

# An Assessment of Alternative Energy Storage Systems in Saudi Arabia

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## ABSTRACT

This study investigates the suitability of non-battery Energy Storage Systems (ESS) for large-scale deployment in Saudi Arabia, with a focus on Flywheel Energy Storage Systems (FESS), Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES), and Gravity Energy Storage Systems (GESS) across their principal configurations. The analysis is framed within the Kingdom's Vision 2030 objective of achieving 50% electricity generation from renewable sources and integrates regional electricity demand patterns for 2023 alongside climatic and geological considerations. A structured Multi-Criteria Decision-Making (MCDM) framework was developed, incorporating sixteen technical, environmental, operational, and economic criteria. The technological performance was assessed using both the Weighted Sum Model (WSM) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Consistency between the two methods, supported by sensitivity analysis of the most influential criteria, demonstrates the robustness of the evaluation. Results show that national summer peak demand reaches approximately 70 GW. The Central and Eastern regions contribute 22.4 GW and 20.9 GW, respectively, highlighting favorable conditions for FESS due to its rapid response and grid-support capabilities. The southwestern region, particularly Asir, exhibits strong suitability for PHES owing to its elevation profile and existing dam infrastructure, whereas GESS aligns well with Saudi Arabia's extensive flat terrain and proximity to large-scale solar developments. The study concludes that non-battery ESS technologies, when matched to regional characteristics and infrastructure, represent technically viable and strategically valuable solutions for enhancing grid flexibility and supporting renewable integration in Saudi Arabia.

**Keywords**-Energy Storage Systems (ESS); Saudi Arabia energy sector; energy transition; sustainable energy solutions; decarbonization strategies; energy storage market in Saudi Arabia

## I. INTRODUCTION

The global transition towards cleaner energy systems has significantly accelerated in recent years, driven by increasing energy demand, rapid technological advancements, and international commitments to climate change mitigation. Renewable Energy Sources (RES) such as solar and wind have emerged as leading alternatives to fossil fuels due to their zero-emission profiles and long-term sustainability. Saudi Arabia, under the framework of Vision 2030, aims to derive 50% of its electricity from renewable sources by the end of the decade. With over 11 GW of utility-scale renewable projects already operational, or under development, the need for reliable and efficient storage solutions to address the intermittency of RES has become critical. As a result, Energy Storage Systems (ESS) have become an essential part of the grid, providing vital services such as load shifting, frequency regulation, voltage support, and energy arbitrage. In addition, high penetration of RES, particularly inverter-based systems like solar Photovoltaic (PV) and wind, results in low or zero grid inertia, as these technologies lack the inherent rotational mass found in conventional synchronous generators. This inertia deficit

increases the risk of frequency instability, especially during sudden fluctuations in generation or demand [1].

In Saudi Arabia, the Red Sea Project is a landmark development, aiming to operate entirely on green energy. The project will incorporate the world's largest battery ESS, with a capacity of 1.3 GWh, utilizing Huawei FusionSolar Smart String ESS [2]. This project demonstrates the technical viability of large-scale battery deployment and the necessity of ESS. However, the limited life cycle and performance sensitivity to ambient temperature, and the need for well-controlled enclosures in harsh climates, are still key challenges for battery-based ESS. The deployment of such ESS across the Kingdom can be costly and pose long-term potential environmental risks [3]. These limitations highlight the need to drive the research on non-battery ESS technologies that are more resilient to environmental factors, capable of long-duration storage, multiple charging and discharging cycles without degradation, and based on sustainable materials.

A variety of ESS technologies have been developed and deployed globally, each with distinct characteristics, operational requirements, and performance metrics. Among these non-battery ESS technologies, Pumped Hydro Energy

Storage (PHES), Flywheel Energy Storage Systems (FESS), and various forms of Gravity Energy Storage Systems (GESS) have gained attention for their scalability, durability, environmental compatibility, and resilience in harsh climates. These technologies offer unique advantages over conventional battery systems, particularly in regions like Saudi Arabia, where extreme ambient temperatures, dust-laden environments, and topographical diversity influence the viability and performance of storage infrastructure. At the same time, the Kingdom's large land area, varied geography, and differentiated regional load profiles present opportunities for tailored ESS deployment strategies.

This study presents an assessment of key non-battery ESS technologies for Saudi Arabia, focusing on operation, regional suitability, and potential integration with ongoing renewable energy projects. Using a Multi-Criteria Decision-Making (MCDM) approach, various criteria across four domains were applied to evaluate Compressed Air Energy Storage (CAES) systems, FESS, PHES, and GESS. The Weighted Sum Model (WSM) was used to aggregate normalized criterion scores and derive an initial ranking, whereas the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was applied in parallel to assess closeness to the ideal solution and confirm ranking consistency. By synthesizing various technologies, insights, and regional energy demand, the research identifies strategic regions and conditions for deploying each storage technology. The objective is to inform infrastructure planning and policy development by aligning technology choices with Saudi Arabia's climatic conditions, geological features, existing infrastructure, and future energy goals. This work makes the following key contributions:

- The study addresses a gap in region-specific ESS planning by assessing the suitability of CAES, FESS, PHES, and GESS technologies across Saudi Arabia. It identifies FESS as optimal for rapid-response urban demand centers, PHES as suitable for the hydrologically favorable southwestern mountains, and GESS as appropriate for most regions requiring modular, long-duration storage. A deployment framework is proposed that aligns technology selection with local grid characteristics, environmental conditions, and infrastructure availability.
- It emphasizes the feasibility of repurposing existing infrastructure, such as dam structures, abandoned oil wells, and mining shafts, to reduce Capital Expenditure (CAPEX) for PHES and GESS while promoting sustainable and efficient land use.
- It acknowledges that no single ESS technology can satisfy all operational requirements and therefore recommends hybrid configurations (e.g. FESS combined with PHES or GESS) to deliver both high-frequency regulation and long-duration energy shifting. The study also identifies future research needs related to system sizing, control strategies, and the assessment of hybrid systems under region-specific constraints.
- It presents a forward-looking agenda for researchers and policymakers, advocating for site-specific techno-economic analyses, pilot-scale validation of GESS technologies, and

the establishment of national funding mechanisms to accelerate the deployment of non-battery ESS solutions across the Kingdom.

## II. ENERGY STORAGE SYSTEM TECHNOLOGIES

### A. Compressed Air Energy Storage Systems

CAES systems function by storing energy in the form of high-pressure compressed air within suitable storage facilities, such as underground caverns or pressurized tanks. During periods of energy demand, the stored compressed air is released and expanded through turbines. This expansion process drives the rotation of the turbine shafts, which are mechanically coupled to electrical generators, thereby converting the stored mechanical energy into electrical energy for grid supply. CAES systems operate through two primary phases: compression and expansion. In the compression phase, ambient air is compressed using an air compressor and stored at high pressure in underground reservoirs or other storage media. In diabatic CAES, the heat generated during compression is expelled into the environment, whereas in adiabatic CAES, the heat is captured and stored for subsequent use. During the expansion phase, the high-pressure air is reheated to increase its energy density before being expanded through turbines connected to a generator to deliver power back to the grid. In diabatic CAES, reheating is typically achieved through the combustion of an external fuel, such as natural gas, whereas in adiabatic CAES, the stored thermal energy from compression is used, eliminating the need for additional fuel [4]. The comprehensive energy conversion efficiency of CAES systems approaches 70%, establishing these systems as viable candidates for utility-scale energy storage applications [4].

CAES is among the few energy storage technologies that are economically feasible for large-scale deployment. These systems achieve efficiency rates ranging from 30% to 70%, depending on their configuration (diabatic or adiabatic), and boast operational lifespans exceeding 40 years, outperforming the durability of Gas Turbines (GTs) and combined cycle units [4]. Additionally, CAES systems offer black-start capabilities with startup times between 10 and 12 min. They also exhibit rapid ramping characteristics, enabling a 25% increase in power output per minute. CAES projects have proven to be commercially viable, especially for large-scale energy storage. One of the notable projects is the Huntorf Plant in Germany, which has been operational since 1978 and stands as the world's first large-scale CAES facility, featuring a generation capacity of 290 MW and a storage capacity of 580 MWh. It relies on a salt dome for underground storage [5-7]. Another example of commercial CAES is the McIntosh Plant in Alabama, USA, which began operation in 1991 and represents a second-generation CAES system. It offers a capacity of 110 MW and a storage capability of 2,600 MWh, made more efficient by the integration of advanced recuperation technology that recycles waste heat generated during the compression process [5-8]. A more recent development is the Norton Energy Storage Project in Ohio, which plans to utilize a vast limestone mine for storage. With a projected storage capacity exceeding 2,000 MW, it exemplifies the scalability potential of CAES systems [9].

### B. Flywheel Energy Storage Systems

FESS store energy in the form of rotational kinetic energy within a high-speed rotating disk operating at angular velocities exceeding 10,000 r/min. The rotor is housed in a vacuum-sealed enclosure to minimize aerodynamic losses and is supported by magnetic bearings, which eliminate mechanical contact, thereby enhancing efficiency, reliability, and lifetime. The rotor is mechanically coupled to an electrical machine that operates as a motor during charging and as a generator during discharge mode [10].

Energy exchange between the flywheel and the grid is managed through power electronic converters, commonly implemented using back-to-back Voltage Source Converters (VSCs), which enable bidirectional power flow and decouple the flywheel's rotational frequency from the grid frequency [11]. This configuration improves operational flexibility and grid compatibility. The energy storage capacity of FESS depends on the system inertia, comprising the flywheel inertia ( $J_{FW}$ ) and machine inertia ( $J_M$ ), and the rotor angular speed ( $\omega_r$ ). Since inertia terms are constant, the stored energy is primarily a function of  $\omega_r$ , as expressed in (1):

$$E = \frac{1}{2} (J_{FW} + J_M) \omega_r^2 \quad (1)$$

FESS were initially developed for short-duration energy storage applications due to their limited energy capacity. Despite this constraint, early flywheel systems demonstrated several key advantages, including millisecond-level response times, high specific power densities of 400–1500 W/kg, round-trip efficiencies exceeding 93%, operational lifetimes of up to 20 years, power densities reaching 1,800 W/kg, and rapid recharge capability [12, 13]. These characteristics make FESS particularly suitable for high-power, short-duration applications.

In practical deployments, FESS have proven effective in renewable energy systems, especially for mitigating wind power fluctuations, where their rapid response and high ramp rates support frequency stabilization and improve grid reliability [12]. They further enhance system dynamics by providing low-frequency oscillation damping through in-phase active power injection [11]. In microgrid applications, FESS offer grid-forming capability and facilitate the integration of RES, thereby improving overall system stability [14].

From a comparative perspective, FESS achieve efficiency levels ranging from 85% to 95% and specific energy values between 5 and 150 Wh/kg [15, 16]. Compared with other mechanical energy storage technologies, they offer superior response characteristics and installation flexibility, as they do not require specific geographical conditions such as those needed for PHES or CAES. Although electrochemical storage systems generally provide higher energy density and are better suited for long-duration storage, FESS outperform them in rapid charge and discharge cycles and operational lifetime. Nevertheless, their deployment is constrained by relatively high initial costs, limited energy storage capacity, and safety considerations associated with high-speed rotating components [17, 18].

### C. Pumped Hydro Energy Storage Systems

PHES systems operate by transferring water between two reservoirs at different elevations. During off-peak periods, electrical energy is converted into potential energy by pumping water to an upper reservoir. During peak demand, the stored energy is released by flowing water back to the lower reservoir, driving turbines to generate electricity. PHES systems achieve round-trip efficiencies of 70–85% and have capacities ranging from 10 MW to 4,000 MW [19]. PHES is characterized by long lifetimes ranging from 40 to 60 years, offering cost-effective and reliable energy storage on a large scale [19-21]. The capacity of a PHES system is determined by two main factors: the height of the water's descent and the volume of the water utilized. These factors also pose significant limitations, as suitable locations must feature considerable elevation differences between reservoirs and sufficient space for constructing large dams [22]. The energy stored by PHES is given by (2):

$$E = \eta \cdot \rho \cdot V \cdot g \cdot h \quad (2)$$

where  $E$  is energy stored,  $\rho$  is the density of water,  $g$  is the acceleration due to gravity,  $V$  is the volume of water moved in  $m^3$ ,  $h$  is the height difference between the two reservoirs in m, and  $\eta$  is the efficiency of the PHES system. PHES is one of the oldest ESS and is considered to be a mature technology. The first centralized energy storage facility was established in 1929 [19]. Currently, this technology is the most widely deployed solution for high-power applications, with more than 129 GW of capacity worldwide.

Several large-scale PHES projects have been developed in recent years to enhance grid stability and facilitate the integration of RES. One notable example is the Fengning Pumped Storage Power Plant in China, which was completed in 2021. With a total capacity of 3.6 GW, this facility is among the largest PHES projects worldwide. Another significant initiative is Snowy 2.0 in Australia, an expansion of the Snowy Mountains Hydro Scheme. Construction commenced in 2019 and is projected to be completed by 2027. Upon full operation, the project will provide 2 GW of power and offer an energy storage capacity of 350 GWh, making it a vital component of Australia's energy transition strategy. Similarly, the Linth-Limmern Pumped Hydro Storage Plant in Switzerland underwent an expansion in late 2017, increasing its overall capacity to 1 GW [23]. On a regional scale, the Hatta Project represents a pioneering effort in the Arabian Peninsula, marking the first large-scale pumped hydro storage initiative in the region. Designed to support the transition to renewable energy, this project has a planned capacity of 250 MW. Initially set for completion in 2024, the project aims to contribute to energy security and sustainability in the region [24]. Despite the various advantages of PHES, such as long lifetime, large capacity, and high maturity level, it suffers from some limitations. These include high capital costs and the requirement for suitable geological sites [3, 19, 20, 25].

### D. Gravity Energy Storage Systems

GES are emerging mechanical energy storage technologies that store energy in the form of gravitational potential energy and exhibit strong potential for large-scale

deployment. In recent years, interest in GESS for renewable energy storage has increased significantly, as evidenced by the growing number of research studies and patent filings, indicating rising engagement from both academic and industrial sectors [26]. In its basic operating principle, GESS store energy by lifting heavy masses during periods of low electricity demand and release energy by lowering these masses during peak demand, thereby converting stored potential energy into electrical energy. Based on structural design and operational mechanisms, GESS implementations are commonly categorized into tower-based, shaft-based, and mountain-based configurations, all of which rely on the same fundamental energy conversion principle.

Tower-based GESS employ electrical machines, high-density weight blocks, reinforced suspension ropes, transmission mechanisms, and a structural support tower. Energy storage and recovery are achieved through controlled lifting and lowering of multiple mass blocks. During charging, motors elevate the blocks to higher elevations, whereas during discharge, the blocks are lowered in a controlled manner, causing the electrical machines to operate in generator mode. Operational efficiency is enhanced through the use of multiple cranes and cantilever arrangements that enable simultaneous lifting and stacking of blocks [27, 28]. System performance is influenced by the selection of electromechanical components, particularly power electronics and braking motors, with permanent magnet synchronous motors commonly employed due to their high torque capability and tolerance to frequent load variations. Structural durability is ensured through reinforced suspension ropes, with performance improvements achievable by increasing rope quantity or incorporating pulley mechanisms. The transmission system, composed of gearboxes and pulleys, regulates speed and torque variations [27-29]. In 2020, small-scale commercial deployment was achieved in Ticino, Switzerland, with storage capacities ranging from 20 to 80 MWh [26].

The energy storage capacity of GESS is governed by the potential energy equation as:

$$E_{potential} = m \cdot g \cdot h \quad (3)$$

For specific tower-based GESS, the total stored energy is calculated as:

$$E_{Tower} = \eta \sum_{i=1}^n m_i \cdot g \cdot h_{eff} \quad (4)$$

where  $\eta$  represents system efficiency,  $m_i$  is the mass of each block,  $g$  is the gravitational acceleration,  $h_{eff}$  is the effective height from the ground to the bottom of the block, and  $n$  is the number of blocks. The average output power is determined by the ratio of stored energy to discharge time,  $P = E/t$ . Tower-based systems typically achieve round-trip efficiencies of 75 to 85%, scalable capacities from MWh to GWh levels, and operational lifetimes of 30 to 40 years. They offer low maintenance requirements, geographic flexibility, and effective integration with RES [27-30].

Shaft-based GESS apply the same operating principle but utilize deep vertical mine shafts or abandoned oil wells and typically employ a single large mass rather than multiple blocks [31]. In this configuration, the effective lifting height is

defined as the difference between shaft depth ( $d_{shaft}$ ) and mass length ( $l_{mass}$ ). The stored energy is therefore given by:

$$E_{shaft} = m \cdot g \cdot \eta (d_{shaft} - l_{mass}) \quad (5)$$

Globally, more than 14,000 suitable mine shafts have been identified, with depths exceeding 300 m in some locations [26]. Shaft-based GESS systems typically offer storage capacities between 1 and 20 MWh, round-trip efficiencies of 80–90%, discharge durations ranging from 15 min to 8 h, and operational lifetimes of up to 50 years. In 2021, a 250-kW prototype was successfully demonstrated by Gravitricity at Leith Harbour in Edinburgh, exhibiting a response time of approximately 1 s and suitability for frequency stabilization and emergency power backup applications [32].

Mountain-based GESS exploit natural elevation differences in mountainous terrain to store energy as gravitational potential energy. In this configuration, weights are transported along inclined slopes using cable cars, mine cars, or rail tracks [26]. Energy is stored by moving masses uphill during periods of surplus electricity and recovered during controlled descent, during which the motor operates in generator mode. System performance is strongly influenced by slope inclination, with optimal gradients reported between 6° and 25°. Shallow slopes reduce energy conversion efficiency, whereas excessively steep slopes impose mechanical constraints on system components [26]. Compared with tower-based configurations, mountain-based systems experience additional efficiency losses due to sliding friction between mine cars and rails, resulting in greater frictional resistance under identical transmission conditions. A prominent example of this technology is being developed by Advanced Rail Energy Storage, which employs modular rail-based systems with scalable capacities from several megawatts to gigawatt-hour levels. A 50 MW project under development in Pahrump, Nevada, repurposes a 20-acre gravel mine and incorporates 210 mine cars transporting 75,000 tons. The system offers discharge durations from 15 min to 24 h, a cycle efficiency of 78%, rapid response within seconds, and an expected operational lifetime of 40 years, providing dispatchable grid support within the California Independent System Operator (CAISO) network [33].

### III. SAUDI ARABIA'S RENEWABLE ENERGY INITIATIVES AND GRID INTEGRATION

Saudi Arabia is undergoing a transformative shift in its energy landscape, with a pronounced focus on renewable energy development. The Kingdom aims to increase RES to 50% by 2030, reducing dependence on fossil fuels and enhancing environmental sustainability. Central to this strategy is the Saudi Power Procurement Company (SPPC), which serves as the principal off-taker for renewable energy projects and facilitates competitive bidding under the National Renewable Energy Program (NREP). To date, Saudi Arabia has launched over 15 large-scale renewable energy projects, with a combined generation capacity exceeding 11,000 MW. These projects span both solar PV and onshore wind technologies and are geographically distributed across key regions, including Makkah, Riyadh, AlJouf, AlQassim, and AlMadinah provinces. Notable commissioned projects include the Sakaka Solar PV Plant with a 300 MW capacity and the

Dumat al-Jandal Wind Farm with 400 MW, which mark the Kingdom's first utility-scale solar and wind projects, respectively. Several high-capacity projects remain under development, such as the Shuaibah 2 Solar Plant at 2,060 MW, Ar Rass 2 producing 2,000 MW, and the Al Henakiyah Solar Project producing 1,100 MW. Additionally, the Sudair Solar Project (1,500 MW), now operational as of 2024, is among the largest single-site solar installations in the region. Wind energy development is also expanding, with the Wa'ad Alshamal Wind Project (500 MW) planned for completion by 2026, Figure 1 summarizes various ongoing renewable energy projects [34].

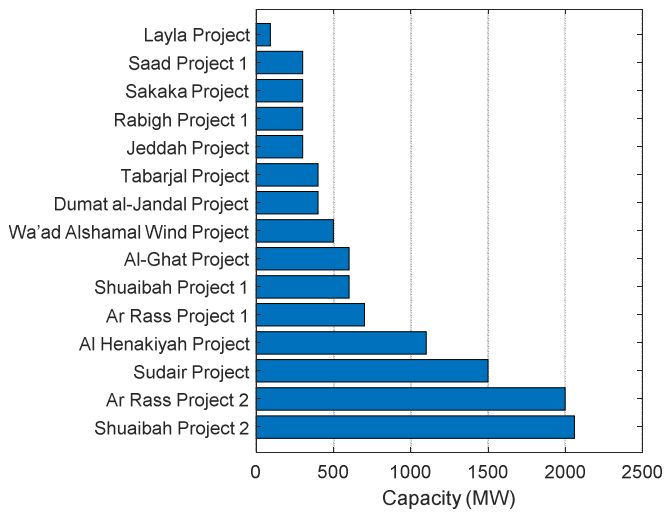


Fig. 1. Capacity of renewable energy projects in Saudi Arabia.

In addition to its rapidly expanding portfolio of renewable energy projects, Saudi Arabia has achieved a historic milestone in cost competitiveness in both solar PV projects and wind turbine projects. For example, the Shuaibah solar PV project achieved a Levelized Cost of Energy (LCOE) of 0.0104 USD/kWh. Wind energy projects, including the Al-Ghat wind project and the Wa'ad Alshamal wind project, also have record-breaking LCOEs of 0.01566 USD/kWh and 0.01702 USD/kWh, respectively [35, 36].

#### IV. KINGDOM OF SAUDI ARABIA CLIMATIC AND GEOGRAPHIC FEATURES

First, one of the most significant considerations is the climatic condition of the country. Saudi Arabia experiences an arid desert climate characterized by high solar irradiance, extreme summer temperatures, minimal rainfall, and frequent dust storms. This harsh climate presents challenges for energy storage. The country is located in one of the highest solar irradiance zones in the world, with annual Global Horizontal Irradiance (GHI) values exceeding 2,200 kWh/m<sup>2</sup> in many regions [37]. Due to its vast area, Saudi Arabia's climate varies significantly not only by season but also by geographic region. In the central and eastern regions, summer temperatures frequently exceed 45 °C, and in some areas can surpass 47 °C during heatwaves. Coastal areas along the Red Sea experience slightly lower, but still intense, temperatures ranging between 27 °C and 38 °C. Winters are generally mild to cool, with

interior temperatures ranging from 8 °C to 20 °C, whereas coastal zones remain warmer, averaging 19 °C to 29 °C [38]. Another defining feature of the Saudi climate is dust storms, particularly during the spring and early summer. These events can significantly reduce air quality and affect the performance and maintenance of energy infrastructure.

Second, the geographical terrain has a considerable influence on the deployment feasibility of ESS technologies. While Saudi Arabia is predominantly flat, vast desert plains provide abundant space for utility-scale solar farms and integrated energy storage. Meanwhile, the southwestern regions of the Kingdom, particularly around Asir and Al Baha, offer elevated terrains with rainfall patterns and natural reservoirs. Moreover, Saudi Arabia has various constructed dams that can be utilized for energy storage. An example is the King Fahad Dam located in Wadi Bisha in the Asir region. It is considered the largest in the Kingdom, with a storage capacity of 325 million m<sup>3</sup> and a height of 68 m. Saudi Arabia has over 100 dams spread around the country with a total capacity of 1,799 million m<sup>3</sup> [39]. Table I summarizes the regional climate and geographical features in the Kingdom.

TABLE I. GEOGRAPHICAL CHARACTERISTICS OF KEY REGIONS IN SAUDI ARABIA [37, 38]

Regions	Geographical terrain	Climatic characteristics
Central and Northern	Desert plains with some rocky areas	Extremely hot in summer and cold in winter
Eastern	Flat desert, coastline	Hot and humid in summer and moderately cold in winter
Western	Mountains on land and coastline	
Southern	Mountains, valleys, green highlands	Moderate climate (hot to moderate in summer and cold in winter)

#### V. METHODOLOGY

This study utilizes a structured MCDM approach to evaluate and rank the deployment suitability of four non-battery ESS within the Kingdom of Saudi Arabia: namely CAES, FESS, PHES, and GESS. The methodology integrates technical, environmental, operational, and economic factors, addressing the critical need for regionally adaptive and climate-resilient energy storage infrastructure in support of national renewable energy goals. Two complementary MCDM techniques, the WSM and the TOPSIS, were employed to ensure methodological rigor and robustness of rankings. The combined use of WSM and TOPSIS is well established in energy storage and power system assessments, where it has been shown to enhance ranking robustness by balancing direct weighted aggregation with distance-based evaluation [40-44]. This complementary application reduces method-specific bias and strengthens the reliability of technology prioritization results.

##### A. Evaluation Framework

To ensure a comprehensive and context-specific assessment, a hierarchical evaluation framework was developed consisting of sixteen criteria grouped under four principal domains: technical performance, environmental resilience, operational feasibility, and economic & regulatory fit. Each criterion was selected based on its relevance to grid

reliability, deployment feasibility, and adaptability to Saudi Arabia's diverse climatic and infrastructural conditions.

The technical performance domain captures the core functional characteristics of each ESS, beginning with round-trip efficiency. Higher efficiency technologies reduce energy losses and improve the viability of integrating storage with intermittent renewable sources. Another critical aspect is response time and grid support capability, which reflects how quickly a storage system can respond to grid disturbances and provide ancillary services such as frequency regulation or spinning reserves. Rapid-response ESS are especially valuable in maintaining grid stability under high shares of variable renewable energy. Scalability is also an important factor, as it determines the flexibility of an ESS to be deployed at varying sizes depending on the load profile and regional needs. Technologies that are modular or capable of incremental expansion are particularly suitable for Saudi Arabia's mixed urban and rural energy landscape.

The environmental resilience domain evaluates how well storage technologies can operate under Saudi Arabia's challenging climatic and geographic conditions. Temperature tolerance is a key consideration, as ESS must maintain reliable performance even during peak summer months when ambient temperatures can exceed 45 °C. Similarly, sand and dust resilience assesses the system's ability to withstand operation in arid and desert environments, where airborne particles pose significant risks to mechanical integrity and thermal management. Topographical fit measures the degree to which a technology's physical siting requirements align with local terrain. For example, PHES systems require elevation differences, whereas shaft-based GESS technologies need vertical infrastructure such as deep wells or mine shafts. Equally important is the absence of special environmental requirements, which reflects a technology's ability to be deployed without the need for rare natural features (e.g., natural reservoirs and caverns). Technologies with minimal siting restrictions offer broader deployment potential across the Kingdom.

The operational feasibility domain focuses on the practical and logistical dimensions of deploying and maintaining ESS. Maintenance requirements assess the frequency and complexity of required servicing. Technologies with low maintenance needs are favored for deployment in remote or infrastructure-limited regions, as they reduce the operational burden over the project lifecycle. Technology Readiness Level (TRL) is another key factor, as it reflects the maturity and commercial deployment experience of the ESS. Technologies with high TRL pose lower risks and typically benefit from more established supply chains and support networks. Operational safety evaluates the system's risk profile, particularly in terms of thermal runaway or other hazards that could affect personnel or adjacent infrastructure. Lastly, black start capability is considered for its strategic value in system restoration, as ESS with this capability can independently restart grid sections following a total system blackout, enhancing national energy security.

The final domain, economic and regulatory fit, encompasses financial viability and alignment with local

market conditions. CAPEX represents a primary barrier to adoption; technologies with lower upfront investment requirements are more suitable for large-scale or decentralized deployment. Levelized Cost of Storage (LCOS) offers a holistic view of long-term cost-effectiveness, capturing all lifecycle costs per unit of delivered energy, including maintenance, efficiency losses, and replacement. The CAPEX and LCOS are assessed based on the most updated deployed projects worldwide. Local supply chain maturity assesses the extent to which domestic capabilities in manufacturing, installation, and servicing are available to support deployment. For example, some ESS depend solely on specific raw materials, which are limited in the region. Finally, future potential accounts for the expected technology trajectory in terms of cost reduction, efficiency improvements, and scalability as research and development and commercial deployment progress. This forward-looking criterion supports strategic investment planning for emerging technologies. Table II summarizes the most recent performance benchmarks for non-battery ESS synthesized from recent studies [13, 45-48]. These values were used to inform expert scoring across technical and economic criteria in the MCDM evaluation framework.

TABLE II. PERFORMANCE BENCHMARKS AND KEY CHARACTERISTICS OF NON-BATTERY ESS

Criterion	CAES	FESS	PHES	GESS
Round-trip efficiency	42%–55%	80%–90%	70%–85%	75%–80%
Response time	Seconds to minutes	<1 s	Minutes	Seconds to minutes
Energy density (Wh/kg)	30–60	5–60	0.5–1.5	0.5–5
CAPEX (USD/kWh)	600–1200	1000–4000	1500–2500	>1500
LCOS (USD/MWh)	100–200	180–300	60–120	70–130
Key features	Large-scale, long-duration storage, suitable for bulk energy shifting, scalable for grid-level applications	Ultra-fast response, very high-power density, long cycle life, ideal for frequency stability	Mature large-scale storage technology, very large capacity, long operational lifetime	Water-independent operation, long lifetime, potential alternative to PHES in water-scarce regions
Limitations	Requires suitable underground caverns, efficiency dependent on thermal management, geographically constrained	Limited energy storage duration, high capital cost, not suitable for long-duration storage	Water & topography dependent, long construction times	Limited real-world deployment, high initial infrastructure

To systematically analyze energy storage alternatives under Saudi Arabia conditions, the sixteen evaluation criteria were defined and coded (e.g., T1, R3, E2). Expert judgment was employed to incorporate qualitative and contextual knowledge that cannot be fully represented through quantitative indicators alone. A panel of six experts with more than ten years of

experience in the field, two representing academy and research institutes, two industrial experts, and two energy policy making experts, was engaged. Experts evaluated the relative importance of criteria and the performance of each ESS alternative under Saudi Arabian conditions. They provided their judgments independently to avoid dominance effects, and individual responses were anonymized prior to aggregation. Table III summarizes the evaluation criteria along with their respective codes and maximum assigned scores, which reflect their relative importance within the decision framework.

TABLE III. EVALUATION CRITERIA, CODES, AND MAXIMUM SCORES

Domain	Criterion	Code	Maximum score ( $M_j$ )
Technical performance	Round-trip efficiency	T1	10
	Response time / ancillary services	T2	5
	Scalability	T3	9
	Energy density	T4	6
Environmental resilience	Temperature tolerance	R1	8
	Sand/dust resilience	R2	7
	Topographical fit	R3	8
	No special environmental needs	R4	7
Operational feasibility	Maintenance requirements	O1	4
	Technology maturity	O2	6
	Operational safety	O3	3
	Black start capability	O4	2
Economic & regulatory fit	CAPEX	E1	7
	LCOS	E2	6
	Local supply chain maturity	E3	6
	Future potential	E4	6

B. Scoring and Aggregation Approach

The scoring and aggregation process followed a structured, quantitative approach that combined expert-driven performance scoring with multi-criteria weighting. The experts evaluated each energy storage technology against these defined criteria under Saudi Arabian operating conditions. Performance scores were assigned using a bounded point-allocation scheme, where each criterion ( $j$ ) was associated with a predefined maximum score ( $M_j$ ). Experts assigned scores  $x_{ij}^k \in [0, M_j]$  independently to avoid dominance effects or bias. The aggregated performance value for each technology–criterion pair was obtained using the arithmetic mean as expressed in (6). The resulting aggregated decision matrix is presented in Table IV.

$$x_{ij} = \frac{1}{K} \sum_{k=1}^K x_{ij}^k, K = 6 \tag{6}$$

Criterion weights  $w_j$  were derived directly from the maximum allowable scores  $M_j$ , which were defined during the point-allocation process to reflect the relative importance of each evaluation criterion. These maximum values were normalized according to (7):

$$w_j = \frac{M_j}{\sum_{j=1}^n M_j} \tag{7}$$

Since TOPSIS requires criteria to be dimensionless and comparable, the aggregated matrix was normalized and weighted, as expressed in (8) and (9), respectively. The resulting normalized matrix and the weighted normalized matrix are presented in Table V.

$$r_{ij} = \frac{x_j}{M_j} \tag{8}$$

$$v_{ij} = w_j \cdot r_{ij} \tag{9}$$

TABLE IV. AGGREGATED DECISION MATRIX

	T1	T2	T3	T4	R1	R2	R3	R4	O1	O2	O3	O4	E1	E2	E3	E4
CAES	5	5	4	5	4	5	3	3	2.5	5	3	0.5	5	3	4	3
FESS	8	5	8	5	5	4.5	7	7	1.5	5	3	1.5	3.5	3	4	4
PHES	7	5	2	3	6	5	5	3	2	5	3	1	3	4	4	3
GESS	7.5	5	8	4	7	5	7	7	2	3	3	1	5	5	5	5

TABLE V. NORMALIZED AND WEIGHTED NORMALIZED DECISION MATRICES

	Normalized decision matrix				Weighted normalized matrix			
	CAES	FESS	PHES	GESS	CAES	FESS	PHES	GESS
T1	0.500	0.800	0.700	0.750	0.050	0.080	0.070	0.075
T2	1.000	1.000	1.000	1.000	0.050	0.050	0.050	0.050
T3	0.444	0.889	0.222	0.889	0.040	0.080	0.020	0.080
T4	0.833	0.833	0.500	0.667	0.050	0.050	0.030	0.040
R1	0.500	0.625	0.750	0.875	0.040	0.050	0.060	0.070
R2	0.714	0.643	0.714	0.714	0.050	0.045	0.050	0.050
R3	0.375	0.875	0.625	0.875	0.030	0.070	0.050	0.070
R4	0.429	1.000	0.429	1.000	0.030	0.070	0.030	0.070
O1	0.625	0.375	0.500	0.500	0.025	0.015	0.020	0.020
O2	0.833	0.833	0.833	0.500	0.050	0.050	0.050	0.030
O3	1.000	1.000	1.000	1.000	0.030	0.030	0.030	0.030
O4	0.250	0.750	0.500	0.500	0.005	0.015	0.010	0.010
E1	0.714	0.500	0.429	0.714	0.050	0.035	0.030	0.050
E2	0.500	0.500	0.667	0.833	0.030	0.030	0.040	0.050
E3	0.667	0.667	0.667	0.833	0.040	0.040	0.040	0.050
E4	0.500	0.667	0.500	0.833	0.030	0.040	0.030	0.050

1) Weighted Sum Model

The WSM was first applied as it provides an absolute aggregated performance score for each alternative using the criterion weights and expert-assigned scores. The overall WSM score for alternative  $i$  is calculated as:

$$S_i = \sum_{j=1}^n w_j \cdot x_{ij} \tag{10}$$

The resulting value  $S_i$  represents the absolute weighted performance of the alternative. A higher score indicates a more favorable overall performance.

2) TOPSIS Model

Following the construction of the weighted normalized matrix  $V = [v_{ij}]$ , the TOPSIS method was applied to determine the relative closeness of each alternative to the ideal solution. The positive ideal solution ( $A^+$ ) and negative ideal solution ( $A^-$ ) were identified for all criteria as:

$$v_j^+ = \max_i \{v_{ij}\}, v_j^- = \min_i \{v_{ij}\} \tag{11}$$

The Euclidean distances of each alternative from the ideal and negative-ideal solutions were calculated using:

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \tag{12}$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \tag{13}$$

The relative closeness coefficient ( $C_i$ ) reflects how near each alternative is to the ideal solution in comparison to the non-ideal solution, and is determined as:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{14}$$

### VI. RESULTS

#### A. Weighted Sum Model Results

The final evaluation results, based on the WSM, reveal distinct performance profiles across the four assessed non-battery ESS. Among the technologies assessed, GESS achieved the highest overall score of 7.9, followed by FESS at 7.5, PHES at 6.1, and CAES at 5.9, as shown in Figure 2.

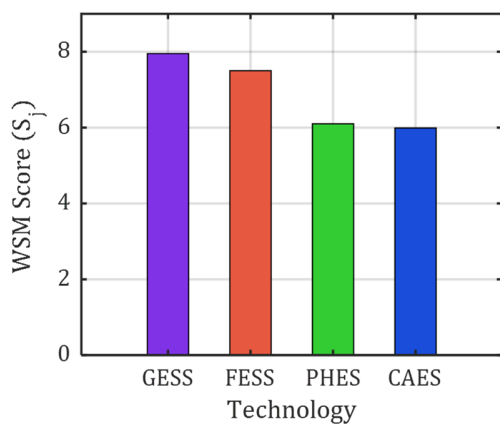


Fig. 2. Total weighted scores of CAES, FESS, PHES, and GESS based on MCDM evaluation using the WSM.

Figure 3 provides a radar plot comparing criterion-level scores across the four technologies. The visualization highlights the multi-dimensional advantages of GESS, particularly its superior adaptability in environmental and economic domains, with notable peaks in temperature tolerance and topographical flexibility. FESS shows dominance in the technical domain, especially in response time and scalability, whereas PHES and CAES exhibit more irregular profiles, reflecting context-specific strengths.

#### B. TOPSIS Results: Ideal Solutions, Distances, and Closeness Coefficients

Using the weighted normalized matrix, the positive ideal solution ( $A^+$ ) and negative ideal solution ( $A^-$ ) were identified by selecting, for each criterion, the maximum and minimum weighted normalized values, respectively. These ideal points represent the best and worst attainable performance across all alternatives. The Euclidean separation of each energy storage technology from the ideal and non-ideal solutions was then

calculated using the standard TOPSIS procedure. Table VI summarizes the computed separation distances.

TABLE VI. EUCLIDEAN DISTANCES FROM POSITIVE AND NEGATIVE IDEAL SOLUTIONS

Technology	$S_i^+$	$S_i^-$
CAES	0.08718	0.04153
FESS	0.03674	0.09394
PHES	0.08515	0.04213
GESS	0.02398	0.09899

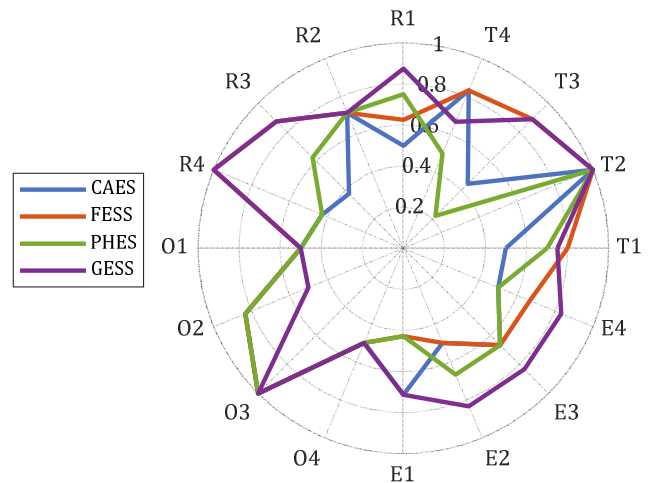


Fig. 3. Radar plot illustrating the performance of CAES, FESS, PHES, and GESS across 16 weighted evaluation criteria.

The relative closeness coefficient ( $C_i$ ) was then calculated as per (14). A  $C_i$  value closer to 1 indicates superior overall performance across the multi-criteria structure. Figure 4 shows the TOPSIS closeness coefficients for the four ESS technologies, highlighting their relative proximity to the ideal solution. GESS achieves the highest coefficient of 0.805, followed by FESS at 0.719, whereas PHES and CAES score considerably lower, 0.331 and 0.323, respectively. These results indicate that GESS and FESS are the closest to the ideal performance profile under Saudi Arabian conditions.

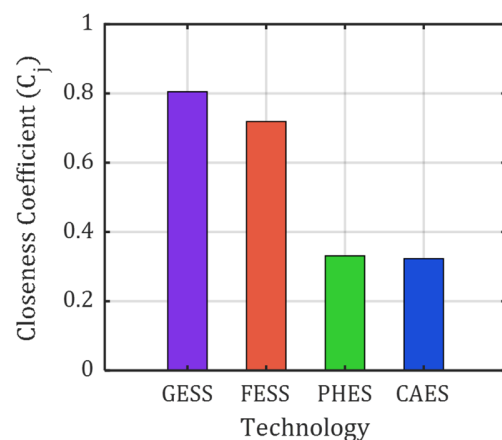


Fig. 4. TOPSIS closeness coefficients for CAES, FESS, PHES, and GESS.

### C. Sensitivity Analysis

A one-at-a-time sensitivity analysis was conducted to assess how variations in criterion importance influence the resulting rankings. The most influential criteria, T1, T3, R3, and E4, were perturbed by  $\pm 10\%$  and  $\pm 20\%$ , whereas the remaining weights were proportionally renormalized. For each perturbation scenario, the full TOPSIS procedure was repeated. Across all sensitivity scenarios, the ranking remained largely stable, with GESS consistently maintaining the highest score and FESS remaining the second-ranked option. PHES and CAES occasionally exchanged positions under extreme perturbations, but these changes were minor and did not alter the overall technology hierarchy. Table VII summarizes the robustness outcomes.

TABLE VII. SUMMARY OF SENSITIVITY ANALYSIS RESULTS

Scenario	Criterion perturbed	TOPSIS closeness coefficient and ranking			
		GESS	FESS	PHES	CAES
+10%	T1	0.805337	0.720982	0.335831	0.320006
		GESS > FESS > PHES > CAES			
-10%	T1	0.804700	0.716864	0.326476	0.325177
		GESS > FESS > PHES > CAES			
+20%	T3	0.816498	0.735222	0.309512	0.323621
		GESS > FESS > PHES > CAES			
-20%	T3	0.793632	0.702520	0.353171	0.321773
		GESS > FESS > CAES > PHES			
+10%	R3	0.807639	0.722606	0.334870	0.317976
		GESS > FESS > PHES > CAES			
-10%	R3	0.802521	0.715290	0.327346	0.327162
		GESS > FESS > PHES > CAES			
+20%	E4	0.814876	0.714081	0.328103	0.316922
		GESS > FESS > PHES > CAES			
-20%	E4	0.795117	0.723777	0.334398	0.329166
		GESS > FESS > PHES > CAES			

The persistence of GESS and FESS in the top two positions across all scenarios demonstrates the stability and robustness of the model. Their dominance is attributed to strong technical and regional adaptability characteristics, which remain influential across perturbed weighting structures. Minor fluctuations between PHES and CAES do not materially affect the decision outcome, as these technologies consistently remain less favorable compared with GESS and FESS. Overall, the sensitivity analysis confirms that the MCDM-TOPSIS framework is robust and not overly sensitive to reasonable changes in expert-assigned criteria importance, supporting the reliability of the baseline ranking.

Therefore, under both the WSM and TOPSIS models (Figures 2 and 4), the results indicate that GESS achieves the highest overall performance, even under all  $\pm 10\%$  and  $\pm 20\%$  criterion weight perturbations. This outcome is mainly driven by strong environmental resilience and economic adaptability, particularly with respect to temperature tolerance, topographical compatibility, and minimal siting requirements. The modular and scalable design of GESS, together with its low reliance on cooling infrastructure, supports its applicability

across diverse regions, including remote and off-grid areas. FESS ranks second, owing to superior technical performance, notably rapid response capability and scalability, making it suitable for urban and high-demand load centers. PHES shows moderate performance, benefiting from technological maturity and favorable mountainous topography, but its scalability constraints and site-specific requirements limit broader deployment. CAES consistently ranks lowest, primarily due to lower round-trip efficiency and reliance on underground caverns, despite its operational maturity and safety advantages.

Overall, these findings underscore the importance of aligning energy storage technology selection with regional characteristics and system requirements, positioning GESS as the most versatile solution for large-scale deployment, while highlighting FESS as a particularly effective option for enhancing grid stability in densely populated and high-load regions.

## VII. DISCUSSION

The demand for flexible and dispatchable capacity in Saudi Arabia is amplified by pronounced seasonal load peaks and spatially uneven demand centers. Consequently, the deployment of non-battery ESS technologies is strategically advantageous, provided that regional load characteristics, system requirements, and local climatic and geographical conditions are carefully considered. Compared with battery-based storage, which is highly sensitive to temperature and typically requires air-conditioned environments, non-battery ESS technologies exhibit greater tolerance to harsh desert conditions, with reduced dependence on active cooling. Systems such as GESS and PHES can operate in unconditioned or semi-open environments, benefiting from mechanical energy conversion mechanisms that are inherently more resilient to high ambient temperatures. These characteristics improve overall energy efficiency and reduce operational and maintenance costs.

Although PHES is among the most mature large-scale storage technologies, its deployment in Saudi Arabia is constrained by topographical and hydrological requirements. Feasible sites are largely confined to the southwestern mountainous regions, including Asir and Al Baha, where elevation gradients and relatively higher precipitation exist. King Fahad Dam represents a potential PHES site due to its height and storage capacity, whereas further developments elsewhere would likely require substantial capital investment to construct artificial reservoirs.

The deployment potential of GESS in Saudi Arabia is relatively broad due to its modular design, geological adaptability, and low water dependency. Tower-based GESS is particularly suited to the Kingdom's flat desert regions, enabling large-scale deployment adjacent to renewable energy power plants. Shaft-based GESS rely on underground vertical excavations and require stable geological formations with low seismic activity, necessitating detailed geotechnical assessment. Another cost-effective approach is the repurposing of abandoned oil wells and mines, which can reduce the LCOE by leveraging existing excavations and grid infrastructure,

thereby limiting new capital investment primarily to mechanical systems and power electronics.

Electricity demand patterns further highlight the importance of storage diversification. As illustrated in the weekly peak load profile for 2023 (Figure 5) [49], Saudi Arabia exhibits pronounced seasonal demand variation, with peak loads approaching 70 GW during summer weeks 30-35, driven largely by air-conditioning demand. This temporal mismatch between generation and consumption underscores the need for storage technologies capable of shifting energy from periods of surplus renewable energy generation to peak demand intervals.

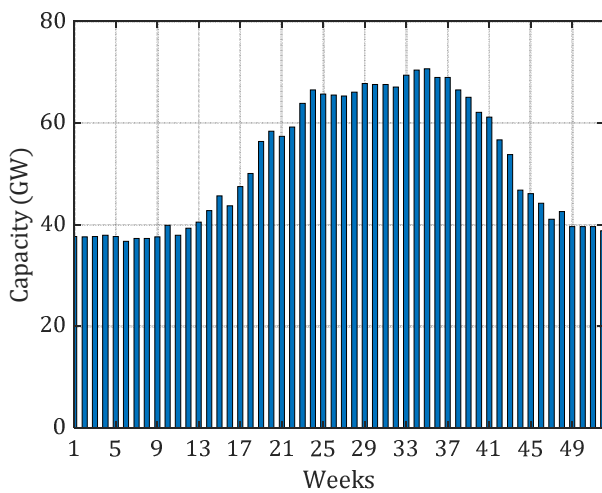


Fig. 5. Weekly peak electricity load profile in Saudi Arabia for 2023.

Regionally, in 2023, the Central and Eastern provinces recorded the highest annual peak loads, reaching 22.4 GW and 20.9 GW, respectively, as shown in Figure 6. These areas are characterized by high energy consumption and urban concentration, making them strategic for the deployment of ESS. According to KAPSARC's regional demand modeling [35], the Central and Western regions collectively account for over 68% of the national population and are dominated by residential and commercial consumers. Electricity demand in these areas is highly sensitive to income levels and cooling needs, particularly during the summer months, leading to significant short-term variability. While the Western region has the second-highest peak demand, it is less populated but hosts the highest concentration of industrial electricity consumption, accounting for 72% of the nation's industrial demand in 2019. Therefore, FESS and tower-based and shaft-based GESS are well-suited for these densely populated, urban regions due to their compact design, rapid response, and effectiveness in high-frequency grid support [35]. On the other hand, the southern region, despite having the lowest overall demand (7.6 GW), offers the most favorable terrain for PHES and GESS, indicating that storage infrastructure planning should prioritize geographical complementarity over demand volume alone. This approach aligns with the concept of distributed energy storage, where systems are sited not only to meet demand but also to optimize efficiency, resilience, and integration with local renewable resources.

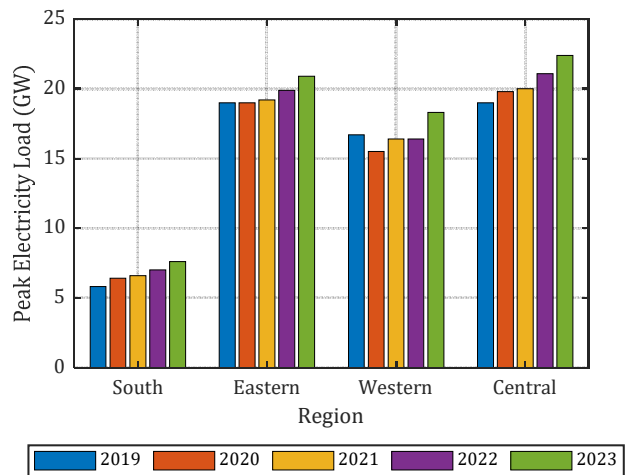


Fig. 6. Regional peak electricity load in Saudi Arabia.

To illustrate the scale of storage required in high-demand regions, a simplified sizing example is considered for the Central region using 2023 peak load data. Assuming a peak demand of 22.4 GW and conservatively neglecting future load growth, supplying 50% of this peak from renewable sources implies approximately 11.2 GW of renewable generation. If 15% of this renewable output must be temporally shifted to match demand patterns, a storage system capable of delivering about 1.68 GW is required. For discharge durations of 4–8 h, this corresponds to an energy storage capacity of 6.7 GWh and 13.4 GWh, respectively. When adjusted for typical round-trip efficiencies of large-scale non-battery ESS, the gross required energy capacity increases to approximately 7.9–8.9 GWh for a 4-h scenario and 15.8–17.9 GWh for an 8-h scenario, depending on the selected technology. Figure 7 presents a map of Saudi Arabia illustrating the recommended energy storage technology for each region based on geographic suitability, resource availability, and alignment with regional demand characteristics.



Fig. 7. Region-specific recommendations for non-battery ESS technologies across Saudi Arabia based on geographic suitability and resource availability.

In addition, the proximity of load centers to renewable generation and storage facilities is a key factor in siting ESS. Locating storage near large-scale renewable power plants or industrial zones can reduce transmission losses, enhance local grid resilience, and enable microgrid applications. Remote and off-grid areas, including parts of the Empty Quarter, present additional opportunities for deploying modular and self-sufficient ESS solutions. These systems can reduce dependence on diesel generators, lower operational costs, and improve energy access in isolated communities or industrial operations such as mining or oil extraction.

### VIII. CONCLUSION AND RECOMMENDATION

In conclusion, the results of the multi-criteria evaluation show that Gravity Energy Storage Systems (GESS) proved to be the most suitable option for widespread deployment in Saudi Arabia, offering strong environmental resilience, economic viability, and adaptability to harsh desert conditions. Flywheel Energy Storage Systems (FESS) excel in technical performance and are best suited for fast-response applications in urban centers, whereas Pumped Hydro Energy Storage (PHES) remains effective for long-duration storage in mountainous regions like Asir and Al Baha, particularly where infrastructure such as the King Fahad Dam exists. Compressed Air Energy Storage (CAES), though operationally mature, is limited by low efficiency and strict siting requirements. These findings reinforce the need for a region-specific Energy Storage System (ESS) strategy that matches each technology with local demand profiles, terrain, and climate. Leveraging existing assets such as dams, oil wells, and mines can further reduce costs and enhance deployment feasibility, especially for PHES and GESS.

Although this study provides a comprehensive multi-criteria assessment of non-battery ESS for Saudi Arabia, several areas warrant further investigation. Future research should expand the expert-based scoring and weighting process, potentially incorporating larger expert panels or hybrid data-driven weighting approaches. In addition, long-term scenario modeling is recommended to complement the regional and weekly electricity demand data used in this study, particularly considering expected load growth, sectoral electrification, and higher renewable energy penetration. Building on the findings, future work should also prioritize detailed techno-economic analyses for PHES and the various GESS configurations (tower-based, shaft-based, and mountain-based). Such evaluations must incorporate regional electricity demand patterns, existing infrastructure, and site-specific geological and topographical conditions to ensure the viability and optimal deployment of these technologies.

Further investigation into hybrid energy storage configurations that combine multiple ESS technologies is essential. This includes the integration of FESS with GESS or PHES to address both short-term grid stability and long-duration energy shifting. Research should focus on the optimization of control strategies, system sizing, and operational parameters to enhance the overall efficiency and reliability of the selected ESS technologies. Additionally, the survey and assessment of abandoned oil wells and mines should be prioritized to evaluate their potential for repurposing

as energy storage infrastructure, particularly for shaft-based GESS applications.

Pilot projects and demonstration initiatives should be encouraged to validate the technical performance, environmental resilience, and cost-effectiveness of GESS under real-world conditions. These efforts should be supported by dedicated national funding mechanisms to facilitate project implementation, mitigate investment-related risks, and accelerate the commercialization of GESS within the Kingdom.

Finally, the integration of non-battery ESS with large-scale solar Photovoltaic (PV) and wind power projects under development, especially in remote or high-demand regions, should be further explored. Such integration will contribute to a more reliable and efficient transition toward renewable energy, reinforcing the sustainability and resilience of the national energy system.

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