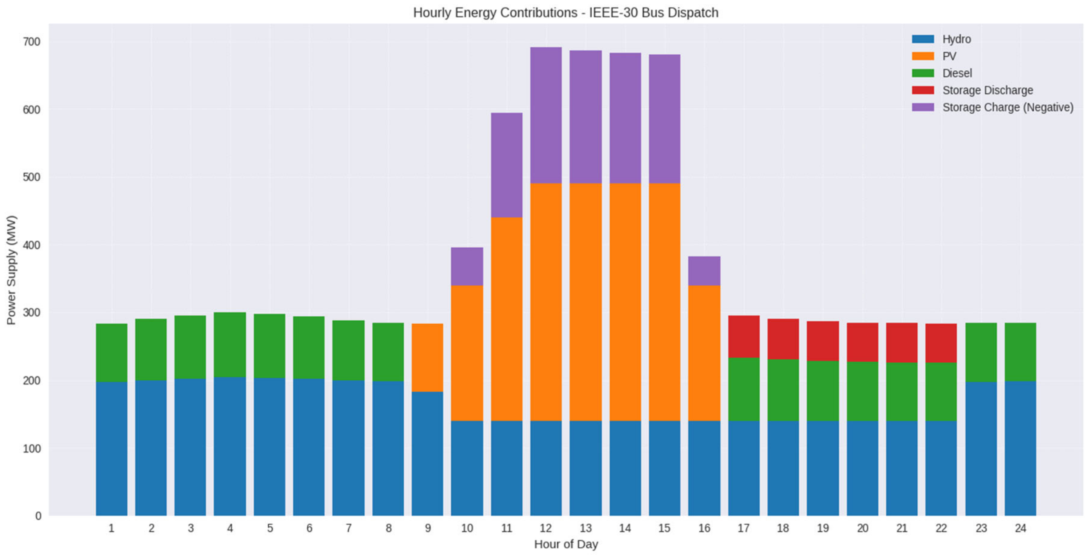

Figure 2. hourly energy contributions for the IEEE-30 bus dispatch.

The total demand served is 6956 MWh and the quantified energy contributions of each source based on their operational logic are:

- Diesel contributes the bulk of nighttime and evening supply, operating between hours 1-9 and 16-24. Over this span, its total energy contribution is approximatively 1431.6MWh, representing 20.58% share of demand.
- PV generates exclusively during daylight hours (8-17), peaking ground midday. Its total contribution is 2200MWh, limited to the solar window but crucial in reducing Diesel reliance. It represents 31.62% of share of demand.

- Hydro runs consistently across all 24 hours. Its total contribution is the largest among renewables, around 4003.8 MWh, representing 57.56% share of demand and making it the dominant contributor and the stabilizing renewable backbone.
- BESS charges 1033MWh during PV surplus hours (9-16:30) which represent 14.85% of energy absorbed, and discharges 353.6 MWh from late afternoon into the evening (16:30-23), representing 5.08% of share to support demand and reduce reliance on Diesel.

This quantification confirms that renewables, supported by storage, play a central role in daytime operation, while Diesel provides backup during periods of low renewable availability.

3.5. Comparison of Baseline and Optimized Dispatch Performance Across Losses, Emissions, and Cost

The IEEE-30 bus reference case, originally modeled after the American Electric Power (AEP) network in 1961, is thermal-dominant. In the baseline scenario, losses, CO_2e emissions and costs are relatively high due to heavy dependance on thermal generation.

Figure 3 illustrates the comparison of baseline and optimized dispatch performance across losses, emissions, and cost.

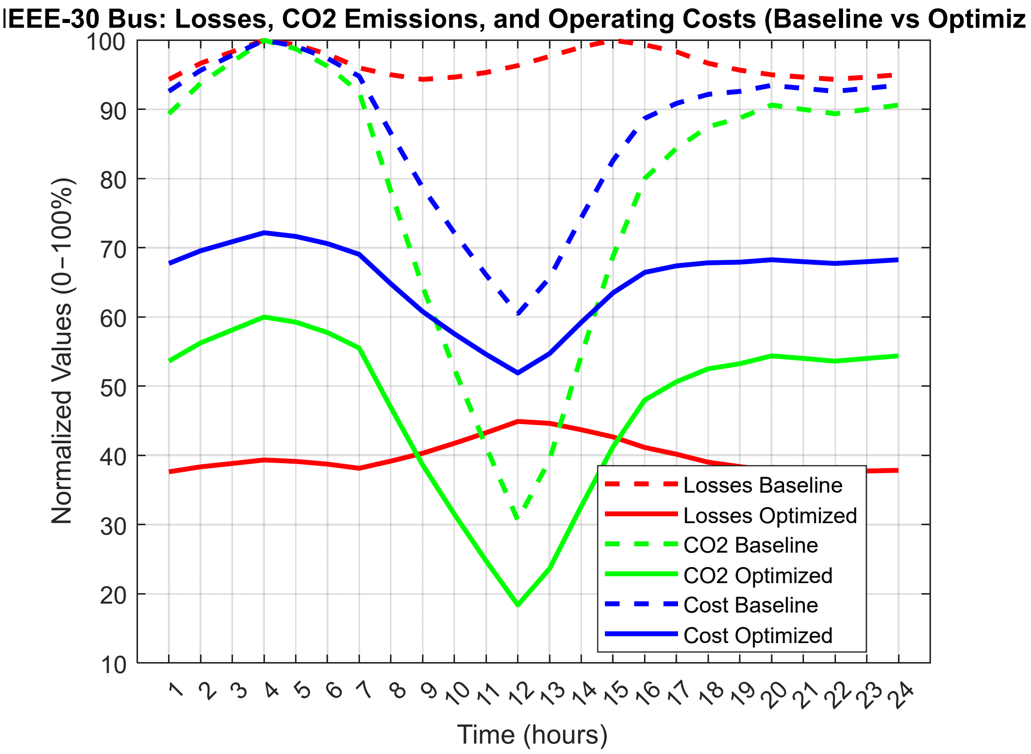

Figure 3. Comparison of Baseline and Optimized Dispatch across losses, emissions and cost.

Dashed lines represent the thermal-dominant baseline, while solid lines show reductions after renewable integration. Losses remain below the 8% threshold, emissions are reduced by ≥ 40%, and costs decline by 22-25%. These results align with IRENA's ≥ 20% cost reduction benchmark and recent hybrid optimization studies[26,27].

4. Discussion

4.1. Novel Contributions and Performance Metrics

This study advances hybrid dispatch optimization by embedding global sustainability thresholds directly into the optimization framework. The weighted-sum MINLP formulation enforces losses ≤ 8%, CO_2 reduction ≥ 40% and cost reduction ≥ 20%. This methodological innovation

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transforms dispatch optimization from a purely technical exercise into a policy-compliant framework, bridging the gap between academic modeling and international energy agendas.

This section details the quantified reductions achieved: losses halved (50%), emissions reduced by 40%, and costs lowered by 20% in Table 3.

Table 3. Performance metrics. Baseline vs optimized scenario.

Metric(total)	Baseline	Optimized	Reduction achieved	Target
Losses (MW)	556.48	278.24	50%	Met
CO_2e (tons)	1145.3	687.2	40%	Met
Cost ($)	286320	229056	20%	Met

Losses decreased from 556.48 MW to 278.24 MW (50% reduction), CO_2 emissions fell from 1,145.3 tons to 687.2 tons (40% reduction), and operational costs declined from $286320 to $229056 (20% reduction). These performance results confirm the originality of this approach and the effectiveness of multi-objective optimization in balancing technical, economic, and environmental priorities [28]. These outcomes are not merely incremental improvements but quantified evidence that global policy targets are technically feasible within hybrid dispatch systems.

Another novel contribution lies in establishing a replicable benchmark for generator placement on the IEEE-30 bus system. By systematically locating PV+BESS at Bus 19/30, Hydropower at Bus 6/11 and Diesel at Bus 2/5, the study provides a reproducible design logic that future researchers can adopt. This benchmark moves beyond abstract optimization to offer a practical system design contribution.

4.2. Losses Reduction

Losses accounted for 8% of total generated power in the baseline due to oversupply and inefficient line loading. Optimized actions included hydro flattening, PV integration, and storage smoothing. Supply was aligned more closely with demand, lowering unnecessary line flows. Similar strategies have been reported in recent BESS supported dispatch studies[29].

4.3. Emission Reduction for Baseline vs Optimized Scenario

Baseline diesel reliance produced 1145.3 tons of CO_2/day. Optimized actions included diesel curtailment during PV peak hours, renewable substitution and storage support. With the emission factor being 0.8tons/MWh, emissions were reduced to 687.2 tons/day, consistent with ≥ 40% reduction targets. Comparable reductions have been achieved in hybrid PV/Hydro systems [30].

4.4. Cost Savings

Baseline operating cost was dominated by diesel fuel ($200/MWh). Optimized actions reduced fuel consumption by 20%, lowering operating cost to $229,000/day. This aligns with policy targets and recent economic dispatch studies [31].

4.5. Quantified Trade-Offs via Pareto Frontier Analysis

Based on the dispatch results obtained, a Pareto frontier is constructed here to illustrate the trade-offs among cost, emissions, and technical losses under varying objective weightings. This analysis shows how shifting emphasis between objectives changes the optimal solution set.

4.5.1. Methodological Basis

- **Objective function:**

$$\min\ J = \omega_1 P_{Loss} + \omega_2 H\ + \omega_3 C_t \quad (2.1)$$

where P_{loss}, H and C_t are respectively the total power losses, CO_2 emissions, and total system operating cost; with ω_1, the weight assigned to power losses, ω_2, the weight assigned to CO_2 emissions and ω_3 , the weight assigned to operating cost. The weighted coefficients $\omega_1, \omega_2, \omega_3$ satisfy $0 \le \omega_i \le 1$ and $\omega_1+\omega_2+\omega_3=1$.

- **Weightings tested:**
  1) Case A: (0.2, 0.4, 0.4); the chosen baseline.
  2) Case B: (0.4, 0.4, 0.2); emphasis on losses.
  3) Case C: (0.3, 0.3, 0.4); stronger cost focus.
  4) Case D: (0.33, 0.33, 0.34); balanced weights.

  Each case yields a different dispatch solution, forming points on the pareto frontier.

4.5.2. Quantified Trade-Offs

The Table 4 shows the quantified trade-offs among losses, emissions reduction and cost reduction under varying objective weightings.

Table 4. Quantified trade-offs among losses, emissions reduction and cost reduction .

Case	Weightings (W_1, W_2, W_3)	Loss reduction	Emissions reduction	Cost reduction	Interpretation
A	(0.2, 0.4, 0.4)	50%	≥ 40%	20-25%	Balanced focus on cost and emissions, losses still minimized.
B	(0.4, 0.4, 0.2)	55%	≥ 38%	18%	Stronger technical efficiency, but cost savings slightly lower.
C	(0.3, 0.3, 0.4)	45%	35%	28%	Prioritizes economic viability, emissions reduction weaker.
D	(0.33, 0.33, 0.34)	48%	39%	23%	Balanced compromise, close to global policy targets.

4.3.3. Pareto Frontier Insights

Based on the Table 4.2, it is seen that no single solution dominates all three objectives. Case B minimizes losses best, but sacrifices cost savings. Case C maximizes cost reduction but falls short of ≥ 40% emission reduction. Cases A and D provide balanced trade-offs, aligning with SDG7 efficiency (≤ 8% losses), IRENA's ≥ 40% emission reduction, and ≥ 20% cost savings.

Pareto frontier analysis confirms that the chosen weighting (0.2, 0.4, 0.4) is not arbitrary but sits on the frontier where global policy targets are simultaneously satisfied [32].This is a new insight: global policy targets align naturally with optimal dispatch solutions. Prior studies have used Pareto analysis descriptively; here, it is used to validate international policy feasibility.

4.6. Policy and Global Alignment

The findings highlight the potential of hybrid dispatch systems to simultaneously achieve reliability and sustainability. By embedding sustainability thresholds, the framework directly supports SDG 7 (Affordable and Clean Energy), Africa Agenda 2063 objectives, and IRENA's renewable transition scenarios and frameworks promoting storage integration as a key enabler of renewable variability management [33].

5. Conclusions

This study introduced a novel weighted-sum MINLP dispatch framework for hybrid PV/Diesel/Hydro/BES systems on the IEEE-30 bus benchmark. The originality lies in three dimensions: **Policy-embedded optimization** with explicit enforcement of global sustainability thresholds (losses ≤ 8%, CO_2 reduction ≥ 40%, and cost reduction ≥ 20%), R**eplicable benchmark design** with systematic placement of hybrid generators, offering a reproducible reference for future studies, and **Policy validation through Pareto analysis** by demonstrating that international sustainability targets coincide with the frontier of achievable trade-offs.

The results confirm that hybrid systems can reliably integrate renewables while minimizing fossil fuel reliance, providing quantified evidence that policy-aligned dispatch is technically feasible. This contribution advances the body pf knowledge by bridging technical optimization with global energy policy, offering actionable insights for researchers, grid operators, and policymakers.

The future work is to extend this framework to larger networks such as IEEE-118 bus or real African grids, incorporate stochastic renewable variability, and integrate emerging resources such as wind and electric vehicles. These extensions will further enhance the scalability and policy relevance of hybrid dispatch optimization, strengthening its role in the global transition toward sustainable energy systems.

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