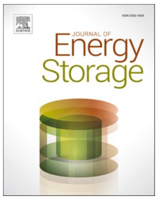
Journal of Energy Storage 128 (2025) 117223

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est



Review article

Role of battery energy storage systems: A comprehensive review on renewable energy zones integration in weak transmission networks

Sadnan Sakib [a], Md. Biplob Hossain [a,b], Muhammad Ahsan Zamee [a], M.J. Hossain [a,*], Md. Ahasan Habib [a]

[a] School of Electrical and Data Engineering, University of Technology Sydney, Ultimo 2007, NSW, Australia
[b] Department of Electrical and Electronic Engineering, Jashore University of Science and Technology, Jashore 7408, Bangladesh

ARTICLE INFO

Keywords:
Battery energy storage systems
Renewable energy zones
Renewable energy sources
Weak grids
Control strategies and energy management
Grid instability
Power quality

ABSTRACT

The challenges posed by non-renewable energy sources—both environmental and economic—are driving Australia's transition to Renewable Energy Zones (REZs). However, integrating REZs into weak grids introduces instability, power quality issues, and non-dispatchable generation, jeopardizing system reliability. While Energy Storage Systems (ESSs) help address these issues, non-battery ESSs often fall short in efficiency, flexibility, and rapid response. In contrast, Battery Energy Storage Systems (BESSs) demonstrate superior performance, effectively stabilizing weak grids, managing power fluctuations, and facilitating renewable energy integration.

Despite significant research on BESSs, a comprehensive review of control strategies, energy management systems (EMSs), and grid support technologies in zonal weak grids remains limited. This paper seeks to bridge this gap by analyzing BESS control methodologies, EMS frameworks, and their impact on grid stability, power quality, and renewable integration. By highlighting the limitations of conventional storage and showcasing the potential of BESSs, this study offers valuable insights for academia and industry alike. Integrating BESS into weak grids is transformative, enhancing renewable energy resilience through adaptive control and energy management systems, crucial for achieving a global carbon-neutral future. The findings provide a roadmap for researchers, grid operators, and policymakers to develop sustainable, resilient energy systems, advancing technological innovation, economic feasibility, and policy strategies toward a carbon-neutral future.

1. Introduction

The global shift toward sustainable energy systems has intensified the focus on renewable energy sources (RESs) as a solution to the environmental and economic challenges posed by fossil fuels. In Australia, fossil fuels have historically dominated electricity generation, accounting for over 86 % of the total energy supply [1]. However, this dependency has resulted in significant environmental degradation, including high per capita greenhouse gas emissions, rising sea levels, and severe weather events [2]. Public health has also been impacted, with increased respiratory and cardiovascular diseases linked to air pollution caused by sulfur dioxide and nitrogen oxides. The urgent need for clean energy alternatives has become particularly evident in regions like Far North Queensland (FNQ), where reliance on diesel generators is both economically unsustainable and environmentally harmful [3]. Additionally, Australia's reliance on imported liquid fuels highlights the vulnerability of fossil fuel systems to global market fluctuations, further emphasizing the need for a transition to sustainable energy solutions. Aging fossil fuel infrastructure exacerbates these issues. Many coal-fired power plants are nearing the end of their operational lifespans, presenting both an opportunity and a challenge for Australia's energy transition [4]. The continued reliance on fossil fuels delays the adoption of renewable systems, perpetuating environmental harm and economic instability.

To address these pressing challenges, the Australian Government has accelerated the adoption of RE through the establishment REZs [1]. To promote REZs integration, Fig. 1 demonstrates the remarkable growth in renewable electricity generation between 2019 and 2020 and 2022–2023, with total output increasing from 59,930.3 GWh to 93,112.3 GWh [6]. This statistic reflects a strong commitment to global climate agreements, such as the Paris Agreement, and highlights the critical role of wind and solar energy in the nation's energy mix [3]. At the same time, the increasing frequency of extreme weather events, such

---

* Corresponding author.
E-mail addresses: sadnan.sakib@student.uts.edu.au (S. Sakib), mdbiplob.hossain-1@uts.edu.au (Md.B. Hossain), zamee.official@gmail.com (M.A. Zamee), jahangir.hossain@uts.edu.au (M.J. Hossain), mdahasan.habib@student.uts.edu.au (Md.A. Habib).

https://doi.org/10.1016/j.est.2025.117223
Received 3 March 2025; Received in revised form 1 May 2025; Accepted 23 May 2025

Nomenclature

AC	Alternating current
ACT	Australian capital territory
BESS	Battery energy storage systems
BIPV	Building-integrated photovoltaics
BMS	Battery management system
SC	Synchronous condensers
CA	Compressed air
Cap Bank	Capacitor bank
CAS	Compressed air storage
Chem	Chemical
DARC	Decoupled Active Reactive Control
DC	Direct current
e.g.	For example
EC	Electrochemical
Elec	Electrical
EMS	Energy management systems
EMSt	Energy management strategies
ESSs	Energy storage systems
FACTS	Flexible AC Transmission Systems
FC	Fuel cells
FLC	Fuzzy logic control
FNN	Fuzzy neural network
FNQ	Far North Queensland
GA	Genetic algorithms
GF	Grid forming
GFI	Grid forming inverters
GFL	Grid-following
HESS	Hybrid energy storage system
Li-ion	Lithium-ion
LVRT	Low voltage ride through
MCFC	Molten carbonate fuel cells
Mech	Mechanical
MPC	Model predictive control
MPPT	Maximum power point tracking
MWh	Mega-Watt hour
NaS	Sodium sulphur
Ni-Cd	Nickel-Cadmium
Ni-MH	Nickel-Metal Hydride
NNC	Neural Network-Based Control
NSW	New South Wales
Pb-Acid	Lead–Acid
PCC	Predictive current control
PHS	Pumped hydro storage
PI	Proportional integral
PLL	Phase-locked loop
PPC	Predictive power control
PSO	Particle swarm optimization
PV	Photovoltaic
PWM	Pulse width modulation
RE	Renewable energy
Ref	Reference
RESs	Renewable energy sources
REZs	Renewable energy zones
RF	Redox flow
RFB	Redox flow batteries
RL	Reinforcement learning
RLS	Reinforcement learning scheme
RWFNN	Recurrent fuzzy neural network
SC	Synchronous condensers
SCap	Supercapacitors
SDG	Sustainable development goals
SG	Synchronous generators
SMC	Sliding mode control
SMES	Superconducting magnetic energy storage
SoC	State of charge
SOFC	Solid oxide fuel cells
SOGI-PLL	Second order generalized integrator
SPWM	Sinusoidal PWMS
STATCOM	Static compensators
SVCs	Static VAR compensators
TC	Thermochemical
TCSS	Thermochemical storage system
UNSDG	United Nations Sustainable Development Goals
VPPs	Virtual power plants
VRC	Voltage restoration control
VRE	Variable renewable energy
VRFB	Vanadium redox flow
VSC	Voltage source converters
WT	Wind turbine
ZWG	Zonal weak grids

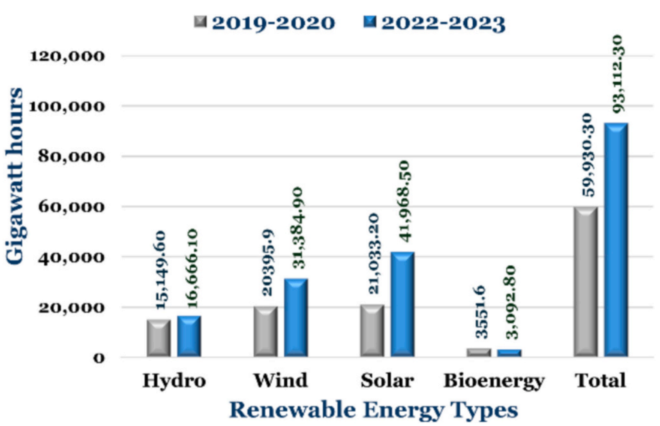


Fig. 1. Electricity generation growth in Australia from RESs from 2019 to 2020 to 2022–2023 [6].

as bushfires and floods, underscores the urgency for robust climate action [4]. These efforts are further supported by localized initiatives, including the Australian Capital Territory's (ACT) adoption of electric vehicles and renewable-powered public transport, which provide scalable examples of decarbonization [5]. Additionally, universities and private institutions are championing net-zero innovations, fostering systemic change [2]. However, the transition remains challenging due to persistent barriers such as policy fragmentation and social inequities. Despite these obstacles, market-driven solutions and inclusive governance frameworks provide a promising pathway to align environmental sustainability with economic growth [7].

Strengthening these efforts, RE technologies have proven their ability to provide diverse and scalable solutions to the limitations of fossil fuels. For instance, tools like spatial decision-support systems enable efficient planning and deployment of wind, solar, and geothermal resources, optimizing energy output and minimizing environmental impact [8]. In urban areas, hybrid renewable systems that integrate solar, wind, and biomass enhance reliability and reduce lifecycle costs [9]. Furthermore, innovations like building-integrated photovoltaics (BIPV) and smart grids improve energy efficiency and facilitate seamless integration into existing infrastructure [10]. Remote regions also stand to benefit significantly, with studies indicating over

90 % of emissions reductions when transitioning from diesel generators to renewables [11]. In addition to addressing environmental concerns, RE fosters economic growth and social equity through mechanisms such as public-private partnerships and feed-in tariffs [12]. While these advancements are promising, challenges in integrating renewables into existing infrastructure remain substantial, particularly in balancing energy supply and demand [13].

Among the most pressing challenges, ensuring grid stability remains a significant obstacle, as inverter-based renewable systems lack the inherent inertia provided by traditional synchronous generators (SGs). This increases the risk of frequency deviations during disturbances and complicates operations, particularly in regions with high renewable penetration [14]. Voltage stability issues add another layer of complexity, necessitating solutions such as virtual inertia emulation, grid-forming inverters (GFI), and Flexible AC Transmission Systems (FACTS) to maintain reliable grid operations [15,16]. These technologies are critical for ensuring that RE can be seamlessly integrated into weak grids. The classification of a power grid as 'weak' or 'strong' is primarily determined by technical factors such as short-circuit strength, system impedance, and inertia [17,18]. Strong grids possess high fault current capacity, low impedance, and abundant synchronous generation, providing robust voltage and frequency stability during disturbances [19]. In contrast, weak grids are characterized by lower short-circuit strength, higher impedance, and reduced inertia, making them more vulnerable to instabilities and posing greater challenges for the integration of renewable energy systems, particularly inverter-based resources [17,18]. Features such as long transmission distances, high concentrations of renewable energy, and diminished fault ride-through capabilities further exacerbate weak grid conditions [19]. In this study, the term "weak grid" specifically refers to power networks exhibiting these characteristics, where renewable energy integration has a pronounced impact on system stability.

In addition to grid stability, the variability of RE introduces significant power quality challenges, such as voltage sags, surges, and harmonic distortions caused by nonlinear inverter behavior [20]. Advanced mitigation technologies, including active power filters and Static VAR Compensators (SVCs), play a vital role in addressing these issues and ensuring consistent grid performance [21]. Furthermore, high-order non-linearity issues, including inter-harmonics and flicker, arise from the dynamic nature of RES and power converters. Addressing these requires the implementation of real-time monitoring systems and harmonic compensators to maintain stability [22,23].

Another critical challenge is the non-dispatchable nature of RESs, such as solar and wind, which are dependent on weather conditions and cannot provide consistent energy output. BESSs offer a transformative solution by converting non-dispatchable resources into dispatchable ones, thereby enhancing grid flexibility and reliability [24]. Furthermore, hybrid energy storage systems (HESSs) that incorporate advanced technologies like hydrogen storage provide additional benefits, ensuring a steady energy supply and cost efficiency while addressing the intermittency of renewables [25].

Significant research and development efforts are being undertaken by academic institutions, industry leaders, and government agencies worldwide to integrate large-scale BESSs into power systems, particularly those characterized by high RE penetration and weak grid conditions to maintain reliable, uninterrupted power supply. Table 1 presents a selection of recent review articles on ESSs, with a particular focus on integrating REZs into weak grids using BESS. This comparative analysis highlights the growing significance of this research area while underscoring the unique contributions of this study. By comparing existing literature with the insights provided in this paper, the table establishes the foundation upon which this research builds and validates the importance of conducting this comprehensive literature review.

This study provides a comprehensive review of RES integration into weak grids, emphasizing the role of Battery Energy Storage Systems (BESSs) in addressing key challenges. The main contributions of this

Table 1
Recent review articles on RE integration and BESS in weak grids.

Ref	RE challenges in weak grids	ESS applications	Limitations of Non-battery ESS	Classification of BESS	Role of BESS in zonal weak grids	Control Strategies involved in BESS for weak grids	EMSt involved in BESS for weak grids	Transition pathway to promote BESS for REZs integration in weak grids
[14]	✓	✗	✗	✗	✗	✗	✗	✗
[20]	✓	✗	✗	✗	✗	✗	✗	✗
[21]	✓	✗	✗	✗	✗	✗	✗	✗
[26]	✗	✓	✓	✓	✗	✗	✗	✗
[27]	✗	✓	✓	✓	✗	✗	✗	✗
[28]	✗	✗	✗	✓	✗	✓	✓	✗
[29]	✓	✗	✗	✓	✓	✗	✗	✗
[30]	✗	✗	✗	✗	✗	✗	✓	✗
[31]	✗	✓	✓	✗	✗	✗	✗	✗
[32]	✗	✓	✗	✗	✗	✗	✗	✗
[33]	✗	✗	✗	✓	✗	✓	✓	✗
[34]	✗	✗	✗	✓	✓	✓	✓	✗
[35]	✗	✗	✗	✓	✗	✓	✗	✗
[36]	✗	✗	✗	✓	✗	✓	✓	✗
This research	✓	✓	✓	✓	✓	✓	✓	✓

paper are as follows:

- **Critical Analysis:** Identifies challenges in renewable energy integration within weak grids, including grid stability, power quality, and non-dispatchable generation.
- **Evaluation of ESSs:** Reviews various Energy Storage Systems (ESSs), particularly non-BESS technologies, discussing their classifications, fundamentals, advantages, limitations, applications, and operational complexities.
- **BESS Technologies:** Examines different BESS types, their foundations, applications, and advantages over non-BESS solutions, highlighting their effectiveness in mitigating renewable intermittency and enhancing grid reliability in weak zonal grids.
- **BESS Deployment Strategies:** Explores BESS architectures (AC, DC, and hybrid) in islanded and grid-connected weak grids, covering advanced control strategies, energy management techniques, and real-world case studies.
- **Pathway for Large-Scale Adoption:** Beyond summarizing BESS benefits, this paper proposes a strategic transition plan to accelerate large-scale BESS adoption in renewable-rich weak grids. This supports a sustainable, clean energy future aligned with the United Nations Sustainable Development Goals (UNSDGs) 7 and 13.

In summary, analyzing the obstacles to RE integration in weak grids, reviewing various ESSs (with a focus on non-battery solutions), examining BESS technologies in weak grid contexts, deploying appropriate BESS zonal weak grid architectures and control and energy management strategies (EMSt), and advocating for BESS in renewable-rich weak grids are the primary contributions of this study.

This paper is organized into ten sections, each addressing critical aspects of RE integration and energy storage solutions in weak grids. The remainder of this paper is organized as follows: Section 2 discusses the review process used in this study. Section 3, examines the challenges of integrating RE into weak grids, focusing on threats to grid stability and reliability. Section 4 explores ESSs as a potential solution to these challenges, providing an overview of their capabilities and limitations. Section 5 addresses the challenges associated with ESS technologies in weak grids and introduces BESS as a promising alternative to overcome these limitations. Section 6 highlights advancements in BESS technologies and their applications in power grids, emphasizing their role in improving grid performance and RE utilization. Section 7 discusses power management control strategies and algorithms essential for optimizing BESS performance in diverse weak grid scenarios. Sections 8 and 9 focus on the practical applications of BESS in electrical grids, demonstrating their effectiveness in mitigating RE integration challenges. Section 10 proposes transition pathways for large-scale BESS integration and outlines directions for future research in this field. Finally, Section 11 concludes the paper by summarizing key findings and underscoring the importance of continued innovation in developing sustainable energy systems.

2. Review methodology

The literature search and selection process for this review followed a systematic approach to ensure a comprehensive and structured analysis of recent advancements in BESSs for REZs and weak transmission networks. The focus was mainly on recently published papers, with sources obtained from academic databases. The search was conducted using relevant keywords related to BESS applications in weak grids, REZs, control strategies, grid stability, and EMS. The retrieved publications were filtered and categorized based on their relevance to keywords, such as “ESS”, “BESS control strategies”, “energy management”, and “weak grids”. The publication is sorted from the search list depending on the approach, such as BESS control strategies and energy management based on REZs integration in a weak grid scenario. The article search and selection process is displayed in Fig. 2. The information was collected from scholarly resources such as journals, conferences, books and websites. Fig. 3 shows the percentages of information sources. Similarly, Fig. 4 illustrates the percentage distribution of the articles across various publishers.

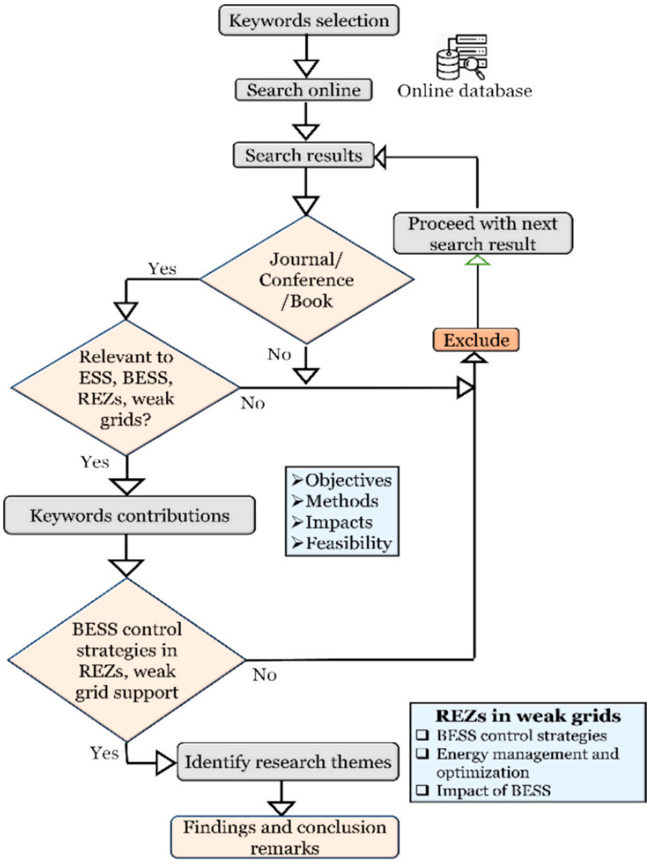


Fig. 2. Flowchart of the article selection method used in this work.

3. Renewable weak grid difficulties and threats

The integration of RESs into weak grids presents a complex landscape of technical, operational, and structural challenges. Weak grids, defined by their low system strength, high impedance, and limited short-circuit capacity, are inherently less robust and more vulnerable to disturbances than their stronger counterparts. These vulnerabilities are magnified as the penetration of RESs increases, driven by the global transition toward sustainable energy [37]. While RE systems offer significant environmental benefits, their intermittent and weather-dependent nature introduces volatility that weak grids struggle to

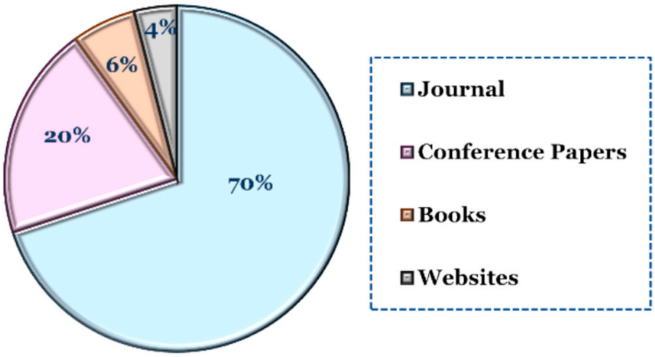


Fig. 3. Sources of articles used in this journal.

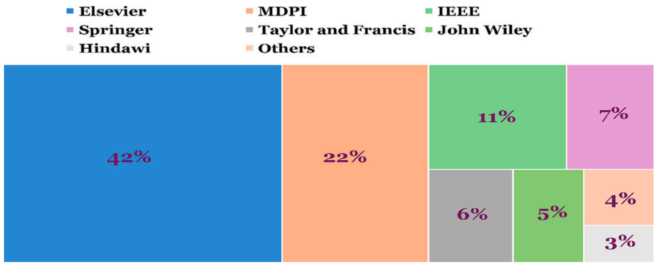


Fig. 4. Distribution of reviewed articles by publisher, focusing on BESS applications in REZs and weak grids.

accommodate [38]. This imbalance sets the stage for a cascade of challenges, ranging from frequency and voltage instability to harmonic distortions and protection system inadequacies, threatening the stability, power quality, and reliability of the entire grid [37–39]. Fig. 5 illustrates the key challenges and their overall impact on grid performance, which are examined in detail in the following subsection.

3.1. Frequency and voltage instability

Frequency and voltage instability are among the most critical challenges in weak grids. The inherent intermittency of RESs, caused by fluctuations in solar irradiance and wind speed, leads to imbalances between supply and demand (Fig. 6a and Fig. 6b). Weak grids, with limited inertia, are less equipped to handle these variations [38,40]. As the displacement of conventional SGs reduces the rotational inertia traditionally used to stabilize grid frequency, weak grids become prone to faster and more severe frequency deviations during disturbances [37,41]. Voltage instability is equally problematic. Weak grids are highly sensitive to active and reactive power fluctuations, meaning sudden changes in RESs output can result in rapid voltage dips or surges [17,18]. This poses risks to grid-connected equipment and overall reliability. Advanced control strategies and reactive power support mechanisms are necessary to maintain voltage stability; otherwise, weak grids face an elevated risk of cascading failures, particularly under high-RES penetration [17,40,41].

3.2. Harmonic distortions and resonance

Harmonic distortions, caused by power electronic converters in RESs, represent a significant threat to power quality in weak grids. These distortions, characterized by the presence of higher-order frequency components, degrade the quality of the voltage waveform, leading to overheating, increased losses, and equipment malfunctions [40,41]. Weak grids, with their limited short-circuit capacity, are less able to suppress these distortions, making them more susceptible to harmonic resonance (Fig. 6c and Fig. 6d). Resonance amplifies specific frequencies, exacerbating system instability and reducing the lifespan of grid infrastructure. Advanced filters and control mechanisms are crucial to mitigating these issues [17,38,39].

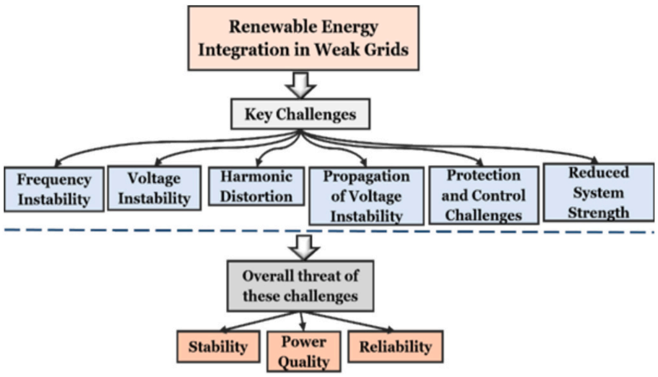


Fig. 5. Challenges and threats of RE integration in weak grids.

3.3. Propagation of voltage instability

The propagation of voltage instability is another critical concern. Due to the high impedance of weak grids, localized disturbances are amplified and can cascade across the network [39,41]. The replacement of SGs with inverter-based RESs further reduces reactive power reserves, intensifying the grid's vulnerability. Without enhanced reactive power compensation and fault ride-through capabilities, weak grids often experience widespread disruptions during fault conditions [17,18,37], as shown in Fig. 6.

3.4. Protection and control challenges

Weak grids also face limitations in protection and control systems. Reduced fault current levels hinder the performance of traditional overcurrent-based protection mechanisms, delaying fault detection and isolation [18,41]. This increases the risk of equipment damage and prolonged outages. Additionally, weak grids demand faster and more adaptive control mechanisms to respond to disturbances. However, the high impedance and reduced system strength often limit the effectiveness of conventional protection strategies. Adaptive protection schemes and dynamic grid management approaches are essential to overcome these limitations [17,37].

3.5. Reduced system strength

System strength, a critical measure of a grid's ability to maintain stable voltage and frequency, is inherently low in weak grids (Fig. 6a and Fig. 6b). High-RES penetration further diminishes system strength by displacing SGs, reducing the grid's fault current capability [39,41]. This increases susceptibility to transient oscillations, voltage instability, and reliability issues. Deploying system-strengthening measures, such as synchronous condensers (SCs) and advanced inverters, is crucial to mitigate these impacts and ensure stable grid operations [17,40].

The next section explores how these challenges can be effectively mitigated, focusing on ESSs as a potential solution for enhancing grid stability and facilitating renewable integration.

4. Addressing weak grid threats: ESSs as a possible solution for renewable integration

The challenges of integrating RE into weak grids, including frequency and voltage instability, harmonic distortions, and reduced system strength, necessitate innovative solutions to ensure grid stability, power quality, and reliability. ESSs emerge as a promising technology to address these issues and facilitate the seamless integration of RESs. This section explores the critical role of ESSs, beginning with a comprehensive classification that highlights their variety and flexibility. It then examines the solutions offered by ESSs, such as improving grid stability, managing intermittency, and providing reactive power support. A detailed analysis of existing ESS technologies is presented, focusing on their principles, benefits, limitations, and applications, followed by a comparative evaluation of their suitability for various grid scenarios. These discussions provide a solid foundation for addressing grid vulnerabilities and advancing the global transition to sustainable and resilient energy systems.

4.1. Classification of ESSs and their application for REZs

The classification of ESSs is fundamental to addressing the challenges of RE integration into weak grids. ESS technologies are categorized into five principal types: Electrochemical (EC), Mechanical (Mech), Thermal

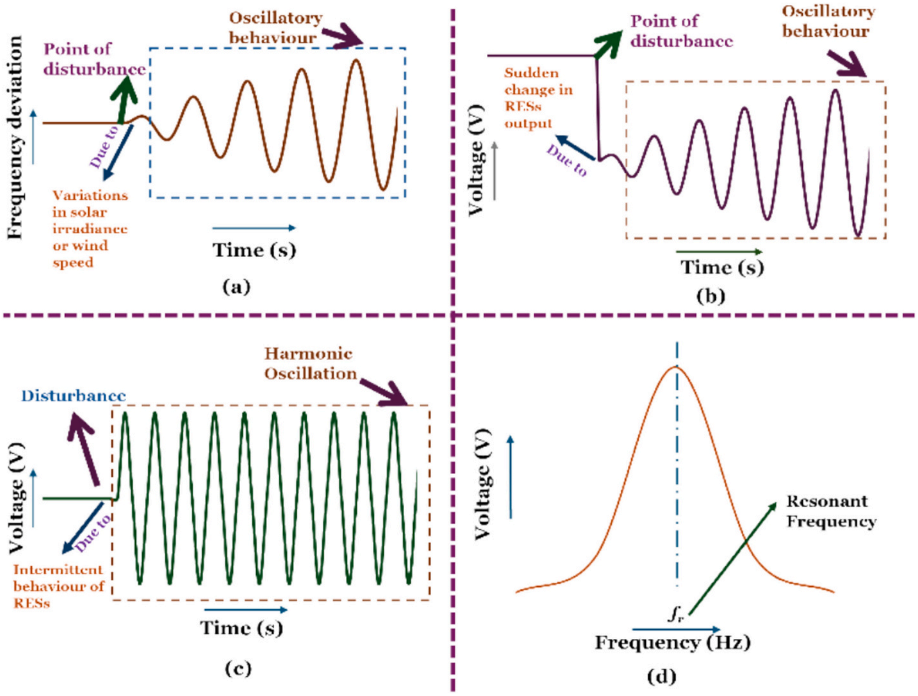


Fig. 6. Threats of RESs integration in weak grids: (a) Frequency Instability, (b) Voltage Instability, (c) Harmonic Distortion and (d) Resonance Effect.

(TCSS), Hydrogen & Chemical (Chem), and Electrical (Elec), each with unique characteristics suited to specific grid applications. These technologies play a pivotal role in enhancing grid stability, managing intermittency, and supporting RE integration. Fig. 7 and Table 2 provide a detailed breakdown of ESS types, highlighting their principles, applications, benefits, and limitations, establishing the foundation for exploring their strategic implementation in addressing weak grid challenges.

4.2. Applications offered by ESSs in weak grids

Having established a comprehensive classification of ESSs in Section 4.1, this section now explores how these distinct technologies collectively offer practical solutions to the challenges posed by weak grids, with Fig. 8 illustrating the key contributions of ESSs in overcoming these grid challenges. By providing rapid-response frequency and voltage stabilization (achieved through systems like Li-ion batteries and flywheels), ESSs compensate for the reduced inertia in inverter-based environments that have largely replaced traditional SGs [26]. Additionally, solutions such as flow batteries and supercapacitors (SCaps) supply much-needed reactive power support in grids with high levels of inverter-based penetration, while advanced technologies like Superconducting Magnetic Energy Storage (SMES) help mitigate power quality issues, including harmonics and voltage sags [43,53]. In managing energy intermittency, hybrid configurations (for instance, PHS combined with Li-ion batteries) smooth out supply–demand mismatches, thereby reducing dependence on fossil-fuel reserves and reinforcing energy availability during peak periods [53]. At the same time, these systems help minimize RE curtailment by storing excess power generated during off-peak times, ensuring it is available when demand

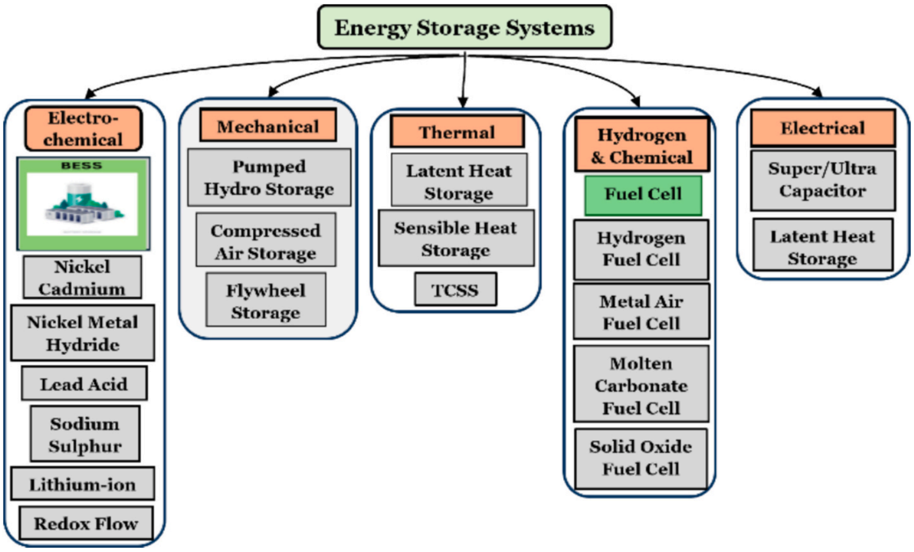


Fig. 7. ESSs classification applying to zonal weak grids.

Table 2
Comprehensive overview of ESSs in weak grids for REZs scenario: attributes, foundations, applications, advantages, and disadvantages.

Ref	ESSs	Key Attributes	Foundations	Applications	Advantages	Disadvantages
[26,42,43]	EC	Capacity: 0.25–300 MWh Efficiency: 65–92 % Lifetime: 5–20 years	Chemical reactions using Cd, Li-ion, and RF electrolytes.	Peak shaving, Frequency regulation, Isolated grid operations	High energy density (Li-Ion), Long lifespan (VRF), Scalability	Toxic material disposal (NiCd), High operating temperature (NaS)
[44–46]	Mech	Capacity: Up to 3 GW Efficiency: 70–95 % Lifetime: Up to 50 years Response Time: 1–2 min	Gravitational energy, pressurized air, and rotational kinetic energy storage	Energy arbitration, Load leveling, Spinning reserve, Voltage support	Long lifespan, High efficiency, Scalability	High installation cost, Greenhouse gas emissions (CA), Limited operational periods (flywheel)
[26,47–49]	TCSS	Efficiency: 50–100 % Storage Medium: Versatile storage mediums (sensible, latent, thermochemical)	Phase change materials, thermal storage in solids/ liquids, and chemical heat reactions.	Solar thermal, Co-generation	Long storage durations, Compatibility with RESs	Lower energy density (Sensible Heat), Complex material handling (TC)
[45,50,51]	Chem	Operating Temperature: 600–1100 °C Efficiency: Up to 65 % Flexible fuel compatibility	EC hydrogen conversion, reactions with oxygen, and molten carbonate or solid oxide electrolytes.	Hydrogen utilization, Co-generation, High-temperature operations.	High energy efficiency, Diverse fuel sources, Co-generation capabilities	High operating temperature, Expensive raw materials
[45,50,52]	Elec	Power Range: 10 kW to 10 MW Efficiency: 90–95 % Response Time: Milliseconds	Electrostatic and phase-change energy storage.	Voltage quality, Frequency support, Peak shaving	Rapid response, High reliability, Low energy losses	High capital cost, Magnetic field management

Fig. 8. Key contributions of ESSs in overcoming grid challenges.

rises. Beyond stability, ESSs strengthen resilience by providing black-start capabilities and facilitating microgrid development, especially in remote or rural areas [32]. Although ESSs can require substantial initial investment, their long-term advantages (such as reduced reliance on peaking plants, lower maintenance expenses, and additional revenue from ancillary services) support their economic viability [54]. Crucially, the ability to accommodate higher levels of RE significantly reduces greenhouse gas emissions, positioning ESSs as a cornerstone of the shift toward more sustainable and carbon-neutral energy systems [4,7,32].

5. Roles of ESSs in mitigating weak grid challenges

Building on the solutions discussed in Section 4, ESSs play a crucial role in addressing weak grid challenges, but non-battery systems like mechanical, thermal, chemical, and electrical storage often face limitations such as slower response times, lower efficiency, and reduced flexibility. In contrast, BESSs provide superior efficiency, adaptability, and rapid response capabilities, making them particularly effective in stabilizing weak grids, managing power fluctuations, and integrating RESs. This section highlights the limitations of non-battery storage technologies and positions BESSs as a more practical and versatile solution for modern grid needs, paving the way for enhanced grid stability and reliable RE integration.

5.1. Limitations of non-battery storage technologies

ESSs such as mechanical, thermal, chemical, and electrical storage systems are essential for addressing grid vulnerabilities and managing RE intermittencies. However, these technologies exhibit significant limitations that constrain their practical deployment. Mech ESSs, including PHS and CAS, are restricted by geographic and structural dependencies. PHS requires large-scale water reservoirs and significant elevation differences, making it unsuitable for flat or water-scarce regions. Despite their high efficiency (70–85 %) and long lifetimes, the upfront installation costs are substantial [32]. CAS, on the other hand, necessitates underground formations for compressed air, adding to its environmental and capital complexities. Flywheel storage, while capable of delivering rapid response times, suffers from limited energy storage capacity, short operational lifespans, and high mechanical wear [55,56]. A detailed comparison of the key attributes, applications, advantages, and disadvantages of these ESS technologies is summarized in Table 2.

Thermal ESSs face challenges tied to their energy density and operational costs. Sensible heat storage systems, which store energy in solids or liquids, exhibit low energy density, making large-scale applications impractical [50,57,58]. Latent heat and thermochemical storage systems (TCSS), though promising in terms of efficiency (up to 100 %), involve high material costs and complex operational processes, particularly in managing advanced phase change materials and chemical reactions [31]. The need for specialized infrastructure further increases deployment expenses, limiting their feasibility for weak-grid integration [50].

Chem ESSs, including hydrogen FCs, molten carbonate fuel cells (MCFC), and solid oxide fuel cells (SOFC), demonstrate high energy efficiency and compatibility with RESs. However, their reliance on high operating temperatures (600–1100 °C) and expensive raw materials significantly hamper their economic viability [27,31,56]. Additionally, the conversion processes for chemical storage often involve complex electrochemical reactions that demand precise control systems, increasing maintenance costs and operational complexity [26,54].

Elec. ESSs, such as SCap and SMES, offer high efficiencies (90–95 %) and rapid response times, making them suitable for power quality applications like frequency regulation and voltage stabilization [31,56]. However, these systems are limited by their low energy density, which restricts their use for long-duration energy storage. Moreover, SMES requires extremely low temperatures for superconductivity, leading to high capital and operational costs associated with cryogenic systems. SCap, while efficient, have limited storage durations and face scalability issues for large-scale grid applications [50,59].

To address these limitations, BESSs emerge as a superior solution due to their flexibility, scalability, and cost-effectiveness. As discussed in the next subsection, BESSs offer the capability to stabilize grid operations, manage renewable intermittencies, and enhance power quality.

5.2. Addressing challenges through BESSs for REZs integration in weak grids

BESSs have emerged as the most advanced and practical solution to overcome the limitations of non-BESSs, ensuring grid stability and the seamless integration of RESs. Unlike mech and thermal systems that face geographic, structural, or operational constraints, BESS offers unmatched flexibility, scalability, and efficiency [34,35]. Fig. 9 highlights the key contributions of BESS in zonal weak grids, showcasing its role in enhancing grid stability, operational reliability, and RE utilization.

BESSs play a pivotal role in stabilizing grid frequency and voltage, responding almost instantaneously to fluctuations caused by RE intermittency. Technologies such as Li-ion batteries excel in delivering fast response times and ensuring grid inertia, where SGs are limited. Additionally, BESS contributes to power quality improvement by addressing voltage sags, harmonic distortions, and grid anomalies, which are increasingly critical in renewable-rich power systems [36,60].

One of the most significant contributions of BESS is its capability to manage renewable intermittency effectively. By storing surplus energy during periods of low demand and discharging it during peak loads, BESS minimizes RE curtailment while enhancing system reliability. This functionality is particularly beneficial for maintaining energy balance in weak or isolated grids, where other storage technologies face limitations [61].

Furthermore, BESS provides resilience through black-start capabilities, allowing grids to recover independently from outages without relying on conventional fossil fuel generators. Technologies such as Li-ion and NaS batteries are particularly suited for this function due to their rapid response times and scalability [33,35]. Black-start capability ensures operational continuity and reinforces grid reliability during unforeseen disruptions.

Despite the higher upfront costs associated with BESS, the technology offers long-term economic and environmental benefits. Continuous advancements in battery chemistries, including VRF and next-generation sodium-based batteries, are improving efficiency, reducing costs, and extending operational lifespans [33,55]. These advancements position BESS as a cornerstone for modern energy storage, enabling greater RE penetration while reducing greenhouse gas emissions [56].

The critical role of ESSs in mitigating grid challenges has been demonstrated, with Battery Energy Storage Systems (BESSs) emerging as a superior and adaptable solution [27,44,55]. Unlike non-battery ESS technologies, which face significant limitations in practical implementation, BESS provides robust solutions to address frequency and voltage instability, power quality issues, renewable intermittency, and grid resilience [34]. By leveraging advanced chemistries and configurations, BESS offers unmatched efficiency, flexibility, and scalability, making it the cornerstone of modern energy storage strategies.

As we transition to Section 6, the focus shifts toward the advancements in BESS technologies and their wide-ranging applications to weak power grids.

6. Advancement of BESS technologies and their applications to weak power grids

Building on the discussion in Section 4 about the limitations of non-BESSs, BESS stands out as a powerful solution for modern power grids. This section focuses on the progress in BESS technologies, their important role in improving weak grid stability and supporting RE integration, and the strategies used to manage and control their operations. By examining the basics, comparing their performance, and exploring innovative control methods, this section highlights why BESS is crucial for solving grid challenges and advancing toward a more sustainable energy future.

6.1. Different types of BESS for weak power grid applications

BESS play a vital role in modern power grids by storing and converting chemical energy into electrical energy, thereby supporting RE integration and addressing grid stability challenges. Key BESS technologies include Li-ion batteries, known for their high energy density and reliability; Pb-acid batteries, which are cost-effective and have a long operational history; NaS batteries, well-suited for large-scale applications despite high-temperature requirements; RFB, offering scalability and extended discharge durations; and Ni-based batteries, recognized for their durability but limited by toxicity or cost. As summarized in Table 3, each technology varies in foundational principles, advantages, and typical applications, providing a spectrum of solutions to meet diverse energy storage needs.

6.1.1. Comparative study among different BESS technologies

BESSs are critical enablers of modern power systems, addressing the challenges posed by the integration of variable renewable energy (VRE) sources such as solar and wind. These systems ensure flexibility, stability, and reliability in the power grid, where the intermittency of RE poses significant challenges to traditional grid operations. As the penetration of RE continues to grow, selecting the right BESS technology for specific applications has become vital. This section provides an in-depth comparative analysis of key BESS technologies, focusing on their performance in terms of efficiency, lifecycle, cost, and application.

BESS encompasses a range of technologies, each with distinct attributes, making them suitable for diverse grid applications. Li-ion batteries, known for fast response, and efficiency (90–95 %), dominate the market and are widely used in utility-scale storage, RE integration, and electric vehicles [65]. Pb-acid batteries, as one of the most established technologies, offer low cost and.

simplicity, making them ideal for backup power and off-grid systems, despite their lower energy density. NaS batteries, operating at high temperatures (~300 °C) with an efficiency of 85–90 %, are well-suited for grid-scale applications like load leveling and RE integration but require robust thermal management systems [34]. RFB provide unparalleled scalability and extended lifespans of 20 years, excelling in long-duration energy storage and grid stabilization, although their lower energy density and high upfront costs limit smaller applications [33]. Ni-based batteries, including Ni—Cd and Ni-MH, are valued for their durability in extreme conditions, catering to niche industrial and specialized markets. As the global energy landscape continues to transition toward RE, BESS technologies will play an increasingly vital role

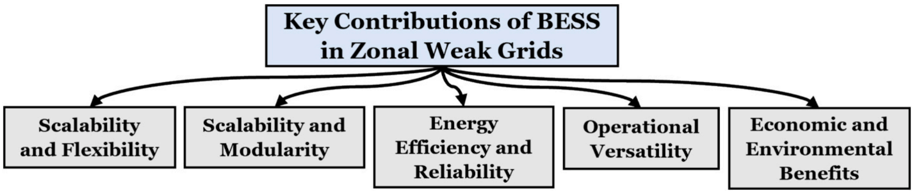


Fig. 9. Key Contribution of BESS in zonal weak grids.

Table 3
Summary of major BESS technologies.

Ref.	Name of BESS	Foundation	Advantages	Applications
[26,62,63]	Li-ion	Movement of Li-ions between the anode and cathode during charge/discharge	- High energy density - Lightweight - Fast response time - Reliability - Long cycle life	- Grid-scale energy storage - Electric vehicles - Consumer electronics
[26,28,54]	Pb-Acid	Chemical reaction between lead dioxide (cathode), lead (anode), and sulfuric acid electrolyte	- Low cost - Ease of deployment - Proven performance	Backup power - Off-grid microgrids
[28,33,34]	NaS	High-temperature operation (~300 °C) using molten sodium and sulfur electrodes	- High energy efficiency (75–85 %) - Extended operational life - Effective for large-scale storage	- Load leveling - RE integration - Grid-scale deployments
[26,59]	RFB, e.g. VRFB	Energy is stored in liquid electrolytes, with redox reactions occurring in separate tanks	- Scalability - Long operational lifespan - Flexible discharge durations	- Long-duration energy storage - Large-scale grid applications
[27,59,64]	Ni-Cd, NiMH	EC reactions involving nickel and cadmium or nickel-metal hydride	- Ni-Cd: Durable, efficient in extreme temperatures - NiMH: Higher energy density	- Backup power - Industrial applications (Ni—Cd) - Consumer electronics (NiMH)

in maintaining grid stability and efficiency [27,53,59]. The comparative analysis, summarized in Table 4, highlights the unique strengths of each technology, providing valuable guidance for stakeholders in selecting the most appropriate solution for specific energy storage needs. Future advancements in cost reduction, lifecycle management, and efficiency are expected to further enhance the capabilities and adoption of these technologies. While this comparative study highlights the relative merits of different BESS technologies, their effective deployment in weak grids critically depends on sophisticated BMSs to ensure stable and reliable operation [33]. The following section explores the pivotal role of BMSs in facilitating BESS integration within weak grid environments.

6.1.2. *Role of BMSs in BESS operation for weak grids*

The efficient and safe operation of BESS heavily depends on robust Battery Management Systems (BMS). A BMSs continuously monitors voltage, current, and temperature while estimating critical states like State of Charge (SOC) and State of Health (SOH) [33]. These capabilities are critical for preventing thermal runaway, overcharging, or deep discharging—issues that accelerate degradation in large-scale BESS deployments integrated into weak grids [33,84]. As shown in Fig. 10, each battery pack employs a dedicated BMS for cell balancing, thermal management, and fault protection. Multiple packs are coordinated via Supervisory System Control (SSC), which optimizes power flow to meet grid demands. Predictive, model-based BMS frameworks further enhance performance by minimizing degradation and enabling adaptive charge/discharge strategies under variable loads [33]. For lithium-ion and flow batteries, BMS functionalities extend to internal state inference and electrolyte flow control, respectively [65]. In renewable-rich weak grids, intelligent BMS integration is vital to stabilize voltage/frequency fluctuations and maximize BESS longevity while delivering services like peak shaving and frequency regulation [33,65,84].

6.2. *BESSs in zonal weak grids*

This subsection discusses BESS in its role in zonal weak grid systems. Weak grid environments, characterized by high impedance and limited fault capacity, pose significant challenges for RE integration and grid stability. BESS emerges as a pivotal solution to manage power quality, mitigate instabilities, and optimize energy usage in such systems. The following subsections explore BESSs in various zonal weak grid configurations and their associated control and EMSt.

6.2.1. *Zonal weak grid configurations*

Zonal weak grids can be classified into islanded weak grids and grid-connected weak grids, each presenting unique operational challenges and opportunities [18,67–69]. By applying the advanced control and EMSt developed for microgrids, BESS plays a critical role in stabilizing voltage and frequency, mitigating RE variability, and ensuring efficient energy utilization within zonal weak grids [70]. The seamless application of these strategies across both microgrids and zonal weak grids highlights the indispensable role of BESS in bridging localized and regional energy systems, creating a cohesive approach to RE integration and grid modernization [12].

6.2.1.1. Islanded zonal weak grid. Islanded zonal weak grids operate independently of a larger grid, relying entirely on localized energy generation, often from RESs [69]. In REZs, these grids are crucial for harnessing and distributing renewable power effectively without direct support from a strong grid. Within islanded weak grids, BESS plays a critical role in stabilizing voltage and frequency, mitigating fluctuations from VRSs, and maintaining the power supply-demand balance [18,68]. Fig. 11 shows the Islanded mode of zonal weak grids with RESs and BESS along with a static switch for transition purposes.

6.2.1.2. Grid-connected zonal weak grid. Grid-connected zonal weak grids operate in synchronization with the central grid, enabling

Table 4
Key information of different BESS [26,27,43,59,62].

Technology	Battery cell energy density (W.h/kg)	Battery cell power density (W/kg)	Capacity (MWh)	Lifespan (Years)	Cost ($/kWh)	Efficiency (%)	Most Suitable Grid Applications
Li-ion	70–250	1000	0.25–25	10–15	300–1500	90–95	High-demand scenarios requiring rapid response
Pb-Acid	50	500	0.25–50	5–15	200–400	70–85	Cost-sensitive projects, backup power systems
NaS	150	100	≤ 300	10–15	300–500	85–90	Large-scale RE integration
RFB	25	100	≤ 250	15–20	11,000	65–85	Long-duration applications requiring high scalability and safety
NiCd	–	–	–	Around 10	800–1500	70–90	Harsh environments with extreme temperatures
NiMH	–	–	–	Around 5	600–1200	65–85	Specialized use cases with limited space or specific temperature demands

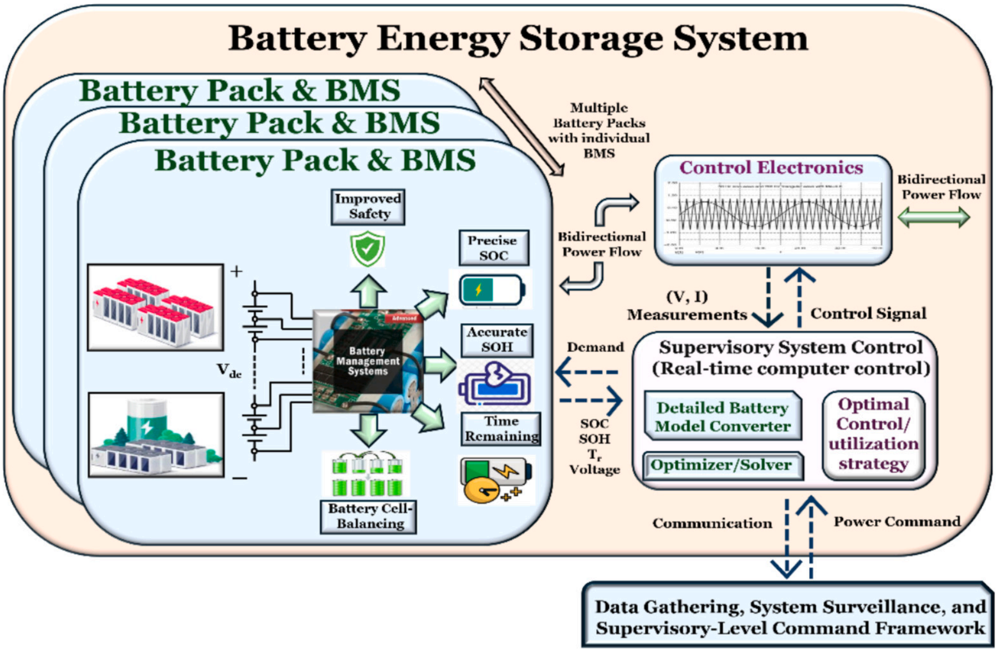


Fig. 10. BESS schematic with hierarchical BMS for weak grids: battery pack integration, SOC/SOH monitoring, and stability optimization.

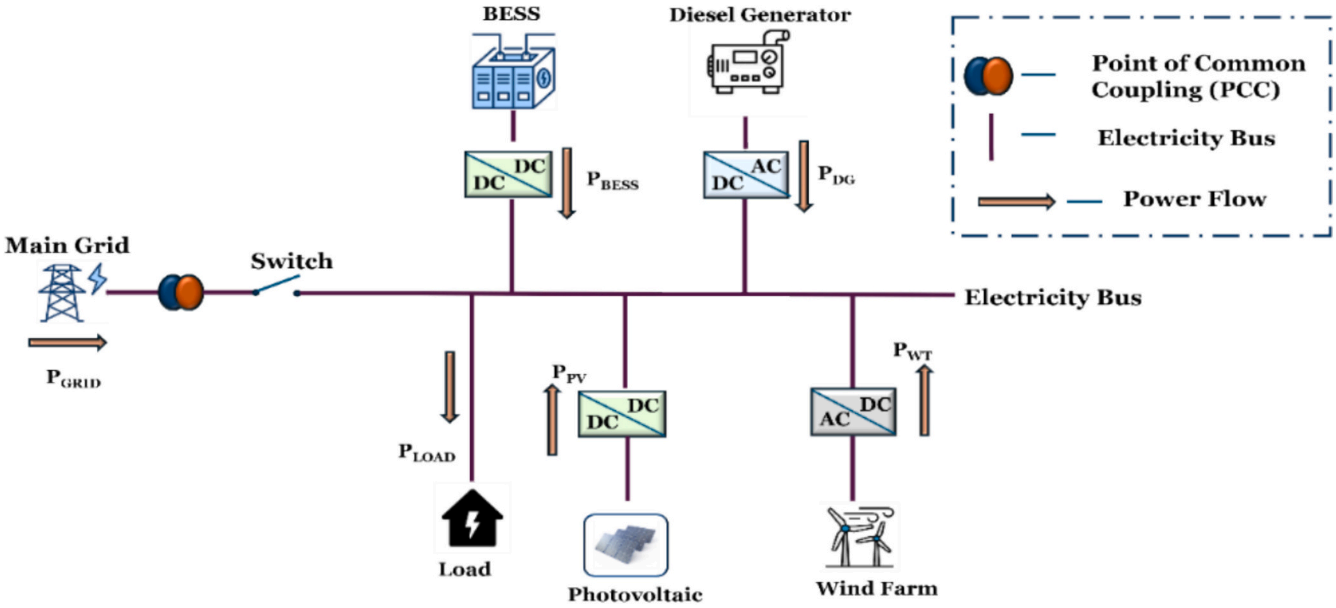


Fig. 11. Islanded mode of zonal weak grids with RESs and BESSs.

enhanced grid stability and efficient integration of REZs [18]. These grids are pivotal for leveraging localized RE while maintaining reliability through the support of the main grid [12,19]. BESS play a central role in managing power quality, optimizing energy flow, and ensuring seamless coordination between local RESs and the central grid [34]. Fig. 12 highlights the general configuration of the grid-connected mode of zonal weak grids along with RESs and BESS [67].

Table 5 further highlights the key role of BESS while integrating the REZs in islanded zonal weak grids along with grid-connected zonal weak grids, discussing its key roles, opportunities involved, challenges associated with it and future potential of BESSs. Each configuration offers unique advantages and challenges in integrating RE, as detailed below.

Further, Table 6 highlights some of the key differences between islanded zonal weak grids and grid-connected zonal weak grids.

6.2.1.3. AC zonal weak grid. AC zonal weak grids are prevalent in traditional power systems and are widely used to interface with RESs such as wind turbines and solar inverters, as shown in Fig. 13 [67]. Operating with AC, these grids ensure compatibility with conventional power systems and RESs. AC weak grids can function in both islanded and grid-connected modes, making them versatile for various applications [67,69]. In these grids, BESS plays a crucial role in ensuring stability and reliability [34]. BESS supports voltage regulation by providing reactive power to stabilize voltage levels, enhances frequency stabilization by managing deviations caused by renewable intermittency and load fluctuations, and facilitates peak shaving by discharging energy during high-demand periods to reduce grid stress [34,77]. Advanced control strategies like droop control and H-infinity robust control are commonly employed to ensure stability and dynamic performance. AC

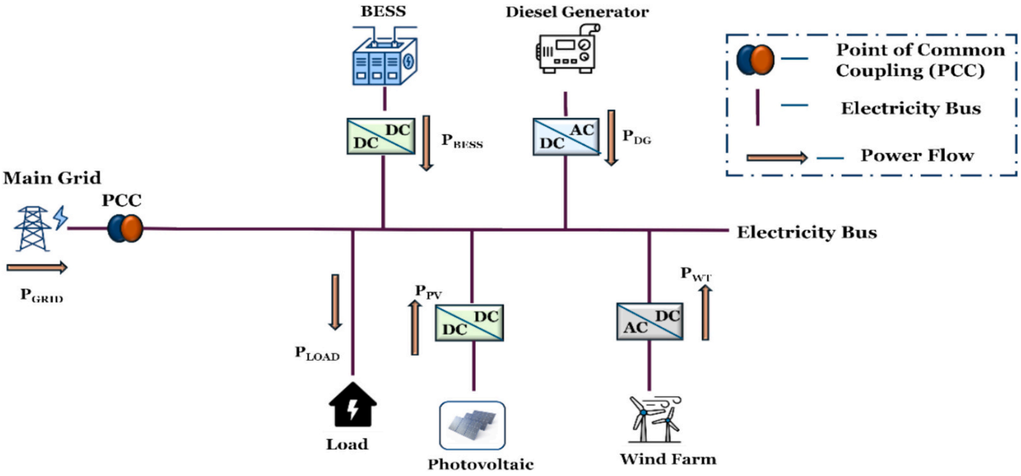


Fig. 12. General configurations of grid-connected mode of zonal weak grids along with RESs and BESS.

weak grids are particularly effective in wind-dominated REZs, where BESS mitigates variability and supports ancillary grid operations seamlessly in both islanded and grid-connected configurations [66].

6.2.1.4. DC zonal weak grid. DC zonal weak grids are gaining prominence due to their high compatibility with modern RE technologies such as solar PV systems and electric vehicle charging stations [71]. Fig. 14 shows the typical DC zonal weak grid architecture with the inclusion of RESs and BESS [67]. Operating with DC, these grids simplify energy management by eliminating the need for complex AC-DC conversions and significantly reducing energy losses [78]. BESS in DC weak grids ensure efficient energy transfer by minimizing losses during the connection of RESs and loads, mitigates power fluctuations to maintain a consistent energy flow and stabilizes voltage levels across the grid. Advanced control strategies, such as DC-DC converters and EMSs, are employed to optimize the grid's performance. DC weak grids are particularly well-suited for solar-dominated REZs, where BESS stores surplus energy during high-generation periods and ensures stability during low-generation periods, addressing variability and maximizing the utilization of RESs [73].

6.2.1.5. Hybrid zonal weak grid. Hybrid zonal weak grids integrate both AC and DC systems, combining the advantages of each configuration to support diverse energy sources and loads [18,19]. Fig. 15 further highlights the hybrid zonal weak grids with the integration of BESS and RESs [67]. These grids offer flexibility and efficiency, making them particularly effective in REZs with mixed-generation resources. In hybrid weak grids, BESS serves as a central component, acting as a buffer to balance supply and demand while facilitating power flow management across AC and DC subsystems [78,79]. BESS also mitigates power quality issues, such as voltage and frequency instability in AC systems and voltage drops in DC systems, ensuring stable operation. Hybrid grids excel in RE integration, enabling optimal utilization of mixed RESs like wind (AC) and solar PV (DC). To ensure stability and efficiency in these complex systems, hybrid controllers such as Model Predictive Control (MPC), Particle Swarm Optimization (PSO), and Fuzzy Logic Control (FLC) are deployed [72,78,79]. These grids are particularly valuable in mixed-generation REZs, where dynamic coordination and optimized performance are essential for reliable and sustainable energy delivery [69,72,73].

7. Power management control strategies and algorithms used for BESSs in weak grids

As the role of BESSs in modern power grids continues to expand, the need for sophisticated control strategies and energy management algorithms has become increasingly apparent. These mechanisms ensure that BESS operates optimally to provide critical services such as frequency regulation, RE integration, and peak load shaving. This section explores the recent advancements in BESS in weak grid operation in terms of control strategies and EMSt.

7.1. Overview of control strategies and energy management

BESSs are pivotal in modern power systems, requiring robust control strategies and EMS to maximize efficiency, enhance grid stability, and optimize energy usage. Advanced controllers are designed to address diverse operational goals, such as managing RE intermittency, balancing supply and demand, and improving economic outcomes.

7.1.1. Control strategies

Control strategies for BESSs are integral to ensuring efficient operation, grid stability, and seamless integration of RESs. Among these, Proportional-Integral (PI) controllers are widely used for their simplicity and reliability in steady-state conditions, while MPC excels in dynamic grid environments by predicting future states and optimizing real-time operations [66,78,80]. Fig. 16 highlights the MPC block diagrams for BESS application in weak grids. FLC is effective for managing non-linear and uncertain systems, making it ideal for renewable integration [79,81], whereas SMC provides high robustness in dynamic conditions but may suffer from inefficiencies due to chattering [84]. Fig. 17 illustrates BESS control using fuzzy FLC. Advanced methods like H-infinity robust control ensure stability under extreme uncertainties [83], and Neural Network-Based Control (NNC) leverages data-driven techniques to adapt and optimize operations dynamically [84]. Fig. 18 further shows some control strategies and algorithms used to optimize BESS for weak grids, especially while integrating it in REZs. RL introduces self-learning capabilities for unpredictable environments (Fig. 18a), while PSO (Fig. 18b) and Genetic Algorithms (GA) (Fig. 18c) focus on optimizing BESS sizing, placement, and scheduling for long-term efficiency [85,86]. Decentralized approaches such as Droop Control balance power among distributed resources [87], and Adaptive Control dynamically adjusts parameters to respond to varying grid conditions [85]. Finally, Decoupled Active-Reactive Control (DARC) ensures stability and efficiency in hybrid systems by managing active and reactive power separately [66,88,89]. These diverse strategies collectively address the challenges posed by renewable intermittency, variability, and operational optimization. The details of these strategies, along with their applications, advantages, challenges, and suitability for various RESs, are summarized in Table 7.

Table 5
Role of BESS for the integration of REZs in Islanded Zonal Weak Grids and Grid Connected Weak Grids [34,52,67,72–75].

Aspect	Details (Islanded Zonal Weak Grids)	Details (Grid Connected Weak Grids)
Key Role of BESS	Stores excess RE during high-generation periods.	Manages power quality by providing voltage regulation and frequency stabilization.
	Discharges energy during low-generation periods to ensure a consistent power supply.	Stores excess RE and discharges it during low-generation periods.
	Mitigates intermittency and reduces RE curtailment.	Reduces RE curtailment and mitigates intermittency.
	Provides ancillary services like voltage regulation, frequency stabilization, and black start capabilities.	Supports peak shaving and energy arbitrage for economic benefits.
	Enables energy arbitrage and peak shaving to enhance economic outcomes.	Improves grid reliability by acting as a buffer between REZs and the central grid.
	Improves overall grid reliability and energy utilization.	
Opportunities	Enhanced grid reliability through seamless integration of RESs.	Enhances grid resilience by integrating RE effectively.
	Improved power quality by mitigating fluctuations and instabilities in isolated systems.	Improves power quality and minimizes disturbances in grid operations.
	Increased penetration of RESs, making islanded grids more sustainable.	Increases the penetration of renewables in centralized systems.
	Economic benefits from operational cost reductions and optimized energy usage.	Reduces operational costs through optimized energy usage.
Challenges	Limited fault current capacity in weak grids, which complicates stability.	Requires robust converters and advanced control systems for seamless operation.
	High sensitivity to disturbances, requiring advanced control and management systems.	High sensitivity to disturbances, requiring real-time adjustments.
	Complex control requirements for managing diverse RE inputs.	Complex coordination with the central grid and distributed resources.
	Need for precise forecasting and real-time adjustments to accommodate variability and intermittency.	Integration challenges due to diverse RESs and configurations.
	Integration challenges due to the remote locations of REZs	
Future Potential of BESS	Evolution of BESS technologies to provide more robust and scalable solutions.	Advances in hybrid control systems to optimize operations across AC and DC subsystems.
	Development of predictive models and advanced control algorithms for real-time optimization.	Development of predictive models for real-time coordination with the central grid.
	Increased deployment in REZs to unlock their full potential.	Increased deployment in grid-connected REZs to maximize resource utilization.

Table 6
Key differences between islanded zonal weak grids and grid-connected zonal weak grids (with AC, DC, and Hybrid Configurations) [18,19,34,67–69,71].

Aspect	Islanded Zonal Weak Grids	Grid-Connected Zonal Weak Grids
Definition	Operates independently of a larger grid, relying entirely on localized generation.	Operates in synchronization with the main grid while integrating local generation.
Primary Power Sources	RESs, such as solar PV and wind, with no external grid support.	Combination of RESs and centralized grid power.
Applications	Ideal for remote and isolated REZs	Suitable for urban and semi-urban areas with centralized grid connectivity.
Key Grid Types	AC Weak Grid: Requires BESS for frequency stabilization and reactive power support.	AC Weak Grid: Relies on BESS for peak shaving, voltage regulation, and grid ancillary services.
	DC Weak Grid: Simplifies power flow and reduces energy losses with direct renewable-BESS connections.	DC Weak Grid: Improves energy transfer efficiency and supports solar-dominated systems with BESS.
	Hybrid Weak Grid: Integrates AC and DC systems for diverse energy sources, with BESS ensuring stability.	Hybrid Weak Grid: Balances mixed energy flows with advanced BESS coordination across AC and DC subsystems.
Economic Potential	Reduces reliance on fossil fuels, operational cost optimization through storage.	Reduces demand charges, supports RE markets, and enhances grid stability.

7.2. *Energy management systems*

EMSs in BESS build upon the robust control strategies discussed in the previous subsection to optimize their operational efficiency, enhance grid stability, and support economic and technical objectives. While control strategies such as PI controllers, MPC, and FLC govern the real-time behavior of BESS, EMSt operate at a broader level to ensure long-term system performance and reliability. These strategies include cost optimization, which leverages electricity price fluctuations to maximize economic returns, and load shifting and peak shaving, which alleviate grid stress and reduce peak demand by strategically managing energy storage and release [65,70,95,118]. Effective State of Charge (SoC) management complements these efforts by maintaining safe operating limits for the battery, thereby extending its lifespan and reliability [96]. RE integration, a key focus of BESS, is facilitated by storing excess energy during high-generation periods and discharging during deficits, thereby mitigating intermittency and reducing curtailment [97,119]. Strategies such as energy arbitrage, frequency and voltage regulation, and black start capabilities further enhance the grid's operational stability and resilience [98,120]. Emerging techniques, such as decentralized energy trading and Demand-Side Management (DSM), promote flexibility and encourage renewable adoption [99,121]. Table 8 provides a detailed overview of these EMSt, highlighting their descriptions, applications, advantages, and challenges, thereby illustrating the critical role of BESS in modern energy systems and their seamless integration into dynamic energy environments.

While conventional control strategies such as PI and droop control offer simplicity and ease of implementation for BESS deployment in weak grids, their rigidity limits their effectiveness in dynamic, renewable-rich environments. In contrast, advanced methods, including MPC, FLC, and RL, demonstrate greater adaptability to grid instability, stochastic generation patterns, and load fluctuations. Among these, hybrid approaches that combine predictive optimization (e.g., MPC and PSO) with real-time adaptability (e.g., FLC or RL) stand out as the most suitable. These integrated strategies enhance system stability and operational efficiency, making them well-aligned with the evolution of intelligent energy systems. Ultimately, the convergence of adaptive control techniques with EMS frameworks is critical to maximizing the role of BESS in strengthening grid resilience and supporting large-scale decarbonization.

After a detailed exploration of power management control strategies and algorithms for BESS in weak grids, the next section provides an in-depth discussion of the application of BESS in electrical grids.

8. Applications of BESS in electrical weak grids

The increasing integration of RE into electrical grids has necessitated the development of robust technologies to address challenges such as intermittency, curtailment, and grid stability. BESSs have emerged as a key solution due to their ability to provide dynamic support across various operational scenarios. This section reviews the role of BESSs in

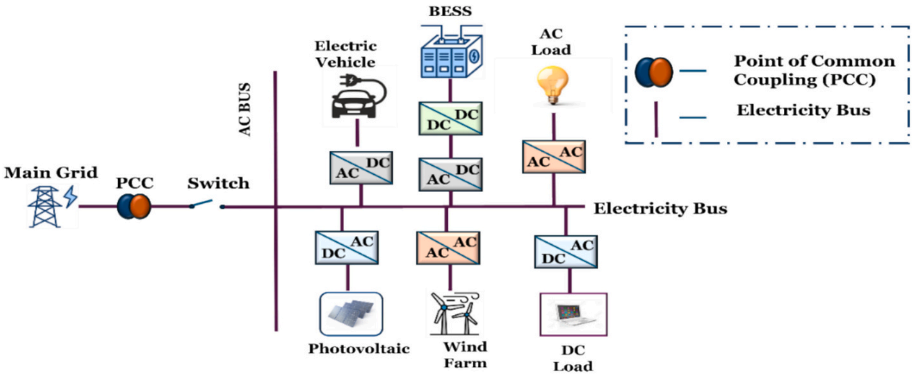


Fig. 13. AC zonal weak grid architecture including BESSs and RESs.

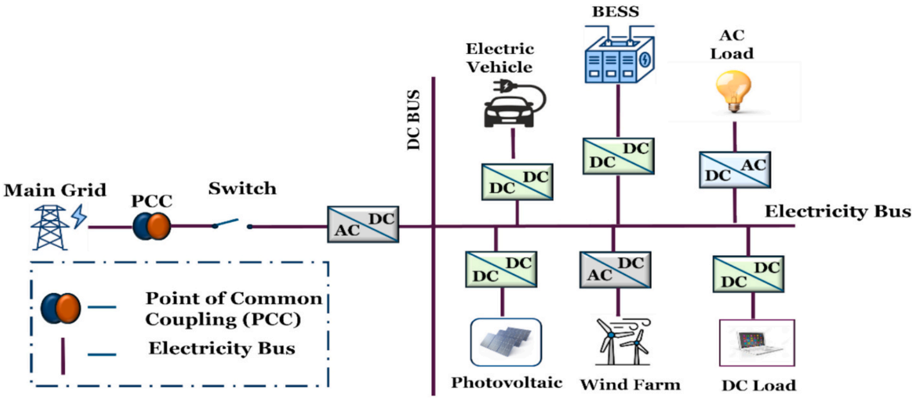


Fig. 14. DC zonal weak grid architecture including BESS and RESs.

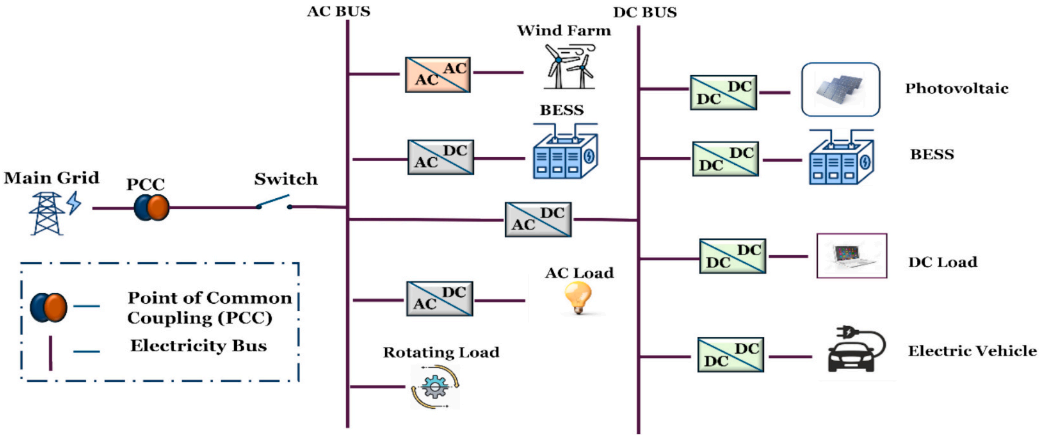


Fig. 15. Hybrid zonal weak grid architecture including BESSs and RESs.

enhancing grid stability and supporting RE integration, synthesizing findings from existing literature and highlighting practical applications.

8.1. *Enhancing grid stability*

The stability of modern power grids is increasingly challenged by fluctuating generation from RESs, growing loads, and aging infrastructure. Various reactive power support technologies have been developed and deployed to address these challenges, ensuring voltage stability, power quality, and operational reliability. Among these, BESS has gained significant attention as a flexible and efficient solution for reactive power support. However, understanding how BESS stands out requires an overview of the available technologies and their comparative performance. The following section is going to discuss the overview and the comparison of the reactive power support technologies followed by the role of BESS in providing reactive power support.

8.2. *Role of BESS in providing reactive power support*

Reactive power support is essential for maintaining voltage levels in power grids, enabling the efficient operation of electrical equipment and ensuring reliable power delivery. Multiple technologies are available to provide reactive power support, each with its strengths, limitations, and suitability for specific grid conditions. These technologies include

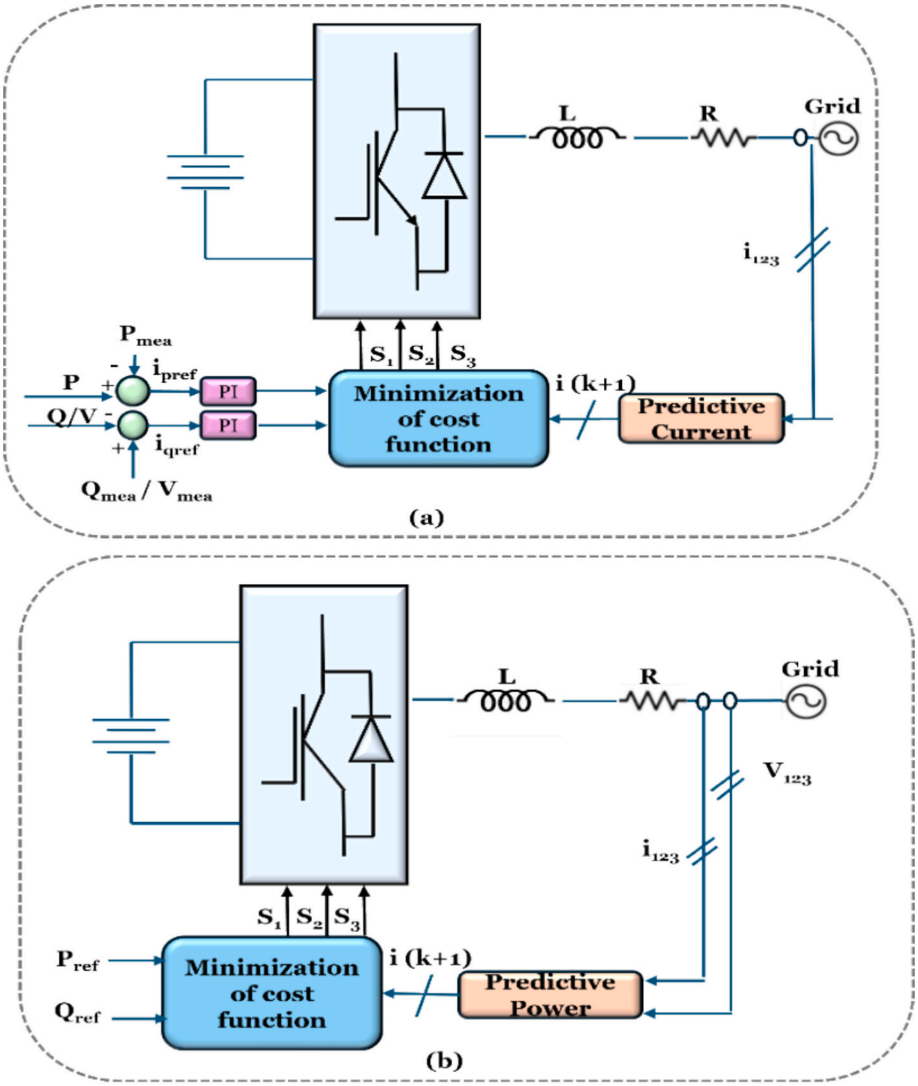


Fig. 16. MPC block diagrams for BESS applications in weak grids; (a) MPC based on Predictive Current Control (PCC), (b) MPC based on Predictive Power Control (PPC) [78].

BESSs, SCs, static var. compensators (SVC), static synchronous compensators (STATCOM), capacitor banks (Cap Bank) and FACTS. Each of these technologies has its response times, dynamic adjustments, cost measurements, scalability, inertia contribution and applications. Table 9 summarizes all the required information in detail for these technologies, including its advantages and disadvantages.

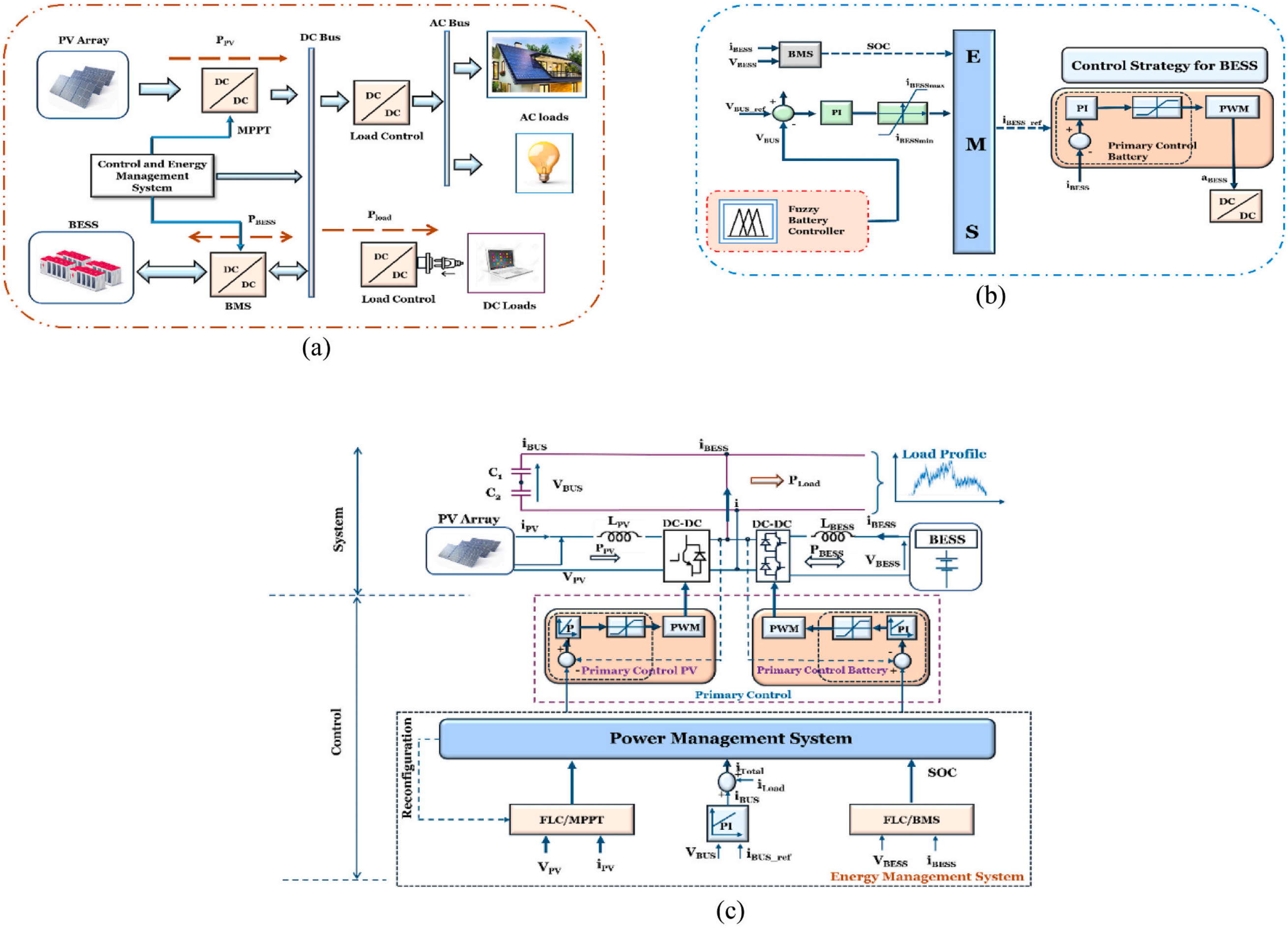
While the technologies shown in Table 9 has served reactive power needs in traditional and evolving grids, the increasing penetration of RE necessitates a more versatile and responsive solution. BESS have emerged as a fruitful technology, combining the fast response and dynamic capabilities of STATCOM with the flexibility of scalable deployments. Table 10 further highlights the key advantages of BESS compared to other technologies. BESS provides not only reactive power support but also active power compensation, making it uniquely positioned to address the challenges of RE integration, load balancing, and transient stability [66,86,108,122]. Unlike traditional reactive power devices, BESS can dynamically adapt to varying grid conditions while offering additional services like frequency regulation and energy arbitrage [106,107,123]. These capabilities position BESS as the most advanced and comprehensive solution for modern grid stability needs.

Reactive power plays a critical role in maintaining voltage stability within power grids, as discussed in the previous section. Unlike active power, which performs the real work of powering loads, reactive power ensures the proper operation of electrical equipment by maintaining voltage levels. With the increasing penetration of RESs, which inherently lack reactive power generation capabilities, maintaining grid voltage has become a significant challenge. BESS have emerged as a viable solution to provide reactive power support due to their fast response times and ability to handle both active and reactive power independently. Fig. 19 shows the active/reactive power control and voltage restoration control of BESS for weak grids used in [109].

The ability of BESSs to control reactive power stems from its bidirectional power flow capabilities. Through advanced inverter technologies, BESSs can dynamically adjust the reactive power it delivers or absorbs, stabilizing voltage levels in real time. This capability of BESS makes it suitable to use in weak grids for several applications and scenarios as highlighted in detail in Table 11.

9. Worldwide projects of BESS for real-world power grid applications

Based on the discussion of reactive power support technologies and the pivotal role of BESSs in providing reactive power support, real-world applications further illustrate the versatility and effectiveness of BESS in addressing grid stability challenges. BESS have become indispensable for modern power grids, as evidenced by numerous global case studies

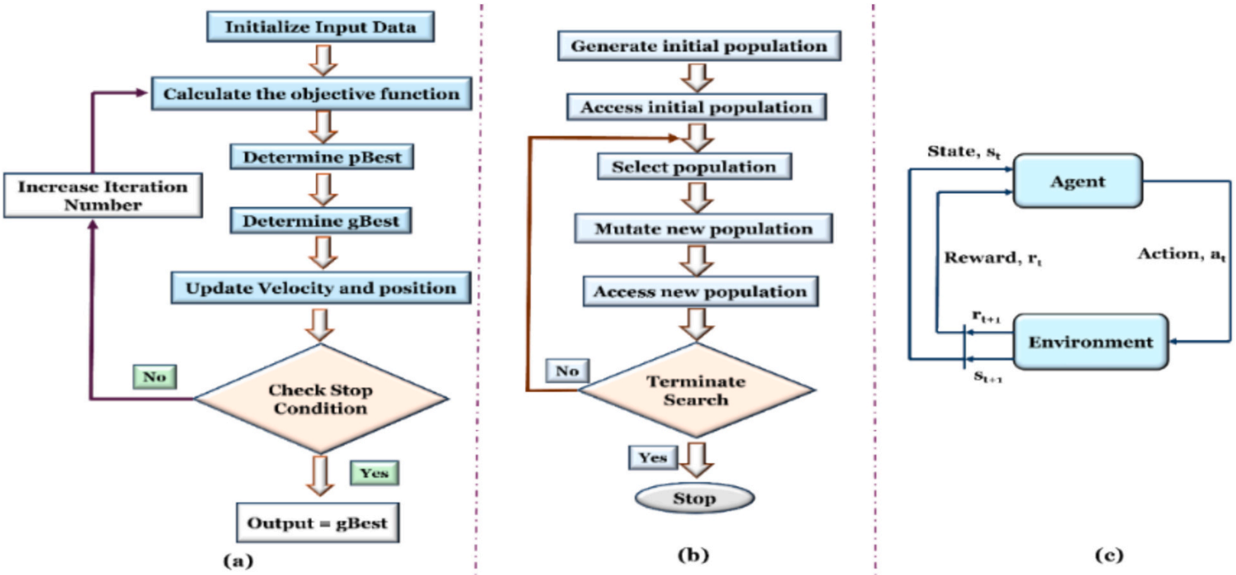


(a)

(b)

(c)

Fig. 17. BESS control using FLC; a) The parallel architecture of a typical DC microgrid of the PV/Battery Hybrid Systems, b) Structure of the PV FLC and c) Control design and configuration of the proposed BESS using FLC [79].



(a)

(b)

(c)

Fig. 18. BESS control strategies for weak grids; (a) General flow chart of PSO [90], (b) General structure of GA [91], (c) Generalized RLS [91].

showcasing their role in enhancing grid stability and supporting RE integration. For example, the Qinghai Luneng Gelmud multi-energy complementary project (China) and the Henan grid-side distributed BESS project (China), both operational since December 2018, use Li-ion batteries with capacities of 50 MW/100 MWh and 100.8 MW/125.8 MWh, respectively, to smoothen output fluctuations, provide peak regulation, and ensure frequency stability [66]. Similarly, the SDG&E Escondido BESS project (USA), operational since 2017, employs a 30

Table 7
Control Strategies and its characteristics for BESS in weak grids.

Control Strategy	Description	Applications	Advantages	Challenges	Suitable RES	Explanation for Suitability	Ref
PI	Basic control for maintaining steady-state voltage and current stability.	Steady-state charging/ discharging operations.	Simplicity, reliability, and ease of implementation.	Limited effectiveness in dynamic environments.	Solar PV, Wind	Handles stable generation conditions with minimal variability.	[34,66,80]
MPC	Predicts future system behavior for real-time optimization.	RE smoothing, load balancing, operational cost minimization.	Handles multi-variable systems, suitable for dynamic grids.	Computationally intensive; requires robust modeling.	Wind, Hybrid Systems	Effective in managing dynamic and variable energy outputs.	[34,66,78,92]
FLC	Rule-based system for managing uncertainty and non-linearity.	Frequency regulation, voltage stabilization, and renewable integration.	High adaptability, no need for precise mathematical models.	Limited performance in highly dynamic systems.	Solar PV, Wind	Adapts to uncertain or fluctuating energy generation patterns.	[66,79,81,86,88]
SMC	Non-linear control using high frequency switching between control laws.	Fast response applications like frequency and voltage regulation.	Robust under variable conditions and disturbances.	Can cause inefficiencies due to "chattering."	Wind, Hybrid Systems	Responds quickly to fluctuating conditions common in wind energy.	[66,82,88,93]
H-infinity Robust Control	Ensures stability under high uncertainty and disturbances.	Grids with significant renewable penetration.	Reliable in extreme scenarios; robust under uncertainty.	Requires complex mathematical modeling and computational power.	Solar PV, Wind	Handles high levels of uncertainty typical of renewable systems.	[66,83]
NNC	Data-driven control using artificial NNC for real-time optimization.	Renewable forecasting, grid balancing, and dynamic conditions.	Learns complex system behaviors, adapts to changing scenarios.	Requires accurate data and significant computational resources.	Solar PV, Wind, Hybrid Systems	Effective for forecasting and optimizing VRE.	[34,66] [84]
RL	Self-learning approach using trial-and-error for optimal control policies.	Dynamic and unpredictable grid environments.	Adaptive to new scenarios without prior programming.	Long training times, and computational resource intensive.	Wind, Hybrid Systems	Adapts to unpredictable generations from hybrid systems.	[34,66,94]
PSO	Optimization inspired by the social behavior of birds and fish.	BESS placement, sizing, and EMSt.	Efficient for solving multi-objective optimization problems.	Sensitive to initial parameters; risk of premature convergence.	Solar PV, Wind	Optimizes placement and sizing to integrate solar and wind systems.	[33,66,86,117]
GA	Evolutionary algorithm mimicking natural selection for optimization.	Optimal sizing and scheduling of BESS.	Effective for complex optimization problems.	Slow convergence; computationally intensive.	Solar PV, Wind	Optimizes long-term operational strategies for renewable systems.	[34,66]
Droop Control	Decentralized method adjusting power output based on system frequency and voltage.	Microgrids and distributed energy systems.	Plug-and-play functionality, decentralized operation.	Limited scalability for large or dynamic systems.	Solar PV, Hybrid Systems	Balances power among distributed resources, especially in microgrids.	[66,87]
Adaptive Control	Real-time adjustment of parameters based on system changes.	Environments with high load and generation variability.	Maintains stability and performance despite changing conditions	Complex design and implementation.	Solar PV, Wind	Responds to changing generation patterns and grid demands.	[66,85]
DARC	Separates active and reactive power control for improved stability and efficiency.	Hybrid RE systems.	Enhances grid stability and reduces power interactions.	Requires precise modeling and coordination.	Hybrid Systems	Ideal for balancing active and reactive power in multi-source setups.	[66,89]

MW/120 MWh Li-ion battery for electricity market participation, while the Virginia Beech Ridge BESS project (USA), with a 31.5 MW/12.06 MWh Li-ion battery, has been facilitating frequency regulation since 2015 [7]. Additionally, projects like the Zhangbei wind-photovoltaic-storage-transmission demonstration project (China) demonstrate the integration of multiple battery types, including Li-ion, RF, and Pb-acid batteries, to provide comprehensive voltage regulation [66]. Recent projects, such as the West Murray Zone GFM BESS Project (Australia) (2023) and the Distributed PV-BESS Curtailment Project (South Australia) (2023), highlight the use of advanced GFI and distributed BESS configurations for mitigating sub-synchronous oscillations and reducing energy curtailment, respectively [110,111]. Moreover, some of the upcoming projects like Waratah Super Battery, Liddell BESS and Orana BESS (Australia, NSW) targeting to ensure grid reliability and stability along with smooth transition for RE integration. A detailed overview of these projects, including their configurations, battery types, and primary functions, is presented in Table 12, illustrating the diverse and impactful applications of BESS in real-world operations.

9.1. *Supporting RE integration*

Building upon the role of BESS in providing reactive power support and enhancing grid stability, another crucial application lies in facilitating the seamless integration of RESs into power grids. The intermittent nature of solar and wind energy, coupled with periods of excess generation, poses significant challenges such as grid instability, energy curtailment, and load mismatches. BESS have proven to be highly effective in addressing these challenges by mitigating intermittency, reducing curtailment, facilitating energy arbitrage, and supporting load balancing. The following subsection will discuss about the how BESS help to mitigate intermittency and reduce curtailment along with how BESS facilitate energy arbitrage and load balancing using some of the projects discussed in Table 12 as reference.

9.2. *Mitigating intermittency and reducing curtailment*

RESs often produce excess power during periods of low demand, leading to curtailment and wasted energy. BESS helps alleviate this by

Table 8
EMSt used for BESSs in weak grids.

Ref	EMSt	Description	Applications	Advantages	Challenges
[65,99]	Cost Optimization	Maximizing economic returns by charging during low-price periods and discharging during high-demand periods.	Energy arbitrage, reducing operational costs, and participating in electricity markets.	Maximizes economic benefits, integrates with dynamic pricing models	Requires accurate price forecasting and complex optimization algorithms.
[95,100]	Load Shifting	Shifting energy usage from peak to off-peak periods to balance supply and demand.	Alleviating grid stress, balancing RE generation and consumption, and reducing peak demand.	Reduces grid congestion, supports renewable integration, and minimizes demand charges.	Requires accurate load forecasts and sufficient BESS capacity.
[70,99]	Peak Shaving	Reducing peak power demand by discharging stored energy during high-demand periods.	Industrial and residential peak load reduction, minimizing energy costs, and improving grid reliability.	Reduces demand charges, enhances grid stability, and improves energy system efficiency.	Limited by the storage capacity and discharge rates of BESS.
[96,99]	SoC Management	Ensuring the battery operates within safe charge and discharge limits to extend lifespan and maintain reliability.	Preventing overcharging and deep discharging, ensuring long-term reliability and efficiency.	Extends battery life, reduces maintenance costs, and improves operational safety.	Requires real-time monitoring and advanced control systems.
[97,99]	RE Integration	Mitigating intermittency by storing excess energy during high-generation periods and discharging during deficits.	Ensuring consistent power supply, reducing RE curtailment, and enhancing grid reliability.	Maximizes RE utilization, reduces curtailment, and improves grid stability.	Requires sophisticated forecasting models and sufficient BESS capacity.
[98,99]	Energy Arbitrage	Leveraging differences in electricity prices by buying low and selling high.	Enhancing profitability in wholesale electricity markets and optimizing battery dispatch.	Increases revenue and optimizes battery usage for market participation.	Highly dependent on accurate price forecasts and market volatility.
[66,101]	Frequency Regulation	Maintaining grid frequency within acceptable limits by rapidly charging or discharging energy.	Grid stabilization, providing ancillary services, and supporting frequency-sensitive loads.	Provides fast response times, supports grid reliability, and enables market participation.	Requires real-time control and precise synchronization with grid operations.
[86,102]	Voltage Regulation	Managing reactive power to stabilize grid voltage levels.	Supporting grid voltage stability, especially in areas with high RE penetration.	Enhances voltage stability, ensures consistent power quality.	Involves complex control algorithms and real-time monitoring.
[99,103]	Black Start Capability	Providing energy to restart the grid after a power outage.	Restarting isolated power systems and supporting critical loads during blackouts.	Improves system resilience and reliability, supports critical infrastructure.	Requires significant storage capacity and advanced control systems.
[34,104]	Energy Trading	Allowing decentralized energy systems to trade energy in local or regional markets.	Peer-to-peer trading in microgrids, supporting decentralized energy markets.	Encourages RE adoption and increases economic opportunities.	Requires blockchain or similar technologies for secure and transparent transactions.
[99,105]	DSM	Aligning energy usage patterns with grid conditions by controlling demand.	Reducing grid stress during peak demand, enhancing grid reliability.	Improves grid flexibility, optimizes resource usage, and lowers operational costs.	Requires coordination between utilities and end-users and advanced communication systems.

Table 9
Comparison of reactive power support technologies for voltage stability [66,86,88,93,106–108].

Technology	Response Time	Dynamic Adjustment	Cost	Scalability	Inertia	Advantages	Disadvantages
SC	Moderate (Seconds)	Limited	High	Moderate	Yes	Provides inertia for grid stability; suitable for high-disturbance scenarios.	Large physical footprint and high maintenance requirements.
SVC	Fast (Milliseconds)	Moderate	Moderate	Moderate	No	Compact design and effective for steady-state voltage regulation.	Limited ability to handle rapidly changing grid conditions.
STATCOM	Very Fast (Milliseconds)	High	High	High	No	Faster response than SVC; ideal for renewable integration and fault ride-through.	Higher capital and operational cost compared to SVC.
Cap Bank	Slow (Fixed Output)	None	Very Low	High	No	Low-cost solution; simple and easy to deploy.	No dynamic adjustment capability; unsuitable for grids with high renewable penetration.

Table 10
Key advantages of BESS compared to other technologies [86,91,106–108].

Feature	BESS	Closest Alternative
Response Time	Milliseconds	STATCOM (Milliseconds to Seconds)
Dynamic Adjustment	Very High	STATCOM (High)
Scalability	Very High (Distributed and Centralized)	Synchronous Condensers (Moderate)
Integration with Renewables	Seamless	STATCOM (Limited to Reactive Power Only)
Dual Active/Reactive Capability	Yes	None

storing surplus energy during high-generation periods and releasing it during low-generation times, ensuring better utilization of RE. For instance:

- The Distributed PV-BESS Curtailment Project (South Australia) integrates distributed PV systems with 13.5 kWh Li-ion batteries to reduce overvoltage and curtailment in low-voltage networks [110].
- The Zhangbei wind-photovoltaic-storage-transmission demonstration project (China) leverages a combination of Li-ion, RF, and Pb-acid batteries to smoothen RE output, enhancing grid stability and RE utilization [66].

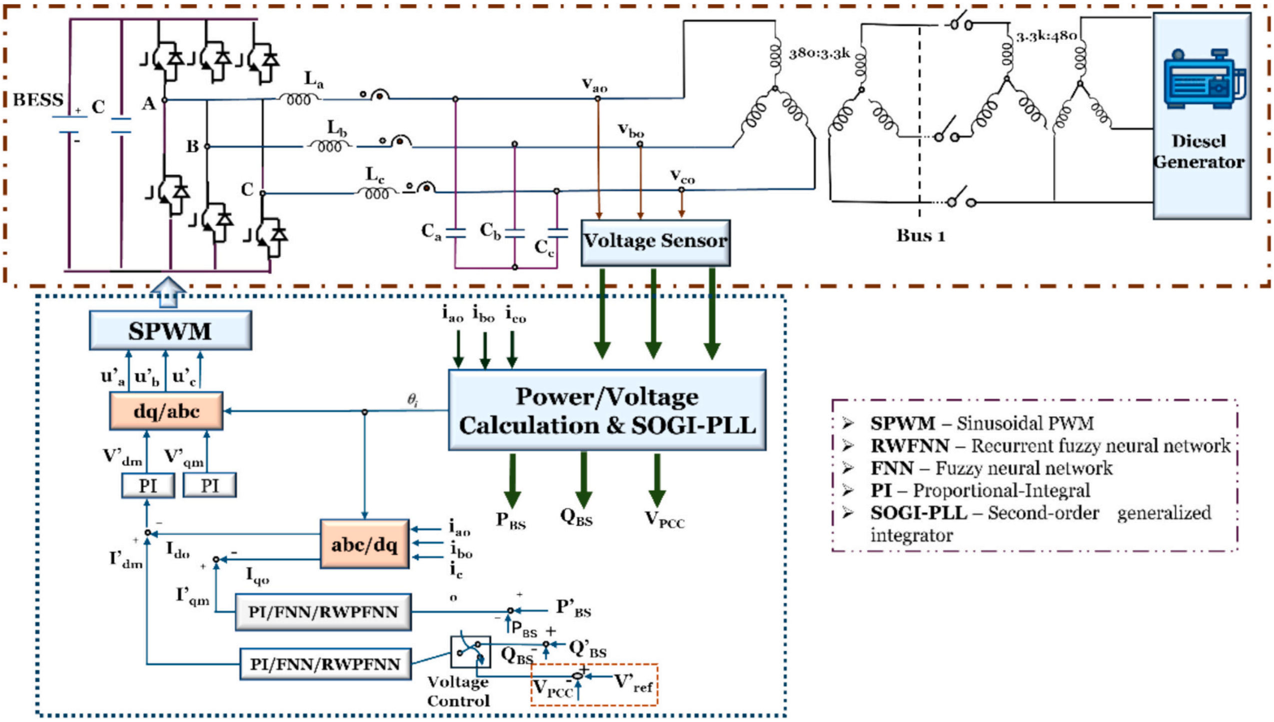


Fig. 19. Active/reactive power control and voltage restoration control (VRC) of BESS.

- The Aomori Rokkasho-Futamata wind farm (Japan) employs a 34 MW/245 MWh NaS battery to address LVRT issues and provide reactive power compensation [66].

9.3. *Facilitating energy arbitrage and load balancing*

Energy arbitrage, where energy is stored during periods of low electricity prices and discharged during high-price periods, is another critical application of BESS. This not only provides economic benefits but also ensures real-time load balancing, minimizing stress on grid infrastructure. Examples include:

- The South Australia Virtual Power Plant (VPP), where residential Li-ion battery systems are integrated into a VPPs to enable DSMs, fast frequency response, and system stress reduction [110].
- The Henan grid-side distributed BESS project (China) utilizes a 100.8 MW/125.8 MWh Li-ion battery system for peak shaving and load leveling, ensuring energy supply aligns with demand patterns [66].
- The Waratah Super Battery (NSW, Australia), scheduled for 2025, will provide 700 MW/1400 MWh capacity to enhance grid reliability following coal plant retirements and to support RE integration [114].

Following a detailed examination of BESS applications in weak electrical grids, the next section shifts focus to the discussion and transition pathway for promoting BESS adoption.

10. Discussion and transition pathway to promote BESSs

The global imperative to reduce carbon emissions and ensure affordable, clean energy (as articulated in the UNSDGs 7 and 13) has elevated the role of BESSs in modern power grids. In contrast to other energy storage options, such as mechanical, thermal, or chemical storage that often contend with slower response times or lower round-trip efficiencies, BESS deliver rapid power injection or absorption, high energy density, and excellent scalability [99,115]. Consequently, BESS have emerged as vital technologies for enhancing the reliability, stability, and economic performance of weak or remote grids as they integrate higher shares of renewables [34,108]. Fig. 20 discusses the factors related to smooth transition pathways to promote BESS to support integration of REZs in weak grids.

Within these weak grids, the variability and non-dispatchable nature of RESs (e.g., solar and wind) can exacerbate issues such as frequency instability, voltage fluctuations, and reduced system inertia. By actively smoothing power outputs, providing ancillary services like frequency regulation and reactive power support, and alleviating curtailment risks during off-peak generation times, BESS address these concerns effectively [34,108]. Moreover, they enable peak shaving and load shifting to better align energy supply with demand, reducing reliance on emission-intensive peaking plants and thereby supporting SDG 13 (Climate Action) [33,76,77].

From a policy and market design perspective, promoting BESS involves establishing robust frameworks and incentives that appropriately recognize and reward the services they provide such as voltage regulation, spinning reserve, black-start capability, or deferred transmission investments. Collaboration among policymakers, grid operators, private sector stakeholders, and local communities is essential to creating transparent market rules, tariff structures, and compensation schemes [77,116]. Additionally, investment in digital infrastructure enhances forecasting, optimal dispatch, and performance analytics for BESS, leveraging machine learning and artificial intelligence to support dynamic, data-driven decision making. Such digitization also opens pathways for novel business models like VPPs and aggregated energy trading, further aligning with SDG 7 (Affordable and Clean Energy) [1,12,115].

Technological innovation remains a cornerstone of this transition pathway. Advancements in battery chemistry, improvements in lifecycle performance, the optimization of recycling processes, and the exploration of next-generation options such as solid-state batteries are critical for alleviating concerns over cost, sustainability, and raw material availability [34,86,89]. These efforts pave the way for more robust, longer-lasting battery solutions with smaller environmental footprints, thereby enabling wider adoption of BESS consistent with the vision of sustainable development.

Table 11
Applications of BESS in Reactive Power Support for Voltage Stability and Grid Reliability in Weak Grid Scenario.

Application	Description	Control Strategies	References
Weak Transmission Networks	High renewable penetration leads to voltage instability.	Voltage Source Converters (VSC)	[66,86]
	BESS compensated by injecting or absorbing reactive power in real time	Dynamic Voltage Regulation	[93]
	BESS supports voltage profiles by reducing dependency on conventional generation.	Reactive Power Optimization Algorithms	[86,88]
Disturbance Recovery	Reactive power critical for restoring voltage following faults or rapid load changes.	Droop Control	[86,88]
	BESS stabilizes voltage by dynamically adjusting reactive power during grid disturbances.	Feedback-Based Control	[88,93]
	Rapid response during fault recovery minimizes cascading grid failures.	Real-Time Monitoring and Control Systems	[93]
Power Quality Improvement	BESS mitigates voltage sags and surges, enhancing reliability and reducing power quality issues.	Independent control of active and reactive power (VSC)	[66,86]
	Voltage stabilization ensures uninterrupted power supply to sensitive loads.	PI Control	[93]
Grid Frequency Stabilization	BESS aids in maintaining grid frequency through reactive power compensation during frequency deviations.	Frequency-Watt Droop Control	[66,86]
	Prevents overloading of transmission lines by balancing power flow	Hybrid Control Algorithms	[66,86]
Integration with RE	Supports higher RE penetration by compensating for the lack of reactive power generation.	Reactive Power-Voltage (Q-V) Control	[86,88]
	Reduces curtailment and stabilizes voltage during periods of high renewable generation variability.	Machine Learning-Based Predictive Control	[73,88]
Voltage Collapse Prevention	Prevents voltage collapse in weak grid areas during peak loads or high renewable penetration periods.	Predictive Load Sharing	[86,88]
	Enables grid operators to maintain grid voltage within operational limits.	Dynamic Voltage Setpoints	[93]
Microgrid Applications	BESS ensures voltage stability in islanded microgrids or during grid disconnections.	SOC-Based Reactive Power Control	[88]
	Balances power between distributed energy resources and loads in real time.	Hierarchical Control Strategies	[34,88]
Emergency Grid Support	Provides reactive power to stabilize the grid during emergency conditions, such as extreme weather events.	Fast Response Droop Control	[86,88]
	Assists in black-start scenarios by stabilizing voltage before active power generation.	Voltage Support Algorithms	[93]

Table 12
BESS case studies with battery types [66,110–114].

Project name (case studies)	Date of operation	Configuration	Main Function
Qinghai Luneng Gelmud multi-energy complementary national project (China)	Dec. 2018	Li-ion battery: 50 MW/100 MWh	1)Instruction tracking; 2) smoothen output fluctuations; and 3) frequency and voltage regulation
Henan grid-side distributed BESS project (China)	Dec. 2018	Li-ion battery: 100.8 MW/125.8 MWh	1)Peak regulation; 2) frequency and voltage regulation; and 3) Emergency response.
Jiangsu Zhenjiang grid-side distributed BESS project (China)	Jul. 2018	Li-ion battery: 101 MW/202 MWh	1) Peak regulation; 2) frequency and voltage regulation; and 3) emergency response.
SDG& E Escondido BESS project (USA)	Feb. 2017	Li-ion battery, 30 MW/120 MWh	Participate in electricity market transactions
Golmud New era energy 50-MWp photovoltaic power station (China)	Jul. 2016	Li-ion battery: 15 MW/18 MWh	1) Instruction tracking; 2) reduction of the abandonment of PV power generation; and 3) Smoothen output fluctuations.
Virginia Beech Ridge BESS project (USA)	May 2015	Li-ion battery: 31.5 MW/12.06 MWh	Participate in the frequency regulation market
West Sendai substation frequency regulation BESS (Japan)	Feb. 2015	Li-ion battery: 40 MW/20 MWh	Frequency regulation
Primus, California Irrigation community project (USA)	Oct. 2012	RFB: 25 MW/100 MWh	1) Smoothen output fluctuations; 2) stability support; and 3) improve power quality.
Zhangbei wind-photovoltaic-storage-transmission demonstration Project (China)	Dec. 2011	Li-ion battery: 14 MW/63 MWh; RFB: 2 MW/8 MWh; Pb-acid batteries: 2 MW/12 MWh; Li-titanate battery: 2 MW/1 MWh	1) Instruction tracking; 2) smoothen output fluctuations; and 3) frequency and voltage regulation
Aomori, Rokkasho-Futamata wind farm (Japan)	Aug. 2008	NaS battery: 34 MW/245 MWh	1) Smoothen output fluctuation; and 2) solve the problem of low-voltage ride through (LVRT) and reactive power compensation.
West Murray Zone GFM BESS Project (Australia)	2023	GF BESS; 200 MW capacity Battery type: Not specified	1)Mitigate sub-synchronous oscillations; 2) enhance grid stability in weak grids; 3) increase renewable hosting capacity
Optimal Sizing BESS for IEEE 39-bus System	2022	Multiple BESS placements across key load points. Battery type: Not specified	1) Improve frequency stability using optimal BESS sizing; and 2) placement under uncertainty
Distributed PV-BESS Curtailment (South Australia)	2023	Distributed PV (5 kW) coupled with BESS (13.5 kWh) in LV networks Battery type: Li-ion	1)Analyze and reduce energy curtailment in distributed PV-

(continued on next page)

Table 12 (*continued*)

Project name (case studies)	Date of operation	Configuration	Main Function
			BESS systems due to overvoltage
South Australia Virtual Power Plant Project	2020	Residential BESS fleet integrated into VPPs Battery type: Not specified	1) Facilitate demand-side response; 2) provide fast frequency response; reduce system stress
Waratah Super Battery (NSW, Australia)	Targeted for 2025	Li-ion battery: 700 MW/1400MWh	1) Provide grid reliability after coal plant retirements 2) Support system security and capacity
Liddell Battery Energy Storage System (NSW, Australia)	2023–2024 (Planned)	Li-ion up to 500 MW	1) Grid reliability as Liddell coal station retires, 2) Frequency control (FCAS) and rapid response, 3) Smoothing renewables (wind/ solar) output
Orana Battery Energy Storage System (NSW, Australia)	–	Likely to be Li ion. Exact size not specified	1) Grid stability & supporting new renewables in the Orana region, 2) Peak shaving / load shifting, 3) Frequency & voltage control

In remote or islanded grids, the transformative impact of BESS is especially pronounced. By substantially reducing diesel fuel consumption, enhancing local grid reliability, and integrating higher levels of renewables, BESS strengthen energy access, improve air quality, and lower operating costs. Overcoming upfront capital barriers can be justified by the long-term benefits of emission reduction, economic savings, and higher-quality power outcomes that advance both SDG 7 and SDG 13 [5,7,115].

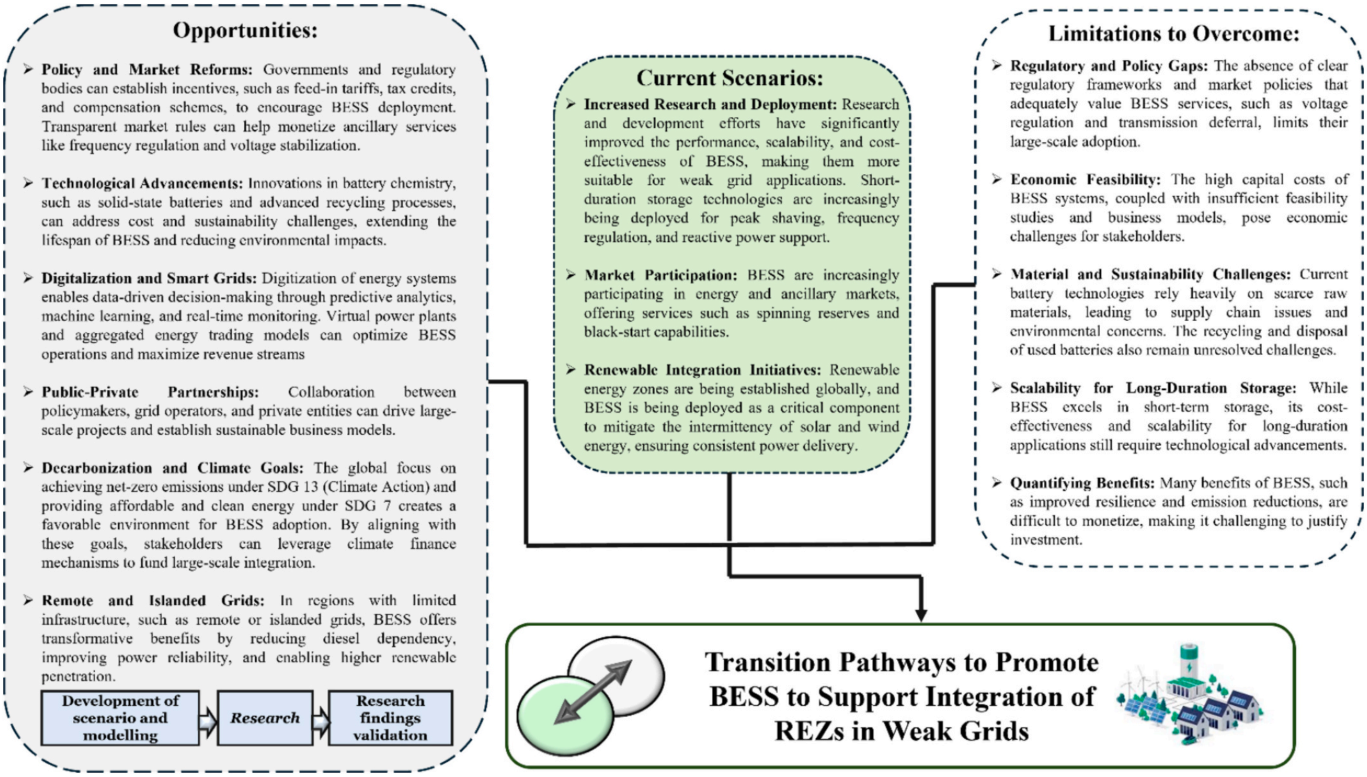
In summary, the transition pathway to promote BESS spans regulatory reforms, technological breakthroughs, market-based incentives, and digitalization strategies, all of which jointly support the global drive for affordable, clean, and resilient energy systems. By aligning these elements, stakeholders accelerate the deployment of BESS, paving the way for a future in which higher levels of renewable penetration are seamlessly integrated into weak grids. This evolution not only advances the objectives of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), but also contributes to the broader sustainability agenda, fostering inclusive, robust, and carbon-neutral energy infrastructures worldwide.

11. Findings and conclusions

This paper provides a comprehensive review of the role of Battery Energy Storage Systems (BESSs) in enhancing renewable energy (RE) utilization within weak grids, driven by the environmental and economic drawbacks of non-renewable sources that have prompted the Australian government to develop Renewable Energy Zones (REZs). It begins by examining the challenges of integrating renewables into weak grids, identifying Energy Storage Systems (ESSs) as a potential solution while acknowledging the limitations of non-BESS technologies.

Focusing on BESSs as a promising alternative, the review compares different battery types and explores their deployment in both islanded and grid-connected weak grids. It also analyzes real-world BESS implementations, emphasizing their impact on grid stability, power flow management, and energy optimization. Additionally, the study investigates advanced control strategies, operational algorithms, and energy management techniques tailored to weak grid environments.

Finally, this paper proposes a strategic transition pathway to accelerate large-scale BESS integration, fostering a more sustainable, climate-



Opportunities:

- **Policy and Market Reforms:** Governments and regulatory bodies can establish incentives, such as feed-in tariffs, tax credits, and compensation schemes, to encourage BESS deployment. Transparent market rules can help monetize ancillary services like frequency regulation and voltage stabilization.
- **Technological Advancements:** Innovations in battery chemistry, such as solid-state batteries and advanced recycling processes, can address cost and sustainability challenges, extending the lifespan of BESS and reducing environmental impacts.
- **Digitalization and Smart Grids:** Digitization of energy systems enables data-driven decision-making through predictive analytics, machine learning, and real-time monitoring. Virtual power plants and aggregated energy trading models can optimize BESS operations and maximize revenue streams
- **Public-Private Partnerships:** Collaboration between policymakers, grid operators, and private entities can drive large-scale projects and establish sustainable business models.
- **Decarbonization and Climate Goals:** The global focus on achieving net-zero emissions under SDG 13 (Climate Action) and providing affordable and clean energy under SDG 7 creates a favorable environment for BESS adoption. By aligning with these goals, stakeholders can leverage climate finance mechanisms to fund large-scale integration.
- **Remote and Islanded Grids:** In regions with limited infrastructure, such as remote or islanded grids, BESS offers transformative benefits by reducing diesel dependency, improving power reliability, and enabling higher renewable penetration.

Current Scenarios:

- **Increased Research and Deployment:** Research and development efforts have significantly improved the performance, scalability, and cost-effectiveness of BESS, making them more suitable for weak grid applications. Short-duration storage technologies are increasingly being deployed for peak shaving, frequency regulation, and reactive power support.
- **Market Participation:** BESS are increasingly participating in energy and ancillary markets, offering services such as spinning reserves and black-start capabilities.
- **Renewable Integration Initiatives:** Renewable energy zones are being established globally, and BESS is being deployed as a critical component to mitigate the intermittency of solar and wind energy, ensuring consistent power delivery.

Limitations to Overcome:

- **Regulatory and Policy Gaps:** The absence of clear regulatory frameworks and market policies that adequately value BESS services, such as voltage regulation and transmission deferral, limits their large-scale adoption.
- **Economic Feasibility:** The high capital costs of BESS systems, coupled with insufficient feasibility studies and business models, pose economic challenges for stakeholders.
- **Material and Sustainability Challenges:** Current battery technologies rely heavily on scarce raw materials, leading to supply chain issues and environmental concerns. The recycling and disposal of used batteries also remain unresolved challenges.
- **Scalability for Long-Duration Storage:** While BESS excels in short-term storage, its cost-effectiveness and scalability for long-duration applications still require technological advancements.
- **Quantifying Benefits:** Many benefits of BESS, such as improved resilience and emission reductions, are difficult to monetize, making it challenging to justify investment.

Fig. 20. Factors related to smooth transition pathways to promote BESS to support integration of REZs in weak grid.

friendly, and cost-effective energy system. It concludes by outlining key directions for future research in this rapidly evolving field. The major findings and conclusions of this study are as follows:

- **Challenges in REZs Integration**: Weak grids, defined by high impedance, limited fault current capacity and short circuit ratio, and vulnerability to disturbances, present significant obstacles to renewable energy (RE) integration. Key challenges include grid stability issues—such as inertia deficits, voltage fluctuations, and frequency instability—along with power quality concerns like sags, surges, and harmonics. Additionally, the non-dispatchable nature of renewables further complicates reliable operation. Addressing these barriers requires innovative solutions to ensure the seamless and stable integration of RE into weak grids.
- **Limitations of Non-BESSs**: Non-BESS energy storage technologies, including mechanical, thermal, and chemical storage systems, face several limitations such as geographic constraints, high installation costs, and complex operational requirements. Mechanical storage methods like pumped hydro storage (PHS) and compressed air storage (CAS) are restricted by environmental and site-specific factors. Chemical storage solutions, such as hydrogen fuel cells (FCs), encounter challenges related to cost and efficiency. While thermal energy storage (TCSS) shows potential, it is limited by low energy density and significant infrastructure demands, making large-scale implementation challenging.
- **BESS as a Promising Solution**: Battery Energy Storage Systems (BESS) offer a flexible, scalable, and cost-effective solution to overcome the limitations of non-battery storage technologies. Lithium-ion (Li-ion) batteries, in particular, stand out due to their high energy density, fast response times, and adaptability, making them well-suited for weak grid environments. Other battery technologies, such as Vanadium Redox Flow Batteries (VRFB) and Sodium-Sulfur (NaS) batteries, also show promise for specific applications. This paper highlights BESS's versatility in addressing renewable intermittency, stabilizing voltage and frequency, and enhancing overall grid reliability. **Deployment of BESS in Islanded and Grid-Connected Zonal Weak Grids**: This review examines the role of BESS in both islanded and grid-connected weak grid environments. In islanded zonal weak grids, BESS ensures voltage and frequency stability while managing local power flows. In grid-connected settings, BESS supports renewable energy integration through peak shaving, reactive power compensation, and dynamic power flow management. The study emphasizes the need for tailored control strategies and hybrid configurations to optimize BESS performance across diverse operational scenarios.
- **Projects on BESS Integration**: Real-world case studies are analyzed to illustrate the practical deployment of BESS in Renewable Energy Zones (REZs) and weak grids. These projects demonstrate how BESS enhances grid stability in high-renewable penetration areas, manages load fluctuations, and reduces renewable energy curtailment. The findings highlight key benefits such as improved power quality, enhanced energy reliability, and economic feasibility, offering valuable insights for policymakers and industry stakeholders.
- **Control Strategies and EMSs**: Effective BESS operation relies on advanced control algorithms, including Model Predictive Control (MPC), Fuzzy Logic Control (FLC), and Neural Network Control (NNC), which enable real-time optimization of power flow, energy storage, and grid stability. Additionally, energy management techniques such as load shifting, state-of-charge (SoC) optimization, and peak shaving play a crucial role in maximizing both the economic and technical benefits of BESS deployment.
- **Future Directions and Transition Pathways**: To enable large-scale BESS adoption, innovative policy frameworks, advanced grid infrastructure, and continued research are essential. Future studies should explore Hybrid Energy Storage Systems (HESSs), novel control algorithms, and lifecycle optimization to further enhance BESS viability in weak grids and REZs. Additionally, the development of adaptive energy systems and robust market regulations is crucial for achieving a sustainable, climate-friendly energy transition.

In conclusion, this paper establishes BESS as a key technology for improving renewable energy utilization and addressing the challenges of weak grid environments. Real-world deployments, such as the 700 MW / 1400 MWh Waratah Super Battery and the 34 MW/245 MWh NaS battery project in Japan, demonstrate the effectiveness of BESS in enhancing stability and reducing curtailment in weak grids. Large-scale battery systems in South Australia—such as the Hornsdale Power Reserve—enhance grid stability by delivering rapid frequency regulation, supporting greater integration of wind and solar energy, and reducing dependence on fossil fuels. With efficiencies reaching up to 95 % and millisecond-level response times, BESS technologies, particularly Li-ion systems, are well-suited for supporting voltage and frequency stability. By providing insights into BESS applications, control strategies, EMS frameworks, and real-world case studies, this review offers a roadmap for advancing BESS deployment in REZs. These findings contribute to the broader goal of achieving clean, affordable, and sustainable energy systems, aligning with the vision of a zero-carbon future.

CRediT authorship contribution statement

Sadnan Sakib: Writing – review & editing, Writing – original draft, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Md. Biplob Hossain:** Writing – review & editing, Writing – original draft, Resources, Methodology, Conceptualization. **Muhammad Ahsan Zamee:** Writing – review & editing, Writing – original draft, Visualization. **M.J. Hossain:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Md. Ahasan Habib:** Software, Investigation, Formal analysis, Data curation.

Declaration of Generative AI and AI-assisted technologies in the writing process

In the course of preparing this manuscript, the author(s) used Quillbot/ChatGPT to paraphrase the sentences for less similarity indexing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] P. Simshauser, F. Billimoria, C. Rogers, Optimising VRE capacity in renewable energy zones, Energy Econ. 113 (2022) 106239.

[2] D. Roche, E. Langham, M. Mouritz, J. Breadsell, D. Sharp, K. Nagrath, S. White, D. McCartney, J. Prendergast, S. Parida, R. Bona, The green wave: adding value through net zero energy strategy, 2022.

[3] W. Jackson, R. Argen, N. Bax, G. Clark, S. Coleman, I. Cresswell, K. Emmerson, K. Evans, M. Hibberd, E. Johnston, M. Keywood, Australia state of the environment 2016: overview, in: Department of the Environment and Energy (Australia), 2017.

[4] P. Adey, S. Pink, R. Raven, P. Hadfield, A. Badger, Y. Strengers, D. Sharp, O. Bock-Brown, B. Lyall, R. Martin, S. Wright, Just Transitions in Australia: Moving Towards Low Carbon Lives Across Policy, Industry and Practice, 2022.

[5] J. Black, H. Nakanishi, Towards net-zero emissions from urban transport: ex post policy evaluation in Canberra, the Australian Capital Territory, Sustainability 16 (19) (2024) 8656.

[6] Energy.gov.au (n.d.) Australian electricity generation – renewable sources. Available at: https://www.energy.gov.au/energy-data/australian-energy-statistics/data-charts/australian-electricity-generation-renewable-sources (Accessed: 25 February 2025).

[7] J. Murray, C. Dey, The carbon neutral free for all, Int. J. Greenh. Gas Contr. 3 (2) (2009) 237–248.

[8] D. Beriro, J. Nathanail, J. Salazar, A. Kingdon, A. Marchant, S. Richardson, A. Gillet, S. Rautenberg, E. Hammond, J. Beardmore, T. Moore, A decision support system to assess the feasibility of onshore renewable energy infrastructure, Renew. Sust. Energ. Rev. 168 (2022) 112771.

[9] S.A. Khaparde, Infrastructure for sustainable development using renewable energy technologies in India, in: 2007 IEEE Power Engineering Society General Meeting, IEEE, 2007, June, pp. 1–6.

[10] M. Piechowski, A. Weerakkody, Integrated renewable energy infrastructure-challenges and opportunities, Energy (2011) 52–57.

[11] V. Kouloumpis, X. Yan, Sustainable energy planning for remote islands and the waste legacy from renewable energy infrastructure deployment, J. Clean. Prod. 307 (2021) 127198.

[12] H.X. Li, D.J. Edwards, M.R. Hosseini, G.P. Costin, A review on renewable energy transition in Australia: an updated depiction, J. Clean. Prod. 242 (2020) 118475.

[13] M. Bagheri, N. Shirzadi, E. Bazdar, C.A. Kennedy, Optimal planning of hybrid renewable energy infrastructure for urban sustainability: Green Vancouver, Renew. Sust. Energ. Rev. 95 (2018) 254–264.

[14] D. Eltigani, S. Masri, Challenges of integrating renewable energy sources to smart grids: a review, Renew. Sust. Energ. Rev. 52 (2015) 770–780.

[15] V. Kumar, A.S. Pandey, S.K. Sinha, Grid integration and power quality issues of wind and solar energy system: a review, in: 2016 International Conference on Emerging Trends in Electrical Electronics & Sustainable Energy Systems (ICETEESES), IEEE, 2016, March, pp. 71–80.

[16] M. Khalid, Smart grids and renewable energy systems: perspectives and grid integration challenges, Energ. Strat. Rev. 51 (2024) 101299.

[17] X. Shen, H. Tang, W. He, H. Wang, Y. Li, D. Li, X. Yu, F. He, Q. Yuan, Study on the impact of renewable energy power generation transient characteristics on system stability in weak grid, J. Phys. Conf. Ser. 2166 (1) (2022) 012054 (IOP publishing).

[18] A. Etxegarai, P. Eguia, E. Torres, A. Iturregi, V. Valverde, Review of grid connection requirements for generation assets in weak power grids, Renew. Sust. Energ. Rev. 41 (2015) 1501–1514.

[19] G.V. Hollweg, S.A. Khan, S. Chaturvedi, Y. Fan, M. Wang, W. Su, Grid-connected converters: a brief survey of topologies, output filters, current control, and weak grids operation, Energies 16 (9) (2023) 3611.

[20] A. Zahedi, A review of drivers, benefits, and challenges in integrating renewable energy sources into electricity grid, Renew. Sust. Energ. Rev. 15 (9) (2011) 4775–4779.

[21] S.K. Khadem, M. Basu, M. Conlon, Power Quality in Grid Connected Renewable Energy Systems: Role of Custom Power Devices, 2010.

[22] H. Eroğlu, E. Cuce, P.M. Cuce, F. Gul, A. Iskenderoğlu, Harmonic problems in renewable and sustainable energy systems: a comprehensive review, Sustain. Energy Technol. Assess. 48 (2021) 101566.

[23] M.P. Bakht, Z. Salam, M. Gul, W. Anjum, M.A. Kamaruddin, N. Khan, A.L. Bukar, The potential role of hybrid renewable energy system for grid intermittency problem: a techno-economic optimisation and comparative analysis, Sustainability 14 (21) (2022) 14045.

[24] P. Osman, J. Hayward, J. Foster, Dispatchability and Energy Storage Costs for Complementary Wave, Wind, and Solar PV systems. Technical Report, 2022.

[25] A. Boretti, Green hydrogen is a necessary component of a grid with an increasing non-dispatchable renewable energy supply, Int. J. Hydrog. Energy 48 (84) (2023) 32589–32597.

[26] M.M. Rana, M. Uddin, M.R. ak, S.T. Meraj, G.M. Shafiullah, S.M. Muyeen, M. A. Islam, T. Jamal, Applications of energy storage systems in power grids with and without renewable energy integration—a comprehensive review, J. Energy Storage 68 (2023) 107811.

[27] S. Koohi-Fayegh, M.A. Rosen, A review of energy storage types, applications and recent developments, J. Energy Storage 27 (2020) 101047.

[28] K.C. Divya, J. Østergaard, Battery energy storage technology for power systems—an overview, Electr. Power Syst. Res. 79 (4) (2009) 511–520.

[29] J. Kim, J. Song, C.H. Kim, J. Mahseredjian, S. Kim, Consideration on present and future of battery energy storage system to unlock battery value, J. Mod. Power Syst. Clean Energy 13 (2) (2025) 622–636.

[30] E. Kalaiyarasan, S. Singaravelu, Efficient Power Management System of PV, (Fuel Cell and BESS-based DC Microgrid System), 2024.

[31] A.G. Olabi, C. Onumaegbu, T. Wilberforce, M. Ramadan, M.A. Abdelkareem, A. H. Al–Alami, Critical review of energy storage systems, Energy 214 (2021) 118987.

[32] R. Kumar, D. Lee, Ü. Ağbulut, S. Kumar, S. Thapa, A. Thakur, R.D. Jilte, C. A. Saleel, S. Shaik, Different energy storage techniques: recent advancements, applications, limitations, and efficient utilization of sustainable energy, J. Therm. Anal. Calorim. 149 (5) (2024) 1895–1933.

[33] M.T. Lawder, B. Suthar, P.W. Northrop, S. De, C.M. Hoff, O. Leitermann, M. L. Crow, S. Santhanagopalan, V.R. Subramanian, Battery energy storage system (BESS) and battery management system (BMS) for grid-scale applications, Proc. IEEE 102 (6) (2014) 1014–1030.

[34] M.A. Hannan, S.B. Wali, P.J. Ker, M.S. Abd Rahman, M. Mansor, V. K. Ramachandaramurthy, K.M. Muttaqi, T.M.I. Mahlia, Z.Y. Dong, Battery energy-storage system: a review of technologies, optimization objectives, constraints, approaches, and outstanding issues, J. Energy Storage 42 (2021) 103023.

[35] M. Müller, L. Viernstein, C.N. Truong, A. Eiting, H.C. Hesse, R. Witzmann, A. Jossen, Evaluation of grid-level adaptability for stationary battery energy storage system applications in Europe, J. Energy Storage 9 (2017) 1–11.

[36] L. Deguenon, D. Yamegueu, A. Gomna, Overcoming the challenges of integrating variable renewable energy to the grid: a comprehensive review of electrochemical battery storage systems, J. Power Sources 580 (2023) 233343.

[37] K.V. Vidyanandan, B. Kamath, Grid integration of renewables: challenges and solutions, Indian J. Power River Valley Dev. (2021) 150–158.

[38] R. Aljarrah, B.B. Fawaz, Q. Salem, M. Karimi, H. Marzooghi, R. Azizipanah-Abarghooee, Issues and challenges of grid-following converters interfacing renewable energy sources in low inertia systems: a review, IEEE Access 12 (2024) 5534–5561.

[39] M.A. Basit, S. Dilshad, R. Badar, S.M. Sami ur Rehman, Limitations, challenges, and solution approaches in grid-connected renewable energy systems, Int. J. Energy Res. 44 (6) (2020) 4132–4162.

[40] M.O. Qays, I. Ahmad, D. Habibi, A. Aziz, T. Mahmoud, System strength shortfall challenges for renewable energy-based power systems: a review, Renew. Sust. Energ. Rev. 183 (2023) 113447.

[41] G.M. Shafiullah, A.M. Oo, D. Jarvis, A.S. Ali, P. Wolfs, Potential challenges: Integrating renewable energy with the smart grid, in: In 2010 20th Australasian Universities Power Engineering Conference, IEEE, 2010, December, pp. 1–6.

[42] M.Y. Worku, Recent advances in energy storage systems for renewable source grid integration: a comprehensive review, Sustainability 14 (10) (2022) 5985.

[43] O. Krishan, S. Suhag, An updated review of energy storage systems: classification and applications in distributed generation power systems incorporating renewable energy resources, Int. J. Energy Res. 43 (12) (2019) 6171–6210.

[44] A.G. Olabi, T. Wilberforce, E.T. Sayed, A.G. Abo-Khalil, H.M. Maghrabie, K. Elsaid, M.A. Abdelkareem, Battery energy storage systems and SWOT (strengths, weakness, opportunities, and threats) analysis of batteries in power transmission, Energy 254 (2022) 123987.

[45] S. Choudhury, Review of energy storage system technologies integration to microgrid: types, control strategies, issues, and future prospects, J. Energy Storage 48 (2022) 103966.

[46] Z. Zhang, T. Ding, Q. Zhou, Y. Sun, M. Qu, Z. Zeng, Y. Ju, L. Li, K. Wang, F. Chi, A review of technologies and applications on versatile energy storage systems, Renew. Sust. Energ. Rev. 148 (2021) 111263.

[47] K.M. Tan, T.S. Babu, V.K. Ramachandaramurthy, P. Kasinathan, S.G. Solanki, S. K. Raveendran, Empowering smart grid: a comprehensive review of energy storage technology and application with renewable energy integration, J. Energy Storage 39 (2021) 102591.

[48] F. Erdiwansyah, F. Mahidin, H. Husin, F. Nasaruddin, M. Zaki, F. Muhibbuddin, A critical review of the integration of renewable energy sources with various technologies, Prot. Contr. Mod. Power Syst. 6 (2021) 1–18.

[49] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sust. Energ. Rev. 13 (2) (2009) 318–345.

[50] M. Faisal, M.A. Hannan, P.J. Ker, A. Hussain, M.B. Mansor, F. Blaabjerg, Review of energy storage system technologies in microgrid applications: issues and challenges, Ieee Access 6 (2018) 35143–35164.

[51] M. Katsanevakis, R.A. Stewart, J. Lu, Aggregated applications and benefits of energy storage systems with application-specific control methods: a review, Renew. Sust. Energ. Rev. 75 (2017) 719–741.

[52] A.A. Kebede, T. Kalogiannis, J. Van Mierlo, M. Berecibar, A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration, Renew. Sust. Energ. Rev. 159 (2022) 112213.

[53] M. Mahmoud, M. Ramadan, A.G. Olabi, K. Pullen, S. Naher, A review of mechanical energy storage systems combined with wind and solar applications, Energy Convers. Manag. 210 (2020) 112670.

[54] A.Z.A. Shaqsi, K. Sopian, A. Al-Hinai, Review of energy storage services, applications, limitations, and benefits, Energy Rep. 6 (2020) 288–306.

[55] R. de Fazio, D. Cafagna, G. Marcuccio, P. Visconti, Limitations and characterization of energy storage devices for harvesting applications, Energies 13 (4) (2020) 783.

[56] S. Nomura, H. Tsutsui, Structural limitations of energy storage systems based on the virial theorem, IEEE Trans. Appl. Supercond. 27 (4) (2017) 1–6.

[57] C.B. Bucur, T. Gregory, A.G. Oliver, J. Muldoon, Confession of a magnesium battery, J. Phys. Chem. Lett. 6 (18) (2015) 3578–3591.

[58] U. Pelay, L. Luo, Y. Fan, D. Stitou, M. Rood, Thermal energy storage systems for concentrated solar power plants, Renew. Sust. Energ. Rev. 79 (2017) 82–100.

[59] R. Gupta, N. Nigam, A. Gupta, Application of energy storage devices in power systems, Int. J. Eng. Sci. Technol. 3 (1) (2011).

[60] T.A. Faunce, J. Prest, D. Su, S.J. Hearne, F. Iacopi, On-grid batteries for large-scale energy storage: challenges and opportunities for policy and technology, MRS Energ. Sustain. 5 (2018) E11.

[61] O.K. Olajiga, E.C. Ani, T.M. Olatunde, Z.Q. Sikhakane, Assessing the potential of energy storage solutions for grid efficiency: a review, Eng. Sci. Technol. J. 5 (3) (2024) 1112–1124.

[62] L. Wang, Y. Bu, Y. Wu, Multi-scale risk-informed comprehensive assessment methodology for lithium-ion battery energy storage system, Sustainability 16 (20) (2024) 9046.

[63] M.S. Rafaq, B.A. Basit, S.A.Q. Mohammed, J.W. Jung, 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 Gen. 16 (10) (2022) 1971–1991.

[64] Z. Zhongming, L. Linong, Z. Wangqiang, L. Wei, Handbook on Battery Energy Storage System, Asian Development Bank, Metro Manila, Philippines, 2018.

[65] K. Darcovich, B. Kenney, D.D. MacNeil, M.M. Armstrong, Control strategies and cycling demands for Li-ion storage batteries in residential micro-cogeneration systems, Appl. Energy 141 (2015) 32–41.

[66] X. Li, S. Wang, Energy management and operational control methods for grid battery energy storage systems, CSEE J. Power Energ. Syst. 7 (5) (2021) 1026–1040.

[67] M.F. Roslan, M.A. Hannan, P.J. Ker, M.N. Uddin, Microgrid control methods toward achieving sustainable energy management, Appl. Energy 240 (2019) 583–607.

[68] R. Bakhshi-Jafarabadi, J. Sadeh, A. Serrano-Fontova, E. Rakhshani, Review on islanding detection methods for grid-connected photovoltaic systems, existing limitations and future insights, IET Renew. Power Gen. 16 (15) (2022) 3406–3421.

[69] E. Rokrok, M. Shafie-Khah, J.P. Catalão, Review of primary voltage and frequency control methods for inverter-based islanded microgrids with distributed generation, Renew. Sust. Energ. Rev. 82 (2018) 3225–3235.

[70] J. Engels, B. Claessens, G. Deconinck, Optimal combination of frequency control and peak shaving with battery storage systems, IEEE Trans. Smart Grid 11 (4) (2019) 3270–3279.

[71] X. Lin, Y. Liu, J. Yu, R. Yu, J. Zhang, H. Wen, Stability analysis of three-phase grid-connected inverter under weak grids with asymmetrical grid impedance by LTP theory in time domain, Int. J. Electr. Power Energy Syst. 142 (2022) 108244.

[72] G. Liang, P. Liyuan, L. Ruihuan, Z. Fen, L. Jinhui, W. Xin, Study on economic operation for micro-grid based on scenario and PSO, in: 2014 International Conference on Power System Technology, IEEE, 2014, October, pp. 3152–3156.

[73] B. Bahmani-Firouzi, R. Azizipanah-Abarghooee, Optimal sizing of battery energy storage for micro-grid operation management using a new improved bat algorithm, Int. J. Electr. Power Energy Syst. 56 (2014) 42–54.

[74] R.C. Dugan, T.E. McDermott, IEEE Power and Energy Society General Meeting, 2011.

[75] M.A. Pedrasa, T. Spooner, A survey of techniques used to control microgrid generation and storage during island operation, Aupec2006 1 (2006) 15.

[76] H. Yu, S. Niu, Y. Zhang, L. Jian, An integrated and reconfigurable hybrid AC/DC microgrid architecture with autonomous power flow control for nearly/net zero energy buildings, Appl. Energy 263 (2020) 114610.

[77] O. Akinsooto, O.B. Ogundipe, S. Ikemba, Regulatory policies for enhancing grid stability through the integration of renewable energy and battery energy storage systems (BESS), Int. J. Frontline Res. Rev 2 (2024) 022–044.

[78] T.T. Nguyen, H.J. Yoo, H.M. Kim, Application of model predictive control to BESS for microgrid control, Energies 8 (8) (2015) 8798–8813.

[79] H. Assem, T. Azib, F. Bouchafaa, C. Laarouci, N. Belhaouas, A. Hadj Arab, Adaptive fuzzy logic-based control and management of photovoltaic systems with battery storage, Int. Trans. Electr. Energ. Syst. 2023 (1) (2023) 9065061.

[80] P.K. Ray, S.R. Mohanty, N. Kishor, Proportional–integral controller based small-signal analysis of hybrid distributed generation systems, Energy Convers. Manag. 52 (4) (2011) 1943–1954.

[81] S. Prabhakar, B.K. Panigrahi, Fuzzy logic controller for optimal power sharing in multi BESS-PV based islanded AC microgrid, in: 2024 IEEE 4th International Conference on Sustainable Energy and Future Electric Transportation (SEFET), IEEE, 2024, July, pp. 1–6.

[82] M.S. Islam, I.J. Bushra, T.K. Roy, S.K. Ghosh, A.M.T. Oo, Enhanced composite controller for PV/PMSG/PEMFC and BESS-based DC microgrids voltage regulation: integrating integral terminal sliding mode controller and recursive backstepping controller, IET Gener. Transm. Distrib. 18 (22) (2024) 3608–3632.

[83] A. Dinesh, K. Chakravarthi, P. Bhui, A.K. Mulla, Robust $H\infty$ control for line power flow tracking in power systems, Int. J. Electr. Power Energy Syst. 156 (2024), https://doi.org/10.1016/J.Ijepes.2023.109704.

[84] M. Kurucan, M. Özbaltan, Z. Yetgin, A. Alkaya, Applications of artificial neural network-based battery management systems: a literature review, Renew. Sust. Energ. Rev. 192 (2024) 114262.

[85] Z. Gong, Y. Su, R. Cai, B. Rao, J. Zhou, An adaptive control strategy for VSG based on energy storage capacity optimization of MMC-BESS, Electr. Eng. (2024) 1–14.

[86] R. Hemmati, N. Azizi, Advanced control strategy on battery storage system for energy management and bidirectional power control in electrical networks, Energy 138 (2017) 520–528.

[87] D. Li, Z. Wu, B. Zhao, L. Zhang, An improved droop control for balancing state of charge of battery energy storage systems in AC microgrid, IEEE Access 8 (2020) 71917–71929.

[88] S.K. Ghosh, T.K. Roy, M.A.H. Pramanik, A.K. Sarkar, M.A. Mahmud, An energy management system-based control strategy for DC microgrids with dual energy storage systems, Energies 13 (11) (2020) 2992.

[89] R. Hemmati, N. Azizi, Optimal control strategy on battery storage systems for decoupled active-reactive power control and damping oscillations, J. Energy Storage 13 (2017) 24–34.

[90] T.Y. Abdalla, A.A. Abed, A.A. Ahmed, Mobile robot navigation using PSO-optimized fuzzy artificial potential field with fuzzy control, J. Intell. Fuzzy Syst. 32 (6) (2017) 3893–3908.

[91] D.A. Dugaev, I.G. Matveev, E. Siemens, V.P. Shuvalov, Adaptive reinforcement learning-based routing protocol for wireless multihop networks, in: 2018 XIV International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE), IEEE, 2018, October, pp. 209–218.

[92] W. Bao, Q. Wu, L. Ding, S. Huang, F. Teng, V. Terzija, Synthetic inertial control of wind farm with BESS based on model predictive control, IET Renew. Power Gen. 14 (13) (2020) 2447–2455.

[93] A. Elsanabary, K. Khairullah, N.F. Ab Aziz, S. Mekhilef, Power management and optimized control of hybrid PV-BESS-grid integrated fast EV charging stations, J. Energy Storage 90 (2024) 111802.

[94] G.G. Farivar, W. Manalastas, H.D. Tafti, S. Ceballos, A. Sanchez-Ruiz, E.C. Lovell, G. Konstantinou, C.D. Townsend, M. Srinivasan, J. Pou, Grid-connected energy storage systems: state-of-the-art and emerging technologies, Proc. IEEE 111 (4) (2022) 397–420.

[95] L. Silvestri, M. De Santis, Renewable-based load shifting system for demand response to enhance energy-economic-environmental performance of industrial enterprises, Appl. Energy 358 (2024) 122562.

[96] D. Pattabiraman, R.H. Lasseter, T.M. Jahns, 2018 IEEE Power & Energy Society General Meeting (PESGM), 2018.

[97] Y. Yang, W. Zhang, J. Jiang, M. Huang, L. Niu, Optimal scheduling of a battery energy storage system with electric vehicles' auxiliary for a distribution network with renewable energy integration, Energies 8 (10) (2015) 10718–10735.

[98] T. Terlouw, T. AlSkaif, C. Bauer, W. Van Sark, Multi-objective optimization of energy arbitrage in community energy storage systems using different battery technologies, Appl. Energy 239 (2019) 356–372.

[99] Y. Yang, S. Bremner, C. Menictas, M. Kay, Modelling and optimal energy management for battery energy storage systems in renewable energy systems: a review, Renew. Sust. Energ. Rev. 167 (2022) 112671.

[100] A. Khalid, A. Stevenson, A.I. Sarwat, Overview of technical specifications for grid-connected microgrid battery energy storage systems, IEEE Access 9 (2021) 163554–163593.

[101] G. He, Q. Chen, C. Kang, Q. Xia, K. Poolla, Cooperation of wind power and battery storage to provide frequency regulation in power markets, IEEE Trans. Power Syst. 32 (5) (2016) 3559–3568.

[102] S.J. Lee, J.H. Kim, C.H. Kim, S.K. Kim, E.S. Kim, D.U. Kim, K.K. Mehmood, S. U. Khan, Coordinated control algorithm for distributed battery energy storage systems for mitigating voltage and frequency deviations, IEEE Trans. Smart Grid 7 (3) (2015) 1713–1722.

[103] S. Izadkhast, R. Cossent, P. Frías, P. García-González, A. Rodríguez-Calvo, Performance evaluation of a bess unit for black start and seamless islanding operation, Energies 15 (5) (2022) 1736.

[104] S. Nguyen, W. Peng, P. Sokolowski, D. Alahakoon, X. Yu, Optimizing rooftop photovoltaic distributed generation with battery storage for peer-to-peer energy trading, Appl. Energy 228 (2018) 2567–2580.

[105] M. Al-Saffar, P. Musilek, Reinforcement learning-based distributed BESS management for mitigating overvoltage issues in systems with high PV penetration, IEEE Trans. Smart Grid 11 (4) (2020) 2980–2994.

[106] H. Tariq, S. Czapp, S. Tariq, K.M. Cheema, A. Hussain, A.H. Milyani, S. Alghamdi, Z.S. Elbarbary, Comparative analysis of reactive power compensation devices in a real electric substation, Energies 15 (12) (2022) 4453.

[107] S. Rusek, R. Goňo (Eds.), Proceedings of the 2015 16th International Scientific Conference on Electric Power Engineering (EPE): May 20–22, 2015, Hotel Dlouhé Stráně, Kouty Nad Desnou, Czech Republic, VŠB-Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Electrical Power Engineering, 2015.

[108] M.N.I. Sarkar, L.G. Meegahapola, M. Datta, Reactive power management in renewable rich power grids: a review of grid-codes, renewable generators, support devices, control strategies and optimization algorithms, Ieee Access 6 (2018) 41458–41489.

[109] F.J. Lin, J.C. Liao, C.I. Chen, P.R. Chen, Y.M. Zhang, Voltage restoration control for microgrid with recurrent wavelet petri fuzzy neural network, IEEE Access 10 (2022) 12510–12529.

[110] B. Yildiz, N. Stringer, T. Klymenko, M.S. Samhan, G. Abramowitz, A. Bruce, I. MacGill, R. Egan, A.B. Sproul, Real-world data analysis of distributed PV and battery energy storage system curtailment in low voltage networks, Renew. Sust. Energ. Rev. 186 (2023) 113696.

[111] F. Arraño-Vargas, S. Jiang, B. Bennett, G. Konstantinou, Mitigation of power system oscillations in weak grids with battery energy storage systems: a real-world case study, Energy 283 (2023) 128648.

[112] H. Alsharif, M. Jalili, K.N. Hasan, Power system frequency stability using optimal sizing and placement of Battery Energy Storage System under uncertainty, J. Energy Storage 50 (2022) 104610.

[113] H.H. Alhelou, B. Bahrani, J. Ma, D.J. Hill, Australia's power system frequency: current situation, industrial challenges, efforts, and future research directions, IEEE Trans. Power Syst. 39 (3) (2023) 5204–5218.

[114] EnergyCo (n.d.) Waratah Super Battery. Available at: https://www.energyco.nsw.gov.au/projects/waratah-super-battery (Accessed: 25 February 2025).

[115] B. Lu, A. Blakers, M. Stocks, C. Cheng, A. Nadolny, A zero-carbon, reliable and affordable energy future in Australia, in: arXiv Preprint arXiv:2007.09586, 2020.

[116] H. Kang, S. Jung, M. Lee, T. Hong, How to better share energy towards a carbon-neutral city? A review on application strategies of battery energy storage system in city, Renew. Sust. Energ. Rev. 157 (2022) 112113.

[117] K. Wichitkrailat, S. Premrudeepreechacharn, A. Siritaratiwat, S. Khunkitti, Optimal sizing and locations of multiple BESSs in distribution systems using crayfish optimization algorithm, IEEE Access 12 (2024) 94733–94752.

[118] D. Zhang, G.M. Shafiullah, C.K. Das, K.W. Wong, Optimal allocation of battery energy storage systems to improve system reliability and voltage and frequency stability in weak grids, Appl. Energy 377 (2025) 124541.

[119] S.A. Assery, N. Chen, X.P. Zhang, Capacity optimization and location of BESS-SC hybrid system for grid inertia support with high wind power penetration, IEEE Access 13 (2025) 63729–63742.

[120] P. Pant, M. Almasri, M. Cornejo, T. Hamacher, Impact of fast ancillary services on grid stability and BESS investment viability, Authorea Preprints (2025).

[121] L. Unruh, A Frequency-dependent Virtual Impedance Approach to Improving Stability With Grid-forming Inverters, 2025.

[122] E. Villa-Ávila, P. Arévalo, D. Ochoa-Correa, J.L. Espinoza, E. Albornoz-Vintimilla, F. Jurado, Improving V2G systems performance with low-pass filter and fuzzy logic for PV power smoothing in weak low-voltage networks, Appl. Sci. 15 (4) (2025) 1952.

[123] Z. Yan, L. Xiong, L. You, G. Han, X. Li, Enhancing power quality in distribution networks with self-adaptive VPI-controlled grid-forming battery energy storage system, J. Phys. Conf. Ser. 2932 (1) (2025) 012014 (IOP Publishing).