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Original Research Article

Grid-Scale Battery Energy Storage for Renewable Energy Integration and Peak Demand Management in Saudi Arabia

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Abstract: Saudi Arabia is expanding renewable energy deployment, while electricity demand is influenced by summer cooling peaks, significant industrial loads, emerging digital infrastructure, and geographically distributed giga-projects. As a result, grid-scale battery energy storage systems (BESS) are becoming essential power-system assets. This review establishes a Saudi-specific framework for deploying BESS to integrate solar and wind generation, manage peak demand, enhance grid reliability, and minimize curtailment. The paper adopts an MDPI-style review methodology, incorporating technology classification, thematic synthesis, multi-criteria decision analysis (MCDA), and implementation-focused discussion. Recent literature from 2020 to 2025 is synthesized, covering battery technologies, energy management systems, hybrid storage, smart grids, planning models, market design, safety, and Saudi renewable-energy development. The review determines that lithium-ion BESS is most appropriate for four-hour grid services, renewable smoothing, and peak shaving, while flow batteries, sodium-ion batteries, hybrid BESS-supercapacitor systems, and hydrogen-linked storage are better suited for longer-duration or lifecycle-sensitive applications. The proposed architecture integrates renewable plants, substations, grid-scale storage units, energy management systems, cybersecurity controls, and performance key performance indicators (KPIs). The study concludes that effective Saudi deployment relies on situating BESS to alleviate network constraints, reduce evening peaks, maintain battery health, enable transparent dispatch, and support the national transition toward a diversified, reliable, and lower-emission electricity system [1-5].

Keywords: Grid-Scale Battery Energy Storage, Renewable Integration, Peak Demand Management, Saudi Arabia, Smart Grids, MCDA, Power System Flexibility, Battery Energy Management, Grid Reliability, Energy Transition.

1. INTRODUCTION

Power systems are moving from centrally dispatched fossil generation toward cleaner, more variable and more digitally managed infrastructure. Solar photovoltaic and wind generation can reduce emissions and fuel exposure, but their output changes with weather, daylight, season and location. These patterns create operational challenges for grid operators because electricity must still be balanced at every moment. Energy storage helps close the gap between renewable production and demand by absorbing surplus energy, returning it during peak periods and providing fast grid support during disturbances [1-6].

Saudi Arabia is a particularly important case for grid-scale BESS because the country combines high solar potential, large industrial loads, rapidly expanding urban development and a national objective to diversify the energy mix. Renewable plants can produce strongly during daytime hours, whereas air-conditioning and commercial demand often intensify later in the day. Without flexible resources, high renewable penetration may lead to curtailment in low-demand periods and higher ramping requirements during evening demand. BESS can shift renewable energy, reduce peak load, stabilise frequency and defer some network upgrades when planned with realistic operating rules [2-12].

Battery storage is not a single-purpose technology. It can perform short-duration services such as frequency regulation, voltage support and ramp control, medium-duration services such as peak shaving and renewable shifting, and resilience services such as reserve support, black-start assistance and outage recovery. A grid-scale asset may therefore create several value streams simultaneously, but those value streams can conflict. A battery dispatched aggressively for price arbitrage may have insufficient reserve for reliability. A battery held only for emergency support may deliver weak economic performance. Saudi planning should therefore evaluate BESS through a balanced framework rather than through capacity size alone [1-17].

This review aims to develop a practical framework for grid-scale BESS deployment in Saudi Arabia, with a focus on renewable-energy integration and peak demand management. The objectives are to: (1) summarize recent evidence on storage technologies and grid applications; (2) evaluate how BESS supports Saudi renewable expansion and load-shape management; (3) present a planning methodology grounded in thematic review and MCDA principles; (4) propose a system architecture and KPI framework; and (5) identify implementation challenges for utilities, developers, regulators, and industrial customers. This paper is structured as a review article, rather than a single-site simulation, because the value of BESS depends on factors such as location, network constraints, tariffs, reliability criteria, and renewable profiles [1-23].

2. METHODOLOGY

This paper applies a systematised review methodology adapted from recent MDPI and Springer energy-storage studies. A recent comprehensive review used an MCDA-oriented structure to classify storage technologies, compare grid applications, and translate findings into policy and planning recommendations [1], and MCDA-oriented structure to classify storage technologies, compare grid applications and translate findings into policy and planning recommendations [1]. The present review follows that model, but narrows the scope to grid-scale BESS for Saudi renewable integration and peak demand management. Literature and technical reports published between 2020 and 2025 were prioritised to meet the required citation period and to reflect current market and technology conditions.

The review process used four stages. First, sources were mapped across battery technologies, power-system services, renewable integration, peak shaving, energy management, safety, cybersecurity and Saudi renewable-energy planning. Second, evidence was grouped by use case: energy shifting, ramp smoothing, reserve provision, frequency response, congestion relief, reliability support and capacity deferral. Third, the use cases were evaluated through an MCDA logic that considered technical performance, duration, round-trip efficiency, response time, capital cost, operating cost, degradation, safety, lifecycle emissions and implementation maturity. Fourth, the findings were synthesised into a Saudi-oriented architecture and deployment agenda [1-18].

A review methodology is appropriate because grid-scale storage planning cannot be reduced to one universal battery size. Storage that is optimal for a remote solar site may not be optimal for an urban substation or industrial cluster. Saudi regions differ in demand density, solar resource, grid congestion, available land, grid-code constraints and reliability priorities. Therefore, this paper proposes a decision framework that can guide site-specific modelling rather than replacing it. Detailed projects should still use hourly load data, renewable-resource data, network constraints, battery degradation models, power-conversion ratings, dispatch simulations and sensitivity analysis [2-19].

Table 1: Review protocol and contribution to the Saudi grid-scale BESS framework

Review stage	Evidence focus	Planning question	Framework output
Evidence mapping	Recent BESS, ESS, Saudi renewable, smart-grid and market sources	Which storage services are technically and institutionally relevant?	Scope, inclusion logic and thematic categories
Use-case definition	Renewable shifting, peak shaving, frequency response, reserve and congestion relief	Which grid problem is the battery expected to solve?	Saudi BESS value-stream map

Review stage	Evidence focus	Planning question	Framework output
MCDA screening	Efficiency, duration, CAPEX/OPEX, LCOS, safety, lifecycle emissions and maturity	Which technology and duration best match the use case?	Decision criteria for BESS selection
Scenario testing	Summer peak, solar ramp, low renewable output, outage, constraint and cyber failure	Can the asset deliver under stress without losing reserve?	Operational validation scenarios
Governance feedback	KPIs, audits, cybersecurity, maintenance, contracts and recycling	How will performance be verified over time?	Implementation and reporting agenda

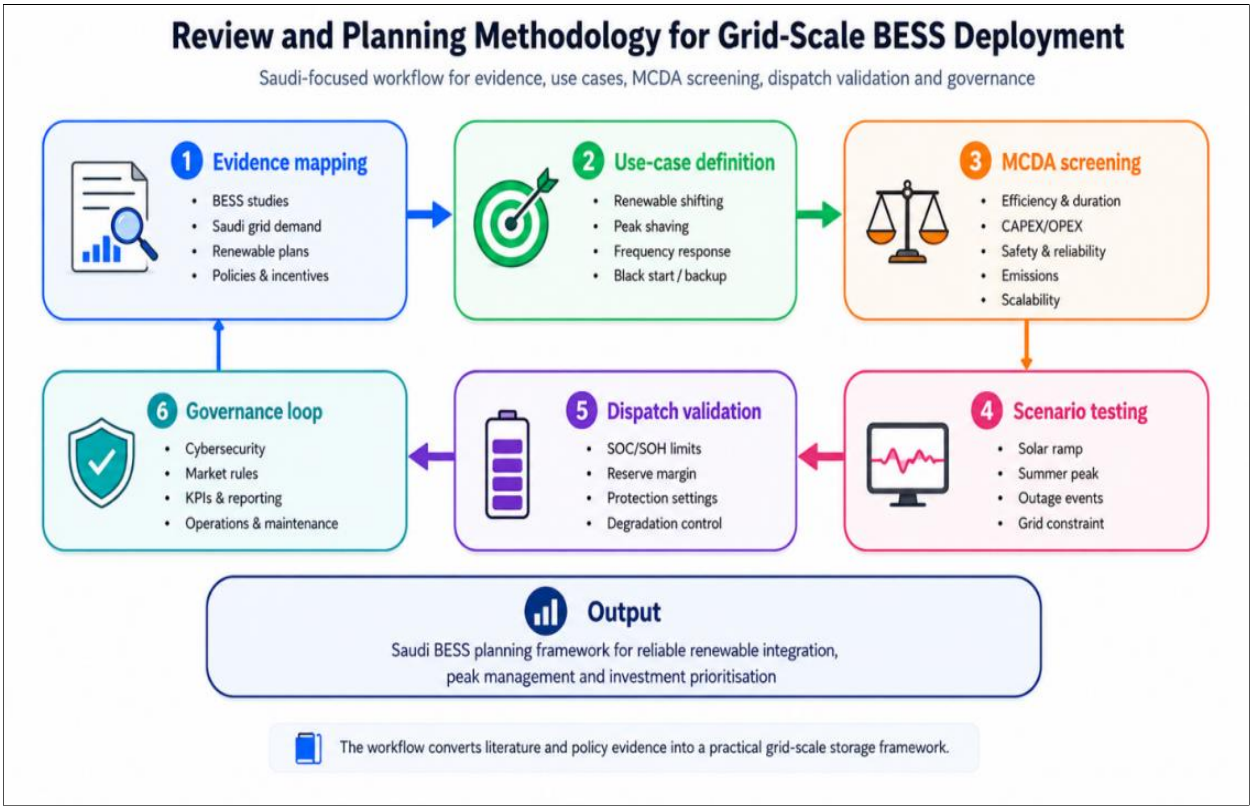

Figure 1: Review and planning methodology for grid-scale BESS deployment

3. Saudi Grid Context and Need for Storage

Saudi Arabia's electricity system must serve high cooling demand, fast urban expansion, petrochemical and industrial clusters, water infrastructure, transport electrification and data-driven economic activity. These demand centres are not always close to the best renewable-resource locations, which makes transmission planning and grid flexibility critical. BESS can improve the utilisation of renewable projects by absorbing surplus generation near the point of interconnection or by supporting constrained load pockets through strategically located storage. This is relevant as Saudi procurement activity has begun to include multi-gigawatt-hour BESS projects designed around four-hour storage duration and independent storage-provider structures [3-23].

Peak demand management is central to the Saudi value case. In hot climates, evening and seasonal peaks can drive investment in generation, substations, feeders and transmission capacity that is used only during limited hours. BESS can shave these peaks by charging during low-demand or high-renewable periods and discharging during system stress. This can reduce the need for peaking generation, improve asset utilisation and support more predictable dispatch. However, peak shaving must be coordinated with reserve obligations. If a battery discharges fully before a disturbance, it cannot provide reliability support. State-of-charge policy is therefore as important as installed capacity [4-20].

Renewable integration is the second major driver. Saudi solar resources are strong, but solar generation peaks during daylight and can fall quickly in late afternoon. Wind output can complement solar in some regions, but it is also variable. BESS can smooth ramp rates, reduce curtailment, provide voltage support through power electronics and allow renewable energy to serve later demand. Hybrid plants that combine PV, wind and BESS may offer more dependable output than standalone renewable plants, especially when dispatch is optimised against load, network conditions and market requirements [2-21].

The third driver is resilience. Extreme weather, equipment faults, cybersecurity incidents, operational errors and supply-chain constraints can affect power-system performance. Batteries cannot replace transmission investment or conventional reliability planning, but they can supply fast active power, support critical feeders and assist restoration when integrated with protection schemes and control centres. Reliability benefits must be measured through indicators such as outage ride-through, unserved energy reduction, frequency response, load-loss probability, forced curtailment and recovery time rather than through energy capacity alone [5-25].

4. Technology Options for Grid-Scale BESS

Lithium-ion batteries dominate many current grid-scale deployments because they combine high round-trip efficiency, fast response, modular construction and declining costs. They are suitable for four-hour storage, peak shaving, renewable shifting and ancillary services. Their limitations include thermal-runaway risk, degradation under high temperature, reliance on critical minerals, warranty restrictions and the need for careful fire-safety design. In Saudi Arabia, thermal management deserves special attention because battery containers may operate near high ambient temperatures, dusty conditions and remote maintenance environments [6-10].

Flow batteries offer advantages for long cycle life, deep discharge and decoupled power-energy sizing. Vanadium redox flow batteries are particularly relevant where duration and cycle life are more important than compactness. Their lower energy density and higher upfront cost can be drawbacks, but they may suit grid nodes that require frequent cycling with lower degradation pressure. Sodium-ion batteries are also gaining interest because they reduce dependence on lithium and cobalt. Their commercial maturity is lower than lithium-ion, yet they may become attractive for stationary applications where cost, safety and supply resilience matter [1-15].

Hybrid energy storage can combine batteries with supercapacitors, flywheels or hydrogen-linked storage. Supercapacitors and flywheels are strong for very fast power response, while batteries are stronger for energy shifting over hours. Hydrogen and other long-duration technologies may complement BESS for seasonal or multi-day balancing, but they involve lower round-trip efficiency and more complex infrastructure. The key planning question is not which technology is universally best, but which technology mix matches the time scale of the grid service. Short events, daily peaks and seasonal adequacy require different solutions [1-26].

Grid-scale BESS also depends on power conversion systems, transformers, communication networks, energy management software and protection settings. The battery cells represent only one layer of the asset. Inverters determine response speed, reactive power capability and grid-code compliance. The energy management system determines dispatch schedules, state-of-charge targets, degradation limits and service prioritisation. Cybersecurity and audit logs are needed because BESS increasingly operates as a digital grid asset connected to control centres, markets and maintenance systems [9-24].

5. Grid-Scale BESS Architecture for Saudi Renewable Integration

A Saudi grid-scale BESS architecture should link four operating layers: renewable and grid inputs, storage hardware, digital control and service outputs. The input layer includes solar PV plants, wind corridors, transmission substations, market signals, weather forecasts, grid constraints and demand forecasts. The storage layer includes battery containers, power conversion systems, transformers, fire detection, cooling systems and auxiliary supply. The digital control layer includes forecasting, dispatch optimisation, state estimation, cybersecurity, safety constraints and operator approval. The output layer includes renewable smoothing, peak shaving, congestion relief, frequency support and reserve provision [4-9].

Figure 2 presents a conceptual architecture. Renewable resources and demand centres feed an energy management system that determines when BESS should charge, discharge, hold reserve or provide grid services. The architecture highlights that BESS value is not created by storage capacity alone. Value is created when battery dispatch is coordinated with renewable forecasts, system peaks, network limits and reliability criteria. A BESS installed without accurate forecasting and governance may reduce one problem while creating another, such as accelerated degradation or insufficient emergency reserve [8-20].

For renewable integration, BESS should be located where it can reduce curtailment, manage ramping and relieve constraints. Co-located BESS can improve the dispatchability of solar or wind plants, while strategically placed network BESS can support substations and feeders that experience local congestion. For peak demand management, batteries should be located near demand pockets or grid nodes where peak reduction has measurable value. The best projects will combine both roles: renewable shifting during normal periods and reliability support during stress periods [3-23].

Operational sequencing is critical. Day-ahead planning should forecast renewable output, system demand and expected peak periods. Intra-day updates should revise dispatch using weather, outages, market and grid signals. Real-time control should maintain power quality, reserve margins and safe operating limits. Post-event review should compare predicted and actual performance, update models and document operational lessons. This closed-loop structure converts BESS from a static infrastructure investment into an adaptive grid resource [9-24].

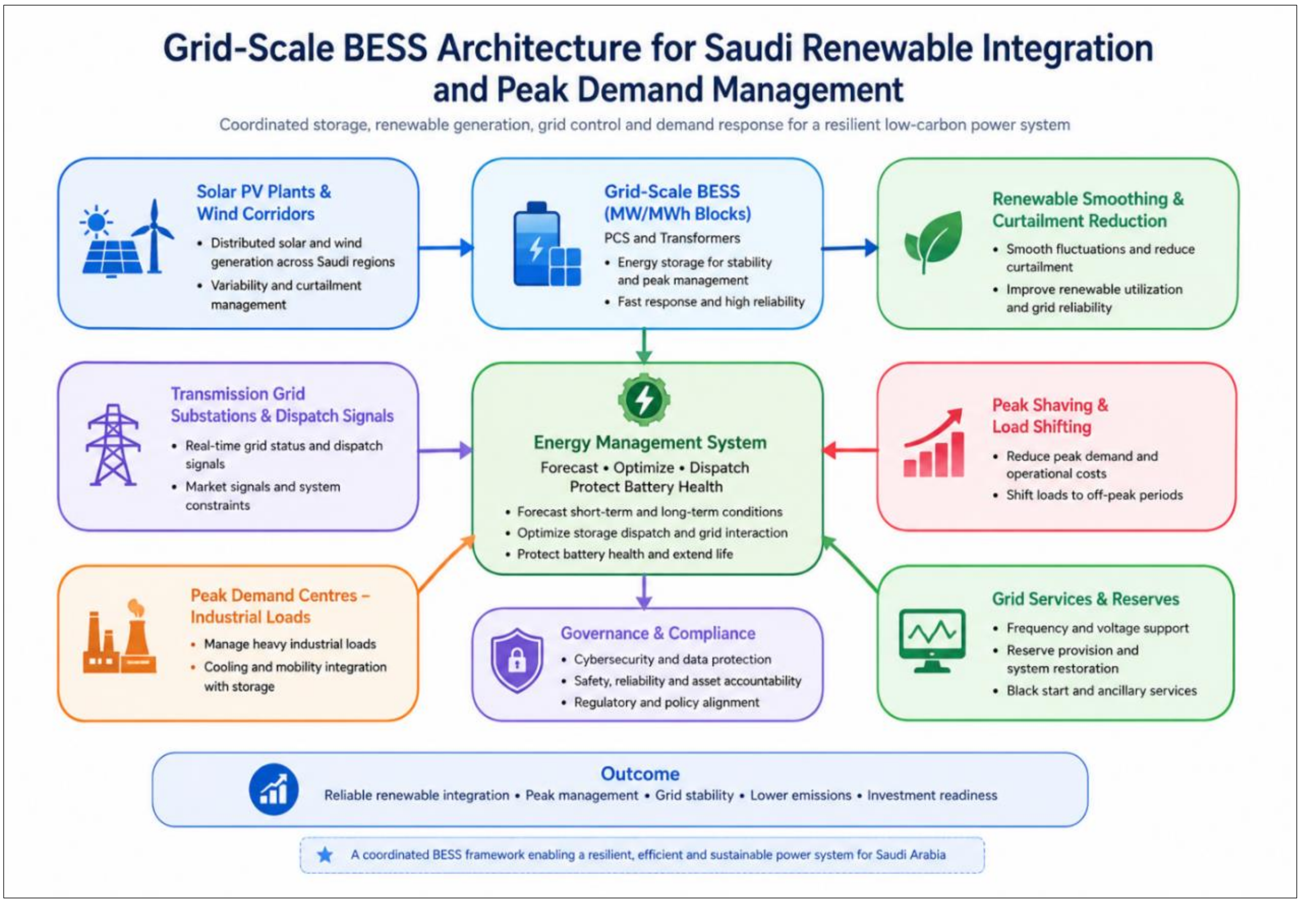

Figure 2: Grid-scale BESS architecture for Saudi renewable integration and peak demand management

6. Peak Demand Management and Operational Value

Peak shaving is often described simply as discharging a battery during high demand, but practical implementation is more complex. The operator must know whether the expected peak will last one hour, four hours or longer; whether a second peak may occur later; whether solar output will recover; and whether the battery must preserve reserve for contingencies. Poor forecasting can lead to early discharge, missed peaks or avoidable generator starts. Therefore, peak demand management requires probabilistic forecasting and conservative reserve rules, not only an economic dispatch calculation [17-20].

BESS can also support capacity deferral. If a substation or feeder is approaching its thermal limit only during a small number of high-demand hours, storage may defer upgrades by reducing peak loading. This value is site-specific and must be compared with the cost, degradation and availability of the storage system. Capacity deferral should not be claimed unless the battery can reliably discharge during the relevant hours, maintain required reserve, and remain available across the peak season. Maintenance schedules and ambient-temperature effects must be included in the analysis [4-17].

Ancillary services create additional value. Batteries can respond quickly to frequency deviations, support voltage through inverter control, provide ramping support and assist restoration. These services can be particularly important in systems with higher renewable penetration because conventional synchronous generation may operate less frequently. However, ancillary services consume headroom, cycling capacity and operational attention. Service stacking should therefore use clear priority rules. During normal operation, the battery may pursue energy shifting and peak shaving; during stressed operation, frequency response and reserve should dominate [1-25].

Environmental value comes from avoided fuel use, reduced curtailment and higher renewable utilisation. Yet battery production has lifecycle emissions and material impacts, so deployment should include lifecycle assessment, recycling plans and end-of-life responsibilities. A battery that improves daily renewable utilisation and avoids frequent generator operation can reduce operational emissions, but its full sustainability claim depends on procurement, battery chemistry, recycling and replacement schedules [1-27].

7. Performance Indicators and Evaluation Framework

A credible Saudi BESS evaluation should use a balanced KPI dashboard. Technical indicators include round-trip efficiency, availability, response time, energy capacity, power rating, ramp rate, state-of-charge accuracy, degradation rate and thermal performance. Grid indicators include renewable curtailment reduction, peak demand reduction, frequency response, voltage performance, congestion relief, load-loss probability and recovery time. Economic indicators include CAPEX, OPEX, levelised cost of storage, avoided generation cost, avoided network reinforcement, fuel savings and revenue from ancillary services [1-6].

The MCDA approach is useful because it forces stakeholders to compare alternatives transparently. A utility may prioritise reliability and curtailment reduction, while a private developer may prioritise bankability and contract revenue. A regulator may prioritise system adequacy, safety and fair cost recovery. The framework can assign weights to technical, economic, environmental and implementation criteria. It should also test sensitivity to battery cost, degradation, fuel prices, renewable curtailment, peak growth and cycling strategy. Sensitivity analysis prevents a project from appearing attractive only under one optimistic assumption [1-23].

Table 2 maps major BESS functions to data requirements, benefits and risk controls. The table shows that each value stream requires both technical data and governance. Peak shaving needs demand forecasts and reserve policies. Renewable shifting needs solar and wind forecasts. Frequency response needs inverter capability and grid-code settings. Capacity deferral needs network constraints and seasonal peak data. Resilience support needs tested procedures and operator training. Without data quality and accountability, storage benefits are difficult to verify [9-24].

Evaluation should include several scenarios: normal operation, high renewable output, low renewable output, summer peak demand, transmission constraint, grid disturbance, battery fault and cyber or communication failure. For each scenario, the BESS should be tested against dispatch rules, protection settings and required reserve margins. Digital twins and simulation platforms can support this testing, but they must be calibrated with real operating data. A model that does not reflect Saudi weather, load shapes or maintenance conditions will provide weak planning guidance [2-19].

Table 2: Grid-scale BESS functions, data requirements, benefits and risk controls

BESS function	Primary data and assets	Expected benefit	Risk control
Renewable shifting	Solar/wind forecast, plant output, SOC/SOH, inverter capacity	Higher renewable utilisation and lower curtailment	Protect reserve and validate forecast error
Peak shaving	Hourly load, seasonal peak history, feeder limits and tariffs	Lower evening peaks and deferred capacity investment	Avoid early discharge and maintain contingency margin
Frequency and ramp support	Grid frequency, ramp forecast, inverter response and reserve headroom	Improved stability during renewable variability	Coordinate with protection and market priorities
Congestion relief	Substation loading, transmission constraints and local demand growth	Reduced overload risk and targeted network support	Confirm location value through power-flow studies
Resilience and recovery	Outage logs, black-start plans, critical-load priorities and communication status	Faster recovery and lower unserved energy	Test procedures, cybersecurity and operator training

BESS function	Primary data and assets	Expected benefit	Risk control
Lifecycle management	Temperature, cycle depth, warranty terms, cooling energy and alarms	Longer asset life and more bankable performance	Audit degradation and maintenance records

8. Implementation Challenges and Policy Considerations

The first implementation challenge is location selection. Storage should be placed where it solves measurable system problems. A low-cost site with weak grid value may underperform a more complex site that reduces curtailment or relieves a constrained substation. Saudi planners should connect BESS siting to renewable project pipelines, industrial growth corridors, transmission constraints and demand centres. Storage procurement should specify the service being purchased, such as capacity, reserve, curtailment reduction or reliability support, rather than only MW and MWh ratings [3-23].

The second challenge is commercial design. BESS requires revenue certainty because its value may be distributed across energy markets, ancillary services, network deferral and reliability. If the market does not reward flexibility, projects may depend on contracts such as storage service agreements. Clear rules are needed for dispatch authority, performance penalties, availability testing, degradation risk, safety compliance and data reporting. Saudi independent storage-provider structures can support bankability if they define obligations clearly and align developer incentives with system reliability [23-28].

The third challenge is safety and cybersecurity. Utility-scale batteries require fire-safety engineering, thermal monitoring, emergency response planning, spacing, ventilation, suppression strategy and clear coordination with civil defence and grid operators. Cybersecurity is equally important because BESS dispatch depends on communication links, software updates and remote monitoring. A compromised storage asset could create operational risk if false signals affect dispatch or protection settings. Therefore, access control, network segmentation, incident response and audited change management should be embedded from the design stage [10-25].

The fourth challenge is human capability. BESS operation requires electrical engineers, protection specialists, battery analysts, data engineers, cybersecurity teams, market operators and maintenance technicians to work together. Training should cover SOC and SOH interpretation, thermal limits, inverter behaviour, dispatch priorities, emergency procedures and performance reporting. Local capability development matters because Saudi storage deployment is expected to scale, and long-term success should not depend entirely on overseas vendor teams [11-29].

Policy can accelerate deployment by clarifying grid-connection procedures, performance standards, safety requirements, market participation and recycling responsibilities. Standards such as IEEE and IEC guidance support interoperability and safety, but Saudi implementation should also account for high temperature, dust, land availability, large-scale renewable procurement and national reliability criteria. Battery recycling and second-life strategies should be planned early so that storage growth does not create a future waste or supply-chain problem [24-30].

9. Research Gaps and Future Agenda

Several research gaps remain. Saudi-specific datasets linking hourly load, renewable output, curtailment, grid constraints, battery operation, temperature and maintenance are limited in public literature. Without such datasets, many studies rely on generic assumptions or international benchmarks. Future research should publish anonymised operational evidence from Saudi BESS pilots, including performance during summer peaks, sandstorm periods, high solar output, grid constraints and outage events. This would help move the field from conceptual support toward validated planning practice [2-11].

Another gap is the integration of BESS with demand-side flexibility. Peak demand can be reduced by batteries, but also by load scheduling, district cooling storage, industrial process flexibility, electric-vehicle charging control and building energy management. The strongest approach may combine storage with flexible loads instead of treating batteries as the only solution. Research should compare BESS-only, demand-response-only and combined strategies under Saudi conditions, especially for cities, industrial zones, water infrastructure and giga-project districts [12-19].

A third gap is degradation-aware economics. Many economic analyses treat battery capacity as stable or apply simplified replacement assumptions. In reality, degradation depends on cycle depth, temperature, state of charge, calendar ageing, power rate and control strategy. Saudi heat conditions make this especially important. Future models should combine electrochemical degradation, thermal management, dispatch optimisation and lifecycle cost. This will support procurement decisions that reward long-term performance rather than only low initial price [6-10].

Future research should also investigate market design. BESS can provide multiple services, but service stacking requires rules for priority, settlement, verification and conflict management. For example, a battery committed to reserve cannot always be used for energy arbitrage. A battery supporting a constrained substation may not be freely dispatched for a national market signal. Saudi market frameworks should therefore define how storage availability, performance and opportunity cost are measured [4-28].

For effective deployment, storage procurement should specify measurable services prior to technology selection. Each bid must detail required response time, duration, and availability testing. Operators should maintain distinct dispatch modes for normal, alert, and emergency conditions, and battery reserves should be safeguarded during adverse weather or outage risks. Peak shaving value should be validated against feeder loading and seasonal demand records, while renewable shifting should be quantified through avoided curtailment and delivered energy. Cybersecurity assessments must address remote access, firmware updates, and communication failures. Maintenance planning should account for high ambient temperatures, dust exposure, and spare parts availability. Financial models should incorporate degradation, cooling energy, insurance, and replacement schedules. Public reporting should distinguish between installed capacity and verified operational performance. Pilot projects are encouraged to publish anonymized lessons to inform future Saudi storage planning. Contracts should incentivize availability, safety compliance, and reliable dispatch rather than capacity alone. Control centers should train operators in interpreting SOC, SOH, and inverter alarms. Grid codes should clarify voltage support, frequency response, and ride-through requirements. Planning models should utilize hourly data to capture operational peaks. Battery recycling responsibilities must be established before large-scale procurement. Industrial sites should coordinate BESS dispatch with process safety and maintenance schedules, while urban substations should assess storage against cable upgrades and transformer loading. Renewable developers should evaluate whether co-located batteries enhance plant dispatchability. Utilities should maintain audit trails for both manual overrides and automated dispatch decisions. Saudi storage programs can strengthen local expertise through commissioning and performance reviews. The most resilient projects integrate engineering rigor, commercial transparency, and operational learning.

10. CONCLUSION

Grid-scale battery energy storage is becoming a central enabler of renewable integration and peak demand management in Saudi Arabia. The review shows that BESS can reduce curtailment, shift solar generation, manage evening peaks, provide ancillary services, support reliability and defer some network investments. However, these benefits depend on planning discipline. A battery is not only an energy container; it is a digitally controlled grid asset that requires forecasting, dispatch optimisation, safety constraints, cybersecurity, maintenance and transparent governance [1-23].

The proposed Saudi framework combines evidence mapping, use-case definition, MCDA screening, scenario testing, dispatch validation and governance feedback. The MCDA-oriented structure uses a comprehensive review tables and figures within the relevant methodological, architectural and evaluation sections so that visual content supports the argument rather than appearing after the conclusion. For practical deployment, decision makers should identify the grid problem first, then select the BESS location, duration, chemistry, dispatch policy and contractual model. This approach can help Saudi Arabia transform storage from isolated projects into a coordinated infrastructure layer for reliable, flexible and low-emission electricity service [3-24].

REFERENCES

1. Areola, R. I., Adebiyi, A. A., & Moloi, K. (2025). Integrated energy storage systems for enhanced grid efficiency: A comprehensive review of technologies and applications. Energies, 18(7), 1848. https://doi.org/10.3390/en18071848
2. Alturki, A. A. (2022). Optimal design for a hybrid microgrid-hydrogen storage facility in Saudi Arabia. Energy, Sustainability and Society, 12, 24. https://doi.org/10.1186/s13705-022-00351-7
3. Almutairi, A., & Alhamed, Y. (2025). Sustainability and grid reliability of renewable energy expansion projects in Saudi Arabia by 2030. Sustainability, 17(10), 4493. https://doi.org/10.3390/su17104493
4. International Energy Agency. (2024). Batteries and secure energy transitions. IEA, Paris.
5. International Renewable Energy Agency. (2024). World energy transitions outlook 2024: 1.5 degrees C pathway. IRENA, Abu Dhabi.
6. Nazaralizadeh, S., Banerjee, P., Srivastava, A. K., & Famouri, P. (2024). Battery energy storage systems: A review of energy management systems and health metrics. Energies, 17(5), 1250. https://doi.org/10.3390/en17051250
7. Rey, S. O., Romero, J. A., Romero, L. T., Martinez, F., Roger, X. S., Qamar, M. A., Dominguez-Garcia, J. L., & Gevorkov, L. (2023). Powering the future: A

comprehensive review of battery energy storage systems. Energies, 16(17), 6344. https://doi.org/10.3390/en16176344
8. Wang, Y., Rousis, A. O., & Strbac, G. (2022). Modelling and optimal energy management for battery energy storage systems in renewable energy systems: A review. Renewable and Sustainable Energy Reviews, 167, 112671. https://doi.org/10.1016/j.rser.2022.112671
9. Lee, S., Seon, J., Hwang, B., Kim, S., Sun, Y., & Kim, J. (2024). Recent trends and issues of energy management systems using machine learning. Energies, 17(3), 624. https://doi.org/10.3390/en17030624
10. Shi, D., Zhao, J., Eze, C., Wang, Z., Wang, J., Lian, Y., & Burke, A. F. (2023). Cloud-based artificial intelligence framework for battery management system. Energies, 16(11), 4403. https://doi.org/10.3390/en16114403
11. Khalid, M. (2021). Smart grids and renewable energy systems: Perspectives and grid integration challenges in Saudi Arabia. Energy Reports, 7, 665-676.
12. Almasoud, A. H., & Gandayh, H. M. (2020). Future of solar energy in Saudi Arabia. Journal of King Saud University - Engineering Sciences, 32, 1-8.
13. Park, S., Ahn, J., Kang, T., Park, S., Kim, Y., Cho, I., & Kim, J. (2020). Review of state-of-the-art battery state estimation technologies for battery management systems of stationary energy storage systems. Journal of Power Electronics, 20, 1526-1540.
14. Sharma, P., Saini, R. P., & colleagues. (2023). Applications of energy storage systems in enhancing energy management and access in microgrids: A review. Energies, 16(16), 5930.
15. Carrasco Ortega, P., Duran Gomez, P., Merida Sanchez, J. C., Echevarria Camarero, F., & Pardinas, A. A. (2023). Battery energy storage systems for the new electricity market landscape: Modeling, state diagnostics, management, and viability - A review. Energies, 16(17), 6334.
16. Vanlalchhuanawmi, & colleagues. (2024). Energy management strategies in distribution system integrating electric vehicle and battery energy storage system: A review. Energy Storage, 6(5), e682. https://doi.org/10.1002/est2.682
17. Barbour, E., Parra, D., Awwad, Z., & Gonzalez, M. C. (2020). Community energy storage: A smart choice for the smart grid? Applied Energy, 278, 115675.
18. Chatzigeorgiou, N. G., Theocharis, A. I., & Zachariadis, T. (2024). Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration. Sustainable Energy Research, 11, 20.
19. Aghaei, J., et al. (2022). Integrated planning of renewable generation and battery storage under uncertainty: A review of optimization approaches. Renewable and Sustainable Energy Reviews, 158, 112114.
20. Zhang, Y., Wang, J., & Liu, X. (2024). Optimal allocation of battery energy storage systems for peak shaving and reliability enhancement in distribution systems. Journal of Energy Storage, 95, 112305.
21. Abo-Khalil, A. G., Alharbi, W., & Al-Quraan, A. (2023). Overcoming the challenges of integrating variable renewable energy to the grid: A comprehensive review of electrochemical battery storage systems. Journal of Energy Storage, 72, 108498.
22. Psarros, G. N., Dratsas, P. A., & Papathanassiou, S. A. (2024). A comprehensive review of electricity storage applications in island systems. Renewable and Sustainable Energy Reviews, 191, 114153.
23. Saudi Press Agency. (2024). SPPC starts the qualification process for the first group of battery energy storage system projects with total capacity of 8000 MWh. SPA, Riyadh.
24. National Institute of Standards and Technology. (2024). The NIST Cybersecurity Framework (CSF) 2.0. NIST, Gaithersburg, MD.
25. IEEE Standards Association. (2020). IEEE Std 2030.2.1-2019: Guide for design, operation and maintenance of battery energy storage systems, both stationary and mobile, and applications integrated with electric power systems. IEEE.
26. European Commission. (2023). Batteries regulation and circular economy requirements for sustainable battery value chains. Official Journal of the European Union.
27. International Energy Agency. (2025). Global critical minerals outlook 2025. IEA, Paris.
28. Hameed, Z., & Traeholt, C. (2025). EPC framework for battery energy storage system projects. arXiv preprint arXiv:2506.13281.
29. Uptime Institute. (2024). Global data center survey results 2024. Uptime Institute Intelligence.
30. King Abdullah City for Atomic and Renewable Energy. (2024). Renewable energy sectors and resource data initiatives in the Kingdom of Saudi Arabia. KACARE, Riyadh.