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IMPORTANCY OF ENERGY STORAGE SYSTEM IN ENERGY SYSTEM

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ABSTRACT

The increasing integration of renewable energy sources into power systems poses new challenges for operators. To maintain system quality and reliability, the incorporation of energy storage systems (ESSs) stands out as a promising solution. This article delves into the current and emerging trends and technologies of grid-connected ESSs. Various ESS technologies, such as mechanical, electrical, electrochemical, chemical, and thermal, are succinctly explored. A particular focus is given to battery ESSs (BESSs), given their heightened relevance amidst the ongoing electrification of transportation. Additionally, the roles that grid-connected ESSs fulfill within the grid are examined. Notably, the integration of BESSs necessitates power electronic converters, prompting a survey of popular converter topologies. These include transformer-based, transformerless (with distributed or common dc-link), and hybrid systems, alongside discussions on implementing advanced grid support functionalities in BESS control. Moreover, the article reviews the evolving standards and grid codes for grid-connected BESSs across various countries. Finally, emerging technologies like flexible power control for photovoltaic systems, hydrogen storage, and repurposing second-life batteries from electric vehicles are explored.

***KEYWORDS**: Battery energy storage system (BESS); energy storage system (ESS); grid codes; hydrogen; power electronic converter; renewable energy.*

I.Introduction

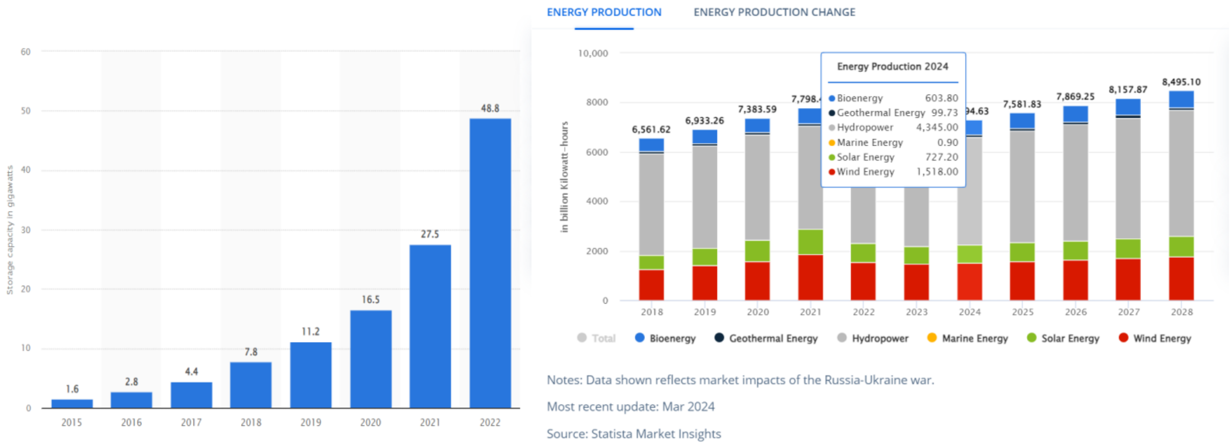
Every energy storage system (ESS) undergoes cycles of charging and discharging, requiring a long-term energy balance for stable and sustainable operation. Fossil fuels, accumulated over millions of years, are no exception. However, their current rate of utilization presents challenges, including resource depletion and greenhouse gas emissions. Urgent action is needed to reduce fossil fuel consumption and restore natural balance by embracing alternative energy sources.

In the near future, sustainable energy sources will likely dominate global energy consumption. Wind, solar, and hydro power, having reached technological maturity, are expected to be primary sources of electric power generation. Although breakthroughs in technologies like nuclear fusion reactors could alter this trajectory, renewable sources currently hold sway.

Electric power grids traditionally relied on flexible generation to match demand. However, the intermittent nature of renewable energy necessitates increased reliance on ESSs to maintain grid stability. As intermittent wind and solar capacity grows, so too must ESS capacity, as depicted in Figure 1.

Investing in ESSs, albeit expensive, becomes necessary when replacing dispatchable conventional plants with intermittent renewables. Yet, promising technologies offer flexibility to generators and loads, reducing the need for ESS intervention. These flexible assets aim to minimize generation-consumption mismatches, thus curbing ESS charge and discharge.

This article provides an overview of grid-connected ESS technologies and their role in future electricity grids dominated by intermittent renewables. Special emphasis is placed on electrochemical ESS technologies, also utilized in electric vehicles (EVs), experiencing rapid growth and development, as illustrated by increasing yearly installed capacity (Figure 1 (b)).



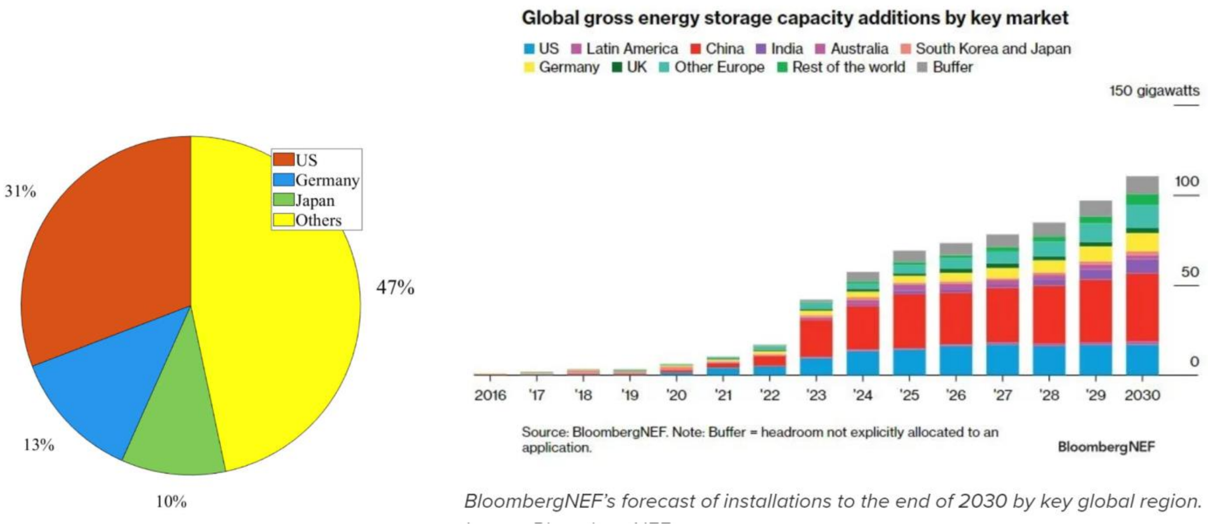
Notes: Data shown reflects market impacts of the Russia-Ukraine war.

Most recent update: Mar 2024

Source: Statista Market Insights

a) **b)**

Cumulative electric energy storage capacity worldwide from 2015 to 2022*(in gigawatts)*



BloombergNEF's forecast of installations to the end of 2030 by key global region.

c) **d)**

Fig. 1. (a) Cumulative electric energy storage capacity worldwide from 2015 to 2022*(in gigawatts* **[1]). (b) Energy production change forecast (c) Cumulative ESS power capacity (data sourced from [7]). (d) Global gross energy storage capacity additions by key market [7])**

Power electronic converters serve as crucial facilitators for integrating ESS technologies into the grid. While comprehensive reviews of power converters for grid and electric vehicle (EV) applications exist in [1] and [2], this article extends the discussion by incorporating the following technological advancements.

1. Control mechanisms and emerging regulations governing grid support functionalities.
2. Progressions in solid-state-transformer (SST) technology.
3. Power disparity limits and stable operating range of modular power converters

The organization of this article is as follows. Section II provides a review of prominent energy storage system (ESS) technologies. Section III expands on selected ESS technologies contributing to the electrification of transportation. In Section IV, the significance and role of ESS in modern electric power grids are discussed. Power electronic interface topologies for grid connection of battery ESSs (BESSs), along with grid codes and standards related to inverter grid connection, are reviewed in Section V. Section VI examines advancements in controlling BESSs to enable additional grid support functionalities. Section VII explores emerging technologies and prospects. Finally, concluding remarks are presented in Section VIII.

II. Energy Storage Technologies

A comprehensive review of available energy storage technologies is available in [3]–[4]. Figure 2 provides an overview of energy storage technologies and their share of current operational ESS capacity, based on data from the U.S. Department of Energy's Global Energy Storage Database [5]. Some features of each category are discussed below.

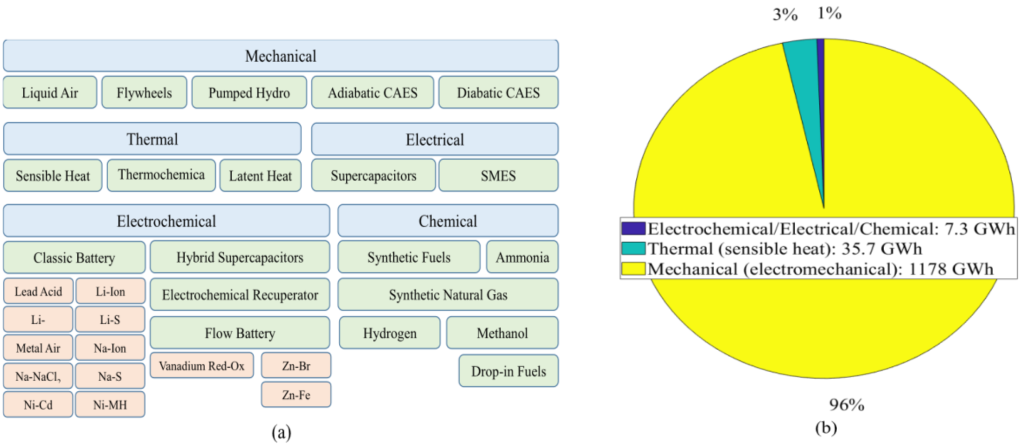
Mechanical: Pumped hydro storage (PHS) is a well-established and widely used form of energy storage, dating back to the 1920s, and currently represents over 90% of grid energy storage capacity. PHS typically involves pumping water back to an elevated storage dam, although large underground caverns can also be utilized for compressed air energy storage (CAES) [6]. CAES operates similarly to PHS, utilizing stored potential energy to drive a turbine.

Thermal: Concentrated solar power (CSP) plants utilize thermal storage for electricity production. CSP operates similarly to conventional steam turbine power plants, but with molten salt often serving as the heat source, concentrated by solar radiation.

Electrical: Prominent electrical energy storage technologies include supercapacitors and superconducting magnetic energy storage, both characterized by low energy density and high power density. Super capacitors find applications requiring fast and frequent charge and discharge, while the cost-effectiveness of superconducting magnetic energy storage remains debatable due to its need for extremely low temperatures [7]

Electromechanical: Batteries are a diverse and rapidly growing form of energy storage technology, significant not only for grid-connected systems but also for the automotive industry [8]. Further discussion on this technology is provided in Sections III, V, and VI.

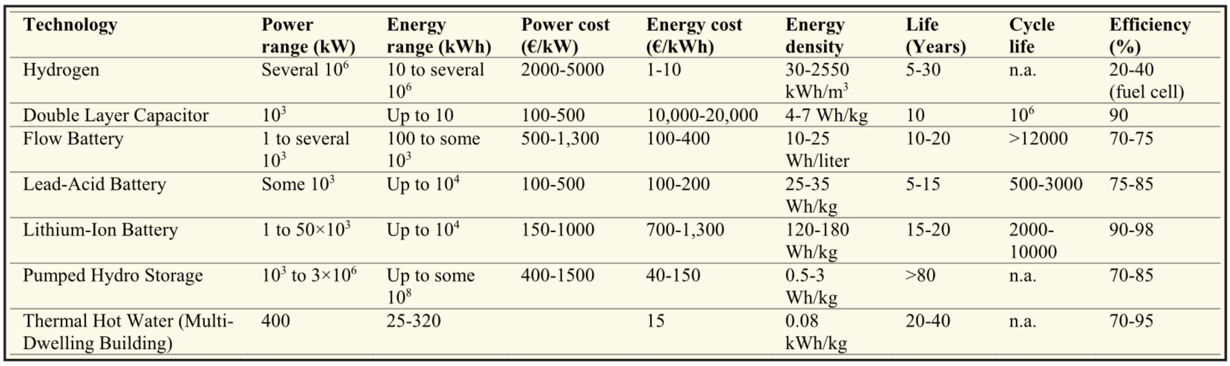
Chemical: Chemical storage, compared to previously discussed technologies, offers unique advantages such as transportability and high-energy capacity, making it suitable for seasonal energy storage options for the power grid [9]. Hydrogen, in particular, is emerging as a focal point in chemical energy storage technology. Electricity generation occurs either indirectly through conventional gas turbine power plants or directly through fuel cells [10]. Given its importance in achieving 100% energy sustainability, hydrogen technology is comprehensively reviewed in Section VII-C.



(a) (b)

Fig. 2. (a) Category of ESS technologies (details available in [18]). (b) Storage capacity distribution among the ESS technologies (data sourced from [7])

Table 1 Key Performance Indicators of ESS Technologies (Data Sourced From [18])



Technology	Power range (kW)	Energy range (kWh)	Power cost (€/kW)	Energy cost (€/kWh)	Energy density	Life (Years)	Cycle life	Efficiency (%)
Hydrogen	Several 10^6	10 to several 10^6	2000-5000	1-10	30-2550 kWh/m^3	5-30	n.a.	20-40 (fuel cell)
Double Layer Capacitor	10^3	Up to 10	100-500	10,000-20,000	4-7 Wh/kg	10	10^6	90
Flow Battery	1 to several 10^3	100 to some 10^3	500-1,300	100-400	10-25 Wh/liter	10-20	>12000	70-75
Lead-Acid Battery	Some 10^3	Up to 10^4	100-500	100-200	25-35 Wh/kg	5-15	500-3000	75-85
Lithium-Ion Battery	1 to 50×10^3	Up to 10^4	150-1000	700-1,300	120-180 Wh/kg	15-20	2000-10000	90-98
Pumped Hydro Storage	10^3 to 3×10^6	Up to some 10^8	400-1500	40-150	0.5-3 Wh/kg	>80	n.a.	70-85
Thermal Hot Water (Multi-Dwelling Building)	400	25-320		15	0.08 kWh/kg	20-40	n.a.	70-95

To compare the main features of selected ESS technologies, Table 1 summarizes their key performance indicators. From the provided data, it's evident why pumped hydro storage (PHS) is the dominant and preferred ESS option. However, its applicability is limited to areas with suitable geographical settings nearby. Examples of recent ESS deployment projects are provided in the Appendix.

Capacitors, batteries, and fuel cells among ESS technologies are closely related as they directly produce a DC voltage without the need for any electromechanical generator. Additionally, they find applications in powering electric vehicles (EVs). A more comprehensive review of these technologies is provided in Section III.

III. Electrochemical Energy Storage

Electrochemical power packs have revolutionized human comforts, providing portable connectivity, mechanical automation, and electrified living environments with exceptional efficiency. Unlike combustion engines constrained by the 51% Carnot efficiency threshold, electrochemical systems come in various form factors, from thin films to cartridges to block modules, simplifying recharging through existing power grid architectures. They also integrate seamlessly according to electric rating requirements via cell stacking.

At the heart of their technological principle lies the Nernst equation: $\Delta G = nF\ E$. Here, released chemical energy (ΔG) results from directed charge migration (n), Faraday's constant (F), and electrochemical potential (E) between substance masses. Early electrochemists realized the potential to decouple electron and ion transport, effectively controlling energy release. This decoupling bridges space and time, supplying electric energy with minimal loss, in stark contrast to mechanical engines relying on pressure–temperature differentials.

Terminologically categorized as electrochemical-energy storage (EES) devices, they exploit chemical potential differences between segregated active materials, representing stored energy. When brought into direct contact, active materials may result in an explosive burst of heat energy from electron-ion diffusion intermixing. EES devices decouple ion transport using internal electrolytes, redirecting electron transport through external loads to perform useful work. EES devices encompass fuel cells, batteries, and capacitors (Figure 3).

Remark: Throughout this section and the article, for ease of reference and to underscore their close association, the definition of EES is expanded to include capacitors (electrical) and fuel cells (chemical) ESS technologies.

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