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Energy Storage Systems

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Abstract- This review paper provides an in-depth analysis of diverse energy storage systems, emphasizing their significance, operating principles, and practical applications in tackling contemporary energy issues. As the global shift towards sustainable energy gains momentum, effective Energy Storage Systems (ESS) play a pivotal role in maintaining the balance between supply and demand, especially in the integration of renewable energy sources. The paper explores an extensive array of energy storage solutions, such as Thermal Energy Storage (TES), Chemical Energy Storage (CES), Electrochemical Energy Storage (EcES), Electrical Energy Storage (EES), Hybrid Energy Storage Systems (HES), and Mechanical Energy Storage (MES). By conducting a comparative assessment, it highlights the strengths and weaknesses of each approach and provides insights into emerging trends and challenges within the sector. Furthermore, the study focuses on optimizing Gravity Energy Storage (GES) systems using the Taguchi method to improve energy efficiency and system reliability, showcasing the potential of GES as a viable and adaptable solution for sustainable energy storage.

Index Terms- TES, CES, EcES, EES, HES, MES.

I. INTRODUCTION

The global energy landscape is undergoing a profound transformation, driven by the shift toward renewable energy sources and the growing need for efficient energy management. Renewable energy technologies, such as solar and wind power, are abundant and increasingly cost- effective; however, their variable nature presents significant challenges in ensuring a consistent and stable energy supply. Energy Storage Systems (ESS) are pivotal in addressing these challenges by storing excess energy produced during peak generation periods and releasing it when renewable output is low or when energy demand spikes, thereby facilitating a reliable and uninterrupted power supply.

This review explores the diverse categories of ESS, including thermal, mechanical, chemical, electrochemical, and electrical storage technologies, each offering unique capabilities for energy storage and controlled discharge. Additionally, it highlights the growing importance of Hybrid Energy Storage Systems (HES), which combine multiple storage technologies to enhance system efficiency and adaptability for various applications. The integration of these systems plays a critical role in stabilizing the energy grid, improving electric vehicle performance, and optimizing energy management in industrial operations. Embracing these advancements is not merely a strategic choice but a necessary step toward creating a sustainable and robust energy framework, ultimately supporting the global movement toward a low-carbon future.

II. ENERGY STORAGE SYSTEMS

Energy Storage Systems can be grouped into several distinct categories based on the mechanisms they use to capture, retain, and discharge energy. The main classifications include:

- Thermal Energy Storage (TES).
- Chemical Energy Storage (CES).
- Electrochemical Energy Storage (EcES).
- Electrical Energy Storage (EES).
- Hybrid Energy Storage Systems (HES).
- Mechanical Energy Storage (MES.)

1. Thermal Energy Storage (TES) systems store thermal energy for future use, typically in heating or cooling applications. The three main types are:

Sensible Heat Storage (SHS): Sensible Heat Storage (SHS) is a commonly utilized technique for storing thermal energy by increasing the temperature of a storage medium, such as water, air, or solid materials like concrete or rocks. Unlike other storage techniques, SHS retains energy without inducing a phase change in the storage material (e.g., no melting or boiling). Instead, the energy is stored as sensible heat, leading to a direct temperature change in the medium. SHS is widely implemented in applications such as residential heating, cooling, and industrial processes, where the stored heat can be released for use as needed. Materials like water and solid substances are popular choices for SHS systems due to their high specific heat capacity and accessibility. Catagories of SHS:

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Aquifer Thermal Energy Storage (ATES): This method retains thermal energy within natural underground water reservoirs, known as aquifers. It serves as a highly effective solution for seasonal energy storage and is widely employed in large-scale operations, particularly for regulating heating and cooling in buildings.

Hot Water Thermal Energy Storage: This system stores heat in large water reservoirs. The heated water can be utilized in residential or industrial environments for space heating, domestic hot water supply, or various other heating requirements. Water is an excellent storage medium because of its high specific heat capacity.

Cavern Thermal Energy Storage: In this method, thermal energy is retained within natural or artificial underground caverns. It is commonly employed for large- scale storage requirements and is particularly effective for storing heat at elevated temperatures, making it well-suited for industrial applications.

Table1.Comparison of (SHS) Systems

Type of SHS.	Benefits.	Drawbacks.
Aquifer Thermal	High storage capacity, cost- effective construction, and low risk of contamination	Susceptible to corrosion, environmental concerns, and risk of blockages.
Hot Water Thermal	Excellent heat retention of water, extensive applicability, and fast charging and discharging capabilities.	Gradual heat loss over time and significant space needed for storage tanks.
Cavern Thermal	Rapid heat injection and extraction rates with the ability to utilize existing caverns.	Extremely high costs for construction and installation, with limited availability of suitable caverns.
Gravel-Water Thermal	Cost-effective, a viable alternative to large water storage tanks, and easily scalable.	Reduced specific heat capacity compared to water, requiring a larger storage system.
Molten Salt Thermal	Operates at high temperatures, space-efficient, and ideal for use in solar power plants.	Elevated freezing point, susceptibility to corrosion, and intricate system maintenance requirements.
Borehole Thermal	Effective for long-term seasonal storage with minimal operational expenses.	Demands significant underground space and involves high initial costs.

Gravel-Water Thermal Energy Storage: This approach utilizes a combination of gravel and water to retain thermal energy. The gravel offers structural stability, while the water serves as the primary heat storage medium. It is commonly applied in scenarios that demand medium to large-scale energy storage.

Molten Salt Thermal Energy Storage: Molten salts serve as a medium for storing thermal energy at extremely high temperatures. This storage method is widely utilized in concentrated solar power (CSP) plants, enabling the retention of solar energy for electricity production, even during nighttime or periods of low sunlight.

Borehole Thermal Energy Storage: Thermal energy is stored in the ground using a network of boreholes filled with a heat-transfer fluid. This method is particularly suitable for long-term, seasonal energy storage and is commonly implemented in heating and cooling systems for buildings.

Table 1 provides a concise overview of the advantages and limitations of various Sensible Heat Storage systems, highlighting factors such as storage capacity, cost-effectiveness, efficiency, and spatial requirements. This summary aids in evaluating their appropriateness for different energy storage applications.

Latent Heat Storage (LHS): The Latent Heat Storage (LHS) system utilizes energy absorption during a material's phase change, such as transitioning from solid to liquid or liquid to vapor. This system leverages the material's ability to undergo a phase transition at a stable temperature, providing an efficient method for storing thermal energy.

When heat is applied, the material experiences either sensible heating (temperature increase) or latent heating (phase transition). Key phase transitions include melting (latent heat of fusion) and vaporization (latent heat of vaporization), which enable effective energy storage and release across various applications.

Table 2 provides a comparative analysis of different Phase Change Materials (PCMs), outlining their primary benefits, drawbacks, and typical use cases. This comparison offers insights into the strengths and limitations of PCMs, facilitating better selection for thermal energy storage and related applications.

Figure 1 depicts the correlation between temperature (T) and energy storage (Q) in phase change materials (PCMs) compared to non-PCMs, illustrating their efficiency and unique energy retention properties.

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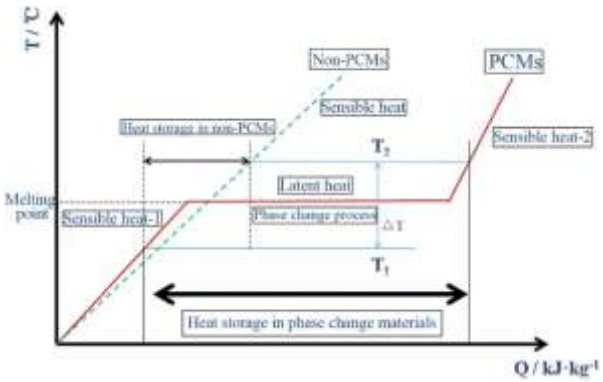

Figure1: Temperature-Energy Relationship for Sensible and Latent Heat Storage

Table2. Comparison of Phase Change Materials

PCM Type	Benefits	Drawbacks
Paraffins	Stable, non-corrosive, and chemically unreactive.	Limited thermal conductivity and moderate expense.
Fatty Acids	Reusable, long-term stability, and non-toxic.	Elevated cost and average thermal conductivity.
Salt Hydrates	Excellent latent heat capacity and cost-effective.	Susceptible to phase separation and challenges with supercooling.

Thermochemical Energy Storage (TCES): Thermochemical Energy Storage (TCES) is a technique for storing energy through reversible chemical reactions. This system harnesses thermal energy by leveraging the enthalpy changes associated with these reactions. During the charging phase, energy is stored through an endothermic reaction, where reactants decompose into simpler components, capturing energy as chemical potential. When energy is required, the process reverses, and the stored energy is released via an exothermic reaction as the components recombine..

Table3. Comparing of Materials Used in (TCES)

	Benefits	Drawbacks
Calcium Hydroxide ($Ca(OH)_2$)	High temperature tolerance, excellent energy density, and broad availability.	Requires high temperatures for energy release and may experience degradation.
Ammonia/Metal Chloride	Low temperature operation, high energy density, suitable for low-temperature applications.	Corrosive nature, requires containment, and involves a complex system.
Magnesium Oxide (MgO)	Moderate temperature range, stable performance, and adequate energy density.	Requires elevated temperatures and may degrade over multiple cycles.
Zeolite/Water	Cost-effective, operates at moderate temperatures, and ideal for medium-scale applications.	Reduced energy density and requires specialized water management.
Sodium Hydroxide (NaOH)	Moderate energy capacity, low-temperature operation, and reversible reaction capability.	Corrosive and demands strict safety precautions for handling.

Chemical Energy Storage (CES): Chemical Energy Storage (CES) systems store energy within the chemical bonds of molecules and atoms. Energy is released through chemical reactions, making these systems ideal for long- term energy storage. CES technologies primarily include hydrogen storage, synthetic natural gas, and solar fuel systems.

Hydrogen Energy Storage (HES): Hydrogen Energy Storage (HES) operates by transforming electrical energy into hydrogen gas, storing it, and later converting it back into usable energy as needed.

Figure 2 demonstrates the core components and operational flow of a Hydrogen Energy Storage System (HES). The process begins with electrical energy input, often derived from renewable energy sources, into an electrolyzer. The electrolyzer facilitates the conversion of electrical energy into hydrogen (H_2) and oxygen (O_2) via electrolysis. The produced hydrogen is then stored in a hydrogen storage unit for future utilization.

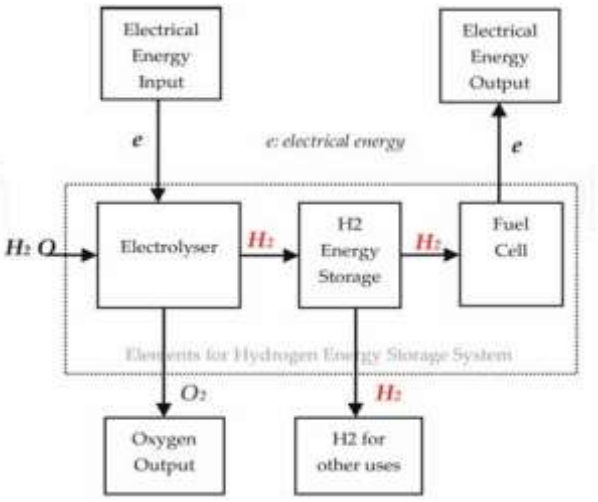

Figure 2 HES System Overview

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Synthetic Natural Gas (SNG): Synthetic Natural Gas (SNG) is generated through the methanation of hydrogen and carbon dioxide. It serves as a viable substitute for conventional natural gas, compatible with existing pipelines and storage infrastructure.

Figure 3 depicts the step-by-step process of producing Synthetic Natural Gas (SNG) from biomass, broken down into six key stages.

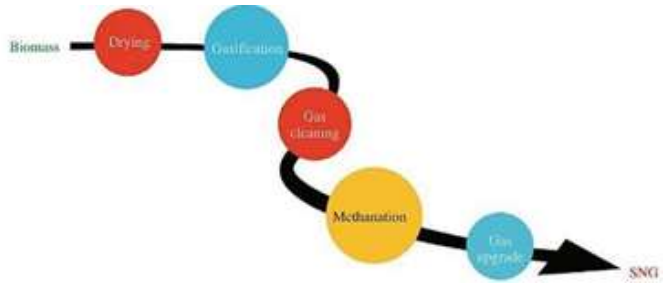

Figure 3. SNG Production Process

Solar Fuel: Solar fuel technology involves converting sunlight into a storable form of chemical energy, commonly as hydrogen or hydrocarbons. This method replicates the process of natural photosynthesis but employs artificial or thermochemical techniques to enhance efficiency and scalability.

Table 4 presents a comparative analysis of the three primary chemical energy storage technologies: Hydrogen, Synthetic Natural Gas (SNG), and Solar Fuel. It outlines their advantages, limitations, and applications.

Table 4. Comparison of CES Technologies

Feature	Hydrogen	SNG	Solar Fuel
Benefits	High energy capacity and emission- free operation.	Compati ble with existing infrastru cture and utilizes CO2 effectiv ely.	Harnesses solar energy directly, environment ally sustainable, and suitable for long- term use.
Drawbacks	Expensive, limited efficiency, and requires dedicated infrastructur e.	Complic ated, lower efficien cy, and reliant on CO2 availabil ity.	Restricted implementat ion, expensive, and intricate.

Electrochemical Energy Storage (EcES): Electrochemical Energy Storage (EcES) systems store energy through electrochemical reactions. These systems are broadly classified into two major types:

Battery Energy Storage (BES): BES systems convert chemical energy into electrical energy using two electrodes (anode and cathode) and an electrolyte. They are categorized into:

- Primary Batteries: Single-use, non-rechargeable batteries.
- Secondary Batteries: Rechargeable, designed for repeated use. Examples include Lead-Acid, Lithium-Ion, Nickel-Cadmium, and Sodium-Sulfur batteries.

Flow Battery Energy Storage (FBES): FBES systems store energy in liquid electrolytes that circulate through the system. These are divided into:

- **Redox Flow Batteries:** Use redox reactions for energy storage.
- **Hybrid Flow Batteries:** Combine solid electrodes with a flowing electrolyte.

FBES systems are highly scalable and particularly advantageous for large-scale applications, such as grid energy storage.

Table 5 compares the two types of Electrochemical Energy Storage (EcES) systems: Battery Energy Storage (BES) and Flow Battery Energy Storage (FBES). The table highlights their energy storage methods, key advantages, and limitations.

Table 5. Comparison table of ECES types

Type	Energy Retention Process	Benefits	Drawbacks
BES	Energy retained within the electrodes	High energy capacity and space-efficient.	Restricted cycle lifespan and disposal concerns. 4o mini
FBES	Energy stored in the electrolyte (fuel) and delivered to the electrodes.	Expandabl e energy storage and extended cycle lifespan.	More intricate and expensive.

Electrical Energy Storage Systems: Electrical Energy Storage (EES) systems are essential for managing energy supply and demand, particularly with the increasing use of renewable energy sources like solar and wind. These systems store electricity when generation exceeds demand and release it when needed. There are three main types of Electrical Energy Storage Systems:

Capacitors: Capacitors store energy within an electric field formed between two conductive plates separated by an insulating material (dielectric). They can store and release

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energy rapidly, making them well-suited for short- term energy storage. The process works as follows:

Charging: When a voltage is applied across the two plates, one plate becomes positively charged, and the other becomes negatively charged. The dielectric material prevents charge movement between the plates, creating an electric field that stores energy.

Energy Storage: The amount of energy a capacitor can store is determined by the surface area of the plates, the distance between them, and the type of dielectric material. The electric field's strength is proportional to the applied voltage and the capacitance, which represents the capacitor's ability to store charge.

Discharging: When connected to a circuit, the stored energy in the electric field is released as current flows from one plate to the other, allowing the capacitor to quickly provide energy.

This rapid charging and discharging capability makes capacitors ideal for applications that require fast cycles. Figure 4 illustrates the basic operation of a capacitor, showing how an electric field is generated when a voltage is applied. The separation between the elements ensures that charges are retained, enabling the capacitor to store and release energy as needed when connected to a circuit.

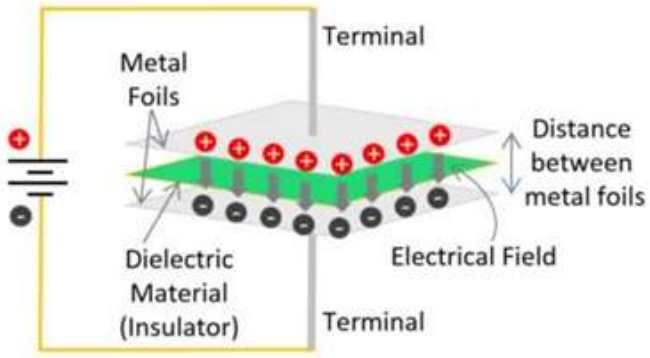

Figure 4. Operating Principle of the Capacitor

Supercapacitors: Supercapacitors, also referred to as ultracapacitors, are a more advanced version of capacitors with much higher energy density. They can store significantly more energy than traditional capacitors because of their larger surface area and thinner dielectric layers.

Superconducting Magnetic Energy Storage (SMES): SMES stores energy within the magnetic field produced by the flow of direct current through a superconducting coil. Once the current flow is stopped, the stored energy can be released to the grid or specific systems.

Table 6 provides a comparison of different types of Electrical Energy Storage (EES) systems.

Table 6. Comparing table of different EES types

Type	Benefits	Drawbacks
Capacitors	High power capacity, rapid response, and excellent efficiency.	Restricted energy storage capacity, suitable for short-term use.
Supercapacitors	Extended cycle life, rapid charging and discharging, and high power output.	Reduced energy density, not ideal for long- term storage.
SMES	Excellent efficiency, quick response, and immediate discharge. 4o mini	High expenses, requires superconducting materials.

Hybrid Energy Storage Systems (HES): The principle behind Hybrid Energy Storage Systems (HES) is to combine two or more types of energy storage technologies to leverage their individual advantages while addressing their limitations. Typically, HES systems integrate a high-power storage system with a high-energy density storage system, enabling them to provide both rapid power responses and sustained energy delivery over extended durations.

Hybrid Energy Storage Systems (HES) are classified according to the specific types of energy storage technologies they combine. These combinations are carefully designed to maximize the benefits of each technology, optimizing both energy storage and power delivery for various applications.
Table 7 presents the two primary characteristics of Hybrid Energy Storage Systems (HES). It emphasizes the balance between power density and energy density, where high- power systems provide quick energy release, and high- energy density systems are suited for storing energy over longer periods.

Table 7.Key Features of HES

Feature	Description
Power Density vs. Energy Density	Merges high-power storage for quick delivery with high- energy density for prolonged energy supply.
Technologies Utilized	High-power: supercapacitors, flywheels, SMES. High-energy: lithium-ion, redox flow batteries, hydrogen storage..

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Battery-Supercapacitor Hybrid
The primary goal is to optimize energy delivery in electric vehicles by employing an adaptive control strategy to enhance battery life under fluctuating load conditions.

HESS Configuration: Combines batteries for long-term energy storage and supercapacitors for quick energy bursts, optimizing performance in electric vehicles.

Adaptive Control Strategy: Utilizes λ tracking for efficient energy management, improving the system's robustness under varying operational conditions.

Efficiency: The system is computationally efficient and has been validated through simulations and experiments, demonstrating better adaptability and overall performance. Figure 5 illustrates the power flow in a Battery-Supercapacitor Hybrid Energy Storage System used in electric vehicles. It depicts how energy is managed and distributed between the battery, supercapacitor, and the electric motor.

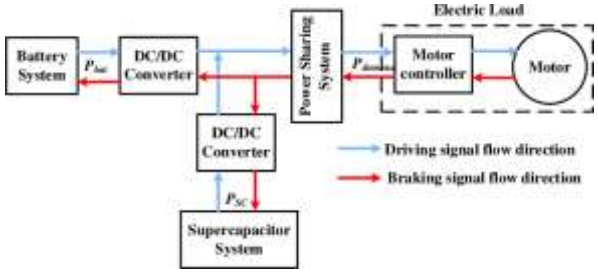

Figure 5: Power Flow Diagram of a Battery- Supercapacitor Hybrid Energy Storage System.

Battery-Flywheel Hybrid: It introduces a strategy that utilizes variational mode decomposition (VMD) optimized with long short-term memory (LSTM) neural networks to effectively manage and distribute power. The objective is to mitigate fluctuations in wind power and ensure grid stability.

Battery-SMES: The Battery-SMES system stabilizes DC microgrids powered by photovoltaic (PV) and wind energy sources through the integration of a Hybrid Battery–Superconducting Magnetic Energy Storage (SMES) system. This approach examines how combining these storage systems helps manage voltage and power fluctuations caused by the intermittent nature of renewable energy sources.

Battery-Fuel Cell Hybrid: The Fuel Cell/Battery Hybrid Power System is designed for small-scale vehicles, such as unmanned aerial vehicles (UAVs). The system integrates a proton exchange membrane fuel cell (PEMFC) with a battery to enhance energy storage efficiency and optimize power management. The hybrid setup extends operational time, improves hydrogen storage efficiency, and reduces emissions compared to conventional energy systems. The study explores system sizing, evaluates hydrogen storage options, and includes a case study demonstrating the system's real-world application and performance.

Table 8 compares various types of Hybrid Energy Storage Systems (HES), emphasizing their strengths and weaknesses. It highlights key benefits, such as rapid response times, efficient energy transfer, and long- duration energy supply.

Table 8. Comparison of HES Types

HES Type	Advantages	Disadvantages
Battery-Supercapacitor Hybrid.	High power density and energy density, quick response.	Limited energy storage compared to standalone batteries.
Battery-Flywheel Hybrid.	Fast energy release, good for short bursts of power.	High maintenance, mechanical wear.
Battery-SMES Hybrid.	Efficient energy transfer, good for grid stability.	Expensive, requires superconducting materials.
Battery-Fuel Cell Hybrid.	Longer duration energy supply, good for electric vehicles.	Complex integration, high cost.

Mechanical Energy Storage (MES) Systems: Mechanical Energy Storage (MES) systems play a vital role in the energy storage sector by converting electrical energy into mechanical energy during periods of low demand and converting it back to electrical energy when required. There are various MES technologies, including Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES), Flywheel Energy Storage (FES), and Gravity Energy Storage (GES). Each technology has distinct characteristics and applications that help balance energy supply and demand.

Pumped Hydro Energy Storage (PHES) Systems
Principle
PHES operates by transferring water between two reservoirs at different elevations. During off-peak hours, electricity is used to pump water from a lower reservoir to a higher one. When energy demand peaks, water is released from the upper reservoir, driving turbines to generate electricity, as illustrated in Figure 1.

Efficiency
PHES systems are known for their high efficiency, with energy efficiency rates ranging from 70% to 85%. They offer large storage capacities and can function for extended periods, making them highly suitable for grid-scale energy management. Figure 6 illustrates a Pumped Hydro Energy Storage (PHES) system, where water is pumped to an upper

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reservoir during periods of low demand and released to generate electricity during high demand, thus effectively balancing the energy supply.

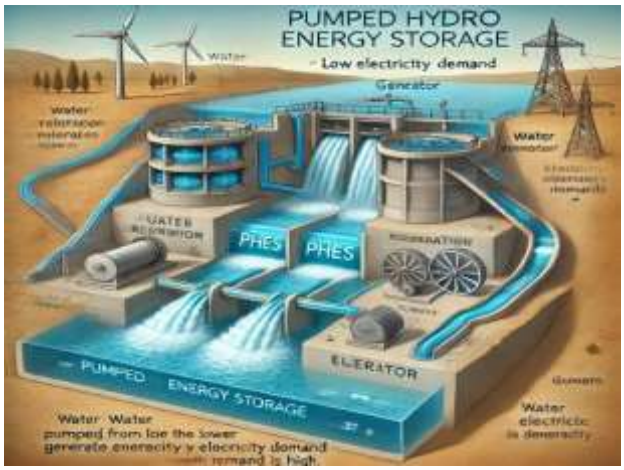

Figure:6 PHES System

Compressed Air Energy Storage(CAES): CAES (Compressed Air Energy Storage) systems use off-peak electricity to compress air into underground caverns. When electricity is needed, the compressed air is heated and expanded to drive turbines, generating electricity. There are several types of CAES systems, including diabatic, adiabatic, and isothermal systems, as detailed in Table 5. These systems vary in how they handle heat during the compression and expansion processes.

Diabatic: In Diabatic CAES, the heat generated during the compression phase is released into the environment. When the stored compressed air is expanded, external heat—typically from natural gas or another energy source—is needed to reheat the air to ensure efficient energy recovery.

Figure 7 presents a diagram of the diabatic compressed air energy storage system, illustrating its components and how the process works.

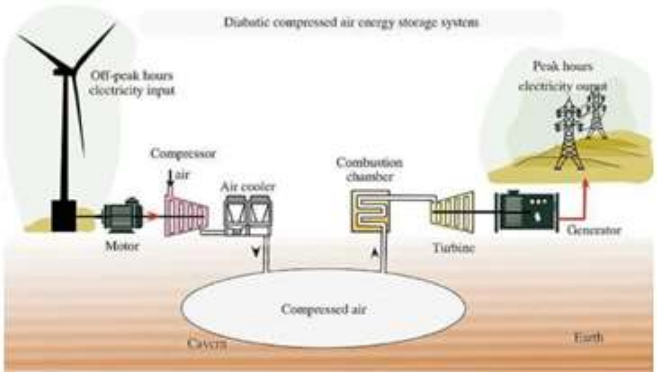

Figure7: Diabatic CAES system

Adiabatic: In Adiabatic CAES, the heat generated during the compression phase is captured and stored in a thermal energy storage (TES) system. During the expansion phase, this stored heat is used to reheat the air, eliminating the need for an external energy source and significantly enhancing efficiency. Figure 8 illustrates the diagram of the adiabatic compressed air energy storage system, highlighting its components and how the process operates.

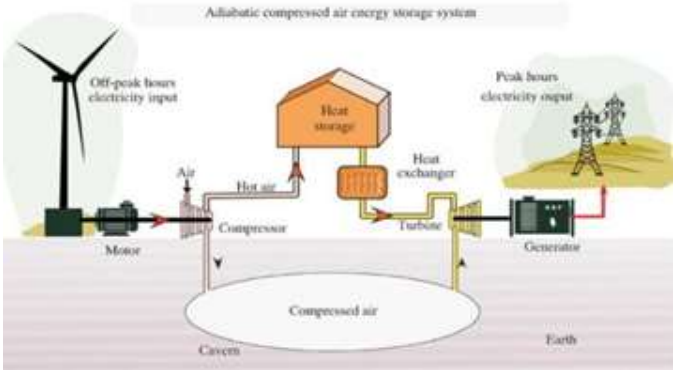

Figure8: Adiabatic CAES system

Isothermal: In Isothermal CAES, compression and expansion are carried out slowly enough to maintain a constant temperature, achieved either by cooling during compression or heating during expansion. This requires advanced engineering but results in highly efficient energy storage with minimal temperature fluctuations.

Table 9 compares three types of Compressed Air Energy Storage (CAES) systems: Diabatic, Adiabatic, and Isothermal. It explains their methods of heat management—where Diabatic systems discard heat, Adiabatic systems store and reuse it, and Isothermal systems maintain a constant temperature. The table also provides information on the efficiency of each system, illustrating performance differences based on how each system handles heat during the compression and expansion processes.

Table 9. Comparison of CAES Types

Type	Heat Management	Efficiency
Diabatic	Heat is released during compression.	42% to 54%
Adiabatic	Heat is captured and reutilized..	Up to 70%
Isothermal	Keep a consistent temperature.	60% to 70%

Flywheel Energy Storage (FES) Systems: The Flywheel Energy Storage (FES) system stores energy by converting electrical energy into rotational kinetic energy using a flywheel. The main components of the system include the rotor (flywheel), an electric motor-generator to

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convert electrical energy into mechanical energy and vice versa, bearings to minimize friction, and housing to reduce aerodynamic drag and ensure safety. The amount of energy stored is directly proportional to the mass and rotational speed of the flywheel. FES is renowned for its high efficiency, quick response time, and long cycle life. The primary elements of the system are the rotor, bearings, housing, and control system, as illustrated in Figure 9.

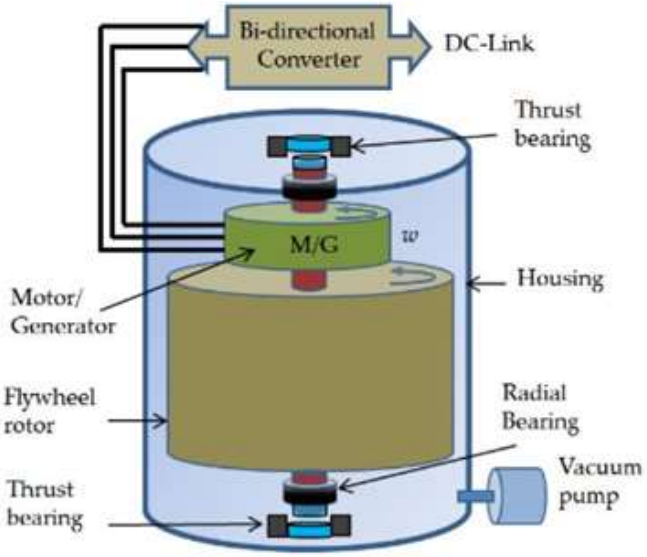

Figure 9: Structure and components of a flywheel

Table 10 provides a comprehensive evaluation of the key strengths and limitations of Flywheel Energy Storage (FES) systems. It highlights the system's overall efficiency and longevity while addressing potential challenges such as storage capacity limitations and costs. This comparison aids in assessing the suitability of FES systems for different energy storage applications and allows for a comparison with other storage technologies.

Table 10. Benefits and Drawbacks of FES

Benefits	Drawbacks
High energy and power density	High self – discharge rate
Long cycle lifespan	Limited storage capacity
Rapid response time	High initial cost
High cycle efficiency (90% - 95)	

Gravity Energy Storage (GES) Systems: Gravity Energy Storage (GES) systems, as shown in Figure 10, operate on the principle of converting electrical energy into potential gravitational energy. This process involves lifting a heavy object, such as a piston or weight, to store energy, which can later be released to generate electricity during periods of high energy demand. The key operational stages and principles of the GES system are outlined as follows:

Energy Storage (Charging Phase)
During periods of low electricity demand (e.g., off-peak hours), excess electrical energy is used to lift a heavy object, such as a large piston or weight, to a specified height.

The energy required to lift the object is stored as potential energy, which is directly proportional to the object's mass and the height to which it is lifted.

This mechanism helps conserve surplus energy instead of allowing it to go to waste.

Energy Release (Discharging Phase)
When electricity demand increases, the elevated object is allowed to descend under the force of gravity.
The gravitational energy released during the descent drives turbines connected to electrical generators, converting the stored potential energy back into usable electrical energy.

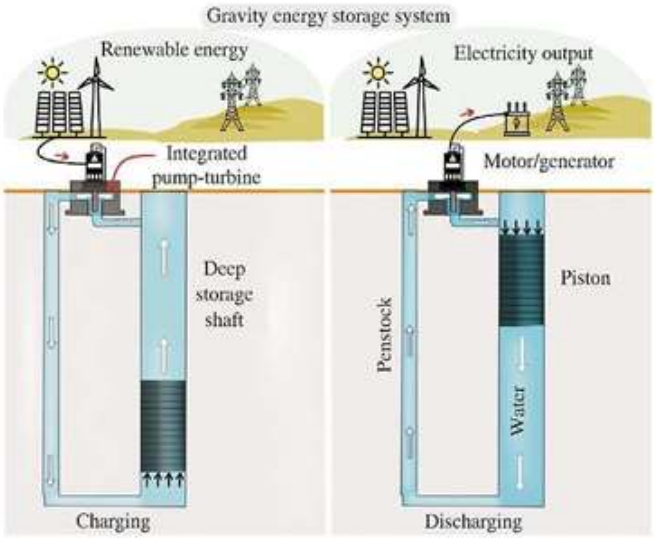

Figure 10: Gravity Energy Storage System

Table 11 outlines the key parameters and their corresponding values or ranges that define the performance of Gravity Energy Storage (GES) systems. It includes factors such as power output, energy storage capacity, the mass of the object used for energy storage, and the height of elevation. Efficiency and operational lifespan are essential for understanding the system's long-term viability. Additionally, the cost per kilowatt-hour serves as a crucial financial metric, offering insights into the economic feasibility of implementing GES technology for large-scale energy storage.

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Table 11. Key Performance Parameters of Gravity Energy Storage Systems

Parameter.	Value/Range.
Power Output	40 MW – 1.6GW
Energy Storage Capacity	200 MWh- 8000 MWh
Mass of Object	5000- 30000 tons
Height of Elevation	500- 1000 meter
Efficiency	70%- 90%
Operational Life	30-50 years
Cost per kWh	50$ - 200$ per kWh

Parametric Optimization for the Design of Gravity Energy Storage System Using the Taguchi Method focuses on optimizing the design parameters of Gravity Energy Storage (GES) systems to improve their efficiency and integration with renewable energy sources.

By applying the Taguchi method—a statistical approach for process optimization—the researchers systematically evaluated various design factors to identify the optimal configurations. This methodology allowed for a thorough analysis of how different parameters influence the performance of GES systems, leading to a more robust and efficient design framework.

Table 12 presents the experimental design and results for optimizing a GES system using the Taguchi Method. This simplified format provides a clearer understanding of how different factors impact system performance. The design consists of 25 trials, each representing a unique combination of six factors (A–F) that influence system performance. These factors and their respective ranges are:

- Factor A (D/Hc): Diameter -to-height ratio of the piston.
- Factor B (L/Hc): Length- to-height ratio.
- Factor C (d/H): Displacement- to-height ratio.
- Factor D (Density Ratio): Ratio of the medium's density involved in energy storage.
- Factor E (Time).: Duration of the process (in minutes).
- Factor F (Hp/Hc).: Ratio of potential energy to height.Responses.:
- P-Hyd: Hydraulic energy output for each trial, representing the system's energy performance.
- S/N Ratio: Signal-to-noise ratio, reflecting the system's efficiency and performance consistency.

Note: The results, tables, and curves have been taken from the Design Expert program.

Using Design Expert software to analyze the P-Hyd response, the Pareto chart in Figure 11 highlights the relative importance of factors influencing the response. The chart ranks factors based on their t-values, with taller bars indicating greater influence.

Factor A-A stands out, surpassing the Bonferroni limit (represented by the red line), marking it as highly significant in impacting P-Hyd. Other factors, such as B-B, AB, AC, and C-C, fall below the significance thresholds, suggesting a minimal or negligible impact.

Positive effects are shown in orange, while negative effects are in blue, offering a clear visual distinction of how each factor contributes to the response. This chart is essential for pinpointing the key parameters for optimization.

Table12: Experimental Design for optimizing Gravity Energy Storage by the Taguchi Method

Trails	Factor A	Factor B	Factor C	Factor D	Factor E	Factor F	P-Hyd	S/N
1	-1	-1	-1	-1	-1	-1	0.1516	-16.38
2	-1	-1	-1	-1	-1	-1	0.4207	-7.5213
3	-1	1	-1	1	-1	-1	0.6338	-3.9613
4	-1	1	1	1	1	1	0.6407	-3.8665
5	-1	1	1	1	1	1	0.6142	-4.2343
6	-1	-1	-1	-1	-1	-1	2.2628	7.0929
7	-1	-1	-1	-1	-1	-1	0.6402	-3.8739
8	-1	1	-1	1	-1	-1	7.8422	17.8888
9	-1	1	1	1	1	1	0.9018	-0.8976
10	-1	1	1	1	1	1	1.6681	4.4445
11	-1	-1	-1	-1	-1	-1	15.8794	24.0167
12	-1	-1	-1	-1	-1	-1	1.6098	4.1357
13	-1	1	-1	1	-1	-1	1.0619	0.5220
14	-1	1	1	1	1	1	1.1507	1.2194
15	-1	1	1	1	1	1	15.6611	23.8964
16	1	-1	-1	-1	-1	-1	2.9424	9.3739
17	1	-1	-1	-1	-1	-1	28.7657	29.1775
18	1	1	-1	1	-1	-1	21.2950	26.5656
19	1	1	1	1	1	1	6.2517	15.9200
20	1	1	1	1	1	1	1.2849	2.1771
21	1	-1	-1	-1	-1	-1	14.1279	23.0015
22	1	-1	-1	-1	-1	-1	17.3392	24.7806
23	1	1	-1	1	-1	-1	2.0415	6.1988
24	1	1	1	1	1	1	24.5772	27.8107
25	1	1	1	1	1	1	8.6147	18.7048

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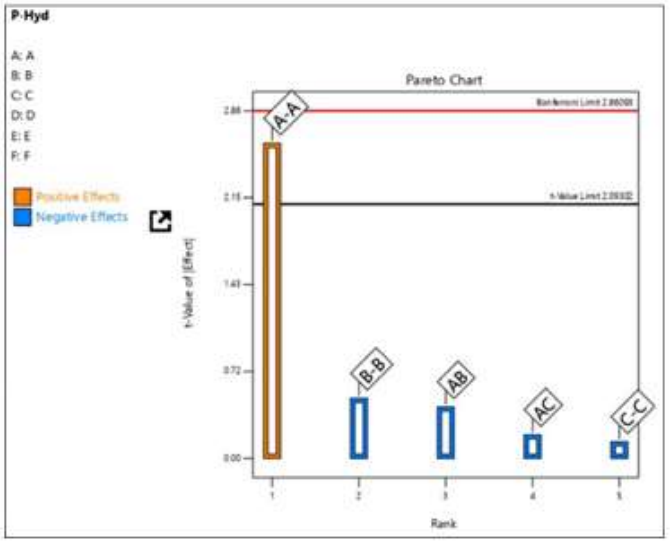

Figure11: Pareto chart of P-Hyd. response

The half-normal plot of the P-Hyd response, shown in Figure 12, illustrates the significance of factors influencing the response. Data points closer to the red diagonal line represent factors with minimal effects, while points farther from the line highlight more significant factors.

In this plot, factor A-A deviates notably from the line, indicating it as the most influential factor on the P-Hyd response. Positive effects are represented in orange, and negative effects are in blue, providing a clear visualization of how each factor contributes to the system's performance. This plot is valuable for identifying the key parameters for optimization.

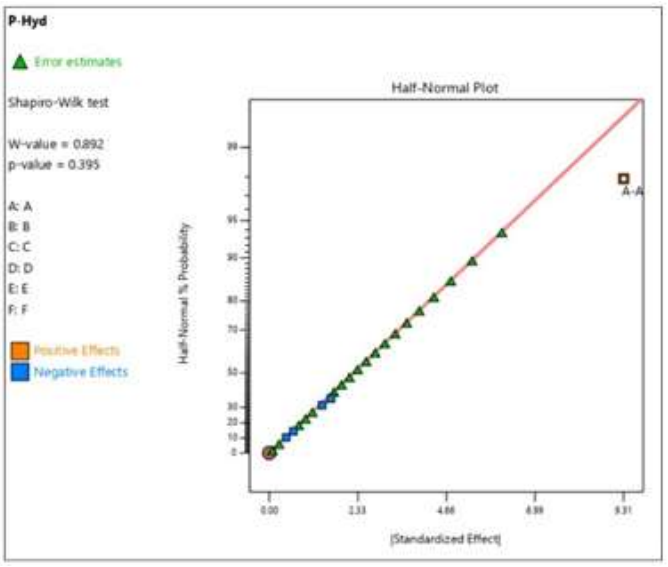

Figure12: Half Normal plot of P-Hyd response

The ANOVA Table 13 analysis confirms that the model is statistically significant (F-value: 3.32, p-value: 0.0397) and effectively explains the variability in the P-Hyd response. Factor A-A is identified as the most influential (p-value: 0.0057), while other terms like B-B and AB are not significant. The non-significant lack of fit (p-value: 0.9765) suggests that the model fits the data well, with any variation likely attributed to noise. Simplifying the model by removing insignificant terms could further enhance its clarity and effectiveness.

Table 13: ANOVA Table of P-Hyd response

ANOVA for selected factorial model

Response 1: P-Hyd

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	583.48	3	194.49	3.32	0.0397	significant
A-A	554.57	1	554.57	9.46	0.0057	
B-B	39.81	1	39.81	0.6789	0.4192	
AB	35.64	1	35.64	0.6079	0.4443	
Residual	1231.24	21	58.63			
Lack of Fit	3.08	2	1.54	0.0238	0.9765	not significant
Pure Error	1228.15	19	64.64			
Cor Total	1814.72	24				

Factor coding is **Coded**.
Sum of squares is **Type III - Partial**

The **Model F-value** of 3.32 implies the model is significant. There is only a 3.97% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case A is a significant model term. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The **Lack of Fit F-value** of 0.02 implies the Lack of Fit is not significant relative to the pure error. There is a 97.65% chance that a Lack of Fit F-value this large could occur due to noise.
Non-significant lack of fit is good -- we want the model to fit.

Table 14 summarizes the fit statistics for the P-Hyd response model. Although the model shows adequate precision with an Adeq Precision value of 4.062, the low R^2 (0.3215) and Adjusted R^2 (0.2246) suggest that it has limited capability to explain variability in the response.

The negative Predicted R^2 (-0.0196) indicates that the model needs refinement, potentially by including higher- order terms or interactions, to enhance its predictive performance.

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Table 14: Fit Statistic of P-Hyd. response.

Fit Statistics

Std. Dev.	7.66	R^2	0.3215
Mean	7.14	Adjusted R^2	0.2246
C.V. %	107.31	Predicted R^2	-0.0196
		Adeq Precision	4.0620

A negative **Predicted R^2** implies that the overall mean may be a better predictor of your response than the current model. In some cases, a higher order model may also predict better.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 4.062 indicates an adequate signal. This model can be used to navigate the design space.

Table 15 presents the final equation representing the P-Hyd response using coded factors, where high levels are coded as +1 and low levels as -1. The constant term (+8.33) represents the baseline response. Factor A has the most significant positive impact (+4.91), significantly increasing P-Hyd, while Factor B (-1.31) and the interaction term AB (-1.24) have smaller negative effects. This equation serves as a valuable tool for predicting P-Hyd and identifying the most influential factors for optimization.

Table15: Final equation of P-Hyd. response.

Final Equation in Terms of Coded Factors

P-Hyd	=	
+8.33		
+4.91	*	A
-1.31	*	B
-1.24	*	AB

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

To analyze the S/N response, Figure 13 presents a Pareto chart that highlights the significance of the factors influencing it. Factor A-A is identified as the most significant, exceeding the Bonferroni limit and showing a strong impact on the response. Other factors, such as AB and B-B, fall below the threshold lines, indicating smaller or negligible effects. Positive contributions are represented in orange, while negative contributions are shown in blue. This chart effectively emphasizes the key factors to prioritize for optimizing the S/N response.

To analyze the S/N response, Figure 13 presents a Pareto chart that highlights the significance of the factors influencing it. Factor A-A is identified as the most significant, exceeding the Bonferroni limit and showing a strong impact on the response. Other factors, such as AB and B-B, fall below the threshold lines, indicating smaller or negligible effects. Positive contributions are represented in orange, while negative contributions are shown in blue. This chart effectively emphasizes the key factors to prioritize for optimizing the S/N response.

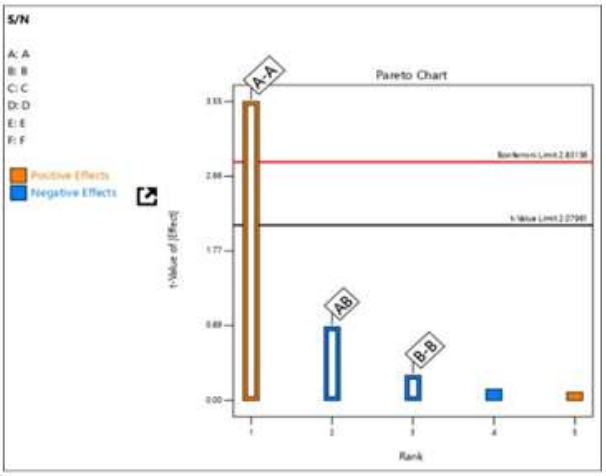

Figure 13: Pareto chart of S/N response

Figure 14 displays the half-normal plot for the S/N response, showing the significance of factors based on their standardized effects. Factors closer to the red diagonal line have minimal impact, while those further from the line are more influential. Factor A-A is the most significant, deviating notably from the line, while AB and B-B show moderate effects. Positive effects are represented in orange, and negative effects are shown in blue, offering a clear visualization of the key contributors for optimization.

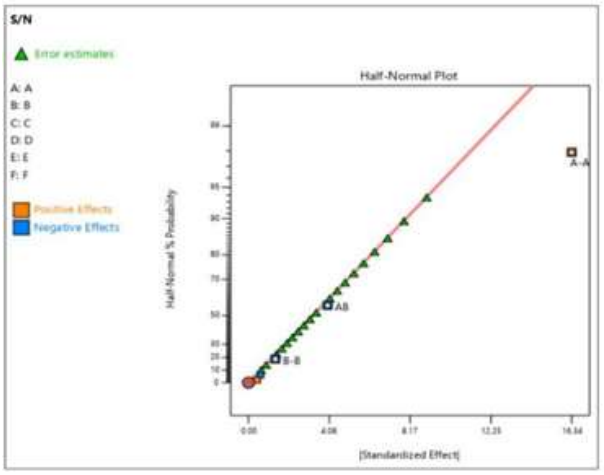

Figure14: Half Normal plot of S/N. response

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Table 16 presents the ANOVA table for the S/N response, confirming the model's statistical significance (p-value: 0.0176), with Factor A-A being the most influential (p- value: 0.0019).

Other factors, such as AB and B-B, are not statistically significant. The non-significant lack of fit (p- value: 0.9855) suggests that the model fits the data well, with any variation likely attributed to noise. This confirms the model's reliability for predicting and optimizing the S/N. response.

Table 16: ANOVA Table of S/N response.

ANOVA for selected factorial model

Response 2: S/N

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1542.74	3	514.25	4.21	0.0176	significant
A-A	1537.68	1	1537.68	12.59	0.0019	
B-B	10.57	1	10.57	0.0865	0.7715	
AB	92.14	1	92.14	0.7544	0.3949	
Residual	2564.78	21	122.13			
Lack of Fit	3.93	2	1.97	0.0146	0.9855	not significant
Pure Error	2560.84	19	134.78			
Cor Total	4107.51	24				

Factor coding is **Coded**.
Sum of squares is **Type III - Partial**

The **Model F-value** of 4.21 implies the model is significant. There is only a 1.76% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case A is a significant model term. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The **Lack of Fit F-value** of 0.01 implies the Lack of Fit is not significant relative to the pure error. There is a 98.55% chance that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

Table 17 presents the fit statistics for the S/N response, indicating that the model explains 37.56% of the variability (R^2) with an Adjusted R^2 of 0.2864 and a Predicted R^2 of 0.1179, showing reasonable consistency.

The Adeq Precision value of 4.601 exceeds the required threshold, confirming that the model has an adequate signal-to-noise ratio for navigating the design space. While the model is adequate, there is potential to improve its predictive capability.

Table 17: Fit Statistic of S/N response

Fit Statistics

Std. Dev.	11.05	**R^2**	0.3756
Mean	9.05	**Adjusted R^2**	0.2864
C.V. %	122.15	**Predicted R^2**	0.1179
		Adeq Precision	4.6009

The **Predicted R^2** of 0.1179 is in reasonable agreement with the **Adjusted R^2** of 0.2864; i.e. the difference is less than 0.2.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 4.601 indicates an adequate signal. This model can be used to navigate the design space.

Table 18 shows the final equation for the S/N response using coded factors, where high levels are assigned a value of +1 and low levels are assigned -1. The constant term (+10.74) represents the baseline S/N value. Factor A has the greatest positive impact (+8.17), causing a significant increase in the S/N response. Factor B (-0.6772) has a small negative effect, while the interaction term AB (-2.00) slightly lowers the response. This equation is useful for forecasting the S/N and understanding the relative importance of each factor based on their coefficients.

Table18: Final equation of S/N response

Final Equation in Terms of Coded Factors

S/N	=
+10.74	
+8.17	* A
-0.6772	* B
-2.00	* AB

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

Summary of Parametric Optimization for the Design of Gravity Energy Storage System:
The analysis of the P-Hyd and S/N responses reveals that Factor A-A is consistently the most influential variable affecting system performance. Both models are statistically significant, with P-Hyd having a p-value of 0.0397 and S/N a p-value of 0.0176, indicating that the models are effective in explaining the variability in the data. The Adeq Precision values of 4.062 for P-Hyd and 4.601 for S/N, both exceeding the threshold of 4, suggest that the models have adequate

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signal-to-noise ratios for exploring the design space. However, the relatively low R^2 values (32.15% for P-Hyd and 37.56% for S/N) indicate that the models only explain a portion of the variability in the responses, suggesting room for further improvement. This could involve adding higher-order terms or interactions to increase the models' predictive capabilities. The final equations for both responses highlight the dominant positive impact of Factor A-A, while Factors B and the interaction term AB show smaller negative effects. These findings provide valuable guidance for optimization efforts, particularly focusing on maximizing the influence of Factor A-A to enhance system performance across both responses.

III. CONCLUSION

Energy Storage Systems (ESS) play a crucial role in modern energy infrastructure, particularly in managing the variability of renewable energy sources. Each type of ESS—thermal, mechanical, chemical, electrochemical, electrical, and hybrid—has its own set of benefits. The results indicate that hybrid systems (HES) offer the greatest flexibility and efficiency by combining multiple technologies. These systems are particularly effective for applications such as grid stabilization and integrating renewable energy.To improve ESS performance, future efforts should focus on enhancing energy conversion efficiency, lowering costs, and ensuring scalability. Policymakers and engineers should prioritize the advancement of hybrid storage technologies, which hold significant potential for meeting diverse energy demands. Collaboration between researchers and industry leaders will be essential in speeding up the adoption of ESS, helping to create a more stable and sustainable energy future.

Conflict of Interest
The author declares no conflict of interest.

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