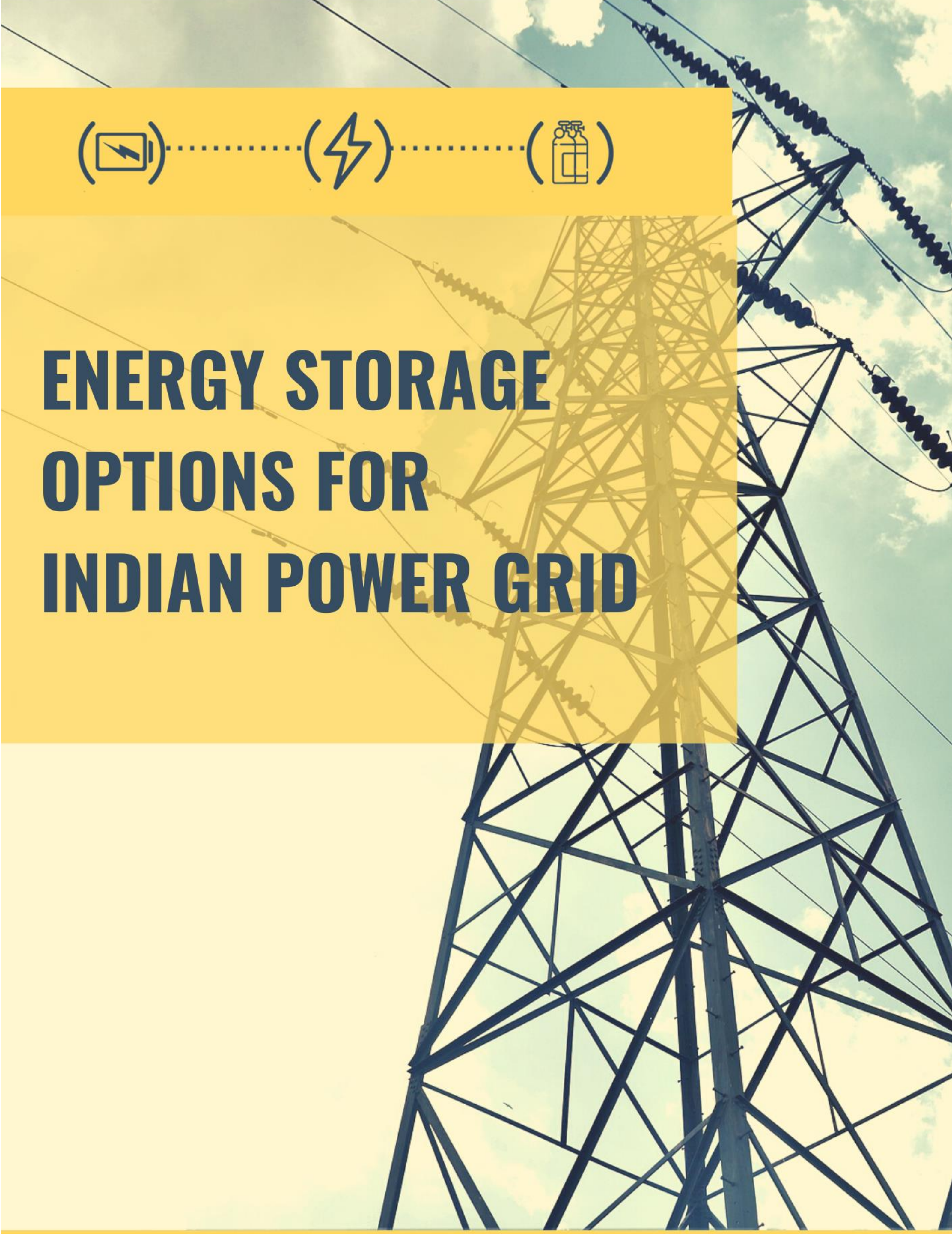

# ENERGY STORAGE OPTIONS FOR INDIAN POWER GRID

CSTEP
CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

# Energy Storage Options for Indian Power Grid

Dr Ammu Susanna Jacob

Dr Mridula Dixit Bharadwaj

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Contributors: Dr Ammu Susanna Jacob and Dr Mridula Dixit Bharadwaj

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**Center for Study of Science, Technology and Policy**

**Bengaluru Office**
18, 10th Cross, Mayura Street,
Papanna Layout, Nagashettyhalli, RMV II Stage,
Bengaluru-560094, Karnataka (India)
Tel.: +91 (80) 6690-2500

**Noida Office**
1st Floor, Tower- A,
Smartworks Corporate Park
Sector-125, Noida 201303
Uttar Pradesh (India)

**Email:** cpe@cstep.in

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## Executive Summary

The Government of India plans to integrate 175 GW of variable renewables into the grid by 2022. At the same time, India's power consumption is steadily increasing. Hence, to ensure energy security and better utilisation of intermittent renewable generation, we require energy storage systems at the grid-scale. There is a range of grid-scale storage options, which can be incorporated in the Indian power grid.

In this article, we analyse the different energy storage systems, their applications in the grid and key policy recommendations on the suitability of energy storage in the grid. The key policy recommendations include the use of energy storage system as a generation, transmission, distribution, and end-user asset. As a generation asset, storage can provide ancillary and bulk energy services along with power quality and grid stability. Careful sizing and siting of storage in the transmission grid can relieve transmission congestion and enable upgrade deferral. Use of storage in distribution will improve power quality, reliability, and provide financial benefits through energy arbitrage. Facilitating the use of short-, medium-, and long-term storages will support the grid completely. The main barrier in having large-scale deployment of storages is its cost. Hence, it is important to restructure the market and regulatory framework to incentivise storage-specific projects.

Suitability of different energy storage systems at different levels of the network is shown in the Table below[1]

| Levels in the network | Applications in the grid | *Short-term* | | | *Medium-term* | | | *Long-term* | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Battery | | | | | | | |
| | | FES | Supercapacitors | SMES | VRLA | LIB | NaS | PHES | CAES | $H_2$ storage | Flow battery | TES |
| **Generation** | *Frequency regulation* | ■ | ■ | ■ | | | | | | | | |
| | *Black start* | | | | | | ■ | ■ | ■ | | | |
| | *Spinning reserves* | | | | | | ■ | ■ | ■ | | | |
| | *Load following* | | | | | ■ | ■ | | | | ■ | ■ |
| | *Renewable energy integration* | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| | *Energy arbitrage* | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| | *Seasonal storage* | | | | | | | ■ | ■ | ■ | ■ | ■ |
| **Transmission** | *Voltage support* | ■ | ■ | | | | | | | | | |
| | *Transmission congestion relief and upgrade deferral* | | | | | | | ■ | ■ | | | |
| **Distribution** | *Distribution congestion relief and upgrade deferral* | | | | ■ | ■ | ■ | | | | | |
| | *Power quality* | | ■ | ■ | ■ | ■ | | | | | | |
| **End-user** | *Power reliability* | | | | ■ | ■ | | | | | | |
| | *Demand shifting and peak reduction* | | | | ■ | ■ | | | | | | ■ |

[1] *Full-form of the abbreviations in the table are given on Page viii*

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## Abbreviation

| | | |
|---|---|---|
| CAES | - | Compressed air energy storage |
| CERC | - | Central Electricity Regulatory Commission |
| DSM | - | Deviation Settlement Mechanism |
| ESS | - | Energy Storage Systems |
| FES | - | Flywheel Energy Storage |
| LIB | - | Lithium-ion Battery |
| LTO | - | Lithium titanium oxide |
| NaS | - | Sodium sulphur battery |
| PHES | - | Pumped hydro energy storage |
| ROW | - | Right-of-Way |
| SMES | - | Superconducting Magnetic Energy Storage |
| T&D | - | Transmission and Distribution |
| TES | - | Thermal energy storage |
| VRLA | - | Valve-regulated lead acid battery |

## 1. Introduction

India's share of grid-integrated intermittent renewables as on October 2019 is around 83 GW. The country plans to install 175 GW and 450 GW of renewables by 2022 and 2030 respectively [1]. With such large-scale integration of renewables into the grid, balancing the grid will be a major challenge for utility operators. Energy Storage Systems (ESS) have the capability to balance the grid, by allowing seamless integration of intermittent renewables into the grid. In addition, the inherent flexibility of ESS benefits the generation, transmission, and distribution aspects of the grid.

Currently, there is a limited presence of ESS in the Indian grid. Of this, a major share (~96%) is contributed by pumped hydro energy storage [2]. Though there are different types of storage options for grid-scale applications, these are yet to be explored.

This article examines the different energy storage options and the use-cases for the power grid in the Indian context. It also discusses the desired characteristics of energy storage systems for specific use-cases and its policy recommendations.

## 2. Types of Energy Storage Systems

ESS can be classified based on the manner in which energy is stored: mechanical, chemical, electro-chemical, thermal, and electrical. Common mechanical storage systems include pumped hydro, compressed air, and flywheels; chemical storage systems include hydrogen storage; electro-chemical storages include batteries and flow batteries; thermal storages include water heaters, ice storages, and chilled water storage; and electrical storages include supercapacitors and superconducting magnetic storages.

The different types of ESS are discussed briefly:

- **Flywheel energy storage (FES)** employs a spinning rotor to store the electrical energy in the form of rotational kinetic energy. It has a fast response time, long life (~ 20 years), and no emissions. However, compared to other storage systems, the self-discharge rates are high (3%-20% per hour). Hence, FES is most suitable for short-term storage.
- **Supercapacitors** store electrical energy in capacitors. Their energy density is thousand times higher than normal capacitors. Short-term ESS like supercapacitors are useful in absorbing and releasing a large volume of energy in a short period. These are suitable for rapid or burst–mode power delivery.
- **Superconducting magnetic energy storage (SMES)** stores energy in a magnetic field created by flowing electricity in a superconducting coil. It has a high efficiency of ~ 95%. However, the demand for high auxiliary energy reduces its scope. SMES is suitable for grid applications where a high power output is required for a short period of time, e.g., sudden load change or voltage-drop in a transmission line.
- **Batteries** store electrical energy in an electro-chemical form with an overall efficiency in the range of 75%-95% depending on its chemistry. Valve-regulated lead acid (VRLA) battery, lithium-ion battery (LIB), and sodium sulphur (NaS) batteries are the current front-runners for grid applications. While VRLA is the most economic and mature technology among these, its limitation is cycle life. Though LIB has the highest energy density and efficiency, it is expensive. NaS batteries are recognised for high efficiency, long life, and minimal self-discharge. However, they operate at high temperatures (~300°C), and hence are subject to material degradation and safety issues.

- **Pumped hydro energy storage (PHES)** has the most installed capacity of storage across the world. PHES pumps water from the lower to upper reservoir when demand is low, while water flows from the upper to lower reservoir during high demand, producing electricity. The overall efficiency of the process is around 75%-85%, with a discharge duration that can last for days depending on the size of the reservoir. However, this technology is highly dependent on topographical conditions.
- **Compressed air energy storage (CAES),** as the name suggests, compresses air and stores it under a pressure of 70 bar and reconverts the compressed air using turbine and a generator producing electrical energy when required. Typical CAES capacity is of the order of 50 MW-300 MW with an efficiency of 50%-70%. It can store energy for longer periods (even for a year) with minimal losses. The major drawback is that it is expensive.
- **Hydrogen storage** with fuel cells can convert the chemical energy in hydrogen to electricity, and hydrogen can be produced with the help of electrolysis during off-peak hours. The hydrogen, thus produced, can be stored in compressed tanks (200-800 bar), liquefied, or as metal hydrides. The multiple processes decrease the overall efficiency of this technique to 40 %, making it cost-intensive.
- In **Flow battery,** the electrolyte is externally stored in tanks outside the battery electrode compartment and is used only when the battery is in operation. This separates its power and energy sizing, making it suitable for long-term storage. Flow battery has high efficiency, long life, and rapid response time (less than half-a-millisecond), and no self-discharge.
- **Thermal energy storage (TES)** stores energy in the form of 'heat' or 'cold' in the storage medium. The storage medium may be natural (underground) or artificial (insulating tanks). There are two types of TES depending on the use of latent or sensible heat. In latent heat storage, there is change in the phase of materials such as solid-to-liquid. An example of latent heat storage is ice storage, where water is frozen during off-peak hours, and cool air is supplied to reduce the air conditioning loads. Here water is the phase-change material. Other phase-change materials include paraffin wax, molten salts, etc. In sensible heat storage, there is no change of phase. Examples involve chilled water storage and water heaters. Though TES has high heat efficiency (70%-90%), the round-trip efficiency is of the order of 30%-60% [3].

The characteristics of different energy storage systems [4]–[8] are discussed in Table 1.

**Table 1:** Characteristics of different energy storage systems[4]–[8]

| ESS | | Specific Energy (Wh/kg) | Specific Power (W/kg) | Discharge time | Round-trip efficiency (%) | Response time | Life (cycles) |
|---|---|---|---|---|---|---|---|
| **FES** | | 5-130 | 400-1600 | 15s-15min | 85-95 | ms - s | $10^5$ - $10^7$ |
| **Supercapacitors** | | 0.1-15 | 0.1-10 | ms-1h | 85-95 | ms | >5x$10^5$ |
| **SMES** | | 0.5-5 | 200-2000 | ms – 5min | >95 | ms | 10000 |
| **Battery** | VRLA | 30-50 | 75-300 | min-h | 70-85 | ms - s | 1500 |
| | LIB | 100-250 | 230-340 | min-h | 85-95 | ms - s | 4000 |
| | NaS | 150-240 | 90-230 | min-h | 85-90 | ms - s | 4500 |
| **PHES** | | 0.5-1.5 | NA | h-days | 75-85 | min | >15000 |
| **CAES** | | 30-60 | NA | h-days | 50-70 | 1-15min | No limit |
| **Hydrogen storage** | | 2000 | >500 | s-days | 40 | ms - min | >1000 |
| **Flow battery (Vanadium-based)** | | 75 | - | min-days | 75 | ms | 13000 |
| **TES** | | 80-250 | - | min-days | 30-60 | ≤ 10 mins | >1000 |

The capital costs of ESS, based on energy, are discussed in Table 2. As the costs have been taken from global literature [7]–[12] the prices are mentioned in US$/kWh.

***Table 2:** Capital cost for ESS from literature* [7]–[12]

| ESS | | Capital cost energy -based (US$/kWh) |
|---|---|---|
| **FES** | | 1500-6000 |
| **Supercapacitors** | | 300-2000 |
| **SMES** | | 1000-10000 |
| **Battery** | VRLA | 100-300 |
| | LIB* | 200-840 |
| | NaS | 263-735 |
| **PHES** | | 5-100 |
| **CAES** | | 2-80 |
| **Hydrogen storage**** | | 2-50 |
| **Flow battery (Vanadium-based)** | | 315-1680 |
| **TES** | | 3-60 |

*1US$ = 70 INR*
**graphite-based anodes. LTO-based anodes cost around 473-1260 $/kWh* [9]
***only hydrogen tank cost considered; Hydrogen fuel cell cost around 500-10000 $/kW*[8]

Fig. 1 shows the comparison of power output and energy stored in different storage systems. The blue, red and green lines show the discharge duration of different storage devices. Based on their discharge duration, ESS can also be classified as short-term, mid-term, and long-term storages. FES, supercapacitors, and SMES fall into short-term storages; batteries can be categorised as mid-term storages; PHES, CAES, hydrogen storage, flow batteries, and thermal energy storages belong to long-term storages. From Table 2, it is evident that short-term storage energy installations cost higher compared to long-term storage options like PHES and hydrogen storage, etc.

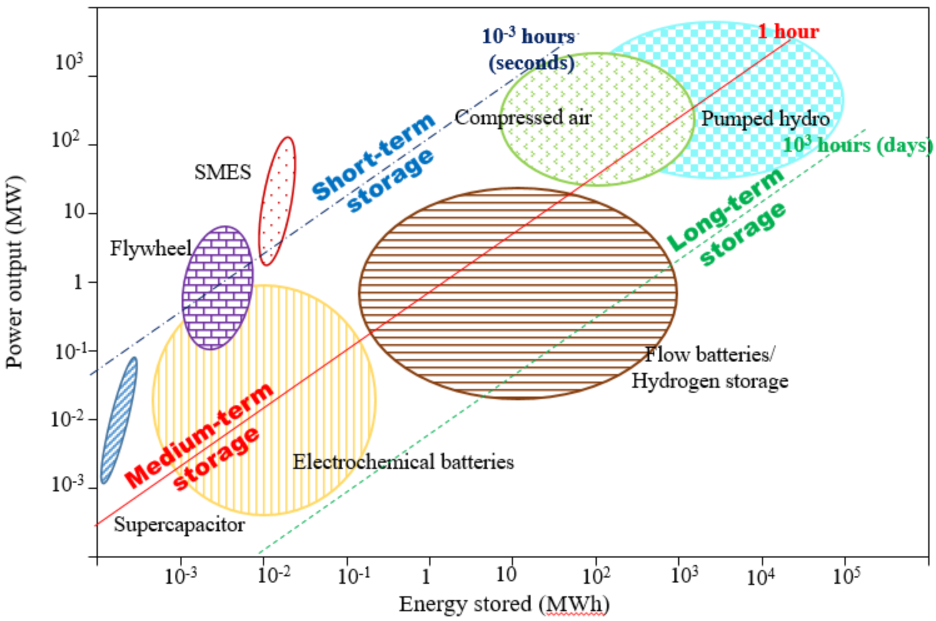


***Figure 1:** Comparison of different energy storage systems based on power output, energy storage, and discharge duration [2]*

## 3. Energy Storage Systems: Applications

ESS storage applications can be categorised into four main groups as shown in Fig. 2.

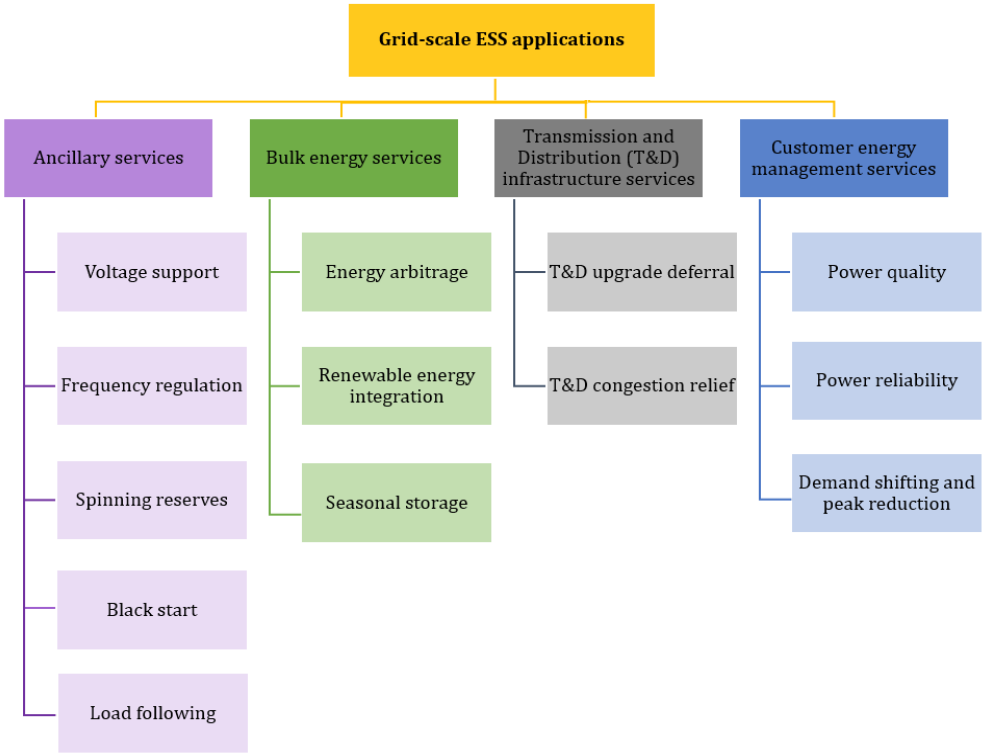


***Figure 2:*** *Different grid-level ESS applications*

**Ancillary services** support the grid while transmitting power from generation to consumers. This is achieved through the following services:

- *Voltage support:* Grid voltage is to be maintained within specified limits, which will eventually help in managing the reactive power. ESS set up close to reactive power generation source can be used as a voltage support resource.
- *Frequency regulation:* ESS helps in correcting the frequency deviations, while maintaining frequency within the permissible limits. Also, ESS can support both the generators and distribution companies with respect to Deviation Settlement Mechanism (DSM) regulations put forth by Central Electricity Regulatory Commission (CERC).
- *Spinning reserves* are those standby generation stations that are utilised when there is an unexpected power shortage. These stations continue to operate until the main generators normalise. To be used as spinning reserves, the ESS must have longer discharge durations.
- *Black start:* ESS can help in energising part of the grid or a generation station when a blackout occurs due to unplanned events.
- *Load following:* When the load changes rapidly, ESS with a fast-response time creates a balance between the load and generation, maintaining the stability of the grid.

**Bulk energy services:** Modern-day grids go through a large amount of variation through renewable generation and unpredictable demand fluctuations, which can be easily managed by ESS. The three main types of bulk energy services are as follows:

- *Energy arbitrage* involves storing energy when the price is low and selling it during peak demand when the price of electricity is high. The operating cost and round-trip efficiency of the ESS is an important parameter when it is involved in arbitrage.
- *Renewable energy integration:* With a large amount of intermittent renewables integrated into the grid, it requires an ESS to absorb the fluctuations to make the power system more flexible. ESS stores the excess energy and injects power when required, thus flattening the power output and reducing renewable energy curtailment.
- *Seasonal storage:* The seasonal mismatches in the power system can be supplied by ESS that have the capability to discharge for days, weeks, or months.

**Transmission and Distribution (T&D) infrastructure services:** It involves upgrade deferral and congestion relief of the transmission and distribution networks. Upgrade deferral delays investment (or avoids in some cases) with the help of small storages. Similarly, congestion in the network occurs when the available energy is not delivered to consumers due to inadequate transmission facilities. An ESS-installed downstream of the congested transmission network charges during off-peak hours and discharges during peak load to reduce the congestion. In addition, ESS relieves network congestion in city limits, where getting Right-of-Way (ROW) for transmission/distribution lines is a major challenge.

**Customer energy management services:** These include the quality and reliability of power provided to the consumers as well as demand shifting and peak reduction.

- *Power quality:* The use of ESS protects the downstream loads (or consumers) from high variations of renewables, low power factor, harmonics, and variation in voltage/frequency.
- *Power reliability:* The ESS supports the customer during an unplanned interruption from the utility. Here, ESS will be installed close to consumer loads.
- *Demand shifting and peak reduction:* ESS helps to reduce the peak demand and shift the demand to non-peak hours for the end-users.

Table 3 shows the desired ESS characteristics for its target application in the power system [4], [12]–[16].

***Table 3:*** *Desired characteristics of grid-scale ESS for different applications* [4], [12]–[16]

| Application categories | Services | Typical ESS considerations | | |
|---|---|---|---|---|
| | | Size (MW) | Response time | Discharge duration |
| **Ancillary services** | Voltage support | ≤ 10 | ≤ 100 ms | ~ 30 min |
| | Frequency regulation | 10-100 | instantaneous | 15 min-1 h |
| | Black start | ≤ 50 | ≤ 2 h | ≤ 16 h |
| | Spinning reserve | ≤ 100 | ≤ 4 h | ≤ 5 h |
| | Load following | ≤ 100 | | ≤ 4 h |
| **Bulk energy services** | Energy arbitrage | ≤ 500 | Minutes | ≤ 10 h |
| | Renewable energy integration | ≤ 500 | ≤ 30 min | 4-6 h |
| | Seasonal storage | 500-2000 | Hours | days - months |
| **Transmission and distribution infrastructure services** | Transmission upgrade deferral | 10-100 | Minutes | 2-8 h |
| | Transmission congestion relief | 1-100 | Minutes | 1-4 h |
| | Distribution upgrade deferral | 0.5-10 | Minutes | 1-4 h |
| **Customer energy management services** | Power quality | ≤ 10 | ≤ 200 ms | ≤ 2 h |
| | Power reliability | ≤ 10 | Minutes | ≤ 4 h |
| | Demand shifting and Peak reduction | 0.001-1 | <15 minutes | minutes-hours |

From Table 3, it is clear that ESS characteristics such as response time and discharge duration should be carefully matched with the requirements of grid applications. For example, bulk energy storages like PHES and CAES can be used for long-term energy discharge, whereas supercapacitors or FES that have limited energy capacity may be used for voltage support or frequency regulation.

### 3.1 Benefits-stacking

A single ESS may also be used for two or more applications in the grid. This enables the ESS asset to receive multiple revenue streams called benefit-stacking. ESS should be chosen carefully, so that its technical potential can support multiple grid-level applications [12].

## 4. Recommendations

ESS helps in mitigating the intermittency and uncertainty associated with renewable energy generators and makes the renewable plants a dependable power source (dispatchable on demand). Based on our analysis, we would like to summarise and recommend the following:

- ESS can be used as generation, transmission, distribution, and end-user asset.
- As a generation asset, ESS can provide ancillary and bulk energy services along with power quality and grid stability.
- Careful sizing and siting of storage in the transmission grid can relieve transmission congestion and help upgrade deferral.

- Use of storage in distribution improves power quality, reliability, and provides financial benefits through energy arbitrage.
- A combination of short-, mid-, and long-term storages is required to support the grid completely.
- Benefit-stacking of ESS assets should be promoted to achieve profitability.
- The main barrier in having large-scale deployment of storages is its cost. Hence, it is important to restructure the market and regulatory framework to incentivise storage-specific projects.

Table 4 shows the suitability of different storages for various applications in the grid. It also shows at what levels of the network these might be beneficial.

***Table 4:*** *Suitability of different storages for various applications in the grid.*

| Levels in the network | Applications in the grid | ***Short-term*** | | | ***Medium-term*** | | | ***Long-term*** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Battery** | | | | | | | |
| | | **FES** | **Supercapacitors** | **SMES** | **VRLA** | **LIB** | **NaS** | **PHES** | **CAES** | **$H_2$ storage** | **Flow battery** | **TES** |
| **Generation** | *Frequency regulation* | | | | | | | | | | | |
| | *Black start* | | | | | | | | | | | |
| | *Spinning reserves* | | | | | | | | | | | |
| | *Load following* | | | | | | | | | | | |
| | *Renewable energy integration* | | | | | | | | | | | |
| | *Energy arbitrage* | | | | | | | | | | | |
| | *Seasonal storage* | | | | | | | | | | | |
| **Transmission** | *Voltage support* | | | | | | | | | | | |
| | *Transmission congestion relief and upgrade deferral* | | | | | | | | | | | |
| **Distribution** | *Distribution congestion relief and upgrade deferral* | | | | | | | | | | | |
| | *Power quality* | | | | | | | | | | | |
| **End-user** | *Power reliability* | | | | | | | | | | | |
| | *Demand shifting and peak reduction* | | | | | | | | | | | |

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