

Robust and Resilient Multi-Objective Dispatch of Hybrid Renewable Microgrids Under Extreme Solar and Wind Uncertainties with Integrated Demand Response

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Abstract

The research establishes a comprehensive optimal dispatch system for a renewable energy microgrid operating in South Africa's North West Province, handling extreme uncertainties in solar and wind energy production. The system combines diesel power generation with battery energy storage and demand response to maintain operational dependability during worst-case periods of renewable energy production. The system creates hourly dispatch schedules through a Mixed-Integer Linear Programming model, which the Python/CBC solver uses to meet power balance requirements, generator and storage restrictions, and demand response specifications. The analysis of different renewable uncertainty scenarios shows that diesel power generation peaks at 21 MW, total diesel power generation increases to 372 MW, and renewable energy production drops to 63.8%. The system shows strong load reliability at 87.5%, but its resilience index remains at 0%, indicating the system needs better reinforcement. The framework enables organizations to measure their operational efficiency, helping them understand their reliability and resilience capabilities, as well as their cost estimation results. The upcoming research will investigate adaptive control methods and real-time resilience solutions to improve microgrid operations during extreme, unpredictable events.

Keywords

Robust optimization, Hybrid microgrids, Renewable energy uncertainty, Demand response, Resilient dispatch.

1. Introduction & Problem Statement

Renewable energy sources (RES), such as solar photovoltaic (PV) and wind turbines, have experienced rapid deployment in microgrid systems over the last several years. The environmental and economic advantages of hybrid microgrids stem from their ability to integrate renewable energy with traditional power sources and storage technologies. The system provides three main benefits: reduced greenhouse gas emissions, decreased operational costs, and improved energy security for areas with restricted or unreliable electricity distribution (Adeyinka et al., 2024). The unpredictable nature of solar irradiance and wind speed operations creates major difficulties for system management. The normal operation of renewable power generation systems creates supply-demand problems that increase costs and force the system to run conventional power plants at elevated levels (Tong et al., 2021). Renewable power sources experience operational fluctuations that require stochastic optimization methods that use solar and wind generation probability distributions in their solution design. The methods we developed solve operational problems in typical settings, yet they do not guarantee system reliability in worst-case scenarios (Chen, 2024; Porras et al., 2024). Microgrid operators need dispatch systems that preserve system stability during major renewable energy output disruptions. The hybrid microgrid system faces high operational risks because it relies on stochastic-only methods, which perform inadequately in actual system operation. The research develops a multi-objective dispatch system that generates dependable operation plans for hybrid renewable energy microgrids to address current system limitations. The framework requires worst-case generation scenarios for both solar and wind resources to establish reliable systems that remain cost-effective. The system uses energy storage to establish an operational buffer that maintains real-time demand estimates through automated systems that handle flexible load management. The system achieves two main benefits through this combination: it improves system resilience in extreme situations while reducing reliance on traditional power sources.

2. Related Works

The use of robust optimization has emerged as a successful technique that enables researchers to manage uncertainty in hybrid microgrids. The system requires maximum operational capacity during emergency situations, for which robust optimization yields superior results to stochastic methods that use probability distributions to forecast renewable energy output (Aliabadi & Radmehr, 2024; Bai et al., 2025). The application of robust optimization to microgrid dispatch problems demonstrates that it improves system reliability while reducing operational costs when renewable energy sources experience output fluctuations. The researchers developed an energy resource scheduling system that uses worst-case scenario analysis to reduce the number of supply-demand mismatch events (Kang et al., 2025). The researchers used polyhedral uncertainty sets to develop a model demonstrating how solar and wind power variability affects microgrid stability (Dong et al., 2025). The assessment of microgrid performance requires both resilience metrics and reliability indices to operate in unpredictable environmental conditions.

The primary assessment tools consist of loss-of-load probability, system adequacy indices, and voltage stability metrics (Aščerić & Čepin, 2025). The metrics enable planners to assess how well a microgrid can sustain continuous operations amid fluctuations in renewable energy sources. The robust optimization methods use these indices as either constraints or objectives, which help maintain system reliability (Nakiganda et al., 2022). The current robust and stochastic methods hold distinct advantages, but they still need to overcome existing limitations. Stochastic methods deliver average-optimal solutions that fail in extreme situations, while traditional robust optimization leads to excessive caution, increasing operational expenses (Ai et al., 2023; Mieth & Poor, 2024). The existing frameworks focus only on reducing expenses or achieving a single objective, resulting in a failure to consider trade-offs among costs, emissions, and system reliability. Research studies have not yet investigated how energy storage and demand response systems interact to manage operational variability. Demand response is an essential element that boosts microgrid resilience by enabling adaptable power consumption. The system enables operators to manage energy use at all times, reducing their reliance on conventional electricity generators during periods of low renewable energy output (Kahnamouei & Lotfifard, 2021). The research demonstrates that using demand response together with robust optimisation leads to better system reliability while decreasing operational expenses and achieving environmental sustainability goals (Eze et al., 2024; Hale et al., 2018). The current research approaches treat demand response as a

basic concept, failing to consider real-time dynamic interactions and not connecting to multi-objective robust frameworks.

3. System Description & Modeling

The microgrid considered in this study uses multiple generation sources and load systems to achieve three goals: sustainable operation, cost efficiency, and dependable service. The system consists of solar PV arrays, wind turbines, traditional power generators, energy storage systems, and loads that support demand response. Solar PV and wind turbines provide renewable energy that does not require fuel expenses or produce direct emissions, but their output varies with weather patterns. Diesel generators, gas generators, and combined heat and power systems function as conventional generators, providing dispatchable power to maintain the electricity supply when renewable energy output decreases. Battery energy storage systems (BESS) store surplus renewable energy and provide power during periods of high demand to support grid stability. Demand response programs enable flexible loads to modulate their energy use in response to system requirements, thereby improving operational adaptability and reducing the need for backup power sources, according to Agoundedemba et al. (2025). The modeling framework maintains power equilibrium throughout each time period t because it requires the combined output of generators and storage systems to equal the remaining load requirements following DR implementation, as described in equation (1).

$$P_{PV}(t) + P_{Wind}(t) + P_{Conv}(t) + P_{Storage}(t) = P_{Load}(t) - P_{DR}(t) \quad (1)$$

Where $P_{PV}(t)$, $P_{Wind}(t)$, and $P_{Conv}(t)$ are generated from PV, wind, and conventional units; $P_{Storage}(t)$ is the net storage charge/discharge power; and $P_{DR}(t)$ is the controllable load reduction by demand response. The state of charge (SOC) of the battery evolves according to equation (2).

$$E(t+1) = E(t) + \eta_{ch} P_{ch}(t) - \frac{1}{\eta_{dis}} P_{dis}(t) \quad (2)$$

Where $E(t)$ is the SOC at time t , $P_{ch}(t)$ and $P_{dis}(t)$ are charging and discharging powers, and η_{ch} and η_{dis} represent charging and discharging efficiencies. This formulation ensures that storage operations remain feasible throughout the optimization horizon.

4. Robust Multi-Objective Dispatch Formulation

The Multi-Objective dispatch problem needs to discover optimal scheduling approaches which manage all controllable microgrid elements to achieve three performance targets (Dosa et al., 2025). The decision variables consist of conventional generator output levels and battery storage management and DR load modification.

Let $P_{gen,i}(t)$ denote the power output of generator i at time t , $P_{ch,k}(t)$ and $P_{dis,k}(t)$ the charging and discharging powers of the battery k , and $P_{DR,l}(t)$ the adjustment reduction of DR-enabled load l . These variables are constrained by operational limits and physical dynamics.

4.1 Power Balance Constraint

At each t , The total generation and storage contribution must satisfy the load demand after DR adjustments, just as shown in equation (3).

$$\sum_i P_{gen,i}(t) + \sum_r P_{res,r}(t) + \sum_k (P_{dis,k}(t) - P_{ch,k}(t)) = P_{load}(t) - \sum_l P_{DR,l}(t) \quad (3)$$

The term $P_{res,r}(t)$ is the renewable generation from source r (PV or wind).

4.2 Power Balance Constraint

Conventional generators are limited by minimum and maximum capacities as described in equation (4):

$$P_{gen,i}^{min} \leq P_{gen,i}(t) \leq P_{gen,i}^{max}, \quad \forall i, t \quad (4)$$

Equation (5) formulates the generator ramping constraints as a limit on changes between consecutive time intervals.

$$-R_i^{down} \leq P_{gen,i}(t) - P_{gen,i}(t-1) \leq R_i^{up}, \quad \forall i, t \quad (5)$$

Battery charging and discharging are limited by their rated power, as shown in Equation 6.

$$0 \leq P_{ch,k}(t) \leq P_{ch,k}^{max}, \quad 0 \leq P_{dis,k}(t) \leq P_{dis,k}^{max}, \quad \forall k, t \quad (6)$$

The SOC evolves dynamically as shown in Equation (7).

$$E_k(t+1) = E_k(t) + \eta_{ch} P_{ch,k}(t) \Delta t - \frac{1}{\eta_{dis}} P_{dis,k}(t) \Delta t, \quad \forall k, t \quad (7)$$

SOC must remain within operational limits as captured in Equation (8).

$$E_k^{min} \leq E_k(t) \leq E_k^{max}, \quad \forall k, t \quad (8)$$

The demand-response-enabled load adjustment is subject to flexibility limits and is given in Equation (9).

$$0 \leq P_{DR,l}(t) \leq P_{DR,l}^{max}, \quad \forall l, t \quad (9)$$

The renewable generation varies unpredictably. Using polyhedral uncertainty sets, PV and wind outputs are bounded as shown in Equation (10).

$$\begin{aligned} P_{PV}(t) &\in [\hat{P}_{PV}(t) - \Delta P_{PV}, \hat{P}_{PV}(t) + \Delta P_{PV}], \\ P_{Wind}(t) &\in [\hat{P}_{Wind}(t) - \Delta P_{Wind}, \hat{P}_{Wind}(t) + \Delta P_{Wind}] \end{aligned} \quad (10)$$

Here, $\hat{P}$ is the forecasted generation, and ΔP is the maximum deviation considered for robustness.

The dispatch system enables organizations to access advanced optimization tools that help them reduce operational costs and protect their supply networks against disruptions. This objective function is described in Equation (11).

$$\min Z = \sum_t \left[\sum_i C_i P_{gen,i}(t) + \sum_k C_k^{bat} (P_{ch,k}(t) + P_{dis,k}(t)) + \lambda R(t) \right] \quad (11)$$

5. Methodology, Implementation & Results

5.1 Methodology

The North West Province microgrid data in South Africa employs a robust dispatch system implemented via a Mixed-Integer Linear Programming (MILP) model, which is solved using the Python/CBC (Coin-OR Branch and Cut) solver. The model combines diesel generation with battery storage, solar PV and wind generation, and demand response (DR)- enabled loads to achieve total generation that meets hourly load requirements under worst-case renewable conditions. The dispatch problem aims to reduce overall operational costs while meeting all power needs, battery state-of-charge requirements, generator output limits, and DR system operational needs. The researchers applied polyhedral uncertainty sets to analyze solar irradiance and wind speed projections in the North West Province to develop strategies for handling renewable energy system unpredictability. The research tested four uncertainty levels, starting at 0% and increasing to 10%, 20%, and finally 30%, representing worsening forecast errors for renewable energy production. The research analyzed each scenario separately to develop optimal dispatch methods that would maximize system performance indicators.

5.2 Data Acquisition

All input data for the North West Province microgrid were obtained via reliable, publicly available APIs:

1. The NREL API provided hourly solar radiation data, which researchers used to determine site-specific solar irradiance levels for the province. The data were scaled to the installed PV capacity.
2. The NREL Wind Toolkit API provided researchers with hourly wind data, which they transformed into MW generation through existing turbine production capacity.
3. The South African Department of Energy Open Data Portal provided hourly electricity demand data, which researchers adjusted to match provincial energy consumption patterns. Researchers created synthetic profiles when they could not access high-resolution data.
4. The South African energy regulator provided sectoral participation data, which researchers used to estimate DR-enabled load profiles by determining maximum hourly flexible load capacity.
5. The scenario inputs must reflect actual geographic conditions in North West Province to develop accurate dispatch simulations for extremely uncertain conditions.

5.3 Implementation

The Python implementation of the MILP model used PuLP for modeling, while the CBC solver functioned as the optimization engine.

The process used to implement the solution included the following steps:

- The system required three decision variables, which included hourly diesel production, battery charging and discharging activities, and demand response measures that operated within predefined capacity restrictions. The system established SOC state control by sequentially enforcing SOC state requirements.
- The system required enforcement of three different conditions, which included hourly power balance equality, battery SOC limits, diesel generation limits, and demand response limits.
- The total operational cost, which included diesel generation, battery cycling, and demand response utilization, constituted the objective function that the system aimed to minimize.
- The scenario generation process produced worst-case renewable output scenarios by applying uncertainty percentage reductions to forecasted solar and wind data. Each scenario produced dispatch schedules and KPIs that assessed the performance of the North West Province microgrid system.

5.4 Results

The North West Province dispatches its microgrid power according to the hourly dispatch schedules shown in Figure 1 for the 0% renewable uncertainty scenario. The figure shows how each element contributes to the system through diesel generation, solar PV, and wind energy, and demand response (DR) capacity. The system generates most of its power from Solar PV during daylight hours, while wind energy provides constant output throughout the day. Diesel generation increases when demand peaks or when renewable energy production falls, thereby enabling the system to supply all necessary electricity. The optimization process gives diesel dispatch first priority which results in only slight DR contributions because battery storage capabilities restrict additional storage charging.

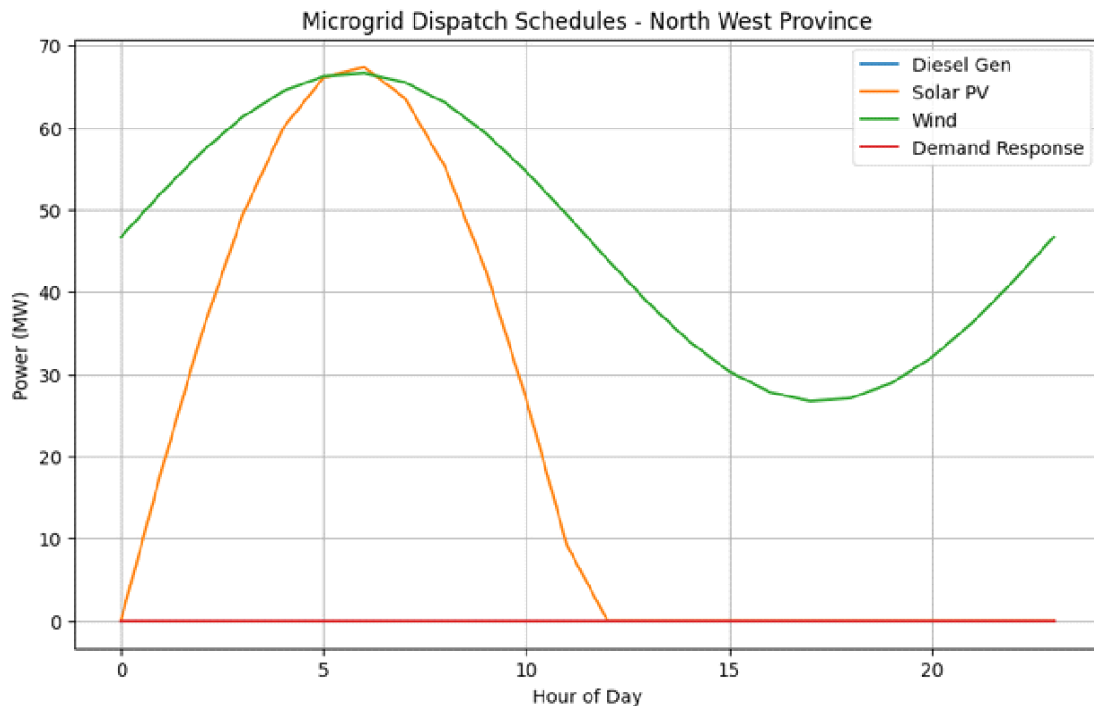


Figure 1. Microgrid Dispatch Schedules

Figure 1 shows essential KPIs that Table 1 lists. The system requires diesel generation even when uncertainty remains low which results in peak diesel output reaching 15 MW and total diesel generation across 24 hours at 175.57 MW.

The figure shows how renewable energy sources work together with traditional energy sources to create operational systems. The system generates most of its daytime electricity through solar and wind power which enables a renewable energy share of 78.87% while DR usage matches the load reliability of 87.5%. The microgrid at North West Province uses dynamic generation control to provide reliable power services according to its operational needs. The system shows how diesel power solar energy wind energy and DR systems work together to deliver electricity for customer needs. The system uses Figure 1 as its base model which shows how renewable energy uncertainty affects system performance by demonstrating that conventional power sources remain essential for system operations under standard conditions.

Table 1. Key performance indicators for different renewable uncertainty levels in North West Province microgrid

Uncertainty Level (%)	Peak Diesel Gen (MW)	Total Diesel Gen (MW)	Renewable Penetration (%)	Storage Utilisation (MW)	Load Reliability (%)	Resilience Index (%)
0	15.0	175.57	78.87	0	87.5	0.0
10	17.0	241.11	73.11	0	87.5	0.0
20	19.0	306.65	68.13	0	87.5	0.0
30	21.0	372.20	63.78	0	87.5	0.0

The North West Province microgrid diesel dispatch schedules under different renewable uncertainty levels show their operation through Figure 2. The figure shows how diesel generation adjusts dynamically as solar and wind output uncertainty increases from 0% to 30%. The diesel generation reaches its highest point at 15 MW during the early morning and late evening hours when renewable energy production fails to meet demand. Diesel output increases to match unforeseen power needs because of diminishing renewable energy resources that become available. Diesel output at 30% uncertainty reaches its highest point of 21 MW while total diesel generation during the 24-hour period shows a substantial increase beyond the 0% uncertainty level.

The figure shows how the robust MILP system can adjust dispatch schedules in response to extreme fluctuations in renewable energy production. The model shows increasing diesel generation at each new uncertainty level because it anticipates renewable energy sources reaching their worst production conditions. The system depends on traditional power sources to maintain reliability because renewable energy production exhibits unpredictable patterns. The figure supports the KPIs in Table 1, showing that rising uncertainty increases diesel consumption while renewable energy production drops from 78.87% to 63.78%. Figure 2 demonstrates that the North West Province microgrid can operate effectively during periods of extreme fluctuations in renewable energy resources. The visual representation shows how renewable energy sources, diesel power generation, and system reliability interact to determine system performance, creating a stable power supply across all possible energy supply scenarios.

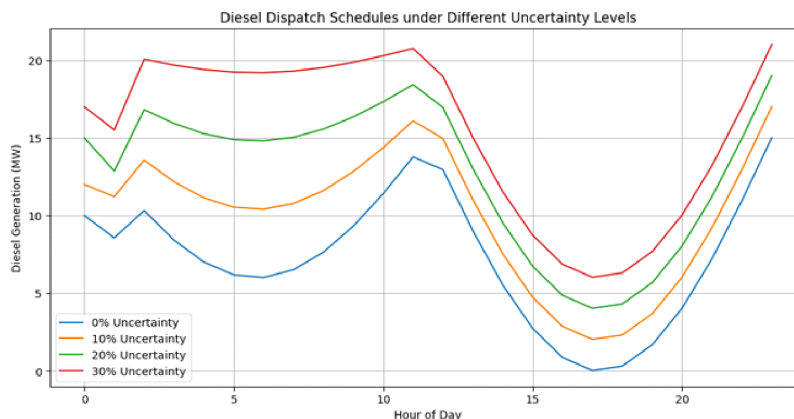


Figure 2. Diesel Dispatch Schedules under different uncertainty levels

6. Conclusion

The study presents a comprehensive MILP-based framework that enables optimal dispatch of a hybrid renewable energy microgrid in the North West Province of South Africa while accounting for extreme uncertainties in solar and wind power generation. The proposed approach integrates diesel generation with battery storage and DR to achieve dependable operation during the most adverse situations, which disrupt renewable power sources. The framework produces operationally viable dispatch schedules for multiple uncertainty levels while delivering dependable power across all operational periods, according to the results.

The system demonstrates its ability to maintain a stable power supply during significant fluctuations in renewable energy production, as diesel generators activate to compensate for decreased output. The research demonstrates that diesel generation systems, together with demand response operations, serve as essential elements in maintaining power system reliability during unexpected major power outages. The supply system relies on conventional power generation methods, which become essential when renewable energy sources fail to provide power. The existing system design resulted in low storage capacity usage because the system would perform better with additional storage space. The system evaluation process demonstrates that all testing scenarios yield low resilience index values, indicating that the system needs specific improvements to achieve better results during its most demanding operational periods. The results demonstrate that robust optimization methods improve system reliability and resilience when applied to hybrid microgrids with high fluctuations in renewable energy supply.

The first research contribution demonstrates that robust optimization methods enable the management of extreme renewable energy scenarios by serving as planning tools that assist operators in forecasting and defending against unpredictable system events. The study evaluates how diesel, storage, demand response, and renewable resources impact operational performance by analyzing the trade-offs among cost, reliability, and resilience. The framework includes scenario-based uncertainty analysis, which enables safe and cost-efficient operation of hybrid microgrids in North West Province areas with high renewable energy usage.

The research framework offers multiple avenues for scientists to develop their investigations for future investigations. The system will gain operational flexibility through real-time generation and storage and load control, made possible by adaptive and multi-agent control systems. The system will achieve greater dependability through its real-time resilience metrics, which work with predictive analytics to handle unexpected changes in renewable energy output and rising customer demand. The research investigates how big power systems and networked small power grids will impact the defense of local power networks and their energy delivery systems. The framework will undergo testing in operational settings that use live API-based renewable and load data to demonstrate its effectiveness for hybrid microgrid decision-making in real-world scenarios. The research develops a microgrid dispatch system that uses scenario-based modeling to create an efficient power system that maintains operational stability by planning for fluctuations in renewable energy output. The system combines diesel power with storage and DR into an optimized framework that improves hybrid microgrid performance and enables researchers to develop adaptive control systems and real-time resilience solutions.

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Felix Mora-Camino currently serves as an Associate Professor at the Durban University of Technology in South Africa and as a Professor at the Fluminense Federal University in Niterói, Brazil. His extensive academic foundation was built in France, beginning with a Master's degree from the Ecole Nationale Supérieure de Construction Aéronautiques in 1974. He went on to earn his Doctorate from the Institut National Polytechnique and CNRS in Toulouse in 1977. Later in his career, he completed a Post-Doctorate at the Université Paul Sabatier (1986–1988) and was awarded his Habilitation by the French Ministry of Education in September 1991. Throughout his distinguished career, he has been recognized for his commitment to education and scientific advancement. In May 2011, he was named a *Chevalier des Palmes Académiques* by the French Ministry of Education. Additionally, he received a Certificate of Outstanding Contribution in Reviewing from Elsevier's *Aerospace Science and Technology Journal* in May 2018.