Static Analysis of Energy Storage Systems in Electric Vehicle Case Study: Lithium-Ion Battery

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Abstract— **his study presents a comprehensive static analysis of energy storage systems (ESS), with a primary focus on their applications in electric vehicles (EVs). The investigation encompasses the operational principles, performance characteristics, and application domains of various ESS technologies, including mechanical, chemical, thermal, electrical, and electrochemical systems. Particular emphasis is placed on battery technologies, offering a detailed comparative assessment between lithium-ion chemistries and alternative storage solutions such as solid-state, sodium-ion, nickel–metal hydride, and lead–acid batteries. The evaluation is conducted based on critical performance indicators, including energy and power density, round-trip efficiency, cycle life, and operational temperature range. The findings reveal that lithium-ion batteries remain the predominant choice for EV integration owing to their superior energy density, high efficiency, and long service life, despite inherent challenges related to cost and thermal sensitivity. Furthermore, emerging technologies such as solid-state and sodium-ion batteries exhibit significant potential in addressing these limitations, underscoring the need for continuous research and technological advancements in sustainable energy storage for transportation systems**

Keywords: Fossil fuels, Renewable energy systems; Electric Vehicles; Energy storage systems, Battery.

I. INTRODUCTION

EVs emit no CO2, NO, or SO2; therefore, they are themed as zero-carbon vehicles and help address the environmental issues associated with fossil fuels [1]. Moreover, EVs offer the advantages of maximizing energy efficiency, improving controllability, and complying with innovative technologies. The performance of EV principally depends on the energy storage systems [2].

Energy Storage Systems (ESS) are widely used in RESs, microgrids, and EVs [3], [4]. The development and importance of ESS in tackling the problems caused by varying power requirements and the incorporation of renewable energy sources are addressed in [5].

The necessity of automation and safety in the automotive sector is highlighted in [5]. This reference, [8], focuses on the design and analysis of EVs with battery systems. Different battery types are considered for EV application [6-8]. These types are comprehensively analyzed in this article. Lithium-ion batteries (LIBs) play a vital role in the EV industry [6]. The technological developments and problems of metal-ion batteriesmmore especially, Li-ion, Mg-ion, and Al-ion batteries for electric vehicle (EV) applications are reviewed in [7].

This article claims the following contributions:

1. Reviewing concisely different ESS
2. Producing a comprehensive comparison between characteristics of batteries and other EES
3. Providing an in-depth analysis of various battery chemistries, including lithium-ion subtypes and alternative technologies.
4. Identifying the most suitable ESS technology for electric vehicle applications based on performance and operational criteria.
5. Contributing to the advancement of sustainable transportation through a consolidated reference for researchers and engineers.

The manuscript has the following structure. An overview of energy storage systems is given in Section 2. Section 3 describes batteries in EVs. Section 4 presents an overview of battery types. Lastly, the conclusion is provided in Section 5.

II. ENERGY STORAGE SYSTEM

Energy storage requirements are expected to double from their existing levels by 2030 [7], [8]. In Fig. 1, the primary energy storage methods are grouped. ESSs could be classified based on a variety of variables, including the types of energy they store, how efficiently they store it, and their uses [9].

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The four types of ESSs that are most utilized in EV applications are chemical storage, mechanical storage, electrical storage, and electrochemical battery systems. Thermal energy storage (TES) systems [10], including sensible heat, latent heat [11], and thermochemical energy storage [12], [13], are widely used for residential heating and cooling, industrial processes, and power generation. Mechanical energy storage (MES) [10] methods, such as pumped hydro storage [14], flywheels [19], gravity energy storage (GES) [19], and compressed air systems, convert and store energy using mechanical means. Chemical energy storage (CES) [20] technologies store surplus electrical energy by converting it into chemical forms such as hydrogen [20], [21] fuel cells [22], [23] or synthetic natural gas [24] that can be efficiently released when needed. Electrochemical storage systems [25], [26], particularly rechargeable batteries like lithium-ion, lead-acid, sodium-sulfur, and metal-air batteries, play a central role in electric vehicles and grid-scale applications due to their high energy and power densities. References [27] stress the necessity for batteries used in EVs to have long lifespans, high specific energy and power densities, temperature tolerance, and high efficiency. Electrical energy storage (EES) solutions [28], including supercapacitors [29], [30] and superconducting magnetic energy storage (SMES) [31], store energy directly in electric or magnetic fields for fast-response applications. Lastly, hybrid energy storage systems (HESS) [32] integrate two or more technologies such as batteries with supercapacitors or fuel cells to capitalize on the strengths of each, offering high efficiency, extended life cycles, and optimized performance, particularly in dynamic environments like electric mobility and smart grids.

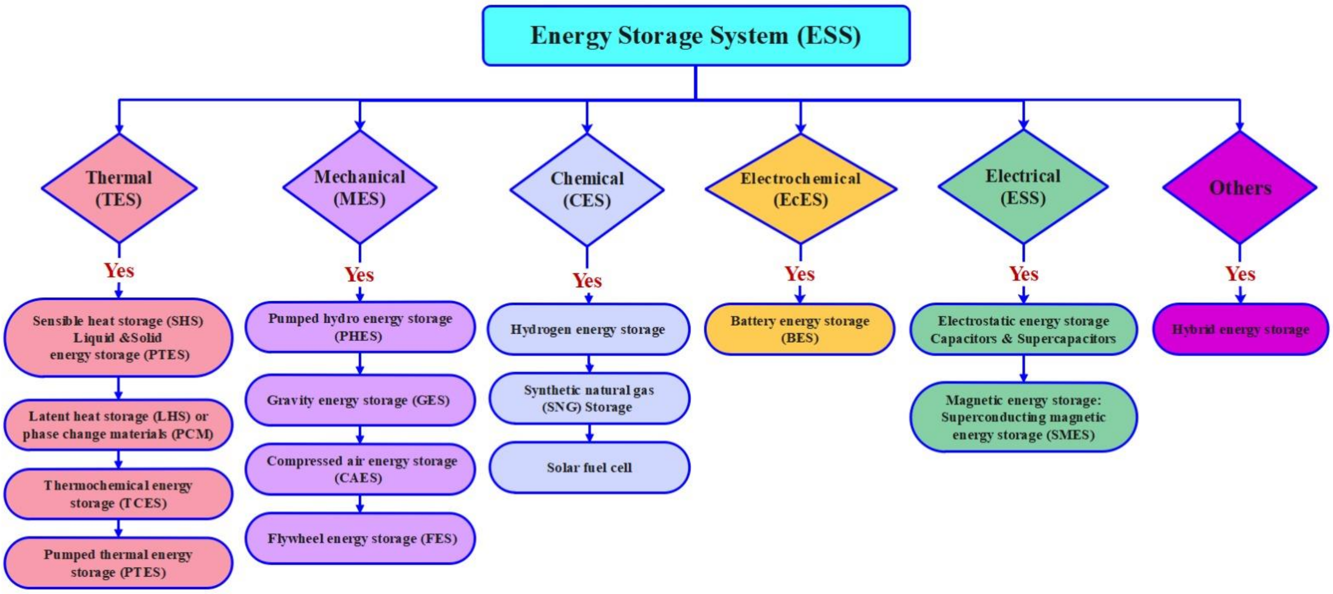

Fig1. Overview of energy storage systems based on the form

III. Characteristics of ESS Technologies

Each ESS energy storage technology has unique properties, as Table 1 illustrates. With nominal capacity up to several megawatts and an energy density between 30 and 300 Wh/kg, batteries are incredibly versatile for both home and commercial applications. With an 80% to 90% efficiency range and a medium to quick response time, they can handle both constant and fluctuating power demands. Batteries also have a moderate cost per kilowatt and a 20-year lifespan, making them more affordable than certain cutting-edge technology. Batteries have these qualities, which make them a dependable, effective, and adaptable energy storage option for a variety of applications.

Table 1. Technical characteristics of ESS technologies

ESS Type	**Energy density**	**Power density**	**Nominal power**	**Efficiency**	**Response**	**Cost (per kW)**	**Lifespan (Cycles)**	**Lifespan (Years)**	**Discharge Depth**	Operating temperature (_C)
Battery	30-300	150–300	Up to several MW	80–90%	Medium-Fast	Medium-high	1000–5000	Up to 20	Shallow	35~50
V2G (1 EV)	200–300	200–300	<10 kW, e.g., 7 kW	>90%	Medium-Fast	high	>1000	Depending on EV use	Shallow	NR
Supercapacitor	<15	Up to 10,000–	10–300 kW	>90%	Very fast	low	100,000–1,000,000	Up to 30	Deep	4.2~77 K

		100,000								
Superconducting magnetic (SEMS)	0.2-2.5	1000-4000	NR	95-99	milliseconds	NR	>125k	Up to 20	Deep	4.2~77 K
Fuel cell	100–1000	10–1000	Up to 50 or 80 MW	30–50%	Slow	high	1000–10,000	Up to 15	NR	NR
Hydro-pumped storage	0.5–1.5	N/A	MW–GW	70–87%	Slow, from seconds to minutes	high	Practically unlimited	Might last up to 100	NR	NR
Flywheel	5–80	100–2000	10–250 kW	90%	لإVery fast	low	>20,000	Up to 20	Deep	-40~+50
Compressed air	30–60	N/A	1–300 MW	65–70%	Slow, from seconds to minutes	Medium-high	10,000	20–40	Deep	35~50
Low temperature TES	100–200	N/A	Up to several MW	30–50%	Slow	Low-Medium	N/A	Up to 40	NR	NR
High temperature TES	80-200	N/A	Up to several MW	Up to 80%	Slow	Low-Medium	N/A	Up to 15	NR	NR

IV. Battery in electric vehicle (BEV)

In the 1900s, lead-acid and nickel-cadmium (NiCd) batteries were the only kinds appropriate for EVs [35-37]. Many variables, such as the kind and quantity of batteries used, the terrain, the weather, and the driving style of the driver, affect the range of driving [35]. Battery capacity is also affected by energy efficiency; a higher percentage of stored energy is correlated with a higher rating for energy efficiency in batteries. Similar to a large-capacity battery, a high-efficiency battery charges faster and may become more fully depleted [34].

V. Types of battery

Different types of BES used in EV are classified in Figure 3. Comparison between types is presented in Table 2. The extended cycle life, low weight, and high energy density of Li-ion batteries make them a popular choice for current electric vehicles. The Li-ion battery infrastructure, which includes fast-charging networks, including Level 1 (standard household outlets), Level 2 (home or public charging stations), and fast-charging networks, is well-established and appropriate for a variety of applications, including consumer electronics, electric cars, and renewable energy storage. Li-ion batteries generally support fast charging, allowing for quick replenishment of the battery. For more information, see the table.

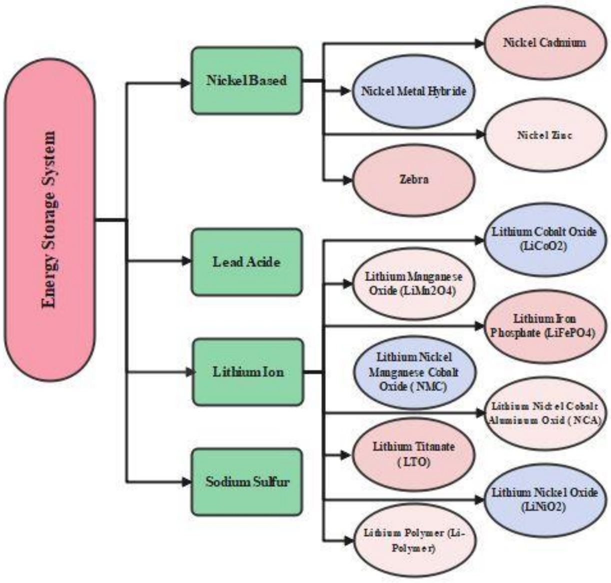

Figure 3 presented different types of BES used in EV

Table 2 : Comparison between types of Lithium-Ion (Li-ion) battery

types	Application	Advantages	Drawbacks
Lithium Cobalt Oxide (LiCoO2) [36]	Widely used in consumer electronics (laptops, smartphones).	High energy density.	Limited cycle life, sensitive to high temperatures.
Lithium Manganese Oxide (LiMn2O4 or Li-Manganese) [37]	Power tools, medical devices.	Enhanced thermal stability,higher discharge currents.	Lower energy density compared to LiCoO2.
Lithium Iron Phosphate (LiFePO4) [38]	Electric vehicles, solar energy storage.	Excellent thermal stability, longer cycle life, lower cost.	Lower energy density than some other types.
Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2 or NMC) [36]	Electric vehicles, power tools.	high energy density and power capability.	lower thermal stability compared to LiFePO4.
Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2 or NCA) [39], [40]	Electric vehicles, laptops.	High energy density, long cycle life.	Costlier than some other types, sensitivity to overcharging.
Lithium Titanate (Li4Ti5O12 or LTO) [41], [42]	Electric vehicles, renewable energy storage.	Extremely long cycle life, high power density, fast charging.	Lower energy density compared to other Li- ion types.

Lithium Nickel Oxide (LiNiO2) [43],	used for high-voltage batteries	high capacity and cost-effectiveness	faced application issues like self-passivation
Lithium Polymer (Li-Polymer)	Consumer electronics, electric vehicles.	Flexible form factor, lighter weight, customizable shapes.	Slightly lower energy density, more complex manufacturing.

As presented in table 3 Nickel-metal hydride (Ni-MH) batteries, once used in early hybrid vehicles, offer moderate energy density and long cycle life but charge slower than lithium-ion types. Variants like Low Self-Discharge, High Capacity, and Fast Charge NiMH address specific needs such as occasional use, rapid charging, and extreme temperatures. Other related technologies like Ni-Cd, Zebra, and Nickel-Zinc present trade-offs in toxicity, freezing recovery, and lifecycle limitations.

A Table 4 compares battery technologies like lead-acid, solid-state, lithium-polymer, and sodium-ion based on their uses, benefits, and drawbacks. While lead-acid is low-cost but low-density, solid-state and lithium-polymer offer higher energy densities, and sodium-based types show promise despite current limitations

Table 3 : Comparison between types of Nickel-Metal Hydride battery

	types	**Application**	**Advantages**	**Drawbacks**
Nickel-Metal Hydride (Ni-MH): [44]	Standard NiMH	toys, flashlights, and portable electronics.	Versatile for general use.	Moderate energy density, moderate self-discharge.
	Low Self-Discharge NiMH (LSD NiMH)	remote controls, emergency equipment	Extended shelf life, suitable for low-drain devices.	Lower capacity than standard NiMH.
	High Capacity NiMH	digital cameras, power tools	Increased capacity for power-hungry devices.	Can be bulkier and heavier.
	Hybrid NiMH (Eneloop)	cameras, wireless mice).	low self-discharge and high capacity.	lower capacity than high-capacity NiMH.
	Nickel–Cadmium Batteries [45]. [46]	--	-boasting a long lifespan of over 3500 cycles and minimal maintenance requirements -short discharge period and minimal internal resistance,	they require high charging rates for efficient operation, posing environmental concerns due to cadmium toxicity.
	Zebra Battery Technology [47]	Provides numerous configurations of tested technology, providing maintenance-free operation and a noticeably longer cycle life.	robustness, affordability, tolerance to ambient temperatures, lack of gassing, lack of self-discharge, and ease of charge estimation	a long thawing time of 12 to 15 hours after freezing and a 90 W energy loss when idle
	Improved Temperature Performance NiMH	Outdoor and automotive applications	Performs well in extreme temperatures.	Specific use cases; not a general-purpose solution.
	Fast Charge NiMH	Devices requiring quick recharging (power tools, certain consumer electronics).	Rapid charging capability.	May have a reduced overall cycle life.
	Button Cell NiMH	Small electronic devices, watches, and medical devices.	Compact size suitable for button-cell formats.	Limited in capacity due to small size.

Table 4 : Comparison between types of Battery energy storage system

	types	**Application**	**Advantages**	**Drawbacks**
Lead-Acid: [48] [49] [50].	Flooded Lead-Acid (FLA) Batteries	Automotive (conventional cars), (UPS), backup power systems.	Low cost, widely available.	Require maintenance, can release gas, must be used in well-ventilated areas.
	Valve-Regulated Lead-Acid (VRLA) Batteries	Absorbent Glass Mat, UPS, telecommunications, security systems, medical equipment.	Maintenance-free, sealed, less prone to gas release.	Can be more expensive, sensitive to overcharging.
	Deep Cycle Lead-Acid Batteries	solar, wind, golf carts, marine applications.	deep discharges, longer cycle life.	Heavier, lower energy density.
	Sealed Lead-Acid (SLA) Batteries	UPS, emergency lighting, electric scooters, Medical equipment, wheelchairs.	Maintenance-free, spill-proof, versatile.	Limited deep discharge cycles, sensitive to overcharging.
	Gelled Electrolyte Batteries:	Renewable energy systems, RVs, boats.	Maintenance-free, sealed,	Sensitive to overcharging, higher cost.

Solid-State Batteries:	All-Solid-State Lithium-Ion Batteries	Electric vehicles, consumer electronics, renewable energy storage.	Higher energy density, improved safety	higher production costs, complex manufacturing processes.
	Solid-State Sodium-Ion Batteries	Energy storage, grid applications.	lower cost, improved safety.	Development and commercialization are still in the early stages.
	Solid-State Lithium-Metal Batteries	Electric vehicles, portable electronics.	Increased energy density, enhanced safety.	Challenges related to dendrite growth, manufacturing complexities.
Lithium-Polymer:	High-Capacity Li-Poly Batteries	Consumer electronics (smartphones, tablets, laptops).	High energy density, lightweight, flexible form factor.	Sensitive to overcharging, potential for swelling or overheating if not handled properly.
	Ultra-Thin Li-Poly Batteries	Smart cards, wearables, compact electronic devices.	Slim and flexible design, lightweight.	Limited capacity compared to larger batteries.
	High-Discharge Li-Poly Batteries	Remote-controlled vehicles, drones, high-performance gadgets.	High current discharge capability, suitable for power-hungry devices.	Lower overall capacity, may have shorter cycle life.
Sodium-Ion: [51].	Hard Carbon Anode Sodium-Ion Batteries	Portable electronics, grid storage	potential lower cost, and safety benefits.	Challenges in achieving high energy density, commercialization progress.
	Prussian Blue Cathode Sodium-Ion Batteries	Grid storage, stationary energy storage.	Reversible sodium-ion intercalation, potential for high capacity.	Limited energy density, performance degradation over cycles.
	Sodium-Sulfur Batteries	Grid storage, stationary applications.	High energy density, potentially lower cost.	Operating temperature constraints, safety concerns, limited cycle life.

Rechargeable battery characteristics including performance based on capacity, energy density, specific energy, and charge cycle life are shown in Table 5. Lithium-ion batteries are the highest performing in terms of energy density and specific energy, although they come at a higher cost compared to lead-acid and nickel-cadmium batteries. Internal resistance impacts energy transfer efficiency, and factors like cost, safety, and reliability are crucial for evaluating battery effectiveness[52].Table 5 compares and contrasts several battery kinds and shows that Li-ion batteries perform better, have more environmentally friendly components, and are very safe. It is unique because of its high energy density (200–400 Wh/L) and extraordinarily high power density (1,500–10,000 W/L), which makes it perfect for uses requiring strong and small energy storage. Along with having a long lifespan (up to 10,000 cycles), a high depth of discharge (up to 95%), and high round-trip efficiency (up to 95%), lithium-ion batteries also allow for more useful energy per cycle. Additionally, they are adaptable and appropriate for a variety of settings due to their efficient operation throughout a broad temperature range (-20°C to 60°C). Lithium-ion batteries are the most popular and cutting-edge choice for contemporary energy storage systems because of these characteristics.

Table 5. Common BESS types and examples of characteristics.

Battery Type	**Lead-Acid**	**Ni-Cd**	**Ni-MH**	**Zn-Br**	**Fe-Cr**	**lithium-ion**	**NaS**	**NaNiCl**	**VRFB**	**ZBFB**
Energy Density (Wh/L)	50–80	60–150	40–80	65–75	20–35	200–400	140–300	160–275	25–33	55–65
Power Density (W/L)	10–400	80–600	250–1000	60–110	70–100	1500–10,000	140–300	150–270	1–2	1–25
Cell Nominal Voltage (V)	2	1.3	1.2	1.67	1.18	4.3	2.08	2.85–3.1	1.4	1.8
Round Trip Efficiency	82%	83%	70	70-80	97.4	95	80	84	70	70%
Depth of discharge	50%	85%	100%	100%	100%	95%	100%	100%	100%	100%
Operating Temperature	−20–60	−40–60	−20–60	−20–60	−40–60	−20–60	300–350	−70–100	10–40	20–50
Charge Efficiency	79%	70%	70%	73%	97.4%	100%	90%	80–95%	97%	70–80%
Energy Efficiency	70%	69–90%	75%	80%	66%	80%	90%	95%	72.3%	82%
Voltage Efficiency	80%	75%	70%	80%	82%	98%	87%	80.9%	74.5%	83%
Life Cycle	1500	2500	800–1200	200–400	300	10,000	5000	3000	13,000	10,000

VI. Conclusion

ESS are primary for system power system to operate efficiently. Different ESS are extensively reviewed and examined in the article. Lithium-ion batteries remain the dominant energy storage solution for electric vehicles, offering superior energy density, efficiency, and cycle life compared to alternatives like lead-acid or nickel-cadmium batteries. However, their widespread adoption faces challenges including high costs and temperature sensitivity, highlighting the need for continued research into performance optimization and cost reduction.

Emerging technologies such as solid-state and sodium-ion batteries show promising potential to address current limitations, though further development is required. As the EV market evolves, ongoing innovation in energy storage systems will be critical to achieving sustainable transportation solutions, demanding sustained investment in research and technological advancement.

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