

Energy Storage Technologies for Desert Conditions: Battery Chemistries, Thermal Storage and Large-Scale Innovations

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Abstract—Saudi Arabia’s targets 50% renewable electricity and over 130 GW of renewable, underpinned by rapid deployment of grid-scale energy storage. The Kingdom’s desert climate—characterized by high temperatures, dust, significant temperature fluctuations, and remote energy demands—presents distinct technical and economic challenges for storage systems. This paper reviews energy storage technologies appropriate for these conditions, with a focus on their deployment in Saudi Arabia. It assesses advanced battery chemistries (lithium-ion, sodium-based, and flow batteries), high-temperature electrochemical systems, and thermal energy storage solutions (including molten salt, sensible, and latent heat storage). The analysis addresses large-scale storage for both grid-connected and off-grid projects, including giga-scale solar-plus-storage and coastal tourism megaprojects such as AMAALA and NEOM. Recent national targets, such as 48 GWh of battery storage, underscore the sector’s strategic significance. The paper concludes with recommendations for research and policy to localize storage technologies, improve reliability, and support national decarbonization and energy security objectives.

Keywords— desert climate, battery energy storage system (BESS), thermal energy storage (TES), molten salt, phase change material, NEOM, AMAALA.

I. INTRODUCTION

Saudi Arabia is implementing one of the most ambitious power-sector transformations worldwide (IRENA, 2023). The Ministry of Energy’s renewable program seeks an optimal generation mix of approximately 50% natural gas and 50% renewables, with the goal of replacing substantial volumes of liquid fuel and enabling up to 130 GW of renewable capacity (Saudi Ministry of Energy, 2024). Rapid deployment of solar photovoltaic and wind projects is underway, with over 40 GW at various stages of development and record-low tariffs achieved in recent auction rounds (IEA, 2024).

To integrate this variable generation while maintaining high reliability in a hot, arid environment, the Kingdom has announced ambitious targets for battery energy storage systems (BESS): 8 GWh online by 2025, 22 GWh by 2026 and up to 48 GWh of storage through public-private partnerships (Saudi Power Procurement Company, 2024). Flagship projects include the Bisha BESS (500 MW for four hours), large-scale storage linked to new solar farms, and off-grid storage systems for coastal tourism megaprojects (Wood Mackenzie, 2024).

Conventional energy storage design assumptions—such as temperate climates, minimal dust, and easy access to water for cooling—do not apply in desert environments. In Saudi Arabia, storage assets must function under ambient temperatures exceeding 45–50 °C, intense solar radiation, frequent dust storms, and, in some cases, fully off-grid conditions (Al-Sulaiman et al., 2022). These factors accelerate battery degradation, complicate thermal management, and increase the need for robust system engineering.

This paper examines the main categories of energy storage technologies relevant to desert conditions and evaluates their suitability for deployment in Saudi Arabia. The analysis emphasizes: electrochemical storage (various battery chemistries), thermal energy storage (TES) for concentrated solar power (CSP) and buildings and integrated, large-scale storage architectures for grid and off-grid systems.

It also relates these technologies to the Kingdom’s evolving project pipeline and policy objectives. Energy storage systems in Saudi Arabia face several environmental and operational stresses (Almasabi et al., 2023): Daytime ambient temperatures in many

regions exceed 45 °C in summer, with surface temperatures significantly higher.

Elevated temperature accelerates capacity fade, side reactions and gas formation in conventional Li-ion batteries, shortening calendar and cycle life and increasing safety risks (Panchal et al., 2020). Large day–night and seasonal temperature ranges cause repeated thermal cycling of storage enclosures and tanks, imposing mechanical stress on seals, electrolyte stability, and structural components (Al-Hallaj & Kiszynski, 2021).

Dust storms can clog filters and reduce heat-transfer efficiency in air-cooled systems, while salt-laden coastal air threatens corrosion in Red Sea megaprojects such as AMAALA (Rahman et al., 2023). Giga-projects (NEOM, AMAALA, Red Sea) and mining operations require islanded microgrids with limited on-site maintenance staff and high reliability requirements, demanding storage solutions with high inherent safety and low maintenance (NEOM Company, 2024).

II. HIGH SOLAR PV PENETRATION

Utility-scale PV plants in Saudi Arabia benefit from excellent irradiation but also experience steep ramps and midday surpluses. Storage systems must therefore handle frequent partial cycling and provide firming, ramp control, and peak shifting services (IRENA, 2023).

These factors significantly influence the selection and design of energy storage technologies, particularly in terms of temperature tolerance, thermal management strategies, safety, and long-duration operational capability.

III. BATTERY ENERGY STORAGE FOR DESERT CONDITIONS

3.1 Lithium-Ion Chemistries

Lithium-ion (Li-ion) batteries dominate early BESS deployments due to their high round-trip efficiency (85–95%), compactness, and declining cost (BloombergNEF, 2024). In Saudi Arabia, grid-scale BESS projects such as Bisha (500 MW/2,000 MWh) and new tenders are expected to use containerized Li-ion solutions (Saudi Electricity Company, 2024).

For desert conditions, lithium iron phosphate (LFP) chemistries are generally favored over nickel-rich

NMC (Zhang et al., 2023). Better thermal stability and lower risk of thermal runaway at high temperatures. Long cycle life at partial states of charge. Good performance in high-cycle grid applications (Xu et al., 2020). Higher energy density, but More sensitive to heat and overcharge, requiring stricter cooling and safety systems (Li et al., 2022). High ambient temperatures exacerbate capacity fade. Most Li-ion vendors specify optimal operating ranges around 15–35 °C, with accelerated degradation above 40 °C (Naumann et al., 2020). As a result, containerized systems in Saudi Arabia require:

Intelligent thermal management that pre-cools during off-peak hours and minimizes HVAC consumption (Börner et al., 2023). Recent projects demonstrate desert-optimized container designs. For example, HiTHIUM’s “Desert Eagle” BESS containers, deployed in Saudi Arabia, use multi-layer insulation and thermal design to keep internal temperatures up to 10 °C lower than ambient and are rated to operate from –30 °C to 60 °C, enabling 4 GWh of long-duration storage for the Saudi Electricity Company (HiTHIUM, 2024).

These innovations indicate that lithium-ion technology can be adapted for use in desert climates, though they entail higher capital costs and increased system complexity (Schmidt et al., 2021).

3.2 Sodium-Based Batteries

Sodium-ion batteries (Na-ion) are emerging as an alternative for stationary storage (Hirsh et al., 2020). Their advantages include: Use of abundant sodium instead of lithium, reducing material cost and supply risk. Potentially better high-temperature tolerance, as some Na-ion chemistries maintain performance at higher ambient conditions compared with conventional Li-ion (Vaalma et al., 2021). However, Na-ion is still an emerging technology with:

Limited long-term field data in harsh climates.

Lower energy density, which is less critical for stationary, but affects the footprint

Fewer bankable suppliers compared to Li-ion (Nayak et al., 2022). Sodium-sulfur (NaS) batteries, an older high-temperature technology, operate at 300–350 °C, which paradoxically makes desert operation easier, since ambient heat slightly reduces the required heating load (Oshima et al., 2020). NaS offers: long duration an high energy density for

stationary applications. Drawbacks include complex safety requirements, potential toxicity, and the need for robust thermal containment (Kumar et al., 2021).

3.3 High-Temperature Na–NiCl₂ (Zebra) Batteries Sodium–nickel chloride (Na–NiCl₂, often called Zebra batteries) operate at ~270–300 °C and are fully sealed (Dustmann, 2020). Their key features:

- Good tolerance to ambient temperature, with negligible impact from hot climates because the internal operating temper For desert microgrids and remote infrastructure, Na–NiCl₂ batteries may be advantageous in scenarios with limited maintenance access, provided that the associated cost premium and start-up energy requirements are acceptable (Gallardo-Lozano et al., 2022). remote infrastructure, Na–NiCl₂ can be attractive where maintenance access is limited, provided that the cost premium and start-up energy are acceptable (Gallardo-Lozano et al., 2022).

3.4 Flow Batteries

Vanadium redox flow batteries (VRFBs) and other flow chemistries decouple power (stacks) from energy (electrolyte volume), making them structurally suited to long-duration storage with high cycle life (Winsberg et al., 2020). Their aqueous electrolytes are non-flammable, which is beneficial for high-temperature environments.

Table 1: Comparison of Energy Storage Technologies for Saudi Desert Conditions

Comparison of Energy Storage Technologies for Saudi Desert Conditions

Technology	Duration	Round-Trip Efficiency	High-Temp Tolerance	Cycle Life	Key Advantage for Desert	Main Challenge
Li-ion (LFP)	2-4 h	85-95%	Moderate (requires cooling)	3,000-5,000	Proven; high efficiency.	High cooling demands, degradation >40°C.
Na-ion	2-6 h	80-90%	Good (better than Li-ion)	2,000-4,000	Abundant materials, lower cost.	Emerging technology, limited field data.
NaS (High-temp)	6-8 h	75-85%	Excellent (operates 300-350°C)	4,500+	Ambient heat reduces heating load.	Complex safety, toxicity concerns.
Na-NiCl ₂ (Zebra)	4-8 h	80-90%	Excellent (operates ~280°C)	3,000+	Intrinsic safety, sealed design.	Start-up energy, cost premium.
Vanadium Flow	8-12 h	70-85%	Moderate-Good (with additives)	10,000+	Decoupled power/energy, high safety.	Electrolyte stability >45°C, complexity.
Molten Salt TES	6-15 h	90-95%	Excellent (operates 290-650°C)	Unlimited	High DNI utilization, dispatchable.	Water for steam cycle, land area.
PCM (Building)	8-12 h	75-90%	Excellent (passive operation)	10,000+	Passive cooling, building integration.	Limited capacity per unit volume.
Green Hydrogen	Days-Seasonal	30-50%	Good (modular systems)	Variable	Long-duration, export potential.	Low round-trip efficiency, high cost.

Table 2

Arabia Major Energy Storage Projects and Specifications

Project Name	Location	Type	Capacity	Duration	Status	Primary Application	Key Desert Features
Bisha BESS	Bisha	Li-ion (LFP)	500 MW / 2,000 MWh	4 hours	Under construction	Grid firming, peak shifting.	Desert-optimized containers, advanced HVAC.
SEC Long-Duration Storage	Multiple sites	Li-ion (NTHLM)	4 GWh total	4-6 hours	Deployment phase	Grid stability, renewable integration.	Multi-layer insulation, -30°C to 60°C rating.
AMAALA Off-Grid	Red Sea Coast	Hybrid (PV+ BESS)	~760 MWh	Multi-hour	Development	24/7 renewable power, desalination.	Coastal corrosion protection, islanded operation.
NEOM Renewable Hub	NEOM	Hybrid (PV+ BESS+ BtL)	Multi-GWh planned	Variable	Planning/ Early dev	Green city power, hydrogen export.	Extreme reliability, dust/sand mitigation.
Tabuk/Hail BESS	Northern region	Li-ion	Multi-hundred MW	2-4 hours	Tendering	Wind/solar firming.	High diurnal temperature swings.
CSP Molten Salt	Various (potential)	Thermal (molten salt)	1,000+ MWh thermal	6-15 hours	Feasibility stage	Dispatchable solar power.	High DNI, dry cooling required.

Standard vanadium electrolytes are typically stable between about 10–40 °C; above 40 °C, precipitation and decomposition issues emerge. Recent research, however, has developed “wide temperature range” electrolytes that remain stable from roughly –5 °C to 45–55 °C using additives or alternative formulations, significantly expanding their environmental suitability (Park et al., 2023).

In desert contexts, flow batteries offer:

- High cycle life (10,000+ cycles) with minimal capacity fade
- High safety (no thermal runaway)
- Easy scaling of energy (larger tanks) for 8–12 hour storage or more (Weber et al., 2021)

But they face:

- Higher system complexity (pumps, tanks, piping)
- Lower round-trip efficiency (~70–85%) than Li-ion

- Sensitivity of electrolyte stability to prolonged >45 °C conditions, which still demands somOngoing advancements in electrolyte research and development may position vanadium redox flow batteries as a robust option for long-duration storage in desert environments, particularly for large solar farms or microgrids requiring multi-hour resilience (IRENA, 2024).rids that require multi-hour resilience (IRENA, 2024).

Table 3

Research and Policy Priorities for Desert Energy Storage (2025-2030)

Priority Area	Key Actions	Expected Outcomes	Timeline	Responsible Entities
High-Temp Battery R&D	Develop LFP/Na-ion cells rated for 45-55°C continuous operation; stabilize flow battery electrolytes to 50°C+	Extended battery life, reduced cooling costs	2025-2028	Universities (KUST, KFUPM), battery manufacturers
Passive Cooling Systems	Test radiative cooling panels, PCM-integrated container walls	30-50% reduction in HVAC energy consumption	2025-2027	Research institutes, BESS vendors
Desert-Grade TES Materials	Characterize molten salts with wider temp ranges; develop PCMs for 26-35°C melting points	Improved CSP economics, building efficiency	2025-2029	National labs, CSP developers
Localization & Manufacturing	Establish local assembly of BESS containers, PCS, and thermal systems	30-50% local content by 2030, job creation	2025-2030	Ministry of Industry, Saudi utilities, private sector
Battery Recycling Ecosystem	Build collection and processing facilities for end-of-life Li-ion and other chemistries; issue desert-specific standards (temperature ratings, IP ratings, fire safety)	Circular economy, critical material recovery	2027-2030	Environmental agencies, recycling startups
Technical Standards	Harmonize specifications, improved reliability	Harmonized specifications, improved reliability	2025-2026	Saudi Standards Authority (SASO), IEEE/IEC liaison
Market Design	Create capacity and ancillary service markets that compensate storage for flexibility and resilience	Investment certainty, fair revenue streams	2025-2027	Ministry of Energy, Saudi Electricity Regulatory Authority
Demonstration Projects	Use NEOM, AMAALA as testbeds for novel storage configurations and control algorithms	Field-validated best practices, technology transfer	2024-2029	Giga-project companies, international partners

Environmental and Operational Stressors on Energy Storage in Saudi Desert Conditions

Stressor	Typical Range/Frequency	Impact on Li-ion BESS	Impact on Thermal Storage	Impact on Flow Batteries	Mitigation Strategies
High Ambient Temperature	45-50°C daily max (summer)	Accelerated capacity fade, thermal runaway risk	Reduces heating load for high-temp systems, minimal impact on molten salt	Electrolyte precipitation/decomposition >40°C	Insulation, active cooling, wide-temp electrolytes
Diurnal Temperature Swing	20-30°C day-night difference	Repeated thermal cycling stress on cells/seals	Mechanical stress on tanks, piping	Cycling stress on seals, pumps	Thermal buffering, flexible materials
Dust Storms	10-30 events/year	Clogged filters, reduced heat transfer in air-cooled systems	Reduced heat transfer in air-side equipment	Pump/filter clogging, reduced cooling efficiency	IP-rated enclosures, positive pressure, frequent filter maintenance, coatings, sealed systems
Salt-Laden Coastal Air	Continuous (Red Sea projects)	Corrosion of containers, electrical connections	Corrosion of tanks, heat exchangers	Corrosion of stacks, piping	Reflective coatings, shading structures
High Solar Radiation	6-7 kWh/m ² /day	Surface heating of containers (>60°C)	Beneficial for CSP, neutral for storage tanks	Minimal direct impact	Autonomous monitoring, predictive maintenance, modular design
Remote Location	Off-grid or weak grid	Limited maintenance access, extended MTR	Limited maintenance, need for robust design	Complex system requires skilled maintenance	SOE management algorithms, cycle optimization
Frequent Partial Cycling	1-2 cycles/day, variable depth	Accelerated degradation if not managed	Minimal impact (cycling tolerant)	Minimal impact (high cycle tolerance)	

3.5 Design and Engineering Considerations

Regardless of chemistry, desert BESS design must address (Kebede et al., 2022):

- Thermal management:

Use of reflective coatings, shading structures, and high-R-value insulation on containers.

Hybrid cooling (evaporative + DX or chilled-water loops) where water availability permits (Al-Zareer et al., 2020).

- Dust and sand protection:

IP-rated enclosures, positive-pressure ventilation, and robust filtration.

Periodic cleaning schedules and monitoring of pressure drop across filters (Elminir et al., 2021).

- Fire safety:

Stringent fire detection and suppression (aerosol, inert gas) for Li-ion systems.

Large spacing between containers in high-risk environments (Wang et al., 2023).

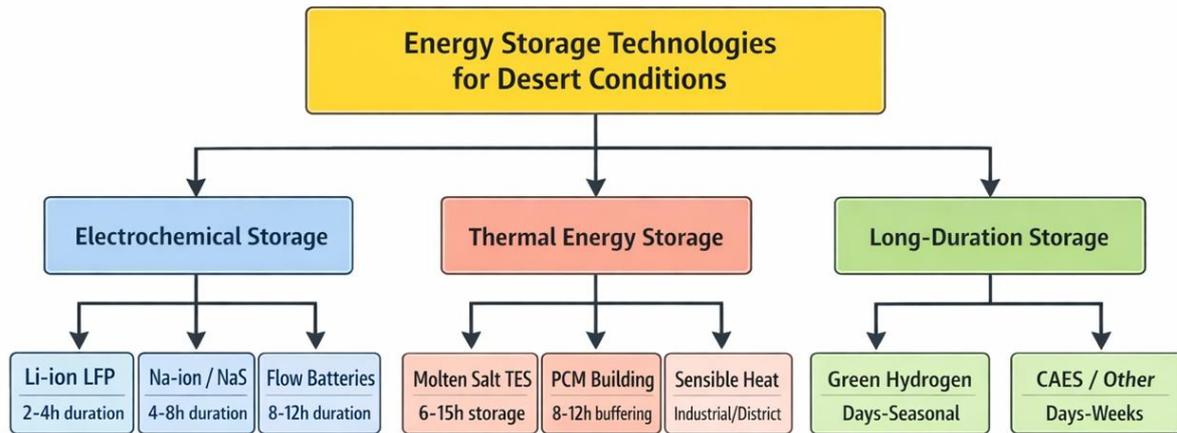
- Grid integration and controls:

Advanced energy management systems (EMS) to manage frequent cycling, optimize state-of-charge buffers, and integrate with demand response or curtailment policies (Hesse et al., 2020).

Saudi projects, such as the Bisha and Tabuk/Hail BESS deployments, already incorporate many of these design features, providing valuable operational experience for future installations (Saudi Electricity Company, 2024).

Figure 1: Energy Storage Technology Categories for Desert Conditions

Caption: Overview of major energy storage technology categories deployed or suitable for Saudi Arabia's desert environment, organized by storage mechanism and duration capability.



IV. THERMAL ENERGY STORAGE (TES) FOR DESERT CONDITIONS

In addition to electrochemical storage, thermal energy storage leverages the desert’s intense solar resource and large day–night temperature differences (Pelay et al., 2020).

4.1 Molten Salt TES in CSP Plants

Concentrated solar power (CSP) with molten salt TES is inherently suited to high-irradiance, desert climates (Liu et al., 2020). In such plants, solar energy is captured via mirrors and stored in tanks of molten salt—often a nitrate mixture—at 290–565 °C or higher, then dispatched through a steam cycle when needed.

International CSP plants with large molten-salt systems (e.g., Bokpoort CSP, partly owned by a Saudi developer) demonstrate multi-hour to overnight storage using tens of thousands of tons of molten salt (NREL, 2021). Recent studies of high-temperature molten salts (up to 650 °C) show that raising storage temperature can increase annual power generation by more than 20% and reduce the levelized cost of electricity by around 20% relative to conventional salts (Khanna et al., 2022).

For Saudi Arabia, CSP with TES is most attractive where:

- Land is plentiful and low-cost
- Direct normal irradiance (DNI) is high
- There is a need for dispatchable, night-time renewable power, for example, to support industrial loads or off-grid resorts (Islam et al., 2021).

Limited water availability for steam cycles and cooling presents a significant constraint, prompting a shift toward dry-cooling configurations (Okazaki et al., 2020).

4.2 Sensible Heat Storage for Industrial and District Applications

Sensible heat storage in packed beds (rock, concrete) or water tanks can support (Zanganeh et al., 2020):

- Industrial process heat (e.g., desalination, district heating/cooling)

- District cooling or campus-scale These systems offer the following characteristics: led-water or ice storage

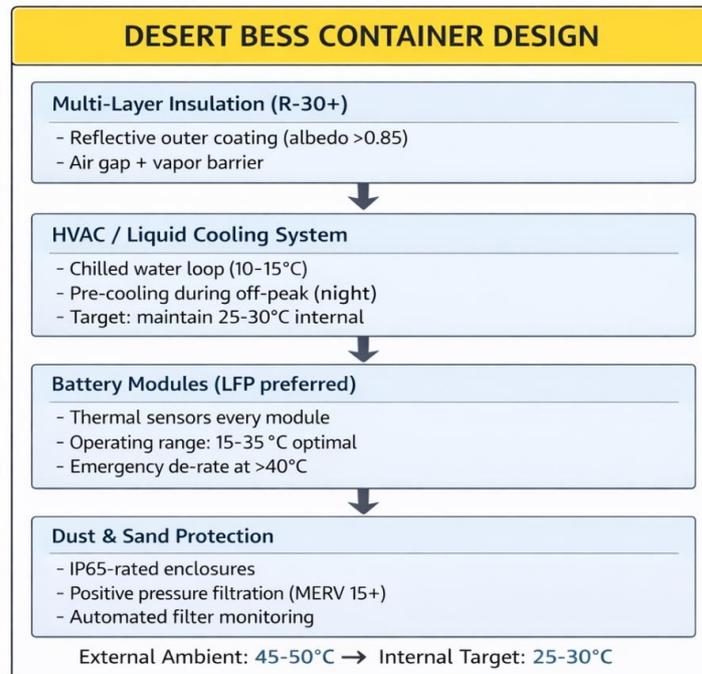
Such systems are characterized by the following attributes:

- Mechanically simple
- Capable of thousands of cycles
- Well-matched to diurnal storage (e.g., store coolness or heat over 8–12 hours) (Kuravi et al., 2021).

For coastal Saudi resorts and urban districts, large chilled-water tanks or stratified storage systems can shift chiller operation to off-peak hours, reducing peak load and enabling better integration of solar PV (Hajiah & Krarti, 2022).

Figure 2: Desert BESS Thermal Management Architecture

Caption: Schematic representation of thermal management systems required for containerized battery energy storage in high-temperature desert environments (ambient >45°C).



4.3 Phase Change Material (PCM) Storage

Phase change materials (PCMs) store energy as latent heat near their transition temperature (Faraj et al., 2020). For building applications in warm and hot arid regions, PCMs embedded in walls or ceilings have demonstrated:

- Reductions in heat transfer of up to ~40–50%
 - Lowered indoor temperature peaks and smaller diurnal fluctuations
 - Cooling energy savings of up to ~30%, depending on PCM type and placement (Kenisarin & Mahkamov, 2023).
- Studies in semi-arid climates similar to parts of North Africa show that PCMs with melting temperatures around 26–30 °C are particularly effective in stabilizing indoor conditions and reducing cooling loads (Fateh et al., 2021).

For Saudi Arabia:

- PCMs can be integrated into building envelopes, especially in highly glazed or lightweight structures, to passively buffer internal spaces.
- They are especially useful in conjunction with night-time ventilation or off-peak cooling, essentially turning the building into a thermal battery (Al-Absi et al., 2020).

4.4 Thermochemical Storage

Thermochemical storage (TCS) uses reversible chemical reactions to store heat with high energy density and negligible losses over long periods (Pardo et al., 2020). While still largely at the R&D or pilot stage, TCS could be relevant to:

- Seasonal cooling or heating storage in desert climates
- Long-duration backup for critical loads. In the Saudi context, thermochemical storage could be explored through research projects associated with universities and innovation zones; however, it is not yet as deployable as molten salt TES or PCM systems (Scapino et al., 2023).

V. LARGE-SCALE AND HYBRID STORAGE ARCHITECTURES

5.1 Grid-Scale PV + BESS

The Kingdom’s tendering program is increasingly bundling solar PV with BESS to provide firm capacity and ancillary services (IRENA, 2023). Typical configurations are:

- 100–500 MW PV plus 200–1,000 MWh BESS for 2–4 hours
- Services: ramp rate control, frequency support, peak shaving, reserve (Denholm et al., 2021). Smart dispatch strategies can:

- Charge batteries when solar is abundant and demand is low
- Discharge during evening peaks or when clouds cause rapid drops in generation (Joos et al., 2020). The 48 GWh storage target is anticipated to be achieved primarily through integrated PV-plus-storage projects (Saudi Power Procurement Company, 2024).

5.2 Off-Grid Solar-Plus-Storage for Giga-Projects
 Projects such as AMAALA are designed to operate entirely on renewable energy, using large solar-plus-storage systems to deliver 24/7 power, including to desalination and wastewater facilities (AMAALA, 2023). The AMAALA off-grid project includes around 760 MWh of battery storage and advanced system modeling (HIL simulation, PSCAD, etc.) to ensure reliability under varying conditions (AlGhamdi et al., 2024). Similar architectures are envisaged for NEOM and other coastal destinations, with storage sized to cope with multi-hour or even multi-day renewable variability (NEOM Company, 2024). Hybrid configurations may combine:

- PV + BESS + diesel or gas-turbine backup (initial phases)
- PV + BESS + CSP-TES for higher renewable fractions

- PV + BESS + green hydrogen for long-duration or seasonal storage in later phases (Heide et al., 2021).

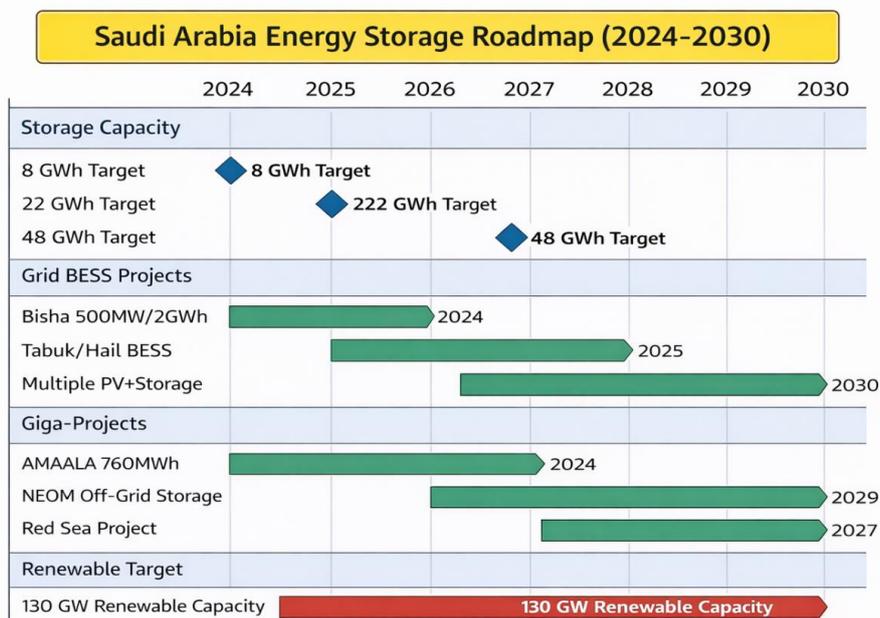
5.3 Long-Duration Storage: Hydrogen and Beyond
 To support very high renewable penetration, especially if the Kingdom exports green electricity or hydrogen, long-duration storage (>8–12 hours, up to days) becomes necessary (IEA, 2023). Options include:

- Power-to-hydrogen-to-power (electrolyser → H₂ storage → fuel cell / turbine)
- Compressed air energy storage (CAES) in suitable geological formations
- Emerging gravity-based or liquid-air technologies (Hunt et al., 2020).

Although these technologies are not yet widely deployed in Saudi Arabia, large-scale hydrogen projects and export memoranda of understanding indicate that hydrogen is likely to play a strategic role in system balancing and monetization of surplus renewables (Griffiths et al., 2021).

Alignment

Figure 3: Saudi Arabia Energy Storage Deployment Roadmap
 Caption: Timeline of energy storage capacity targets and major project milestones supporting Saudi Arabia’s renewable energy transition.



Energy storage is explicitly recognized by the Ministry of Energy as a key enabler for increasing the share of renewables in the power mix and ranking Saudi Arabia among the top global energy storage markets (Saudi Ministry of Energy, 2024).

associated programs require storage

Support 130 GW of renewables and 50% renewable electricity

- Storage smooths variability and enables dispatchable solar and wind.

Reduce liquid fuel use in power generation

- By shifting solar energy to evening peaks, storage displaces oil-fired generation and frees crude for export (IEA, 2024).

Enable off-grid sustainable tourism and smart cities

- Giga-projects such as AMAALA and NEOM rely on storage to guarantee 24/7 green power and support desalination, mobility, and cooling loads (NEOM Company, 2024).

VI. STRENGTHEN GRID RELIABILITY AND RESILIENCE

- BESS systems provide frequency response, black-start capability, and backup during contingencies, which is crucial as the system becomes more inverter-dominated (Kroposki et al., 2020). if announced projects and targets are achieved, Saudi Arabia is projected to possess storage capacity comparable to leading markets such as China and the United States, reinforcing its position as a global energy leader in both fossil fuels and advanced clean-energy infrastructure (Wood Mackenzie, 2024).

search and Policy Priorities

To fully adapt storage technologies to desert conditions and maximize national benefit, several research and policy directions are important:

6.1 Technology and Materials Research

- High-temperature-tolerant battery chemistries

- Optimize LFP and Na-ion cells specifically for 45–55 °C operation with minimal degradation (Zhang et al., 2023).

- Continue R&D on flow battery electrolytes with extended temperature ranges, such as additives that stabilize vanadium electrolytes up to ≥ 50 °C (Park et al., 2023).

- Advanced thermal management

- Develop passive cooling solutions (radiative panels, PCM-based container walls) to reduce HVAC energy consumption in BESS containers (Börner et al., 2023).

- Desert-grade TES materials

- Investigate molten salts with wider stability ranges and lower freezing points (Khanna et al., 2022).

- Tailor PCMs with melting points tuned to the Saudi climate and building typologies (Kenisarin & Mahkamov, 2023).

6.2 Localization and Supply Chains

- Encourage local manufacturing of BESS modules, containers, PCS, and control systems, leveraging the scale of Saudi projects (IRENA, 2023).

- Develop a battery recycling ecosystem to manage end-of-life Li-ion and other chemistries in a harsh environment, minimizing environmental impact and recovering critical materials (Harper et al., 2021).

6.3 Standards, Regulation, and Market Design

- Establish desert-specific technical standards for storage (temperature ratings, dust ingress protection, fire safety) (ISO, 2022).

- Design capacity, ancillary service and storage markets that fairly reward fast response, long-duration storage and resilience services (Joskow, 2020).

- Integrate storage planning into national transmission and distribution expansion studies, considering climate-specific constraints (IRENA, 2024).

6.4 Demonstration & Knowledge-Sharing

- Use giga-projects as living laboratories for novel storage configurations and control algorithms (NEOM Company, 2024).

- Encourage collaboration between utilities, universities, global suppliers and local startups on field trials in desert testbeds (King Abdullah University of Science and Technology, 2023).

VII. CONCLUSION

Energy storage is central to Saudi Arabia's strategy to transition from an oil-dominated power system to a diversified, low-carbon mix under (Saudi, 2023). Desert conditions impose demanding requirements, including high temperatures, dust, significant cooling loads, and remote operation, but also provide advantages such as exceptional solar resources and large, relatively inexpensive land areas (IRENA, 2023).

This paper has outlined how a portfolio of storage technologies can address these challenges in the Saudi context:

- Li-ion BESS (especially LFP) will likely dominate near-term deployments, supported by desert-optimized containers and sophisticated thermal management (BloombergNEF, 2024).
- Sodium-based and high-temperature batteries offer promising alternatives where safety, high temperature tolerance and long-duration capability are prioritized (Dustmann, 2020; Vaalma et al., 2021).
- Flow batteries may become increasingly attractive for multi-hour storage as electrolyte formulations are adapted for wider temperature ranges (Park et al., 2023).
- Thermal storage—from molten salts in CSP plants to PCMs in buildings—provides robust, often lower-cost options for heat and cooling management in hot-arid climates (Liu et al., 2020; Faraj et al., 2020).

Large-scale integration of these technologies in grid-connected plants and off-grid giga-projects directly supports Saudi Arabia's targets for 130 GW of renewables, 50% renewable electricity, and tens of gigawatt-hours of storage. Future research and policy should prioritize technology localization, development of high-temperature materials, and system standards tailored to desert environments. These measures will help ensure that storage assets deployed today remain reliable and cost-effective throughout their operational lifetimes. By pursuing these initiatives, Saudi Arabia can reinforce its position as both a global energy exporter and a

leader in resilient, desert-optimized renewable and storage systems.

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