energies

MDPI

Systematic Review

A Systematic Review of Hierarchical Control Frameworks in Resilient Microgrids: South Africa Focus

Rajitha Wattegama [1,*], Michael Short [1,*], Geetika Aggarwal [1], Maher Al-Greer [1] and Raj Naidoo [2]

[1] School of Computing Engineering and Digital Technologies, Teesside University, Middlesbrough TS1 3BX, UK; g.aggarwal@tees.ac.uk (G.A.)
[2] Department of Electrical, Electronic and Computer Engineering, University of Pretoria, P.O. Box 14679, Hatfield, Pretoria 0028, South Africa
* Correspondence: r.wattegama@tees.ac.uk (R.W.); m.short@tees.ac.uk (M.S.)

Abstract

This comprehensive review examines hierarchical control principles and frameworks for grid-connected microgrids operating in environments prone to load shedding and under demand response. The particular emphasis is on South Africa's current electricity grid issues, experiencing regular planned and unplanned outages, due to numerous factors including ageing and underspecified infrastructure, and the decommissioning of traditional power plants. The study employs a systematic literature review methodology following PRISMA guidelines, analysing 127 peer-reviewed publications from 2018–2025. The investigation reveals that conventional microgrid controls require significant adaptation to address the unique challenges brought about by scheduled power outages, including the need for predictive–proactive strategies that leverage known load-shedding schedules. The paper identifies three critical control layers of primary, secondary, and tertiary and their modifications for resilient operation in environments with frequent, planned grid disconnections alongside renewables integration, regular supply–demand balancing and dispatch requirements. Hybrid optimisation approaches combining model predictive control with artificial intelligence show good promise for managing the complex coordination of solar–storage–diesel systems in these contexts. The review highlights significant research gaps in standardised evaluation metrics for microgrid resilience in load-shedding contexts and proposes a novel framework integrating predictive grid availability data with hierarchical control structures. South African case studies demonstrate techno-economic advantages of adapted control strategies, with potential for 23–37% reduction in diesel consumption and 15–28% improvement in battery lifespan through optimal scheduling. The findings provide valuable insights for researchers, utilities, and policymakers working on energy resilience solutions in regions with unreliable grid infrastructure.

Keywords: microgrid; hierarchical control; load-shedding; energy resilience; predictive control; energy storage; renewable integration

Check for updates

Academic Editor: Michael Negnevitsky

Received: 13 December 2025
Revised: 16 January 2026
Accepted: 21 January 2026
Published: 26 January 2026

1. Introduction

Decarbonisation requirements, NetZero goals, Sustainability Development Goals, technology breakthroughs, and rising costs associated with extraction and processing of fossil fuels are all contributing to a significant shift in the global energy sector [1]. Microgrids have emerged as a critical solution for enhancing energy resilience, integrating renewable resources, and maintaining power availability during grid disturbances [2,3].

They also bring benefits related to increased access to affordable electricity and are seen as particularly beneficial in rural areas or areas where wider grid interconnection has proved difficult or costly to achieve. In the developing world, grid infrastructure is often inadequate and supply–demand mismatch and grid outages are common, and load-shedding (where scheduled, sometimes frequent power outages) has become a common strategy for managing supply–demand imbalances. South Africa represents a particularly acute case of this phenomenon, experiencing up to 12 h of daily load-shedding at peak intensity periods, threatening economic stability and putting essential services such as healthcare, education, telecommunications, transportation, and governance at risk [4–8].

Typically load-shedding is a utility-controlled, pre-announced interruption of the energy supply deployed in order to prevent a complete grid collapse, as opposed/contracted with critical (unplanned) blackouts brought on by system faults (such as the loss of a generation unit), unexpected or abnormal grid operating conditions (significantly higher than forecast peak load), or natural disasters (such as power line lighting strikes) [9]. Load-shedding is especially severe in South Africa, where planned outages can last up to 12 h per day during periods of high intensity, endangering vital services, research continuity, and economic stability. In this environment, microgrid becomes a vital part of corporate and social continuity, rather than a specialised reliability solution [7,10].

The standard microgrid framework has mostly concentrated on using islanding detection and quick transition technologies to react to unplanned grid disruptions [11]. However, the nature of scheduled load-shedding presents fundamentally different challenges and opportunities for microgrid control systems. Unlike unplanned outages, load-shedding events are predictable in advance with known timing and duration, enabling control strategies that can proactively optimise resource allocation and prioritise critical loads. This difference requires a fresh review of hierarchical control structures to see how they may be adjusted or fully redesigned for these operating conditions [12–14]. Figure 1 conceptually illustrates the shift from conventional reactive protection-based microgrid operation to proactive optimisation enabled by predictive control under scheduled load-shedding conditions.

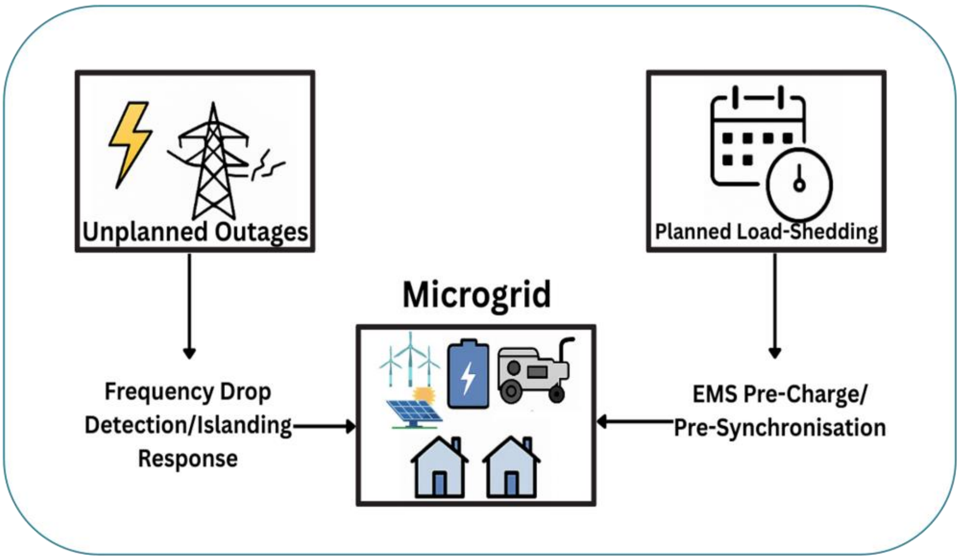

Figure 1. Reactive Protection vs. Proactive Optimisation.

The concept behind this review is that microgrids in load-shedding conditions need specific control strategies that are somewhat different from those made for grids with steady, reliable and dispatchable baseload power [15]. The primary research question examines how hierarchical control frameworks can be adapted to leverage the predictive nature of load-shedding schedules to enhance resilience, reduce operating costs, and maintain power quality [16]. This review seeks to address four subsidiary questions:

- What modifications to primary control layer are needed for scheduled versus unscheduled islanding?
- How can secondary control incorporate load-shedding schedules to improve frequency and voltage regulation?
- What tertiary control strategies show a peak potential of economic optimisation in load-shedding contexts?
- What evaluation metrics are most appropriate for assessing microgrid performance in these environments?

This paper makes several contributions to the field of microgrid control systems. First, it provides a comprehensive synthesis and critical analysis of existing literature on hierarchical control frameworks specifically applied to load-shedding-prone networks [17,18]. Second, it proposes a novel conceptual synthesis and classification framework for microgrid control strategies. This framework analyses strategies not solely by topology, but by their fundamental approach to scheduled versus unscheduled outages, integrating predictive grid availability data as a core analytical dimension, a focus underexplored in prior hierarchical control reviews. Third, it identifies and analyses key research gaps in current methodologies and suggests promising directions for future work. Finally, it offers practical insights for utilities, microgrid developers, and policymakers working to enhance energy resilience in regions experiencing chronic electricity shortages [19,20].

The review structure proceeds as follows: Section 2 provides essential background on microgrid evolution, hierarchical control principles, and the specific context of load-shedding in South Africa. Section 3 details the systematic methodology employed for literature identification, selection, and analysis. Section 4 presents a comprehensive analysis of the three control layers and their adaptations for load-shedding environments. Section 5 examines case studies from South Africa and other regions with similar challenges. Section 6 discusses research gaps, future pathways, and implementation considerations. Finally, Section 7 presents conclusions and recommendations for researchers and practitioners.

2. Background

2.1. Evolution of Microgrids and Hierarchical Control

The concept of microgrids has evolved significantly since initial explorations of distributed energy systems in the late 20th century. Modern microgrids represent integrated energy systems that can operate both connected to the main grid and in islanded mode, comprising distributed generation, energy storage, controllable loads, and management systems. The theoretical foundation for microgrids rests on the principles of distributed control theory, power electronics, and energy economics, which together enable localised energy autonomy while maintaining grid compatibility [21–25].

Hierarchical control architectures have become the dominant ideology for microgrid management, typically organised into three distinct layers with different timescales and functions [26]. This structure effectively mirrors organisational principles used in traditional power system operation but adapted for smaller-scale systems with higher penetration of inverter-based resources [27,28]. The primary control layer operates on millisecond to second timescales, implementing local voltage and frequency regulation through techniques such as droop control. The secondary control layer functions on second to minute timescales, restoring system parameters to nominal values and coordinating multiple distributed resources. The tertiary control layer operates on minute to hour timescales, managing economic dispatch, grid interaction, and long-term optimisation [29–32].

https://doi.org/10.3390/en19030644

The implementation approaches for hierarchical control have evolved through several generations. Early systems relied on centralised architectures with all computation performed by a single controller, which created single points of failure and communication bottlenecks [21]. Subsequent developments introduced decentralised architectures where control decisions were made locally without coordination, improving reliability but potentially sacrificing global optimisation. The current state of the art employs distributed architectures that balance local autonomy with system-wide coordination through communication between neighbouring units, enhancing both resilience and efficiency [33–37].

2.2. Load-Shedding Context: The South African Case Study

South Africa is a strong example of a country facing regular load-shedding, and its experience offers lessons for other regions that struggle with similar power problems. The energy crisis has been caused by several long-term issues, such as low investment in new power stations, old and unreliable infrastructure, problems with coal supply, and management challenges at the state-owned utility Eskom [38,39]. These factors together have made it difficult to meet the country's electricity demand and have led to frequent power cuts that affect homes, businesses, and industries across the nation. Load-shedding in South Africa is carried out in planned stages to protect the power grid from total failure. The system includes several stages, from Stage 1 (least severe) to Stage 8 (most severe), and each stage represents about 1000 MW of power that must be taken off the grid. When electricity demand is much higher than supply, higher stages are applied. While Eskom dominates the national generation fleet and grid, the evolving landscape includes Independent Power Producers (IPPs) and municipal distributors. The microgrid control strategies reviewed herein are concerned with the technical response to grid unavailability, making them applicable to interconnection with any utility or IPP [40–42].

The economic impacts of load-shedding have been severe, with estimates suggesting losses of approximately R500 million per stage per day to the South African economy. This leads to major losses in industrial operations including manufacturing, mining, and agriculture, while small businesses often struggle to stay open [43]. Power cuts have also disrupted hospitals, schools, and communication networks, causing problems for daily life and public safety. These effects build up across society, slowing down economic growth and affecting the well-being of communities [44–47]. Because of these challenges, there is growing interest in local power solutions such as microgrids that can keep running during outages. These systems combine renewable energy sources, batteries, and smart controls to supply steady power when the main grid fails [19].

A special feature of South African load-shedding is that it is scheduled in advance. Unlike sudden blackouts, load-shedding follows published timetables showing when each area will lose power, typically in 2–4 h blocks. The following Figure 2 shows a simple outline of these load-shedding stages and how long each outage normally lasts [48].

Table 1 summarises the different stages of load-shedding implemented in South Africa, highlighting their typical duration, frequency, and associated economic impact.

Table 1. Load-Shedding Stages in South Africa and Their Impacts.

Stage	Reference	Power Shed	Frequency	Typical Duration	Economic Impact
Stage 1	[48]	1000 MW	Few times per week	2 h	Minimal
Stage 2	[48]	2000 MW	Daily	2–4 h	Moderate
Stage 3	[48]	3000 MW	Daily	4–6 h	Significant
Stage 4	[48]	4000 MW	Daily	6–8 h	Substantial
Stage 5+	[48]	5000+ MW	Multiple times daily	8–12 h	Severe

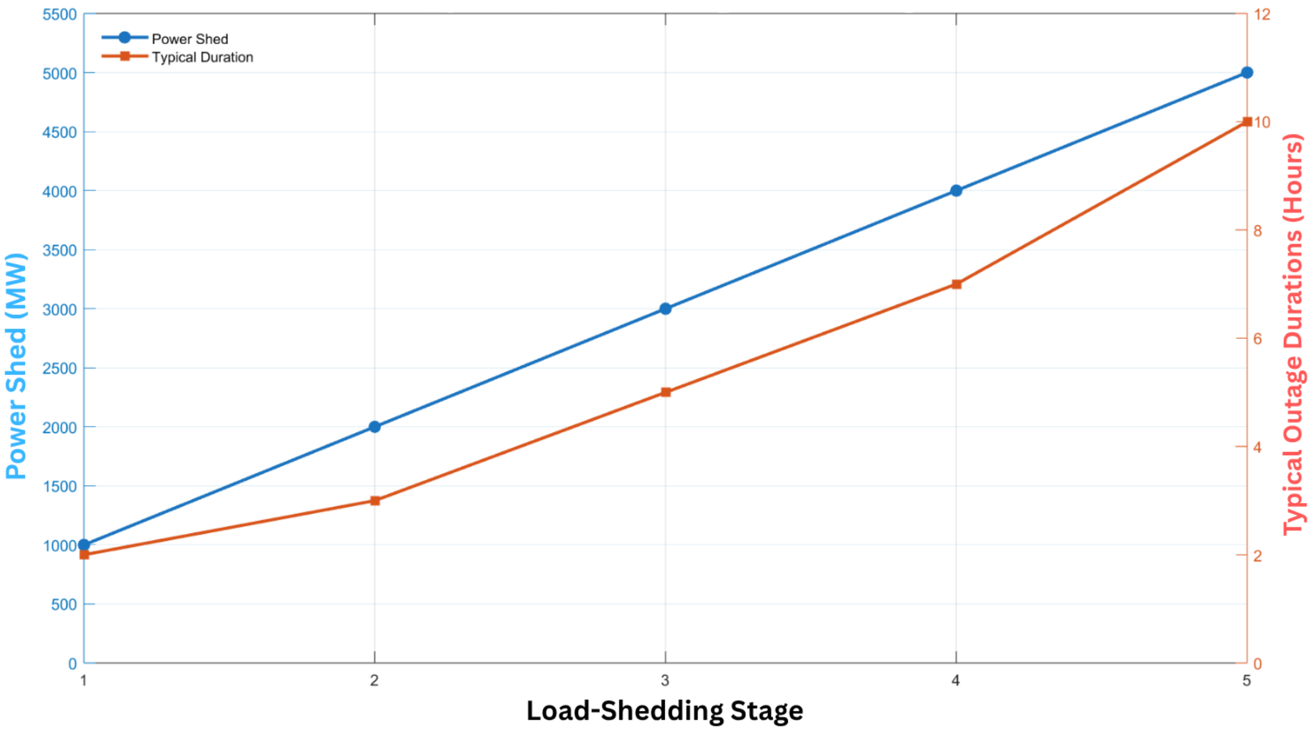

Figure 2. Power Shed vs. Shedding Stage vs. Outage Durations [48].

Scheduled load-shedding method makes it possible to plan ahead and manage energy use more effectively [49]. For example, batteries can be charged before a cut, generators can be started on time, and important loads can be prioritised [50]. This planned approach changes the way energy systems operate, moving from reacting to emergencies to preparing for them in advance. It allows for better use of available resources and helps reduce the negative effects of power cuts on both people and businesses [50].

2.3. Theoretical Framework for Microgrid Resilience

The concept of resilience in power systems has evolved beyond traditional reliability considerations to encompass a system's ability to anticipate, withstand, adapt to, and rapidly recover from disruptive events [51]. For the purpose of this review, resilience is specifically defined as the microgrid's capability to anticipate, withstand, adapt to, and rapidly recover from scheduled load-shedding events. This distinguishes it from general reliability against random faults. Key related concepts are defined in Table 2 below. Key technical terms used throughout this review are defined in Appendix A.

Table 2. Definitions of Key Performance Concepts.

Term	Definition in Context
Reliability	The probability of the system performing without unscheduled interruption.
Resilience	The ability to anticipate, withstand, adapt, and recover from scheduled load-shedding events.
Availability	The percentage of time power is supplied to critical loads, including during scheduled outage windows.
Robustness	The ability to maintain operation amidst parameter variations and component tolerances.

For microgrids operating in load-shedding environments, resilience incorporates multiple dimensions including technical performance, economic efficiency, and social acceptability. The theoretical foundations of microgrid resilience are drawn from complex adaptive systems theory, fault tolerance principles, and multi-objective optimisation frameworks [52]. Figure 3 presents the theoretical framework adopted in this review for analysing microgrid resilience in load-shedding environments.

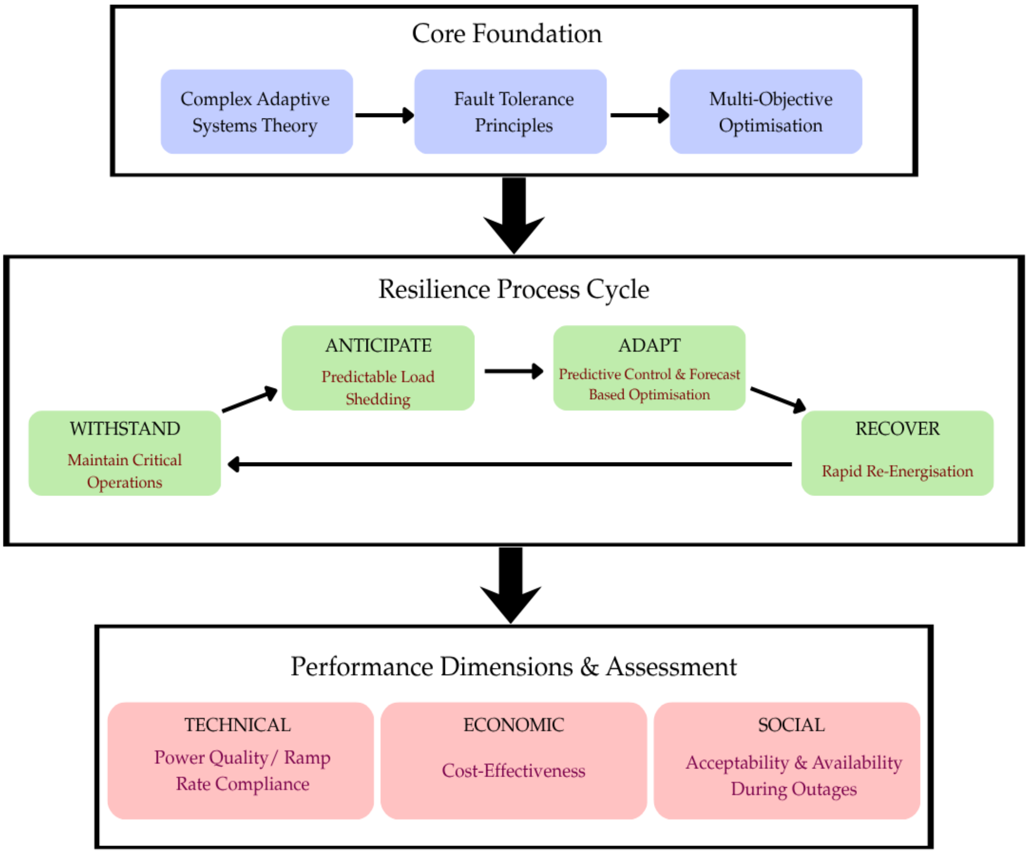

Figure 3. Theoretical framework for microgrid resilience [52].

A key theoretical aspect relevant to load-shedding contexts is the gap between resilience to predictable versus unpredictable events. While traditional microgrid resilience has focused primarily on unexpected disturbances such as equipment failures and extreme weather, load-shedding represents a predictable disturbance that enables preparatory actions. This gap introduces important theoretical considerations from predictive control theory and foresight-based optimisation that are less relevant for unexpected outage scenarios [52,53].

The analytical framework for assessing microgrid resilience in load-shedding environments must incorporate metrics beyond standard reliability indices like SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index) [54]. Specifically, it should include resilience-specific metrics such as availability during scheduled outages, ramp rate compliance during transitions, power quality maintenance, and cost-effectiveness of mitigation strategies. These metrics provide a more comprehensive assessment of microgrid performance in load-shedding contexts [55].

3. Methodology

3.1. Systematic Literature Review Protocol

This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure comprehensive and reproducible literature identification, screening, and selection [56]. The research protocol was developed to address the specific research questions while minimising selection bias and ensuring coverage of both technical and socioeconomic aspects of microgrid control in load-shedding environments.

https://doi.org/10.3390/en19030644

The literature search was conducted across five major databases: Scopus, Web of Science, IEEE Xplore, ScienceDirect, and JSTOR. Additional grey literature was identified through Google Scholar, research institution repositories, and industry reports. The search strategy employed targeted keyword combinations. For example, the Scopus search string was TITLE-ABS-KEY ((microgrid OR "micro-grid") AND ("hierarchical control" OR "resilient control") AND ("load-shedding" OR "scheduled outage"*)) AND PUBYEAR > 2017. Similar Boolean logic was adapted for other databases. The search timeframe was limited to publications between January 2018 and August 2025 to capture the most recent advancements in control strategies while ensuring sufficient literature volume for analysis.

Figure 4 presents the results of the systematic literature review (SLR) screening process across the selected academic databases. The stacked bar chart shows how the total number of records was progressively reduced through each stage of the review.

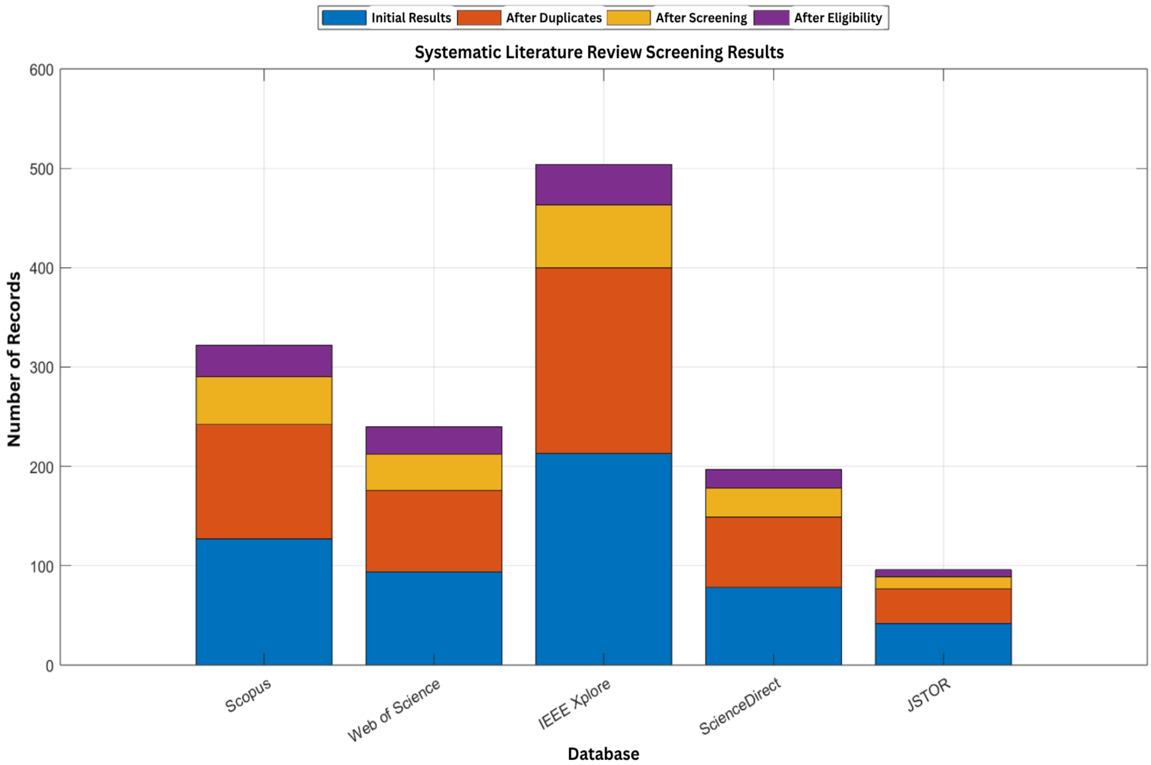

Figure 4. Stacked percentage bars of Number of Records vs. Databases.

Table 3 details the database-specific search strategies and the progressive filtering of records applied during the systematic literature review process.

Table 3. Search Strategy and Results.

Database	Search Terms	Initial Results	After Duplication Removal	After Screening	After Eligibility Assessment
Scopus	("microgrid" OR "micro-grid") AND ("hierarchical control" OR "resilient control") AND ("load-shedding" OR "scheduled outages")	127	115	48	32
Web of Science	TI = ("microgrid" OR "micro-grid") AND TS = ("control framework" OR "adaptive control") AND TS = ("load-shedding" OR "energy crisis")	94	82	36	28

Table 3. *Cont.*

Database	Search Terms	Initial Results	After Duplication Removal	After Screening	After Eligibility Assessment
IEEE Xplore	(“microgrid” OR “micro-grid”) AND (“hierarchical control” OR “resilient control”) AND (“load-shedding” OR “scheduled outages”)	213	187	63	41
ScienceDirect	Title/Abstract/Keywords: “microgrid” AND “hierarchical control” AND “load-shedding”	78	71	29	19
JSTOR	“microgrid control” AND “load-shedding”	42	35	12	7
Total		554	490	188	127

The 127 studies identified through this systematic process form the core literature analysed in Sections 4–6. Additional references cited in Sections 1 and 2 and for methodological guidance provide necessary foundational context.

3.2. Inclusion and Exclusion Criteria

The inclusion criteria for literature selection were [57]:

(1) peer-reviewed journal articles, conference proceedings, or technical reports.
(2) publications focusing on microgrid control systems.
(3) studies addressing scheduled outages or load-shedding contexts specifically.
(4) publications in English.
(5) studies presenting original research, case studies, or comprehensive reviews.

The exclusion criteria were [57]:

(1) publications focusing solely on uninterruptible power supply (UPS) systems without microgrid integration.
(2) studies of distribution network management without microgrid components.
(3) publications not specifically addressing control strategies.
(4) duplicate publications across databases.

The screening process involved three phases: title screening, abstract screening, and full-text assessment. The screening process was conducted primarily by the first author, with verification and oversight from supervisory co-authors. Uncertain cases or disagreements regarding inclusion were resolved through discussion and consensus among the research team.

3.3. PRISMA Flow Diagram

The literature selection process followed the standard PRISMA framework with identification, screening, eligibility assessment, and inclusion phases [58]. The initial search identified 554 records across all databases, reduced to 490 after duplicate removal. Title and abstract screening excluded 302 records that did not meet inclusion criteria, resulting in 188 records for full-text assessment. After eligibility evaluation, 127 studies were included in the qualitative synthesis. The PRISMA flow diagram below illustrates this process visually (Figure 5).

The completed PRISMA 2020 Checklist corresponding to this review is provided as Supplementary Materials.

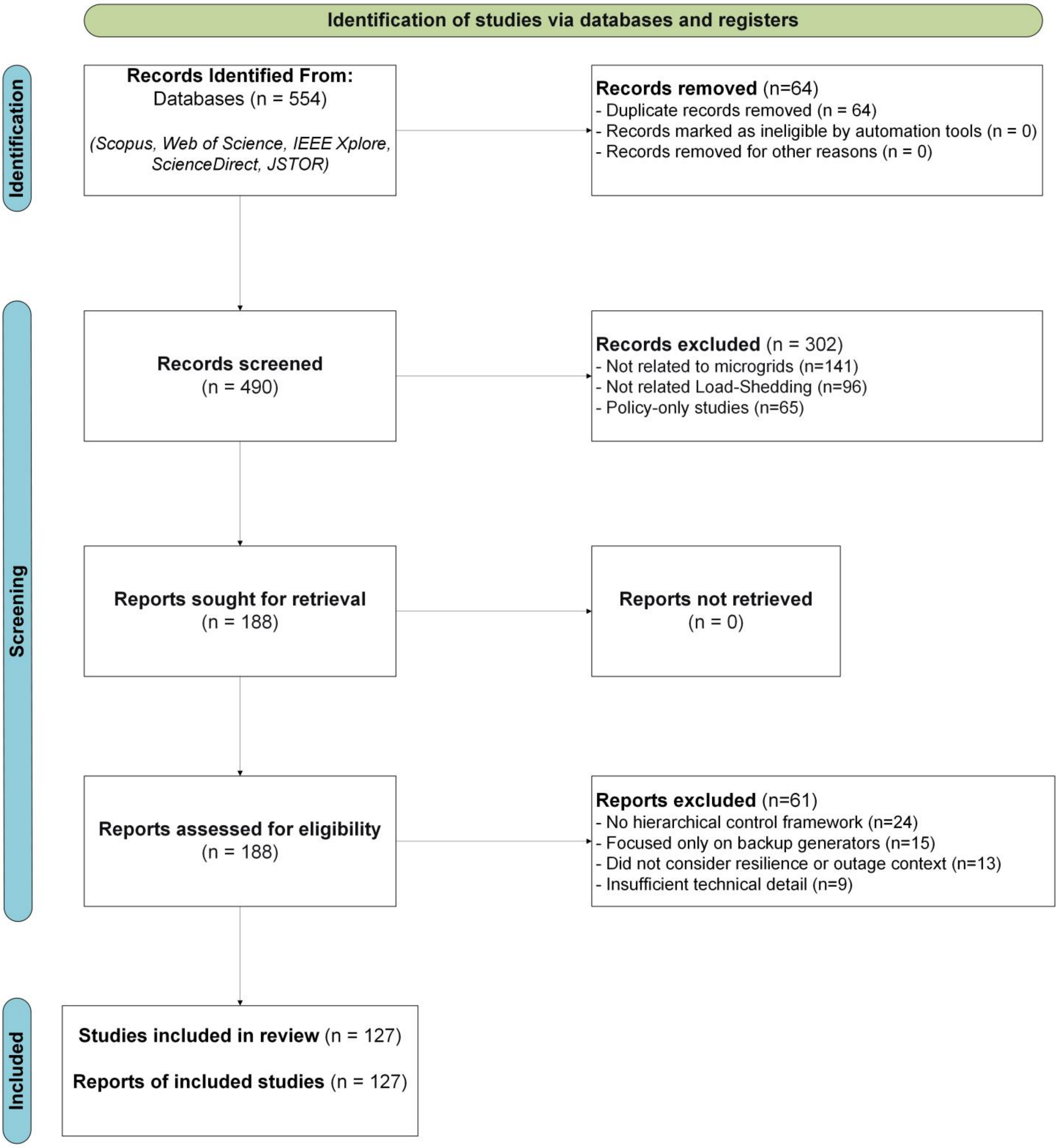

Figure 5. PRISMA Flow Diagram.

3.4. Data Extraction and Analysis Methods

The data extraction process was performed by the first author and cross-verified by a second reviewer to ensure consistency. The extracted information included study characteristics (author, year, publication type), microgrid configuration (resources, scale, location), control strategies (primary, secondary, tertiary techniques), load-shedding context (type, frequency, duration), performance metrics, and key findings. This information was organised in a structured database to facilitate comparative analysis and identification of trends across studies [59].

The analytical approach employed both qualitative and quantitative methods. Qualitative content analysis identified themes, patterns, and relationships across literature. Quantitative analysis examined publication trends, methodological approaches, and performance metrics where standardised data was available [60]. The synthesis methodology employed a narrative synthesis approach complemented by tabular and visual representations of findings where appropriate. The analysis specifically explored differences in control strategies between scheduled and unscheduled outage contexts to address the core research questions.

3.5. Limitations

This review is subject to limitations inherent to systematic literature reviews. The search was confined to five major academic databases and English-language publications, potentially omitting relevant studies in other languages or grey literature. The keyword-based search strategy may not have captured all pertinent articles. Furthermore, the rapid evolution of control technologies means literature published after the search conclusion (August 2025) is not included.

4. Hierarchical Control Analysis for Load-Shedding Contexts

Modern microgrids employ a hierarchical control structure to coordinate distributed generation, storage, and demand-side resources under both grid-connected and islanded conditions. This architecture ensures stability, reliability, and optimal energy use across different time horizons [61,62]. In load-shedding environments, such as those observed in parts of South Africa, the hierarchical framework becomes even more critical enabling predictive, outage-aware coordination that transforms reactive stability control into proactive resilience management [63]. Figure 6 illustrates the temporal response of grid frequency following a disturbance and the corresponding operation of the primary, secondary, and tertiary hierarchical control layers.

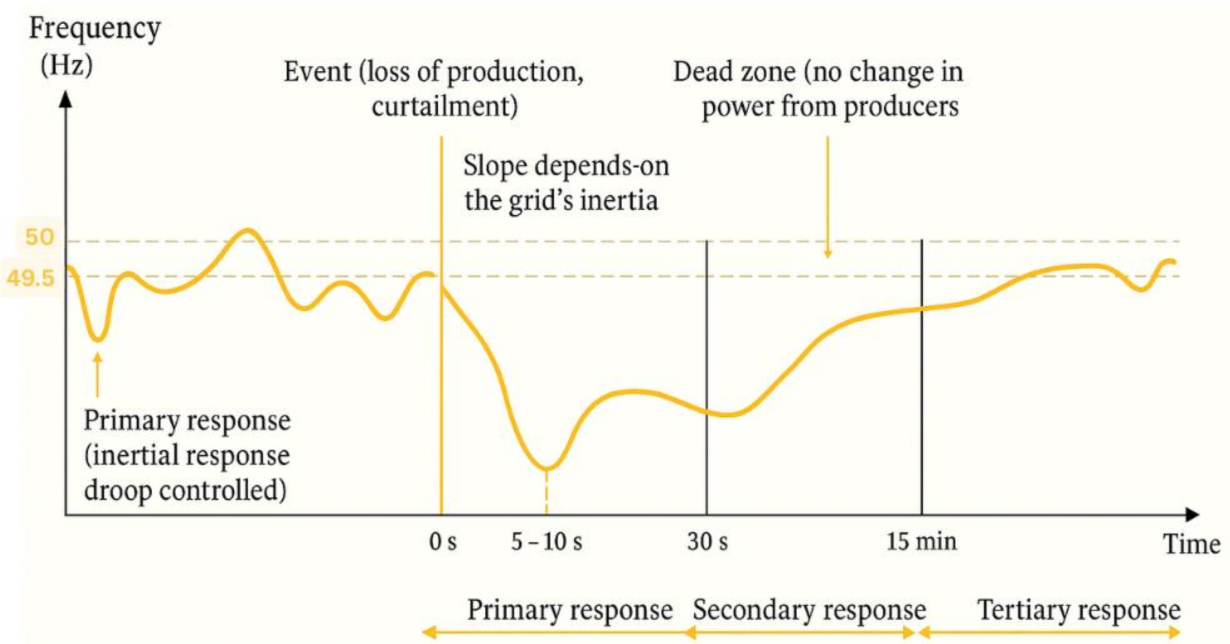

Figure 6. Grid Frequency Response and Hierarchical Control Layers.

Figure 6 illustrates the sequential operation of hierarchical control layers following a grid disturbance such as a loss of generation or a scheduled outage [64,65]. The vertical axis represents grid frequency (Hz), while the horizontal axis shows the temporal progression of control actions from milliseconds to minutes. The figure highlights how these three layers complement one another: primary control stabilises, secondary restores, and tertiary optimises. This structured temporal coordination enables resilient and cost-efficient microgrid performance, particularly under predictable load-shedding conditions [66].

4.1. Primary Control Layer Adaptations

Studies show the primary control layer forms the foundation of microgrid resilience, responsible for immediate response to grid disturbances and maintaining stable operation during islanded mode [67]. In load-shedding contexts, primary control requires specific adaptations to leverage the predictable nature of scheduled outages while maintaining capability for unexpected disturbances. Conventional primary control techniques such as droop control methods (P-f and Q-V droop) remain fundamental but require enhancements for optimal performance in load-shedding environments [68]. Figure 7 contrasts conventional reactive responses to unexpected islanding (right) with the adapted proactive strategies suited to scheduled load-shedding (left).

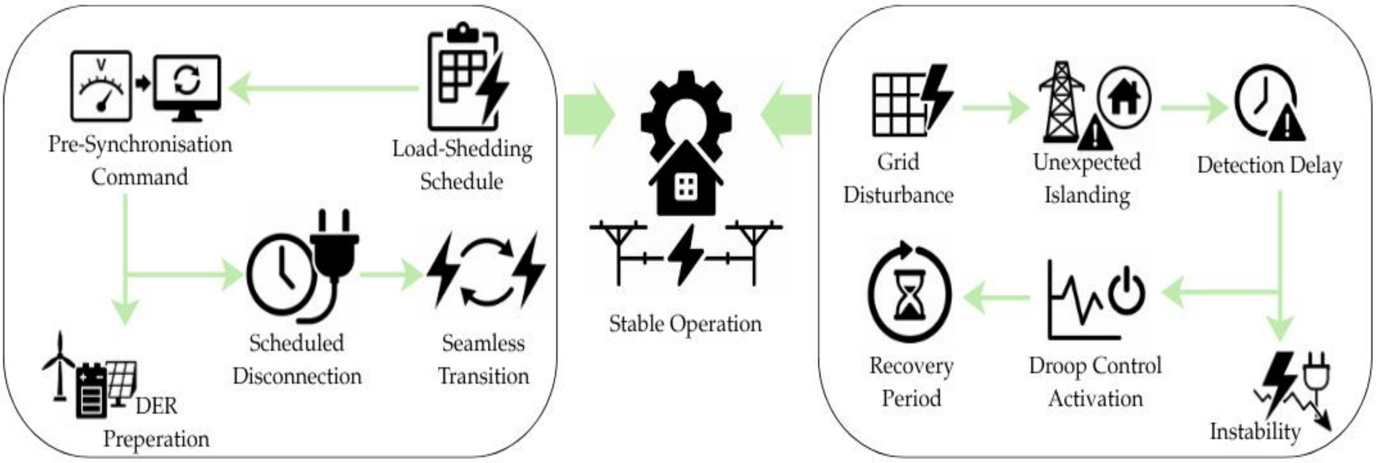

Figure 7. Comparison of Reactive and Proactive Primary Control Pathways in Microgrid Operation.

This visual comparison illustrates the fundamental paradigm shift from reactive protection to predictive optimisation within the primary control layer of hierarchical microgrid frameworks [69]. The most significant adaptation for primary control in load-shedding contexts involves pre-synchronisation strategies that exploit known outage schedules. Unlike unexpected islanding events that require rapid detection and response, scheduled load-shedding enables proactive preparation where distributed energy resources can be pre-synchronised to the microgrid voltage and frequency before the main grid disconnection occurs [33]. This approach eliminates the transition instability typically experienced during islanding detection and switchover, resulting in seamless transitions with minimal voltage or frequency deviation. Research demonstrates that pre-synchronisation can reduce transition disturbances by 60–75% compared to conventional islanding detection approaches [70,71].

Another critical adaptation involves energy storage system (ESS) control strategies specifically designed for the regular, deep cycling required in load-shedding environments. Conventional ESS controls focus on energy shifting and frequency regulation but must be modified to address the predictable, yet demanding discharge cycles required during scheduled outages. Advanced techniques include state-of-charge management algorithms that anticipate upcoming outages and ensure sufficient reserve capacity, and cyclic ageing considerations that modify charging strategies to extend battery lifespan under frequent deep discharge conditions. Studies show that load-shedding-adapted ESS controls can extend battery cycle life by 15–28% compared to conventional approaches [72–74].

Inverter control strategies also require modification for load-shedding contexts, particularly regarding voltage and frequency regulation during extended islanded operation [75]. Conventional voltage-frequency (V-f) control modes must be enhanced with adaptive droop coefficients that can adjust based on anticipated load patterns during outages and available generation resources. Research indicates that predictive droop adjustment based on load forecasts and outage schedules can improve voltage regulation by 30–40% during extended islanded operation compared to fixed droop coefficients [76–78]. Table 4 summarises key primary control adaptations proposed in the literature for microgrids operating under scheduled load-shedding conditions.

Table 4. Primary Control Adaptations for Load-Shedding Contexts.

Control Function	Reference	Conventional Approach	Load-Shedding Adaptation	Performance Improvement
Islanding Detection	[79]	Passive/active detection methods	Schedule-based pre-synchronisation	60–75% reduction in transition disturbances
ESS Control	[79,80]	Energy shifting, frequency regulation	Outage-aware SOC management, cyclic ageing consideration	15–28% battery cycle life extension
Inverter Control	[81,82]	Fixed droop coefficients	Predictive droop adjustment based on load forecasts	30–40% improvement in voltage regulation
Load Management	[83,84]	Under-frequency load-shedding	Priority-based load scheduling aligned with outage timing	45–60% reduction in critical load interruptions

4.2. Secondary Control Layer Enhancements

As demonstrated in the studies, the secondary control layer serves a critical function in restoring system parameters to nominal values after primary control action and coordinating multiple distributed resources [85]. In load-shedding environments, secondary control enhancements focus on incorporating forecast information about upcoming outages to optimise resource coordination and maintain power quality throughout extended islanded operations. Conventional secondary control typically employs PI controllers for frequency and voltage restoration but must be augmented with predictive capabilities for load-shedding contexts [85].

Figure 8 illustrates the operational improvement achieved when secondary control incorporates predictive intelligence. Predictive frequency regulation represents a significant enhancement for secondary control in load-shedding environments. By leveraging known outage schedules and load forecasts, secondary control can implement proactive setpoint adjustment that anticipates the frequency deviations likely to occur during islanded operation and pre-position resources to minimise these deviations. Advanced approaches incorporate model predictive control (MPC) techniques that optimise frequency response across the entire outage period rather than simply reacting to deviations [86]. Research demonstrates that predictive frequency regulation can reduce frequency deviations by 40–50% during the first minute of islanded operation compared to conventional restoration approaches [85,86].

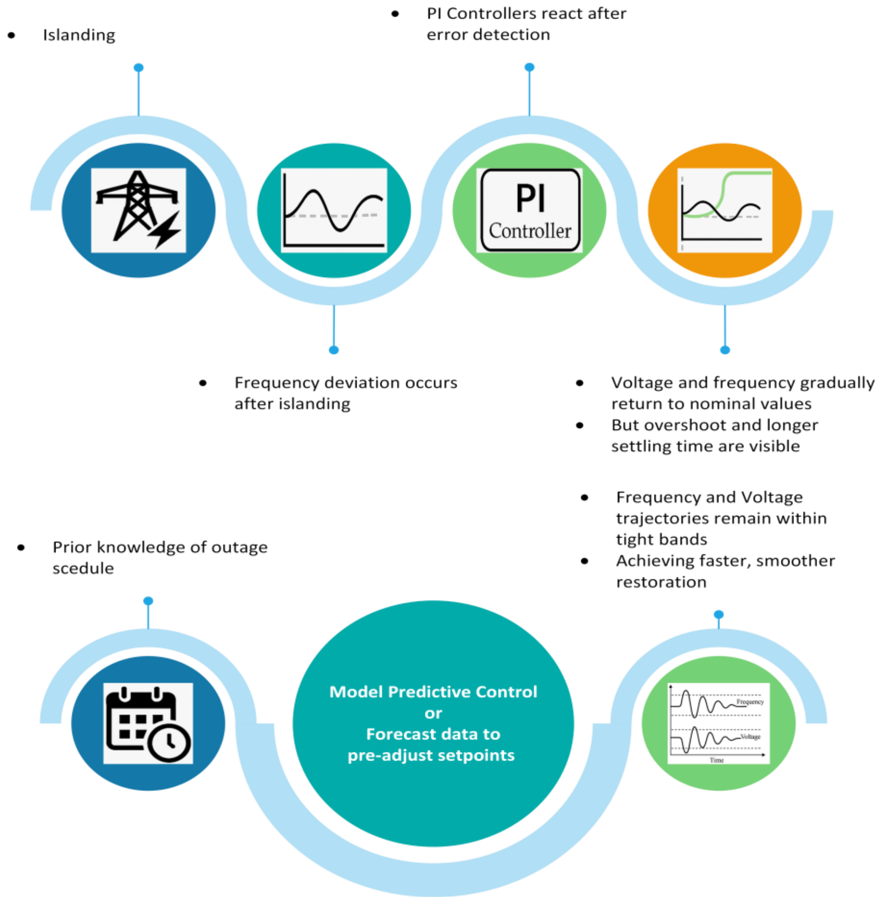

Figure 8. Predictive versus Conventional Secondary Control Behaviour during Load-Shedding Events.

Voltage management strategies similarly benefit from incorporating outage schedules into secondary control decision-making. Load-shedding-adapted voltage regulation employs coordinated VAR control that anticipates reactive power requirements during islanded operation and prepositions inverter resources to maintain voltage within tighter tolerances [87]. Particularly effective are distributed consensus algorithms that coordinate multiple inverters to optimise voltage profile across the microgrid during extended outages. Studies show that coordinated predictive voltage control can maintain voltage within ±2% of nominal during islanded operation compared to ±5% with conventional approaches.

Communication architectures for secondary control require careful consideration in load-shedding contexts. While conventional microgrids often rely on continuous communication for secondary coordination, load-shedding environments create periodic communication challenges during grid outages that may affect cloud-based services or wide-area communication links [88,89]. Resilient communication strategies include hybrid architectures that maintain critical coordination through local networks during outages and communication-aware control algorithms that can maintain system stability even with intermittent connectivity. Research indicates that communication-aware secondary control can maintain system stability with up to 60% packet loss compared to complete failure with conventional approaches under similar conditions [88,89]. Latency thresholds for consensus algorithms are typically in the order of 100–500 ms for effective frequency restoration.

4.3. Tertiary Control Layer Optimisation

The evidence suggests that the tertiary control layer provides the highest level of microgrid management, focusing on economic dispatch, optimisation, and grid interaction. In load-shedding environments, tertiary control opportunities are particularly significant due to the predictable nature of outages that enable sophisticated optimisation across multiple time horizons [90,91]. Conventional tertiary control typically employs economic dispatch algorithms that minimise operating costs but must be enhanced to address the unique cost structures and constraints of load-shedding contexts [14]. Figure 9 illustrates an outage-aware tertiary control optimisation framework tailored for microgrids operating under predictable grid unavailability.

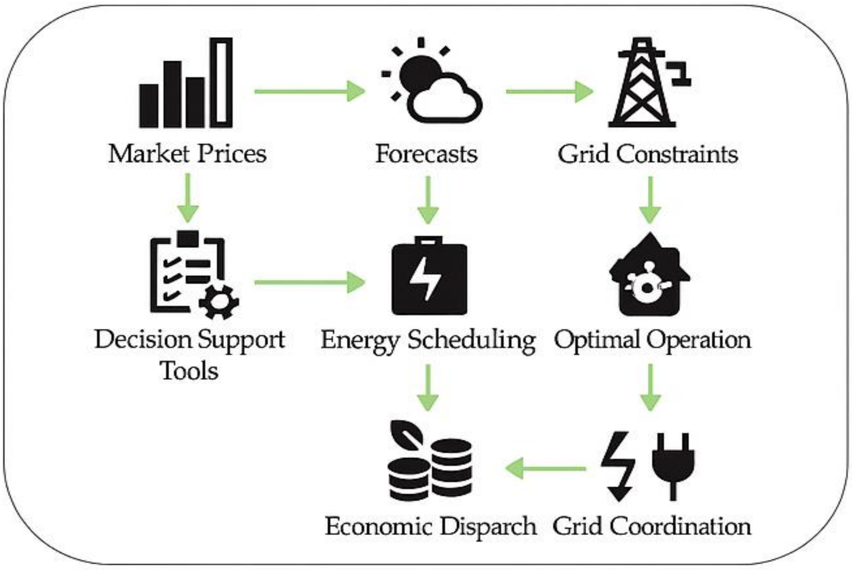

Figure 9. Outage-Aware Tertiary Control Optimisation Framework.

Outage-aware economic dispatch represents a fundamental enhancement for tertiary control in load-shedding environments. By incorporating known outage schedules, tertiary control can optimise resource commitment decisions across both grid-connected and islanded periods, considering the different cost structures and constraints during each operational mode [32]. Advanced techniques include multi-period optimisation that schedules resources to minimise overall costs across anticipated grid availability patterns, and reliability-weighted economic dispatch that prioritises availability for critical loads during outage periods. Research demonstrates that outage-aware economic dispatch can reduce operating costs by 18–25% compared to conventional economic dispatch in load-shedding environments [92,93].

Demand response integration becomes particularly valuable in load-shedding contexts when coordinated with known outage schedules. Tertiary control can implement predictive demand scheduling that shifts flexible loads to grid-available periods and minimises consumption during anticipated outages to reduce storage requirements. Sophisticated approaches include multi-objective optimisation that balances economic efficiency, comfort constraints, and resilience requirements through priority-based load management. Studies show that predictive demand scheduling can reduce storage requirements by 30–40% for equivalent levels of critical load protection during outages [94–96].

Hybrid energy system coordination represents another critical enhancement for tertiary control in load-shedding environments. With known outage schedules, tertiary control can optimise the operation of diverse resources including solar PV, energy storage, diesel generators, and emerging technologies like hydrogen systems to ensure reliable power during outages while minimising costs and emissions. Advanced techniques include fuel consumption optimisation for diesel generators that minimises runtime while maintaining readiness, and renewable utilisation maximisation that schedules storage to capture excess solar generation for use during outages. Research indicates that optimised hybrid system coordination can reduce diesel consumption by 23–37% while maintaining equivalent reliability levels [97–99]. Table 5 provides a comparative summary of tertiary-level optimisation strategies reported for load-shedding contexts.

Table 5. Tertiary Control Optimisation Strategies for Load-Shedding Contexts.

Optimisation Strategy	Reference	Key Techniques	Performance Benefits	Implementation Considerations
Outage-Aware Economic Dispatch	[92,93]	Multi-period optimisation, reliability-weighted dispatch	18–25% operating cost reduction	Requires accurate outage schedules and load forecasts
Predictive Demand Scheduling	[94–96]	Priority-based load management, time-shifting of flexible loads	30–40% storage requirement reduction	Needs detailed load flexibility information
Hybrid System Coordination	[97–99]	Fuel consumption optimisation, renewable utilisation maximisation	23–37% diesel consumption reduction	Requires sophisticated forecasting and optimisation algorithms
Resilience-Economic Tradeoff Analysis	[100]	Multi-objective optimisation, cost–benefit analysis of resilience measures	Improved allocation of resilience investments	Demands quantification of outage costs and resilience benefits

4.4. Comparative Analysis of Control Strategies

The preceding analysis has detailed the specific adaptations required for primary, secondary, and tertiary control layers to function effectively in load-shedding environments. To synthesis these findings and provide a clear overview of the research landscape, Table 6 presents a comparative analysis of prominent hierarchical control strategies documented in the literature. This comparison consolidates key techniques, their principal findings, and identifies critical research gaps, offering a consolidated reference to guide future research and implementation efforts in this specialised field.

Table 6. Comparative Analysis of Hierarchical Control Strategies for Load-Shedding Environments.

Reference Number	Control Layer	Technique	Key Findings	Gaps
[67,68,75,101]	Primary	Conventional & Adaptive Droop Control	Foundational for islanded operation; adaptive coefficients based on forecasts improve voltage regulation by 30–40%.	Limited stability guarantees under significant forecast errors; increased computational burden on local controllers.
[70,71,102,103]	Primary	Schedule-based Pre-synchronisation	Enables seamless microgrid islanding, reducing transition disturbances by 60–75% compared to reactive detection methods.	Highly dependent on the accuracy and reliability of utility-provided load-shedding schedules.
[85,86,91,104]	Secondary	Model Predictive Control (MPC)	Optimises frequency response across outage horizons, reducing deviations by 40–50% and improving economic dispatch.	Computationally intensive; requires an accurate dynamic model of the microgrid, which can be difficult to obtain.

Table 6. *Cont.*

Reference Number	Control Layer	Technique	Key Findings	Gaps
[21,88,89,105]	Secondary	Distributed Consensus Algorithms	Enhances resilience to single-point failures; maintains voltage regulation within ±2% of nominal during islanding [4,65].	Performance degrades with communication delays and packet loss; vulnerable to coordinated cyber-attacks.
[92,93]	Tertiary	Outage-Aware Economic Dispatch	Reduces operating costs by 18–25% by optimising resource commitment across both grid-connected and islanded periods [5,106].	Highly sensitive to the accuracy of long-term load and renewable generation forecasts.
[94–96]	Tertiary	Predictive Demand Scheduling	Leveraging load flexibility reduces required storage capacity by 30–40% for equivalent critical load protection [6].	Requires detailed, often privacy-sensitive, load flexibility data and effective consumer engagement strategies.
[97–99]	Tertiary	Hybrid System Coordination (MPC for Solar–Storage–Diesel)	Can reduce diesel consumption by 23–37% while maintaining reliability through optimal scheduling of diverse assets [66,91].	Requires sophisticated forecasting and optimisation algorithms; integration of emerging technologies like hydrogen is still nascent.
[107,108]	Cross-Layer	Artificial Intelligence (AI) & Deep Reinforcement Learning	Shows promise for adaptive control and outage prediction in uncertain environments, potentially outperforming model-based approaches [7,37].	"Black box" nature challenges explainability and trust; requires extensive, high-quality data for training; significant computational resources.
[109–111]	Cross-Layer	Cyber–Physical Security Frameworks	Resilient protocols can maintain operation with multiple compromised nodes [8,33].	Lack of standardised security protocols across vendors; holistic frameworks that span all control layers are still under development.

Beyond hierarchical layer adaptations, the choice of overall system architecture significantly impacts resilience. Centralised control offers optimal global coordination but creates a single point of failure. Fully decentralised schemes enhance reliability but may sacrifice system-wide economic optimisation. The distributed consensus approaches underpinning modern hierarchical control, as reviewed herein, offer a balance, enabling coordinated, outage-aware optimisation while maintaining robustness through local autonomy [33,88].

4.5. Cyber–Physical Security Considerations

The cyber–physical security of microgrid control systems takes on heightened importance in load-shedding environments where system operation frequently transitions between grid-connected and islanded modes [112]. These transitions create additional attack surfaces and vulnerabilities that must be addressed through resilient control architectures. Research indicates that microgrids in load-shedding contexts face risks from false data injection attacks that could manipulate outage schedules or resource availability information, potentially causing operational disruptions [113].

Resilient communication protocols are essential for maintaining secure operation in load-shedding environments. Distributed consensus-based control approaches show guarantee for maintaining system stability even in the presence of communication failures or cyber-attacks [113]. Techniques such as reputation-based algorithms for voltage and frequency control and W-MSR and RCA-T algorithms for resilient active power sharing can maintain system operation even with multiple compromised nodes. These approaches require minimal computational resources at the distributed generator level, making them suitable for implementation in resource-constrained environments [114].

Cyber-security integration must be considered across all control layers in load-shedding contexts. Primary control requires secure measurement verification to ensure accurate islanding detection and response. Secondary control needs resilient consensus algorithms that can tolerate malicious actors in the communication network. Tertiary control demands secure optimisation processes that cannot be manipulated by false price signals or outage schedule information. A holistic approach to cyber–physical security that addresses vulnerabilities across all control layers is essential for reliable microgrid operation in load-shedding environments [113,115].

The mathematical formulations for key control strategies discussed in this section are provided in Appendix B.

5. Case Studies and Real-World Applications

5.1. South African Industrial and Commercial Applications

South Africa has become a living laboratory for microgrid deployments tailored to its chronic load-shedding environment. Many industrial and commercial sites have adopted advanced control strategies and hybrid energy systems, enabling them to maintain power supply when the main grid is unstable or unavailable [40]. These deployed systems typically employ smart metres for energy monitoring and baseline control. While the use of Phasor Measurement Units (PMUs) for high-fidelity, time-synchronised data is less prevalent at the microgrid level due to cost, their potential for enhancing state estimation and fast control is a noted area for future advancement [63]. The drive toward microgrid adoption is largely a response to the severe economic disruptions caused by load-shedding, which have compelled businesses to seek resilient and cost-effective energy solutions. Across sectors such as mining, manufacturing, agriculture, and retail, there is a growing recognition of microgrids not merely as backup systems but as integral components of long-term operational strategy. This shift is supported by advancements in control technologies that allow for seamless integration of solar PV, battery storage, and diesel generators into coordinated systems [19].

Moreover, the regulatory landscape in South Africa is gradually evolving to facilitate greater private investment in embedded generation and microgrid projects. Commercial entities are increasingly leveraging energy management systems (EMS) that incorporate predictive analytics based on load-shedding schedules to optimise self-consumption and reduce reliance on diesel. Despite these advances, challenges remain, including high capital expenditure, technical skill gaps, and the need for standardised interconnection protocols. Nonetheless, the trend indicates a move toward smarter, more automated microgrids capable of participating in demand response and providing grid services when connected. These developments not only enhance site-level resilience but also contribute to national energy stability by reducing demand on the strained utility grid during peak periods [19,49,50].

One noticeable example is the University of the Free State (UFS), specifically its QwaQwa campus in the Free State. The campus has developed a solar-diesel hybrid system without batteries that allows it to continue operating despite frequent grid interruption. This system centralises diesel generation and integrates solar PV, helping to reduce diesel use and simplify generator maintenance. Though the installation does not strictly follow all microgrid control layers such as tertiary predictive scheduling, it shows a practical adaptation of hybrid energy for load-shedding environments [116]. Figure 10 summarises selected South African industrial, commercial, and institutional microgrid case studies reviewed in this section.

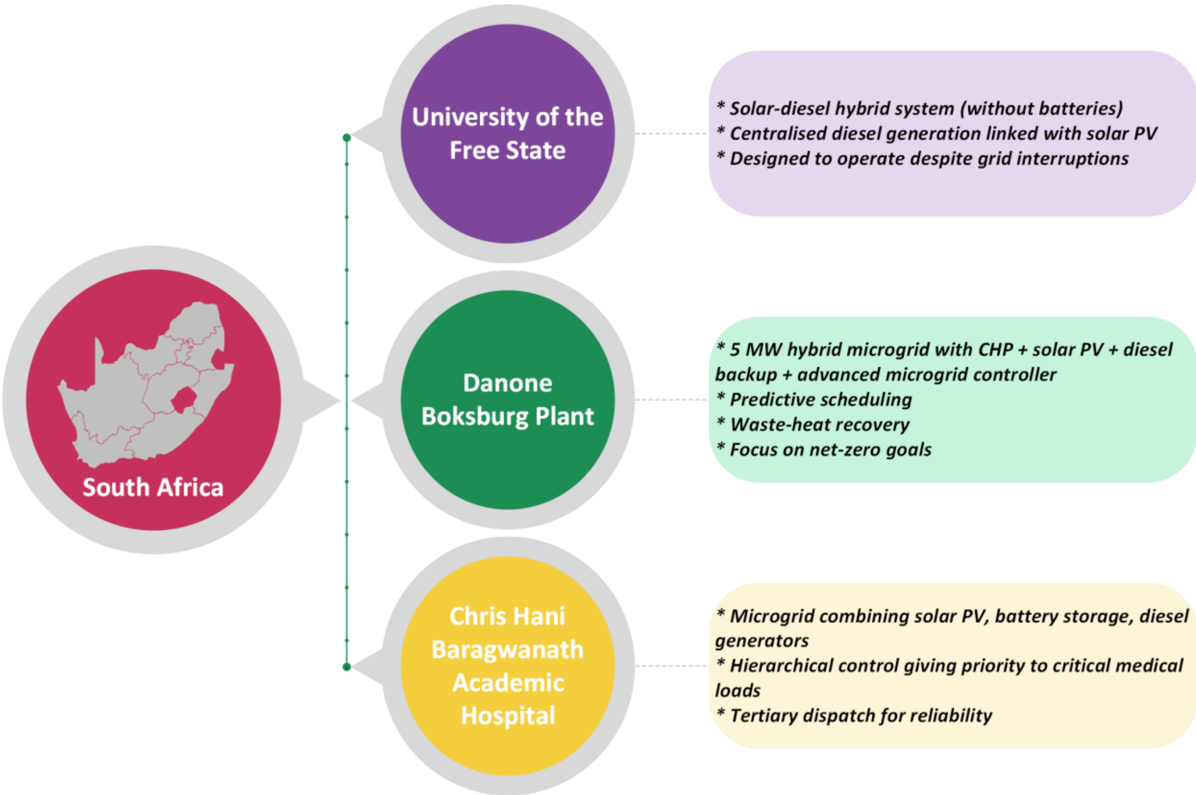

Figure 10. South African Case Studies.

Another significant application is at the facility operated by Danone Boksburg in Gauteng. This manufacturing plant is installing a 5 MW hybrid microgrid that combines a combined-heat-and-power (CHP) unit, existing solar photovoltaic (PV) generation, diesel backup, and a microgrid controller. The setup is designed not only to ensure power continuity but also to support the company's Net Zero goals. The CHP system enables waste heat recovery, and the microgrid controller coordinates all resources of solar, CHP, diesel and the grid to provide resilient power. This project, delivered by Clarke Energy and reported through industry and press sources including PR Newswire, represents a relevant example of a hybrid microgrid system deployed under South African load-shedding conditions [117,118].

And then, looking at critical infrastructure: at Chris Hani Baragwanath Academic Hospital in Johannesburg, a dedicated microgrid has been deployed. It combines solar PV, battery storage, diesel backup and a hierarchical control system that prioritises critical medical loads during outages. The tertiary control layer emphasises reliability even if it incurs higher operational cost to ensure uninterrupted power for life critical systems [119].

Together, these South African examples highlight how hybrid microgrids, hierarchical controls, and integration of multiple energy sources are being deployed to address scheduled outages and grid fragility. They illustrate how major industrial plants, campuses, and critical hospitals are increasingly adopting control strategies that go beyond simple diesel backup, moving instead to intelligent coordination of generation, storage and demand.

5.2. International Examples in Similar Contexts

Besides South Africa, other regions facing frequent or scheduled power outages provide valuable comparative examples of how microgrid control strategies can be adapted to resilient operation.

In Pakistan, for example, there are industrial microgrids designed for regions where outage schedules may not be public or reliable. One such implementation is at the Lahore Industrial Estate. There, a hierarchical control system incorporates statistical forecasting of outages based on historical blackout patterns, so that the microgrid can prepare ahead of time. Although official schedules may be absent or unreliable, the system still maintained high availability reported at 95.2% for manufacturing processes while reducing operating costs by about 27%. This shows how predictive strategies can work even in uncertain conditions [120]. Figure 11 presents international microgrid case studies from regions experiencing frequent or scheduled power outages.

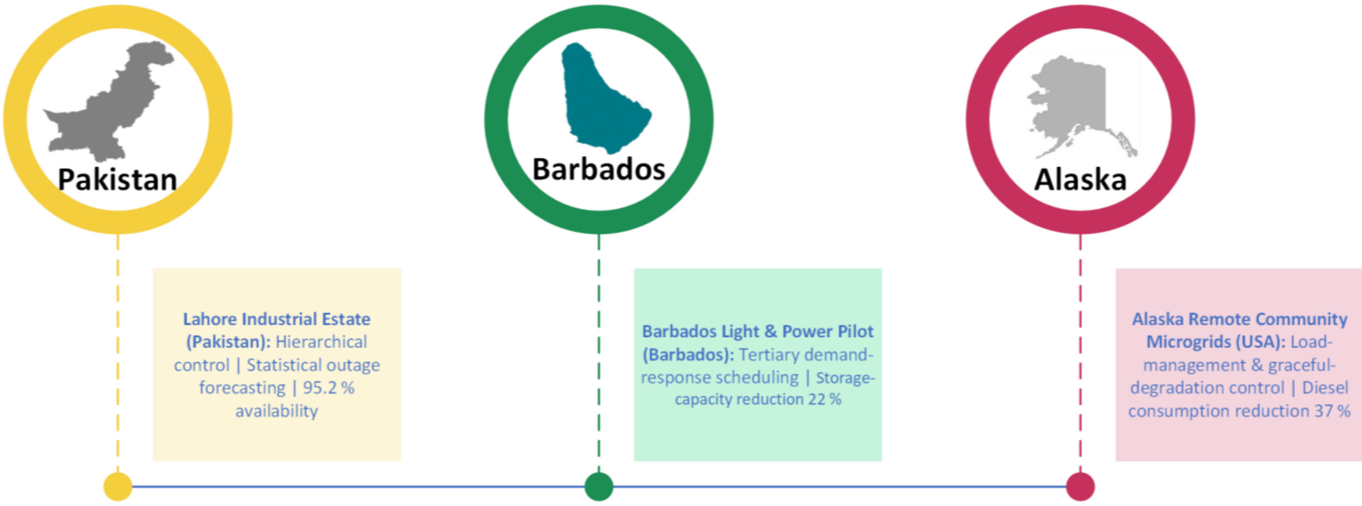

Figure 11. International Case Studies.

In the Caribbean region, island nations also contend with constrained grid capacity and planned power interruptions, making microgrids particularly relevant. For instance, a pilot by Barbados Light & Power demonstrates the use of tertiary-level demand response: non-critical loads are automatically shifted to periods when the grid is unavailable or when generators are the only source. This strategy allowed for a 22% reduction in required battery storage capacity while preserving service reliability. It shows how smart load scheduling and demand flexibility are vital when storage resources are expensive or limited [121].

Further afield, in remote northern communities such as those served by Alaska Village Electric Cooperative (AVEC), microgrids face self-imposed or resource-driven outages rather than grid operator-mandated ones. These systems adopt "graceful degradation" strategies: when full power cannot be guaranteed, they ensure that essential services remain powered and non-essential loads are shed in a controlled way. Through such load-management techniques and coordinated generation and storage, diesel consumption has been reduced by approximately 37% while maintaining acceptable levels of service for critical needs [122,123].

These international cases provide useful contrasts and lessons: whether in industrial estates in Pakistan, island microgrids in the Caribbean or remote cooperatives in Alaska, the key themes recur forecasting or scheduling of outages, demand flexibility, intelligent control architecture and storage optimisation. Each context differs in its constraints and strategy emphasis, but all illustrate that advanced control frameworks can improve reliability and reduce operational cost in scheduled-or-semi-scheduled-outage environments.

6. Discussion

6.1. Performance Comparison and Lessons Learned

Cross-case analysis of microgrid implementations in load-shedding environments reveals several consistent patterns regarding control strategy effectiveness. Systems that incorporate predictive capabilities whether based on published schedules as in South Africa or statistical forecasting as in Pakistan consistently outperform reactive approaches across multiple metrics, including operating costs, fuel consumption, and equipment lifespan. The integration of demand response into hierarchical control frameworks emerges as a critical factor in optimising the cost-resilience tradeoff, with systems leveraging load flexibility demonstrating significantly lower infrastructure costs for equivalent reliability levels, as evidenced by the Barbados Light & Power case. The control architecture selection significantly influences implementation complexity and ultimate performance. The South African case studies, particularly the University of the Free State's centralised diesel-solar hybrid and Danone Boksburg's integrated CHP-PV-diesel system, demonstrate the practical application of different architectural philosophies. Centralised architectures show advantages in optimisation capability but can create single points of failure. In contrast, distributed or hybrid approaches, as seen in the Alaska Village Electric Cooperative's implementation, show superior resilience to communication failures and component outages. Hybrid approaches that balance centralised optimisation with distributed execution appear most promising for load-shedding environments, providing optimisation benefits while maintaining resilience during communication disruptions [116–123].

The radar chart presented in Figure 12 provides a comprehensive visual comparison of microgrid control strategy performance across six international case studies operating in load-shedding environments. The radar chart metrics were normalised on a 0–1 scale relative to the best-performing case study for each individual metric. Quantitative data (percentage availability, cost reduction) were extracted directly from the referenced sources [116–123] and converted using min–max normalisation to enable visual cross-comparison.

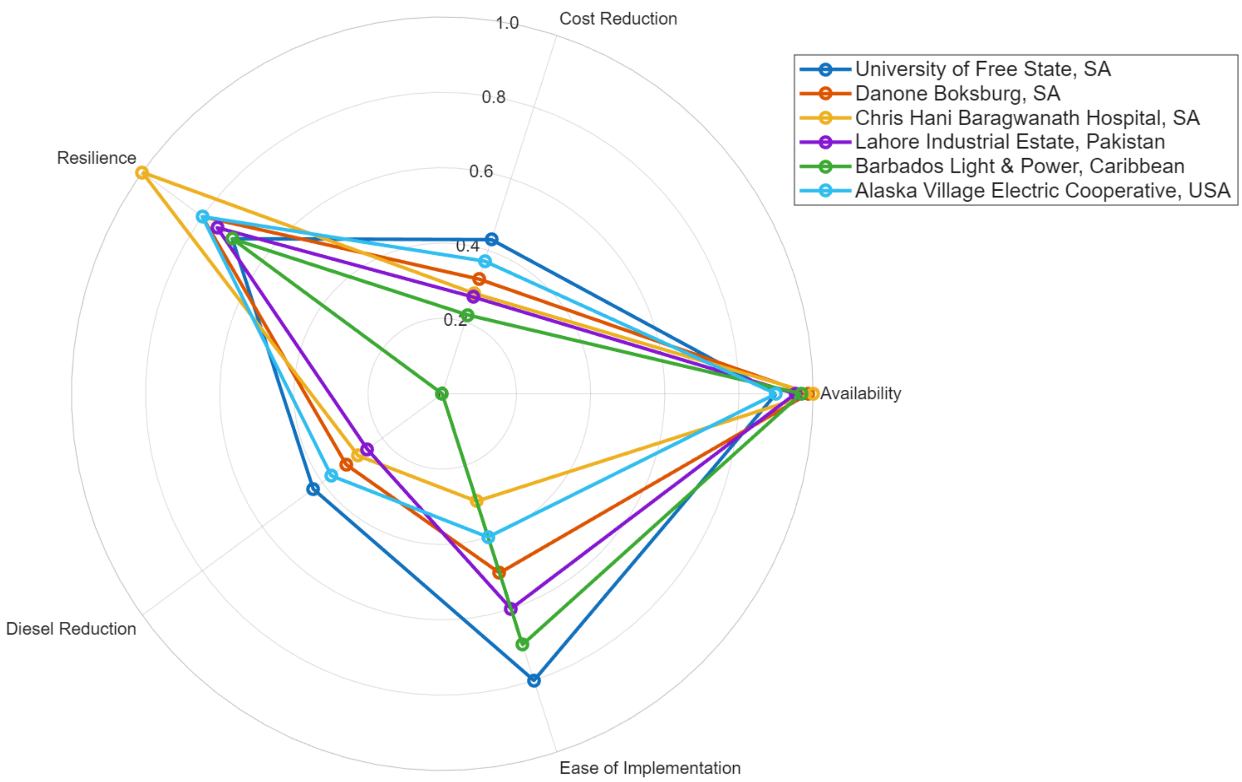

Figure 12. Comparative Performance of Microgrid Control Strategies in Load-Shedding Environments.

Trade-off Patterns:

- ○ The University of Free State (SA) case shows that simplified control architectures without battery storage can still achieve high availability and cost reduction, though with limitations in overall optimisation potential [116].
- ○ Barbados Light & Power exemplifies how demand response integration can compensate for storage limitations, achieving strong availability with minimal diesel dependency [121].

Performance Leaders:

- ○ Chris Hani Baragwanath Hospital (SA) demonstrates perfect availability (1.0) for critical medical loads, reflecting the reliability-first approach essential for healthcare infrastructure, though with moderate cost and diesel reductions due to higher reliability requirements [119].
- ○ Danone Boksburg (SA) and Alaska Village Electric Cooperative (USA) show balanced performance across all metrics, indicating well-optimised hybrid control strategies that maintain high availability while achieving significant fuel and cost savings from 32–37% diesel reduction [117,118,122,123].

Economic analysis across case studies reveals that the business case for advanced control systems in load-shedding environments depends strongly on outage frequency, duration, and criticality of operations. Systems experiencing frequent extended outages Stage 4–6 in South African terminology, such as the industrial and hospital cases documented, demonstrate rapid return on investment for sophisticated predictive control systems. The performance metrics from the South African and international cases consistently show significant diesel consumption reductions of 23–37%, operating cost savings of 18–27%, and storage requirement reductions of 22–40%, validating the economic and technical value of adapted hierarchical control frameworks.

A key lesson is the adaptability of the predictive control paradigm itself. Whether using official schedules (South Africa), statistical forecasting (Pakistan), or resource availability forecasts (Alaska), the core technical adaptations for hierarchical control layers are geared towards exploiting predictability. Therefore, the conceptual framework presented is broadly applicable to regions with frequent, predictable power deficits, with local implementation shaped by data availability, resource mix, and regulation. Table 7 compares the performance of representative microgrid control strategies across international load-shedding case studies.

Table 7. Comparative Performance of Microgrid Control Strategies in Load-Shedding Environments.

Case Study	Control Strategies	Availability During Outages	Cost Reduction	Implementation Challenges
University of Free State, SA [116]	Centralised hybrid (solar-diesel) control, simplified microgrid operation	High (critical operations maintained)	43% runtime reduction (diesel)	Limited predictive scheduling, no battery storage
Danone Boksburg, SA [117,118]	Predictive scheduling, CHP-storage coordination, microgrid controller	98.7% (manufacturing processes)	32% diesel consumption reduction	System integration complexity
Chris Hani Baragwanath Hospital, SA [119]	Reliability first dispatch, critical load prioritisation	100% (critical medical loads)	28% energy cost reduction	Medical equipment sensitivity, high-reliability requirements

Table 7. *Cont.*

Case Study	Control Strategies	Availability During Outages	Cost Reduction	Implementation Challenges
Lahore Industrial Estate, Pakistan [120]	Statistical outage prediction, adaptive resource scheduling	95.2% (manufacturing processes)	27% operating cost reduction	Unreliable official outage information
Barbados Light & Power, Caribbean [121]	Demand response integration, load flexibility exploitation	96.8% (service reliability)	22% storage cost reduction	Consumer behaviour management
Alaska Village [122,123]	Coordinate strategy and "graceful degradation"	High (Essential loads maintained)	37% diesel consumption	Coordinated generation, storage

6.2. Research Gaps and Future Pathways

Despite significant advances in microgrid control systems for load-shedding environments, several important research gaps remain unaddressed in the current literature. The standardisation of evaluation metrics represents a critical gap, with existing studies employing inconsistent performance measures that complicate cross-study comparison and technology assessment. There is a pressing need for standardised resilience metrics specifically designed for load-shedding contexts that capture availability during scheduled outages, power quality maintenance, and cost-effectiveness of mitigation strategies. Developing these metrics would significantly advance the field by enabling more meaningful comparison of different control approaches and their effectiveness in various operating environments [73,106].

The integration of artificial intelligence techniques into hierarchical control frameworks represents a promising pathway for addressing the complex optimisation challenges in load-shedding environments. Machine learning approaches show particular promise for outage prediction refinement in contexts where official schedules are unreliable or unavailable, using historical patterns and real-time grid condition data to improve forecast accuracy [35]. Deep reinforcement learning techniques offer potential for adaptive control optimisation that continuously improves performance based on operational experience, potentially outperforming conventional model-based approaches especially in uncertain environments. Research in these areas remains nascent but shows significant potential for enhancing microgrid resilience in load-shedding contexts [124].

Hydrogen integration as a long-duration storage solution for extended outages represents another important research pathway. While current microgrids in load-shedding environments typically rely on battery storage for shorter outages and diesel generation for extended periods, hydrogen systems offer potential for zero-emission resilience during prolonged outages. Control strategies for coordinating electrolysers, fuel cells, and renewable generation in microgrid contexts require significant research, particularly regarding dynamic efficiency optimisation and lifecycle cost minimisation. The development of hydrogen-ready control frameworks that can seamlessly integrate emerging hydrogen technologies as they become economically viable represents an important direction for future research [125,126].

Standardisation and interoperability issues present both a challenge and opportunity for microgrid control in load-shedding environments. The lack of standard communication protocols between equipment from different vendors significantly increases implementation complexity and cost, particularly when integrating legacy systems with advanced controls. Research developing open architecture frameworks for hierarchical microgrid control could significantly reduce these barriers, enabling plug-and-play integration of diverse resources and facilitating more widespread adoption of advanced control strategies.

Particularly valuable would be standardised interfaces for outage schedule integration that would enable consistent communication of load-shedding information to microgrid control systems across different implementations [125–127].

6.3. Implementation Considerations and Policy Implications

The implementation of advanced control systems in load-shedding environments involves significant practical considerations beyond the technical challenges. Financial constraints often represent the primary barrier to adoption, with sophisticated control systems requiring substantial upfront investment despite their potential for operational savings. Innovative business models such as Energy-as-a-Service arrangements where third parties finance, install, and operate control systems in return for performance-based payments show promise for addressing these financial barriers. These models align well with microgrid control in load-shedding contexts since the performance improvements are readily measurable and valuable to facility operators [128,129].

Regulatory frameworks significantly influence the feasibility and effectiveness of microgrid control strategies in load-shedding environments. Policies regarding grid interconnection standards, energy export regulations, and rate structures all impact the economic viability of advanced microgrid controls. Particularly important are regulations governing the ability of microgrids to export power to the main grid during periods of availability, which can significantly improve economics through revenue generation. Policy reforms that create transparent technical standards for microgrid interconnection and establish fair compensation mechanisms for services provided to the main grid would significantly accelerate adoption of advanced control strategies [10].

Technical capacity building represents another critical implementation consideration for microgrid control in load-shedding environments, particularly in developing economies where these challenges are most prevalent. The operation and maintenance of sophisticated control systems require specialised skills that may not be readily available in all contexts, potentially compromising long-term performance. Implementation approaches that incorporate comprehensive training programmes for local technicians and remote monitoring and support capabilities can address these challenges and ensure sustainable operation. The development of simplified interface designs that make complex control strategies accessible to operators with varying technical backgrounds represents an important direction for both research and practice [10,14].

7. Conclusions

This review presented a novel conceptual synthesis framework for analysing hierarchical control adaptations in microgrids facing scheduled load-shedding-prone networks, with particular emphasis on South Africa's current energy crisis. The analysis reveals that conventional microgrid control strategies require non-trivial adaptation to address the unique challenges and opportunities presented by scheduled rather than unexpected outages. The predictable nature of load-shedding enables proactive control strategies that can significantly enhance performance across multiple dimensions including reliability, cost-effectiveness, and equipment lifespan.

Specifically, primary control layers benefit from pre-synchronisation strategies that exploit known outage schedules to achieve seamless and bumpless transitions between grid-connected and islanded modes. Secondary control layers can incorporate forecast information to optimise frequency and voltage regulation throughout extended outage periods. The tertiary control layer offers particularly significant opportunities through outage-aware economic dispatch that optimises resource commitment across both grid-connected and islanded periods. Across all layers, the integration of artificial intelligence techniques shows promise for addressing the complex prediction and optimisation challenges in these environments.

Case studies from South Africa and similar contexts demonstrate the practical effectiveness of adapted control strategies, with implementations achieving 95–100% availability during load-shedding events while reducing diesel consumption by 23–37% and operating costs by 18–28%. These results highlight the significant value that advanced control strategies can deliver in load-shedding environments, particularly for critical facilities where outage costs are high.

As a direct continuation of this work, future research will involve the development of calibrated simulation models and a pilot implementation at the University of Pretoria campus to empirically evaluate the effectiveness of the proposed conceptual framework under realistic operating conditions. Despite these advances, important research gaps remain in standardisation of evaluation metrics, integration of emerging technologies like hydrogen storage, and development of open architecture frameworks that reduce implementation complexity. Addressing these gaps will require collaborative efforts between researchers, industry practitioners, and policymakers to create an enabling environment for advanced microgrid control deployment.

For policymakers, this review highlights the importance of establishing clear technical standards for microgrid interconnection, creating fair compensation mechanisms for services provided to the main grid, and supporting research and development efforts through targeted funding programmes. For practitioners, the findings emphasise the value of incorporating predictive capabilities based on outage schedules, integrating demand response into hierarchical control frameworks, and adopting hybrid architectures that balance centralised optimisation with distributed execution.

As load-shedding continues to affect millions of consumers worldwide, particularly in developing economies, advanced microgrid control strategies offer a pathway to enhanced resilience, reduced costs, and improved sustainability. The insights from this review provide a foundation for further research and implementation efforts aimed at realising this potential.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en19030644/s1, PRISMA 2020 Checklist [130].

Author Contributions: Conceptualization, R.W., M.S., G.A., M.A.-G. and R.N.; methodology, R.W., M.S., G.A. and M.A.-G.; software, R.W., M.S. and G.A.; validation, R.W., M.S., G.A., M.A.-G. and R.N.; formal analysis, R.W., M.S. and G.A.; investigation, R.W., M.S. and G.A.; resources, M.S., G.A. and M.A.-G.; data curation, R.W., M.S. and G.A.; writing—original draft preparation, R.W., M.S. and G.A.; writing—review and editing, R.W., M.S., G.A. and M.A.-G.; visualization, R.W., M.S., G.A. and M.A.-G.; supervision, M.S., G.A., M.A.-G. and R.N.; project administration, M.S., G.A., M.A.-G. and R.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: The authors are grateful to Teesside University, UK, for funding the PhD scholarship of Rajitha Wattegama.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

AC	Alternating Current
API	Application Programming Interface

CHP	Combined Heat and Power
DC	Direct Current
DER	Distributed Energy Resources
ESS	Energy Storage System
MPC	Model Predictive Control
MV	Medium Voltage
PI	Proportional-Integral
PV	Photovoltaic
SOC	State of Charge
UPS	Uninterruptible Power Supply
VAR	Volt-Ampere Reactive
V-f	Voltage-Frequency

Appendix A. Glossary of Key Terms

Term	Definition
Hierarchical Control	A layered control architecture for microgrids typically comprising primary (fast local control), secondary (medium-term coordination), and tertiary (long-term optimisation) layers.
Islanding	The process by which a microgrid disconnects from the main utility grid and operates independently to power its local loads.
Load-Shedding	A controlled process whereby the electricity utility intentionally disconnects certain areas from the power supply to prevent a total grid collapse when demand exceeds available generation capacity.
Energy Storage System (ESS)	A system that captures energy produced at one time for use at a later time, typically using batteries, flywheels, or other technologies.
Model Predictive Control (MPC)	An advanced control method that uses a dynamic model of the system to predict its future behaviour over a time horizon and optimises control actions accordingly, well-suited for systems with known future constraints like load-shedding schedules.
Pre-synchronisation	The process of matching voltage, frequency, and phase angle of a distributed energy resource to the microgrid before connection, enabling seamless transition during scheduled islanding events.
Distributed Energy Resources (DER)	Small scale power generation resources located close to where electricity is used, such as solar panels, wind turbines, and small natural gas generators.
Resilience	The ability of a power system to anticipate, withstand, adapt to, and rapidly recover from disruptive events, maintaining energy availability for critical loads.

Appendix B. Mathematical Formulations of Key Control Strategies

This appendix provides detailed mathematical formulations of the control strategies discussed in the main text.

Appendix B.1. Primary Control: Conventional Droop Control

The fundamental P-f (Active Power-Frequency) and Q-V (Reactive Power-Voltage) droop control for inverters in islanded mode is given by [75]:

$$f = f_0 - k_p(P - P_0)$$

$$V = V_0 - k_q(Q - Q_0)$$

where

- f and V are the actual frequency and voltage
- f_0 and V_0 are the nominal frequency and voltage
- P and Q are the actual active and reactive power
- P_0 and Q_0 are the nominal active and reactive power
- k_p and k_q are the droop coefficients

For load-shedding-adapted predictive droop control, the coefficients become time varying:

$$k_p(t) = k_{p,0} + \Delta k_p(L_f(t),\ G_f(t))$$

$$k_q(t) = k_{q,0} + \Delta k_q(L_f(t),\ G_f(t))$$

where:

- L_f is the forecasted load
- $G_f(t)$ is the forecasted generation
- Δk_p and Δk_q are adjustment functions based on forecasts

Note: The adjustment functions Δk_p and Δk_q must be designed within small-signal stability margins. Aggressive changes based on forecasts can introduce instability; stability analysis is recommended for such predictive strategies [75–77].

Appendix B.2. Model Predictive Control Formulation

The MPC problem for microgrid economic dispatch can be formulated as [86]:

$$\min u(t) \int_{t_0}^{t_0+T} \Big[C_g(P_g(t)) + C_{deg}(P_b(t)) + C_{ls}(P_{ls}(t)) \Big] dt$$

Subject to:

- Power balance: $P_g(t) + P_b(t) + P_{ren}(t) = P_{load}(t) - P_{ls}(t)$
- Storage dynamics: $\frac{dSOC}{dt} = -\frac{P_b(t)}{E_{rated}}$
- Generation limits: $P_{g,min} \le P_g(t) \le P_{g,max}$
- Storage limits: $SOC_{min} \le SOC(t) \le SOC_{max}$
- Load-shedding constraints: $0 \le P_{ls}(t) \le P_{ls,max}$

  where:

- C_g, C_{deg}, C_{ls} are cost functions for generation, battery degradation, and load-shedding
- P_g, P_b, P_{ren}, P_{load}, P_{ls} are powers from generators, battery, renewables, load, and load-shedding
- SOC is the state of charge
- E_{rated} is the rated battery energy capacity

Consensus Algorithm for Secondary Control

The distributed consensus algorithm for frequency restoration can be expressed as [85]:

$$\omega_i[k+1] = \omega_i[k] + \epsilon \sum_{j \epsilon N_i} \big(\omega_j[k] - \omega_i[k]\big) + \alpha(f_{nom} - f_i[k])$$

where:

- ω_i is the frequency correction at node i
- N_i is the set of neighbours of node i
- ϵ is the consensus gain
- α is the restoration gain

- f_{nom} is the nominal frequency
- f_i is the measured frequency at node i

References

1. Kabeyi, M.J.B.; Olanrewaju, O.A. Sustainable energy transition for renewable and low carbon grid electricity generation and supply. *Front. Energy Res.* **2022**, *9*, 743114. [CrossRef]
2. Kostenko, G.; Zaporozhets, A. Enhancing of the power system resilience through the application of micro power systems (microgrid) with renewable distributed generation. *Syst. Res. Energy* **2023**, *3*, 25–38. [CrossRef]
3. Hamidieh, M.; Ghassemi, M. Microgrids and resilience: A review. *IEEE Access* **2022**, *10*, 106059–106080. [CrossRef]
4. Maswanganyi, M.C. Exploring the Impact of Load-Shedding on Small, Micro, and Medium Enterprises Operating Within the City of Tshwane Metropolitan Area. Ph.D. Dissertation, University of Limpopo, Polokwane, South Africa, 2024.
5. Mathibe, M.L. South Africa's Energy Crisis and Its Implications for Trade Dynamics. Ph.D. Dissertation, University of the Western Cape, Bellville, South Africa, 2024.
6. Banderker, S.; Naidoo-Chetty, M. The Perceived Psychosocial and Economic Impact of Load-Shedding in Selected Small and Micro Medium Enterprises. Available online: https://internationalbusinessconference.com/wp-content/uploads/2024/10/CP102-Naidoo_Chetty-impact-of-loadshedding-final-corrected.pdf (accessed on 12 December 2025).
7. Naidoo, C. The impact of load shedding on the South Africa economy. *J. Public Adm.* **2023**, *58*, 7–16.
8. Pothireddy, K.M.R.; Vuddanti, S.; Salkuti, S.R. Optimal assortment of methods to mitigate the imbalance power in the day-ahead market. *Electr. Eng.* **2025**, *107*, 7933–7954. [CrossRef]
9. Capitanescu, F. Are we prepared against blackouts during the energy transition?: Probabilistic risk-based decision making encompassing jointly security and resilience. *IEEE Power Energy Mag.* **2023**, *21*, 77–86. [CrossRef]
10. Nkambule, M.S.; Hasan, A.N.; Shongwe, T. Analyzing the Economic Viability of Microgrid Solutions in the South African Market. *IEEE Access* **2025**, *13*, 29091–29121. [CrossRef]
11. Aslani, F.; Li, S. Islanding Detection Methods and Challenges for Distribution Generation: A Technological Review. *IEEE Access* **2025**, *13*, 133568–133595. [CrossRef]
12. Fathabadi, A.S.; Snook, C.; Dghaym, D.; Hoang, T.S.; Alotaibi, F.; Butler, M. Systematic hierarchical analysis of requirements for critical systems. *Innov. Syst. Softw. Eng.* **2025**, *21*, 569–593. [CrossRef]
13. Vita, V.; Fotis, G.; Pavlatos, C.; Mladenov, V. A new restoration strategy in microgrids after a blackout with priority in critical loads. *Sustainability* **2023**, *15*, 1974. [CrossRef]
14. Juma, S.A.; Ayeng'O, S.P.; Kimambo, C.Z.M. A review of control strategies for optimized microgrid operations. *IET Renew. Power Gener.* **2024**, *18*, 2785–2818. [CrossRef]
15. Madiba, T.; Bansal, R.; Mbungu, N.; Bettayeb, M.; Naidoo, R.; Siti, M. Under-frequency load shedding of microgrid systems: A review. *Int. J. Model. Simul.* **2022**, *42*, 653–679. [CrossRef]
16. Roudnil, S.; Zadeh, S.G.; Feyzi, M.R.; Ghavifekr, A.A. Enhancing Multimicrogrid Resilience: A State-of-the-Art Survey on Model Predictive Control-Based Energy Management Strategies. *Int. J. Energy Res.* **2025**, *2025*, 9088459. [CrossRef]
17. Cai, G.; Zhou, S.; Liu, C.; Zhang, Y.; Guo, S.; Cao, Z. Hierarchical under frequency load shedding scheme for inter-connected power systems. *Prot. Control Mod. Power Syst.* **2023**, *8*, 34. [CrossRef]
18. Babagana, A. Load Shedding and Voltage Management Strategies for Enhancing Resilience in Remote DC Microgrids. Doctoral Dissertation, University of Strathclyde, Glasgow, UK, 2025.
19. Abiodun, K.; Gautam, A.; Newman, A.; Nock, D.; Pandey, A. The role of microgrids in advancing energy equity through access and resilience. In *Tutorials in Operations Research: Emerging and Impactful Topics in Operations*; INFORMS: Catonsville, MD, USA, 2022; pp. 175–190.
20. Baca, M.; Schenkman, B.; Hightower, M. Use of advanced microgrids to support community resilience. *Nat. Hazards Rev.* **2021**, *22*, 05021012. [CrossRef]
21. Ahmad, G.; Hassan, A.; Islam, A.; Shafiullah; Abido, M.A.; Al-Dhaifallah, M. Distributed Control Strategies for Microgrids: A Critical Review of Technologies and Challenges. *IEEE Access* **2025**, *13*, 60702–60719. [CrossRef]
22. Rodriguez-Gil, J.A.; Mojica-Nava, E.; Vargas-Medina, D.; Arevalo-Castiblanco, M.F.; Cortes, C.A.; Rivera, S.; Cortes-Romero, J. Energy management system in networked microgrids: An overview. *Energy Syst.* **2024**, 1–32. [CrossRef]
23. Zuo, K.; Wu, L. A review of decentralized and distributed control approaches for islanded microgrids: Novel designs, current trends, and emerging challenges. *Electr. J.* **2022**, *35*, 107138. [CrossRef]
24. Junior, S.; Teixeira, M.E.; Freitas, L.C.G. Power electronics for modern sustainable power systems: Distributed generation, microgrids and smart grids—A review. *Sustainability* **2022**, *14*, 3597. [CrossRef]
25. Shahgholian, G. A brief review on microgrids: Operation, applications, modeling, and control. *Int. Trans. Electr. Energy Syst.* **2021**, *31*, e12885. [CrossRef]

26. Liu, J.; Zhuan, X.; Shang, L.; Su, S.; Xie, Q. The Hierarchical Structure and Control Signal Transmission of Microgrid Hierarchical Control: A Review. *IET Power Electron.* **2025**, *18*, e70057. [CrossRef]
27. Mohammed, N.; Alhelou, H.H.; Bahrani, B. (Eds.) *Grid-Forming Power Inverters: Control and Applications*; CRC Press: Boca Raton, FL, USA, 2023.
28. Ohanu, C.P.; Rufai, S.A.; Oluchi, U.C. A comprehensive review of recent developments in smart grid through renewable energy resources integration. *Heliyon* **2024**, *10*, e25705. [CrossRef]
29. Behera, M.K.; Saikia, L.C. An improved voltage and frequency control for islanded microgrid using BPF based droop control and optimal third harmonic injection PWM scheme. *IEEE Trans. Ind. Appl.* **2021**, *58*, 2483–2496. [CrossRef]
30. Sadnan, R.; Poudel, S.; Dubey, A.; Schneider, K.P. Layered coordination architecture for resilient restoration of power distribution systems. *IEEE Trans. Ind. Inform.* **2022**, *19*, 6069–6080. [CrossRef]
31. Mohandes, B.; Wahbah, M.; El Moursi, M.S.; El-Fouly, T.H. Renewable energy management system: Optimum design and hourly dispatch. *IEEE Trans. Sustain. Energy* **2021**, *12*, 1615–1628. [CrossRef]
32. Khan, M.W.; Li, G.; Wang, K.; Numan, M.; Xiong, L.; Khan, M.A. Optimal control and communication strategies in multi-energy generation grid. *IEEE Commun. Surv. Tutor.* **2023**, *25*, 2599–2653. [CrossRef]
33. Khan, M.Y.A.; Liu, H.; Yang, Z.; Wang, J.; Zhang, Y. Hierarchical control of microgrid: A comprehensive study. *Electr. Eng.* **2025**, *107*, 13681–13712. [CrossRef]
34. Kordestani, M.; Safavi, A.A.; Saif, M. Recent survey of large-scale systems: Architectures, controller strategies, and industrial applications. *IEEE Syst. J.* **2021**, *15*, 5440–5453. [CrossRef]
35. Gutiérrez-Escalona, J.; Roncero-Clemente, C.; Husev, O.; Matiushkin, O.; Blaabjerg, F. Artificial Intelligence in the Hierarchical Control of ac, dc and Hybrid ac/dc Microgrids–A Review. *IEEE Access* **2024**, *12*, 157227–157246. [CrossRef]
36. Zhou, B.; Zou, J.; Chung, C.Y.; Wang, H.; Liu, N.; Voropai, N.; Xu, D. Multi-microgrid energy management systems: Architecture, communication, and scheduling strategies. *J. Mod. Power Syst. Clean Energy* **2021**, *9*, 463–476. [CrossRef]
37. Sarathkumar, D.; Maheswari, P.; Manivel, M.; Jayakumar, T.; Sivakumar, R.; Parrthipan, B. Decentralized and Distributed Control Strategies for Microgrids: A Review of Key Techniques and Applications. In Proceedings of the 2025 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS), Bhopal, India, 18–19 January 2025; IEEE: New York, NY, USA, 2025; pp. 1–6.
38. Guo, X. *Crime in the Dark: Role of Electricity Rationing*; No. HEIDWP18-2024; Graduate Institute of International and Development Studies Working Paper; Graduate Institute of International and Development Studies: Geneva, Switzerland, 2024.
39. Yearwood, G.E. The Rainbow Nation Goes Dark: Unjust Energy Production and Load Shedding in South Africa. Bachelor's Thesis, Fordham University, New York, NY, USA, 2025.
40. Behrens, T.; Daniyan, I.; Bello, K.; Adediran, A.A. Towards Addressing Energy Crisis in South Africa: A Systematics Literature Review. In Proceedings of the 2024 International Conference on Science, Engineering and Business for Driving Sustainable Development Goals (SEB4SDG), Omu-Aran, Nigeria, 2–4 April 2024; IEEE: New York, NY, USA, 2024; pp. 1–8.
41. Gwaka, L.T. We have a lot to say about loadshedding: Exploring citizen engagements and perceptions on power cuts in South Africa. *Energy Res. Soc. Sci.* **2025**, *122*, 104019. [CrossRef]
42. Lekunze, A.R. Rethinking the (Un) just Transition: A Review of the Impact of Neoliberal Approaches to Energy Governance in South Africa. *J. Law Soc. Dev.* **2024**, *11*, 1–18 pages. [CrossRef] [PubMed]
43. Bookbinder, R. Politicising energy transitions: The political economy of reducing dependence on coal in South Africa's minerals energy complex. *Environ. Politics* **2025**, *34*, 1000–1021. [CrossRef]
44. Bangani, S. Librarying Under the Candlelight: The Impact of Electricity Power Outages on Library Services. *Open Inf. Sci.* **2024**, *8*, 20240008. [CrossRef]
45. Kgarose, M.F.; Makhubele, D.K.; Setaise, L.C. Is Load Shedding Another Pandemic, Post COVID-19 at Institution of Higher Learning in South Africa? *Rudn. J. Public Adm.* **2023**, *12*, 447–456. [CrossRef]
46. Cloete, K.; Pienaar, L.; Van der Merwe, M. Is persistent loadshedding pulling the plug on agriculture in the Western Cape, South Africa? *Agrekon* **2023**, *62*, 228–240. [CrossRef]
47. Mabunda, M.V.; Mukonza, R.M.; Mudzanani, L.R.; Manyaka, R.K. Implications of Loadshedding on Small and Medium Enterprises' Contributions to Local Economic Development in the Collins Chabane Local Municipality, South Africa. *J. Public Adm.* **2024**, *59*, 455–476. [CrossRef]
48. Matsuda-Dunn, R.; McKenna, K.; Desai, J.; Mukoma, P. *Determining and Unlocking Untapped Demand-Side Management Potential in South Africa: Demand Response at the Grid Edge*; No. NREL/TP-6A40-88042; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2024.
49. Machimana, L.I.; Gumbo, A.D.; Moyo, H.; Mugari, E. The Impact of Load-Shedding on Scheduled Water Delivery Services for Mohlaba-Cross Village, Greater Tzaneen, South Africa. *Water* **2024**, *16*, 2033. [CrossRef]

50. Ahmed, I.; Razzak, A.; Ahmed, F. Sustainable hybrid renewable energy management system for a community in island: A model approach utilising Hybrid Optimization of Multiple Energy Resources optimization and priority setting-based Supervisory Control and Data Acquisition operation. *IET Smart Grid* **2024**, *7*, 940–966. [CrossRef]
51. Dehghani, A.; Sedighizadeh, M.; Haghjoo, F. An overview of the assessment metrics of the concept of resilience in electrical grids. *Int. Trans. Electr. Energy Syst.* **2021**, *31*, e13159. [CrossRef]
52. Zaporozhets, A.; Babak, V.; Kostenko, G.; Zgurovets, O.; Denisov, V.; Nechaieva, T. Power System Resilience: An Overview of Current Metrics and Assessment Criteria. In *Systems, Decision and Control in Energy VI: Volume I: Energy Informatics and Transport*; Springer: Cham, Switzerland, 2024; pp. 35–58.
53. Han, J. Enhanced Frequency Control in Future Low-Inertia Power Systems Based on Digital Twins of Distributed Energy Resources. Doctoral Dissertation, University of Strathclyde, Glasgow, UK, 2025.
54. Dowejko, J.; Jaworski, J. Beyond Traditional Grid: A Novel Quantitative Framework for Assessing Automation's Impact on System Average Interruption Duration Index and System Average Interruption Frequency Index. *Energies* **2025**, *18*, 2671. [CrossRef]
55. Clavijo-Blanco, J.; González-Cagigal, M.; Rosendo-Macías, J. Statistical characterization of reliability indices in medium voltage networks using a Monte Carlo-based method. *Electr. Power Syst. Res.* **2024**, *234*, 110585. [CrossRef]
56. Rethlefsen, M.L.; Kirtley, S.; Waffenschmidt, S.; Ayala, A.P.; Moher, D.; Page, M.J.; Koffel, J.B. PRISMA-S: An extension to the PRISMA statement for reporting literature searches in systematic reviews. *Syst. Rev.* **2021**, *10*, 39. [CrossRef] [PubMed]
57. Carrera-Rivera, A.; Ochoa, W.; Larrinaga, F.; Lasa, G. How-to conduct a systematic literature review: A quick guide for computer science research. *MethodsX* **2022**, *9*, 101895. [CrossRef] [PubMed]
58. Agrawal, S.; Oza, P.; Kakkar, R.; Tanwar, S.; Jetani, V.; Undhad, J.; Singh, A. Analysis and recommendation system-based on PRISMA checklist to write systematic review. *Assess. Writ.* **2024**, *61*, 100866. [CrossRef]
59. Christou, E.; Parmaxi, A.; Zaphiris, P. A systematic exploration of scoping and mapping literature reviews. *Univers. Access Inf. Soc.* **2025**, *24*, 941–951. [CrossRef]
60. Paul, J.; Barari, M. Meta-analysis and traditional systematic literature reviews—What, why, when, where, and how? *Psychol. Mark.* **2022**, *39*, 1099–1115. [CrossRef]
61. Jahromi, M.Z.; Yaghoubi, E.; Yaghoubi, E. Optimal generation and distribution planning in smart microgrids under conditions of multi-microgrid disconnection using a hierarchical control strategy. *Electr. Eng.* **2025**, *107*, 10413–10432. [CrossRef]
62. Del Duca, A. Optimal Hierarchical Management and Control of Battery Energy Storage Systems in the Smart Grid. Master's Thesis, Politecnico di Milano, Milan, Italy, 2021.
63. Adan, J.; Rafy, M.; Srivastava, A.K. Cyber Resilience in Solar-Rich Networked Microgrids: A Real time End-to-End DER Outage Management Framework. *IEEE Trans. Ind. Appl.* **2025**. [CrossRef]
64. Yousef, M.Y.; Mosa, M.A.; Ali, A.; El Masry, S.M.; Ghany, A.A. Frequency response enhancement of an AC micro-grid has renewable energy resources based generators using inertia controller. *Electr. Power Syst. Res.* **2021**, *196*, 107194. [CrossRef]
65. Shazon, N.H.; Masood, N.A.; Ahmed, H.M.; Deeba, S.R.; Hossain, E. Exploring the utilization of energy storage systems for frequency response adequacy of a low inertia power grid. *IEEE Access* **2021**, *9*, 129933–129950. [CrossRef]
66. Fresia, M.; Procopio, R.; Urazbayeva, A. Inverter-Based Nanogrid Design with Integration of Primary, Secondary and Tertiary Controls–A Case Study. In Proceedings of the 2025 IEEE International Conference on Environment and Electrical Engineering and 2025 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Chania, Crete, Greece, 15–18 July 2025; IEEE: New York, NY, USA, 2025; pp. 1–6.
67. Khosravi, N.; Çelik, D.; Bevrani, H.; Echalih, S. Microgrid stability: A comprehensive review of challenges, trends, and emerging solutions. *Int. J. Electr. Power Energy Syst.* **2025**, *170*, 110829. [CrossRef]
68. Al-Ismail, F.S. A critical review on DC microgrids voltage control and power management. *IEEE Access* **2024**, *12*, 30345–30361. [CrossRef]
69. Zhang, J.; Li, J.; Wang, N.; Wu, B. An enhanced predictive hierarchical power management framework for islanded microgrids. *IET Gener. Transm. Distrib.* **2022**, *16*, 503–516. [CrossRef]
70. Hmad, J.; Houari, A.; Bouzid, A.E.M.; Saim, A.; Trabelsi, H. A review on mode transition strategies between grid-connected and standalone operation of voltage source inverters-based microgrids. *Energies* **2023**, *16*, 5062. [CrossRef]
71. Ullah, S.; Khan, L.; Sami, I.; Hafeez, G.; Albogamy, F.R. A distributed hierarchical control framework for economic dispatch and frequency regulation of autonomous AC microgrids. *Energies* **2021**, *14*, 8408. [CrossRef]
72. Prakash, K.; Ali, M.; Siddique, N.I.; Chand, A.A.; Kumar, N.M.; Dong, D.; Pota, H.R. A review of battery energy storage systems for ancillary services in distribution grids: Current status, challenges and future directions. *Front. Energy Res.* **2022**, *10*, 971704. [CrossRef]
73. Aslam, M.U.; Miah, S.; Amin, B.M.R.; Shah, R.; Amjady, N. Application of energy storage systems to enhance power system resilience: A critical review. *Energies* **2025**, *18*, 3883. [CrossRef]

74. Rafaq, M.S.; Basit, B.A.; Mohammed, S.A.Q.; Jung, J. A comprehensive state-of-the-art review of power conditioning systems for energy storage systems: Topology and control applications in power systems. *IET Renew. Power Gener.* **2022**, *16*, 1971–1991. [CrossRef]
75. Shahgholian, G.; Moradian, M.; Fathollahi, A. Droop control strategy in inverter-based microgrids: A brief review on analysis and application in islanded mode of operation. *IET Renew. Power Gener.* **2025**, *19*, e13186. [CrossRef]
76. Kreishan, M.Z.; Zobaa, A.F. Optimal allocation and operation of droop-controlled islanded microgrids: A review. *Energies* **2021**, *14*, 4653. [CrossRef]
77. Qashqaie, F.; Saghafi, H.; Sadeghi, R.; Fani, B. Impedance-Based Adaptive Droop Control for Is-landed AC Microgrids and Overview. *Int. Trans. Electr. Energy Syst.* **2025**, *2025*, 5660985. [CrossRef]
78. Wang, C.; Cheng, B.; He, X.; Xi, L.; Yang, N.; Zhao, Z.; Lai, C.S.; Lai, L.L. Integrated Underfrequency Load Shedding Strategy for Islanded Microgrids Integrating Multiclass Load-Related Factors. *IEEE Trans. Smart Grid* **2025**, *16*, 4305–4323. [CrossRef]
79. Islam, M.; Nagrial, M.; Rizk, J.; Hellany, A. General aspects, islanding detection, and energy management in microgrids: A review. *Sustainability* **2021**, *13*, 9301. [CrossRef]
80. Collath, N.; Tepe, B.; Englberger, S.; Jossen, A.; Hesse, H. Aging aware operation of lithium-ion battery energy storage systems: A review. *J. Energy Storage* **2022**, *55*, 105634. [CrossRef]
81. Xu, W.; Wang, B.; Liu, J.; Li, D. An Improved Droop Control Strategy for Grid-Connected Inverter Applied in Grid Voltage Inter-Harmonics and Fundamental Frequency Fluctuation. *Electronics* **2021**, *10*, 1827. [CrossRef]
82. Comden, J.; Zamzam, A.; Bernstein, A. *Data-Driven Chance-Constrained Design of Voltage Droop Control for Distribution Networks*; No. NREL/CP-5D00-80428; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2022.
83. Abrar, S.F.; Masood, N.-A.; Alam, M.J. An adaptive load shedding methodology for renewable integrated power systems. *Heliyon* **2024**, *10*, e40043. [CrossRef]
84. Ibiam, N.H.; Kahwash, F.; Ahmed, J. Priority Load Management for Improving Supply Reliability of Critical Loads in Healthcare Facilities Under Highly Unreliable Grids. *Energies* **2025**, *18*, 1343. [CrossRef]
85. Rodriguez-Martinez, O.F.; Andrade, F.; Vega-Penagos, C.A.; Luna, A.C. A review of distributed secondary control architectures in islanded-inverter-based microgrids. *Energies* **2023**, *16*, 878. [CrossRef]
86. Zhao, Z.; Zhang, X.; Zhong, C. Model predictive secondary frequency control for islanded microgrid under wind and solar stochastics. *Electronics* **2023**, *12*, 3972. [CrossRef]
87. Vijithasena, R.; Scaciota, R.; Bennis, M.; Samarakoon, S. Stability-Aware Joint Communication and Control for Nonlinear Control-Non-Affine Wireless Networked Control Systems. *arXiv* **2025**, arXiv:2509.02247.
88. Wang, Y.; Deng, C.; Liu, Y.; Wei, Z. A cyber-resilient control approach for islanded microgrids under hybrid attacks. *Int. J. Electr. Power Energy Syst.* **2023**, *147*, 108889. [CrossRef]
89. Cai, X.; Gao, B.; Nan, X. Resilient distributed secondary control for islanded ac microgrids under FDI attacks. *Electr. Power Syst. Res.* **2025**, *238*, 111123. [CrossRef]
90. Bhargavi, K.M.; Jayalakshmi, N.S.; Gaonkar, D.N.; Shrivastava, A.; Jadoun, V.K. A comprehensive review on control techniques for power management of isolated DC microgrid system operation. *IEEE Access* **2021**, *9*, 32196–32228. [CrossRef]
91. Hu, J.; Shan, Y.; Yang, Y.; Parisio, A.; Li, Y.; Amjady, N.; Islam, S.; Cheng, K.W.; Guerrero, J.M.; Rodríguez, J. Economic model predictive control for microgrid optimization: A review. *IEEE Trans. Smart Grid* **2023**, *15*, 472–484. [CrossRef]
92. Bakht, M.P.; Mohd, M.N.H.; Sheikh, U.U.; Khan, N. Optimal design and performance analysis of hybrid renewable energy system for ensuring uninterrupted power supply during load shedding. *IEEE Access* **2024**, *12*, 5792–5813. [CrossRef]
93. Bakht, M.P.; Salam, Z.; Gul, M.; Anjum, W.; Kamaruddin, M.A.; Khan, N.; Bukar, A.L. The potential role of hybrid renewable energy system for grid intermittency problem: A techno-economic optimisation and comparative analysis. *Sustainability* **2022**, *14*, 14045. [CrossRef]
94. da Costa, V.B.F.; de Doile, G.N.D.; Troiano, G.; Dias, B.H.; Bonatto, B.D.; Soares, T.; de Freitas Filho, W. Electricity markets in the context of distributed energy resources and demand response programs: Main developments and challenges based on a systematic literature review. *Energies* **2022**, *15*, 7784. [CrossRef]
95. Tian, C.; Li, J.; Wang, C.; Lin, L.; Yan, Y. Demand Response Strategy Considering Industrial Loads and Energy Storage with High Proportion of Wind-Power Integration. *Sensors* **2024**, *22*, 7335. [CrossRef]
96. Khan, M.A.; Saleh, A.M.; Waseem, M.; Sajjad, I.A. Artificial intelligence enabled demand response: Prospects and challenges in smart grid environment. *IEEE Access* **2022**, *11*, 1477–1505. [CrossRef]
97. Guo, C.; Luo, F.; Cai, Z.; Dong, Z.Y. Integrated energy systems of data centers and smart grids: State-of-the-art and future opportunities. *Appl. Energy* **2021**, *301*, 117474. [CrossRef]
98. Ma, H.; Wang, Y.; He, M. Collaborative optimization scheduling of resilience and economic oriented islanded integrated energy system under low carbon transition. *Sustainability* **2023**, *15*, 15663. [CrossRef]
99. Hemeida, A.M.; Omer, A.S.; Bahaa-Eldin, A.M.; Alkhalaf, S.; Ahmed, M.; Senjyu, T.; El-Saady, G. Multi-objective multi-verse optimization of renewable energy sources-based micro-grid system: Real case. *Ain Shams Eng. J.* **2022**, *13*, 101543. [CrossRef]

100. Wang, J.; Cao, S.; Li, R.; Xu, W. Energy Symbiosis in Isolated Multi-Source Complementary Microgrids: Diesel–Photovoltaic–Energy Storage Coordinated Optimization Scheduling and System Resilience Analysis. *Energies* **2025**, *18*, 5741. [CrossRef]
101. Issa, W.; Sharkh, S.; Abusara, M. A review of recent control techniques of drooped inverter-based AC microgrids. *Energy Sci. Eng.* **2024**, *12*, 1792–1814. [CrossRef]
102. Dawn, S.; Ramakrishna, A.; Ramesh, M.; Das, S.S.; Rao, K.D.; Islam, M.; Ustun, T.S. Integration of renewable energy in microgrids and smart grids in deregulated power systems: A comparative exploration. *Adv. Energy Sustain. Res.* **2024**, *5*, 2400088. [CrossRef]
103. Wu, E.M.-K. Power Schedule Optimization and Dynamics Analysis for Prospective Islanded Microgrids. Doctoral Dissertation, University of Calgary, Calgary, AB, Canada, 2024.
104. Moreno-Castro, J.; Guevara, V.S.O.; Viltre, L.T.L.; Landera, Y.G.; Zevallos, O.C.; Aybar-Mejía, M. Microgrid management strategies for economic dispatch of electricity using model predictive control techniques: A review. *Energies* **2023**, *16*, 5935. [CrossRef]
105. Wang, Z.; Wang, J.; Ma, M.; Yang, H.; Chen, D.; Wang, L.; Li, P. Distributed event-triggered fixed-time fault-tolerant secondary control of islanded AC microgrid. *IEEE Trans. Power Syst.* **2022**, *37*, 4078–4093. [CrossRef]
106. Sayed, K.; Elsayed, M.M.; Mohamed, A.; Eid, A. Key performance indicators for resiliency assessment in power systems with renewable energy and electric vehicles integration. *Renew. Sustain. Energy Rev.* **2026**, *225*, 116135. [CrossRef]
107. Fathollahi, A. Machine Learning and Artificial Intelligence Techniques in Smart Grids Stability Analysis: A Review. *Energies* **2025**, *18*, 3431. [CrossRef]
108. Al-Saadi, M.; Al-Greer, M.; Short, M. Reinforcement learning-based intelligent control strategies for optimal power management in advanced power distribution systems: A survey. *Energies* **2023**, *16*, 1608. [CrossRef]
109. Alain, G.-C.; Escamilla-Ambrosio, P.J.; Al Faruque, M.A. A review of resilience enhancement techniques for cyber-physical systems. *IEEE Access* **2025**, *13*, 138061–138082. [CrossRef]
110. Lu, X.; Xiao, L.; Li, P.; Ji, X.; Xu, C.; Yu, S.; Zhuang, W. Reinforcement learning-based physical cross-layer security and privacy in 6G. *IEEE Commun. Surv. Tutor.* **2022**, *25*, 425–466. [CrossRef]
111. Zhang, T.; Huo, Y.; Gao, Q.; Ma, L.; Wu, Y.; Li, R. Cooperative physical layer authentication with reputation-inspired collaborator selection. *IEEE Internet Things J.* **2023**, *10*, 22165–22181. [CrossRef]
112. Gokulraj, K.; Venkatramanan, C.B. Advanced machine learning-driven security and anomaly identification in inverter-based cyber-physical microgrids. *Electr. Power Compon. Syst.* **2024**, 1–18. [CrossRef]
113. Khalaf, M.; Ayad, A.; Salama, M.M.A.; Kundur, D.; El-Saadany, E.F. Mitigation of cyber-attacks on wide-area under-frequency load-shedding schemes. *IEEE Trans. Smart Grid* **2022**, *14*, 2377–2389. [CrossRef]
114. Hou, S.; Chen, J.; Chen, G. Distributed control strategy for voltage and frequency restoration and accurate reactive power-sharing for islanded microgrid. *Energy Rep.* **2023**, *9*, 742–751. [CrossRef]
115. Sugunaraj, N.; Balaji, S.R.A.; Chandar, B.S.; Rajagopalan, P.; Kose, U.; Loper, D.C.; Mahfuz, T.; Chakraborty, P.; Ahmad, S.; Kim, T.; et al. Distributed Energy Resource Management System (DERMS) Cybersecurity Scenarios, Trends, and Potential Technologies: A Review. *IEEE Commun. Surv. Tutor.* **2025**, *28*, 224–277. [CrossRef]
116. Erasmus, S.; Esterhuysen, N.; Maritz, J. Campus Microgrids within the South African context: A case study to illustrate unique design, control challenges, and hybrid dispatch strategies. *Energies* **2023**, *16*, 1519. [CrossRef]
117. Ohlhoff, C.; Meissner, H. Sustainability in the SA Dairy Industry: A Status and Progress Report. 2024. Available online: https://milksa.co.za/sites/default/files/GEN047%20Sustainability%20in%20the%20SA%20Dairy%20Industry%20-%20Oct%202024.pdf (accessed on 12 December 2025).
118. Danone to Develop Resilient Microgrid in South Africa Anchored by Hydrogen Ready Combined Heat and Power Technology. Available online: https://www.prnewswire.co.uk/news-releases/danone-to-develop-resilient-microgrid-in-south-africa-anchored-by-hydrogen-ready-combined-heat-and-power-technology-301923581.html (accessed on 17 November 2025).
119. Mukwevho, O. Assessing the Effectiveness of Green Buildings in Reducing Energy and Water Consumption in Gauteng City Region, South Africa. Master's Thesis, University of Johannesburg, Johannesburg, South Africa, 2023.
120. Mumtaz, M.A.; Rehman, A.U.; Ayub, M.; Muhammad, F.; Raza, M.W.; Iqbal, S.; Elbarbary, Z.M.S.; Alsenani, T.R. Techno-economic and environmental analysis of hybrid energy system for industrial sector of Pakistan. *Sci. Rep.* **2024**, *14*, 23736. [CrossRef]
121. Bleu, F.; Li, L.; Ng, L.; Price, N.; Williams, S. Assessing the Feasibility of Microgrid and Battery Storage Systems for Critical Facilities in Barbados. Ph.D. Thesis, Duke University, Durham, NC, USA, 2025.
122. How Alaska Fits into the Global Microgrid Movement | From the Grid. Available online: https://www.uaf.edu/acep-blog/how-alaska-fits-into-the-global-microgrid-movement%20.php (accessed on 17 November 2025).
123. Dispatch from Alaska: Energy Lessons from Life Off the Grid—RMI. Available online: https://rmi.org/dispatch-from-alaska-energy-lessons-from-life-off-the-grid/ (accessed on 17 November 2025).
124. Korovushkin, V.; Boichenko, S.; Artyukhov, A.; Ćwik, K.; Wróblewska, D.; Jankowski, G. Modern optimization technologies in hybrid renewable energy systems: A systematic review of research gaps and prospects for decisions. *Energies* **2025**, *18*, 4727. [CrossRef]

125. Indrajith, B.; Gunawardane, K.; Hossain, A.; Li, L.; Nicholson, R.; Zamora, R. Hydro-gen-Integrated Microgrids: A Comprehensive Review of Hydrogen Technologies and Energy Management Strategies. *IEEE Access* **2025**, *13*, 178625–178651. [CrossRef]
126. Califano, M.; Califano, F.; Sorrentino, M.; Rosen, M.; Pianese, C. Hydrogen-based microgrid: Development of medium level controls in a multilevel algorithm framework. *Int. J. Hydrogen Energy* **2024**, *52*, 1173–1189. [CrossRef]
127. Li, S.; Oshnoei, A.; Blaabjerg, F.; Anvari-Moghaddam, A. Hierarchical control for microgrids: A survey on classical and machine learning-based methods. *Sustainability* **2023**, *15*, 8952. [CrossRef]
128. Sułek, A.; Borowski, P.F. Business Models on the Energy Market in the Era of a Low-Emission Economy. *Energies* **2024**, *17*, 3235. [CrossRef]
129. Singh, M.; Kesselring, A.; Klobasa, M. Re-Imagining Energy Services: Empirical Analysis of Demand-Side as-a-Service Business Models and Use Cases in Energy Sector. In Proceedings of the Spring Servitization Conference, Tilburg, The Netherlands, 12–14 May 2024.
130. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]