The electric system needs to balance supply and demand on a moment to moment basis. Energy commodities such as coal, oil and natural gas can be readily stored in massive quantities. However, the storage of electricity has been relatively complex and expensive. Today, with the changing ways in which electricity is generated and used, increased penetration of renewable energy sources and smart grid are making storage more attractive than before. The appearance of newer and cost-effective technology options is making it likely that energy storage will finally become a reality in the near future.

**Energy Storage Applications**

Energy storage provides several benefits for electric power utilities, transmission companies, electricity generators, and electric power end users. The applications of energy storage can be summarized as follows:

- **Improve integration of renewable energy sources**: Energy storage can be used to dispatch renewable energy sources such as wind and solar [1]. Moreover, electricity generated during off-peak times can be “time-shifted” so that the energy can be sold during peak times.

- **Transmission and distribution deferral**: Defer the need for additional transmission/distribution upgrades by supplementing the existing transmission/distribution facilities i.e. saving capital that otherwise goes underutilized for years.

- **Arbitrage**: Arbitrage involves purchasing inexpensive electricity when its demand and cost are low; and then selling the electricity when demand and price are high. Storage systems that are used for this purpose generally have the capacity to store large amounts of energy, interact with the power grid at the transmission level, and operate on a diurnal cycle of charge and discharge [2].

- **Spinning reserve**: Energy storage systems including batteries, capacitors, and flywheels interact with the grid via an electronic power controller and respond within minutes to compensate for generation or transmission outages. Therefore, they can accommodate some of utilities’ spinning reserve requirements without any difficulty.

- **Transmission support**: Energy storage improves the performance of the transmission system by increasing the load carrying capacity of it; a benefit
accrues if additional load carrying capacity defers the need to add more transmission capacity and/or additional T&D equipment. This provides a benefit to the owner of the transmission system.

- **Stabilize the transmission and distribution grid:** Energy storage facilities designed to support transmission and distribution networks maintain the stability and reliability of the grid by quickly injecting active power into the grid with a short discharge, but a faster reaction time [3].
- **Improve load following and frequency regulation:** Energy storage can act as a buffer that isolates the rest of the power grid from sudden changes in the load and it can also help to maintain frequency regulation during irregular grid conditions, large and rapid changes in the load [4].
- **Decreased Transmission Losses:** Similar to any process involving conversion or transfer of energy, energy losses occur during transmission [5]. If energy storage is charged during night time when losses are low and discharged during day time (on-peak), it will help to reduce $I^2R$ losses.
- **Voltage Support:** An important technical challenge for electric grid system operators is to maintain acceptable voltage levels in the system. Energy storage with reactive power capability can provide voltage support and respond quickly to voltage control signals (i.e. on the order of ms for STATCOM).
- **Enable more efficient use of existing generation assets:** Energy storage can reduce the need for cycling large coal-fired plants (i.e. peakers) and creates efficiencies along the grid. Moreover, it also reduces dispatch costs incurred by generation assets.
- **Reduce greenhouse gas emission:** The introduction and use of energy storage technologies can reduce overall greenhouse gas emissions through the use of a clean and reliable energy source as an alternative to fossil fuel generation.

**Energy Storage Technologies**

A brief description of each of energy storage technologies is provided below:

**Battery Energy Storage System (BESS)**

Batteries are one of the most cost-effective energy storage options available, which stores energy electrochemically [6]. A battery system is made up of a set of low voltage or power battery modules connected in series and/or parallel to achieve a desired electrical characteristic. Batteries are charged when they undergo an internal chemical reaction under a potential applied to the terminals. They deliver the absorbed energy, or discharge, when they reverse the chemical reaction. Some of the key factors of batteries for storage applications include: high energy density, round trip efficiency, cycling capability, life span, and initial cost [7], [8].

Batteries store dc charge, so power conversion is necessary to interface a battery with an ac power system. Advances in battery technologies offer increased energy storage densities, greater cycling capabilities, higher reliability, and lower cost [9]. Battery energy storage systems have emerged as one of the most promising near-term storage technologies for power applications, offering a wide range of power system applications such as frequency regulation, spinning reserve, and power factor correction [10].
Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage refers to the compression of air to be used later as energy source. CAES is a peaking gas turbine power plant that consumes less than 40% of the gas used in a conventional gas turbine to produce the same amount of electric output power. This is because, unlike conventional gas turbines that consume about 2/3 of their input fuel to compress air at the time of generation, CAES pre-compresses air using the low cost electricity from the power grid at off-peak times and utilizes that energy later along with some gas fuel for use during peak periods [11].

To make the CAES concept work depends on locating the plants near appropriate underground geological formations, such as underground mines, caverns created inside salt rocks or depleted gas wells.
Electrochemical Capacitors (Super capacitors)

Electrochemical capacitors commonly called super capacitors store electrical energy in two series capacitors of the electric double layer (EDL), which is formed between each of the electrodes and the electrolyte ions. The distance over which the charge separation occurs is just a few angstroms. The extremely large surface area makes the capacitance and energy density of these devices thousands of times larger than conventional electrolytic capacitors [12].

The electrodes of these super capacitors are often made with porous carbon material. The electrolyte is either aqueous or organic. The aqueous capacitors have a lower energy density due to a lower cell voltage but are less expensive and work in a wider temperature range. The asymmetrical capacitors that use metal for one of the electrodes have a significantly larger energy density than the symmetric ones do and have a lower leakage current [11].

Electrochemical capacitors have lower energy density compared to lead-acid batteries, but they can be cycled tens of thousands of times and they have faster charge and discharge capability compared to batteries.

Flywheel Energy Storage (FES)

Modern flywheel energy storage systems consist of a huge rotating cylinder (comprised of a rim attached to a shaft) that is substantially supported on a stator by magnetically levitated bearings that eliminate bearing wear and increase system life. To maintain efficiency, the flywheel system is operated in a vacuum environment to reduce drag. The flywheel is connected to a motor/generator mounted onto the stator that interacts with the utility grid through power electronics [11].

The stored energy on a flywheel depends on the moment of inertia of the rotor and the square of the rotational velocity of the flywheel. The moment of inertia depends on the radius, mass, and height (length) of the rotor. Energy is transferred to the flywheel when the machine operates as a motor i.e. the flywheel accelerates, charging the energy storage
device. The flywheel is discharged when the electric machine regenerates through the drive i.e. the flywheel decelerates [6].

The energy storage capability of flywheels can be improved either by increasing the moment of inertia of the flywheel or by rotating it at higher velocities, or both. Some designs utilize hollow cylinders for the rotor allowing the mass to be concentrated at the outer radius of the flywheel, improving storage capability with a smaller weight increase [13].

Some of the key features of flywheels are long life (20 years or 10s of thousands of deep cycles), low maintenance and environmentally inert material. Flywheels can bridge the gap between short term ride-through and long term storage with excellent cyclic and load following characteristics [11].

![Figure 4: A typical FES [11]](image)

**Pumped Hydro**

A typical pumped hydro plant consists of two interconnected reservoirs i.e. lakes, tunnels that connect one reservoir to another, hydro machinery, valves, a generator-motor, transformers, a transmission switchyard and connection to transmission system. The product of the total volume of water and the differential height between the reservoirs is proportional to the amount of stored energy [12].

The global capacity of pumped hydro storage plants installed up to day totals more than 95 GW with around 20 GW operating in US. The main function of these plants was to provide off peak base loading for large coal and nuclear power plants to optimize the overall performance and provide peaking energy each day. Nowadays, their duties have been expanded to include providing ancillary services such as frequency regulation [12].
Superconducting Magnetic Energy Storage (SMES)
Superconducting magnetic energy storage systems store energy in the field of a large magnetic coil with direct current flowing. It can be converted back to alternative current as needed. Although superconductivity was discovered in 1911, it was not until the 1970s that SMES was first proposed as an energy storage technology for power systems [15].

A magnetic field is created by circulating a DC current in a closed coil of superconducting wire. The path of the coil circulating current can be opened with a solid state switch which is modulated to be either on or off. Due to the high inductance of the coil, when the switch is off i.e. open, the magnetic coil behaves as a current source and will force current into the capacitor which will charge to some voltage level. Proper modulation of the solid-state switch can hold the voltage across the capacitor within the proper operating range of the inverter. An inverter then converts the DC voltage into AC voltage [16].

SMES are highly efficient at storing electricity (greater than 95% efficient), and provide both real and reactive power. Power is available almost instantaneously, and very high power output is provided for a short period of time. Due to their construction, they have a high operating cost and are therefore best suited to provide constant, deep discharges and constant activity [3].
Case Studies

Two studies are presented below which demonstrates the application of BESS to improve integration of renewable energy sources. The proposed structure is seen in Figure 7.

BESS for Wind Farms

In this application, the BESS is utilized to minimize the wind’s variability at an individual wind farm of 60 MW capacity through an hourly dispatch [18]. For the study, it is assumed that the average wind power output for the next hour (\(P_{\text{set}}\)) can be forecasted with 10% mean absolute error of the wind farm power output [19], [20] and the BESS will compensate the differences between the hourly dispatch level, \(P_{\text{set}}\), which comes from the forecast, and the wind farm power output, \(P_{\text{wind}}\). The power at the battery, \(P_{\text{bess}}\), then can be expressed as \(P_{\text{bess}}=P_{\text{set}}-P_{\text{wind}}\) and the total power flowing to the grid becomes \(P_{\text{total}}=P_{\text{wind}}+P_{\text{bess}}\).
During the study, the basic assumptions regarding the BESS include AC/DC converter losses of 3%, the State of Charge (SOC) of the battery is allowed to change between 30% and 100% and each battery contributes the same amount of current (uniform SOC among battery cells).

The simulation results obtained with an 8 MW (max 4 hour discharge i.e. 32 MWh) BESS is shown in Figure 8.

![Figure 8: BESS dispatch performance (Pbess: BESS power, Pwind: wind power, Ptotal: net injected power, in MW)](image)

It is seen from Figure 8 that the wind power can be dispatched with the help of the BESS and the undesired fluctuations of the wind power are eliminated.

**Economical Evaluation**

Other than dispatching wind power, the BESS can also be used for:
- Curtailment Mitigation for Wind Farms
- Frequency Regulation
- Voltage Regulation
- Reserve Capacity
- Delay in line upgrade
- Peak Shaving

which makes it economically more feasible for this application.

In order to perform the economical analysis, certain assumptions for the BESS are made in the study and these are tabulated in Table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESS Power Rating</td>
<td>8 MW</td>
</tr>
<tr>
<td>BESS Energy Rating</td>
<td>32 MWh</td>
</tr>
<tr>
<td>BESS Cost</td>
<td>$ 25M</td>
</tr>
</tbody>
</table>

Table 1: Assumptions for Economic Analysis
Using these assumptions, the value streams considered with BESS and the return on investment (ROI) with BESS is calculated and shown in Table 2.

Table 2: Value Stream for BESS

<table>
<thead>
<tr>
<th>Value Stream</th>
<th>Avoided Cost/Revenue</th>
<th>Unit</th>
<th>Explanation of Calculation</th>
<th>Yearly Avoided Cost/Revenue ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hourly Dispatch [21]</td>
<td>5.00</td>
<td>$/MWh</td>
<td>60 MW wind farm with 30% capacity factor</td>
<td>$788,400.00</td>
</tr>
<tr>
<td>Curtailment Mitigation</td>
<td>47790.00</td>
<td>$</td>
<td>Prevention of about 1500 MWh wind curtailment</td>
<td>$47,790.00</td>
</tr>
<tr>
<td>Frequency Regulation [22]</td>
<td>36.43</td>
<td>$/MWh</td>
<td>8 MW for 15 min</td>
<td>$638,253.60</td>
</tr>
<tr>
<td>Voltage Regulation [23]</td>
<td>30.00</td>
<td>$/MWh</td>
<td>20% more power transfer</td>
<td>$946,080.00</td>
</tr>
<tr>
<td>Reserve Capacity [22]</td>
<td>6.32</td>
<td>$/MWh</td>
<td>10% of 32 MWh battery</td>
<td>$177,162.24</td>
</tr>
<tr>
<td>Delay in line upgrade</td>
<td>309417.14</td>
<td>$</td>
<td>Delay of upgrade for a line of around 30 miles</td>
<td>$309,417.14</td>
</tr>
<tr>
<td>Peak Shaving [24]</td>
<td>121000.00</td>
<td>$/MW</td>
<td>25% of 8 MW Energy Storage</td>
<td>$242,000.00</td>
</tr>
</tbody>
</table>

From the analysis, it is seen that the ROI with BESS in one year is around 13%. This result shows that in order to make BESS economically feasible, it should be used for multiple functions besides dispatching wind farms.

**BESS for PV Solar Farms**

Similar to dispatching wind farms, BESS can be used to dispatch solar PV systems [25]. For this study, a 300 kW (max 1 hour discharge i.e. 300kWh) BESS is used to dispatch a 1.5 MW Solar PV system. It is assumed that the average solar power output for the next hour \( P_{set} \) can be forecasted with 10% mean absolute error of the solar PV power output and the BESS will compensate the differences between the hourly dispatch level, \( P_{set} \), which comes from the forecast, and the PV solar farms power output, \( P_{solar} \). The power at the battery, \( P_{bess} \), then can be expressed as \( P_{bess} = P_{set} - P_{solar} \) and the total power going to grid becomes \( P_{total} = P_{solar} + P_{bess} \).

It is again assumed that AC/DC converter of the BESS has 3% losses, the State of Charge (SOC) of the battery is allowed to change between 30% and 100% and each battery contributes the same amount of current.

The simulation results obtained with these assumptions is shown in Figure 9.
Figure 9: BESS dispatch performance (Pbess: BESS power, Psolar: Solar PV system power, Ptotal: net injected power, in MW)

Figure 9 shows that with the help of the BESS, the solar PV system power output can be dispatched on an hourly basis similar to the wind case and the effects of cloud cover and fluctuations can be eliminated.

In order to make BESS economically more feasible for this application similar to the wind case, the BESS should also be used for multiple purposes such as:

- Mitigating Clouding Intermittency
- Voltage regulation and reactive support
- Improving Capacity Factor

References