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Levelized Cost of Storage Framework for Solid-State Batteries in 400V/800V Electric Vehicle Powertrains

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Abstract. Electric Vehicle (EV) manufacturers are adopting a range of powertrain architectures, with voltage systems ranging from 400V to 800V. The voltage ranges improves the efficiency and performance of EV powertrains. This improvement transforms EVs into more than just transportation systems. They also integrate the EVs as critical distributed energy storage units, and helps in grid stability, and energy load balancing through vehicle-to-grid (V2G) integration. Solid-state batteries (SSBs) represent an advanced energy storage technology, which enable EVs to operate efficiently at higher voltage configurations. To evaluate their feasibility and cost-effectiveness, the Levelized Cost of Storage (LCOS) serves as a critical metric. A low LCOS indicates improved cost-efficiency, and is achieved through careful optimization of capital expenditure (CapEx), reduced operational expenditure (OpEx), and minimized energy losses, during operation. In contrast, a high LCOS, exposes inefficiencies in system integration, lifecycle design, or operational management. This paper develops a detailed LCOS framework, for the deployment of SSBs in 400V and 800V EV powertrain topologies. The model uses mathematical formulations across various automotive platforms. Simulation results show that 800V EVs have a lower LCOS, compared to 400V systems. These findings support the economic and technical viability of SSBs in high-voltage EV powertrains.

Key words. Electric Vehicle, Solid State Battery, Levelized Cost of Storage

Acronyms - LLZO (Lithium Lanthanum Zirconium Oxide ($Li_7La_3Zr_2O_{12}$), SSB (Solid-State Battery), LCOS (Levelized Cost of Storage), $Li_7P_3S_{11}$ (Lithium Phosphorus Sulfide (solid electrolyte material), VRFB (Vanadium Redox Flow Battery), PEO (Polyethylene Oxide)

1. Introduction

In recent times, EVs with 400V and 800V powertrain architectures are more than just mediums of transportation. Beyond propulsion, EVs are increasingly being viewed as distributed energy storage units. They can store excess energy from renewable sources or discharge power back into the grid through vehicle-to-grid (V2G) applications. SSBs, used in these EVs, are well-positioned to meet this demand. SSBs are emerging as a critical innovation in energy storage, offering advanced characteristics such as high gravimetric and volumetric energy densities, superior ionic conductivity, and enhanced thermal stability. Their architecture, which replaces liquid electrolytes with solid electrolytes, eliminates leakage risks and improves electrochemical stability [1]. Several automakers are focusing on the development and integration of SSBs in EVs. Toyota, through its joint venture with Panasonic, Prime Planet Energy & Solutions Inc., is set to begin limited production of SSBs in 2025 [2][3]. Honda is developing an all-solid-state battery (ASSB), with a focus on mass production and plans to deliver batteries, offering a 1,000-kilometer range, which exceeds current EV standards [4][5]. BMW's SSB initiative targets 1,200 Wh/l energy density, offering extended range, reduced charging frequency, and ultra-fast charging to enhance EV performance and usability [6][7]. Nissan, as part of its Ambition 2030 strategy, plans to launch an EV, with in-house developed all-solid-state batteries by 2028 [8]. Volkswagen Group, through its subsidiary PowerCo, is partnering with QuantumScape to industrialize next-generation lithium-metal SSB technology [9]. Together, these initiatives show the automotive industry's unified focus on SSBs as a critical component of next-generation EVs. Conventional lithium-ion and lead-acid batteries are constrained by intrinsic limitations, such as limited cycle life, thermal instability, and lower energy densities [10]. These undermine their suitability for high-performance dual-use applications. In contrast, SSBs reveal improved lifecycle durability and thermal stability. However, their integration into energy storage systems require techno-economic evaluation, using key metrics like the Levelized Cost of Storage (LCOS). LCOS, a fundamental metric for assessing the lifecycle cost-effectiveness of energy storage technologies, is expressed as the total cost per unit of energy delivered by a system. It factors key parameters such as capital expenditure (CapEx), operational expenditure (OpEx), current-dependent conduction losses, and lifecycle energy output efficiency [11]. The deployment of SSBs in 400V and 800V systems introduces some challenges as well. These include optimizing power converter topologies, managing thermal constraints under high current densities, and ensuring reliable operation at higher voltages [11]. These factors critically impact LCOS metrics and define the techno-economic feasibility of SSB implementation, across different powertrains. The paper analyzes the adoption of SSBs in EVs, and develops an LCOS model through comparative analysis. The model is applied to 400V and 800V architectures, to identify optimal configurations, with results compared and concluded, alongside future recommendations. A key objective is to determine which EV voltage architecture is better suited to maximize the superior performance of SSBs.

2. Levelized Cost of Storage Analysis for Solid-State Batteries

The estimation of LCOS for SSBs is important for automobile consumers, as it evaluates the long-term cost-efficiency of electric vehicles. A low LCOS reflects reduced energy expenditures, extended battery longevity, and enhanced vehicle performance. This provides consumers with a more economically viable and reliable EV solution.

2.1 Solid-State Batteries

SSBs are an advanced electrochemical energy storage system that use solid-state ion-conducting electrolytes, in place of conventional liquid or polymer gel electrolytes found in lithium-ion batteries [10]. The adoption of solid electrolytes improves safety by removing flammable liquid components, and mitigating thermal runaway mechanisms. This reinforces thermal, chemical, and structural stability under high-stress operational conditions. The mechanical robustness of solid-state electrolytes, effectively mitigates dendrite formation, increasing the operational lifespan of the battery. Organic polymer electrolytes contribute additional advantages, such as superior flexibility and interfacial compatibility. This ensures reliable functionality under mechanical and thermal stresses [10]. However, these advantages are also accompanied by technical challenges. High manufacturing costs arise from the requirements for defect-free material synthesis, and the precision engineering of seamless electrolyte-electrode interfaces. Furthermore, the inherent solid-solid interfacial resistance and brittleness of inorganic electrolytes hinder performance and compromise structural durability. The relatively low ionic conductivity of organic polymer electrolytes, combined with the complexity of compact cell designs, further complicates scalability issues. This creates obstacles to the widespread commercialization of SSBs [1].SSBs are classified based on electrolyte composition and structural configuration, to address different performance and application demands. Electrolyte types include organic polymer electrolytes, such as polyethylene oxide (PEO) doped with lithium salts. They provide excellent interfacial compatibility and flexibility, but suffer from low ionic conductivity (10^{-6} - 10^{-4} S/cm), and limited mechanical strength. Inorganic solid electrolytes, such as sulfides ($Li_7P_3S_{11}$) and oxides ($Li_7La_3Zr_2O_{12}$, LLZO), offer high ionic conductivities (>10-3 S/cm)) and excellent mechanical strength. This is essential for suppressing dendrites, but face challenges like brittleness and interfacial instability [1]. Structurally, SSBs are divided into All-Solid-State Batteries (All SSBs), Almost-Solid-State Batteries (Almost SSBs), and Semi-Solid-State Batteries (Semi-SSBs). All SSBs eliminate liquid entirely, enhancing safety and thermal stability, but suffer from high interfacial resistance. Almost SSBs incorporate <5% liquid electrolyte by weight to reduce interfacial resistance, while maintaining safety. Semi-SSBs, with ~10% liquid content, balance performance with manufacturability [10].

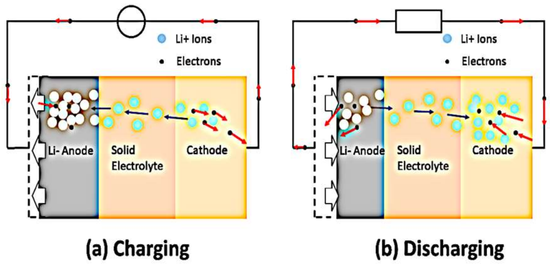

Figure 1. Solid-State Battery Charging and Discharging Mechanism. Source:[12]

During SSB charging, electrons flow through an external circuit to the anode, as seen in Figure 1. At the same time, lithium ions are transported from the cathode to the anode via the solid-state electrolyte, driven by the electrochemical gradient and ionic conductivity. During discharge, the process reverses: lithium ions migrate back to the cathode through the solid-state electrolyte, and electrons flow through the external circuit to deliver power to the load [12]. The solid-state electrolyte serves as an ionic conductor and physical separator, and effectively removes short-circuit risks. This further mitigates issues such as electrolyte leakage and thermal runaway, commonly associated with liquid electrolytes. SSBs operate within a voltage range of 3.2–4.2 V per cell, comparable to conventional lithium-ion batteries [10]. Another key point is the performance of SSBs. It is strongly influenced by interfacial impedance at the electrode-electrolyte junction, which controls ionic mobility and charge transfer resistance. Optimizing this interface requires precise engineering of material properties, surface morphology, and electrolyte compatibility. This improves ionic transport pathways and reduce resistive losses [1]. These engineering factors and challenges influence the LCOS for SSBs, as they directly affect lifecycle efficiency, manufacturing scalability, and overall system cost-effectiveness.

2.2 Levelized Cost of Storage

The comparison of energy storage technologies is difficult due to differences in the definition and calculation of LCOS. Factors such as discharge duration, cycle frequency, and system assumptions vary across technologies, making comparisons inconsistent [13]. LCOS is a key engineering metric that calculates the discounted cost per unit of discharged energy over the system's lifecycle. It is similar to the Levelized Cost of Electricity (LCOE) for power generation, and offers a standardized method to assess and compare the efficiency and economic performance of energy storage technologies [11]. The LCOS framework of an energy system includes technical parameters such as the system's energy output, discharge duration, cycle life, and round-trip efficiency. These factors are used to provide an accurate assessment of the cost per unit of energy delivered, expressed in kilowatt-hours (kWh) or megawatt-hours (MWh). Delivered energy is determined by the application-specific discharge profile (in this case, SSBs), annual cycle count, and overall storage system capacity [14]. LCOS for energy storage systems in EVs, is fundamentally influenced by the operating voltage level, with 400V and 800V architectures. This affects efficiency, energy output, and cost metrics. The selection of voltage architecture directly influences LCOS optimization and must align with application-specific requirements. High-performance and long-range EVs are better suited to 800V systems due to their higher energy transfer efficiency, reduced losses, and superior fast-charging capabilities, all of which enhance lifecycle cost-effectiveness. Conversely, 400V systems remain appropriate for cost-sensitive applications such as entry-level or mid-range EVs, where the focus is on reducing upfront costs rather than maximizing energy efficiency [13].

3. Methodology

This section provides a comprehensive analysis of three LCOS models, based on the application of various electrochemical energy storage technologies. The assessment of these models forms the basis for developing the proposed SSB LCOS framework, which is further elaborated and refined in this section.

3.1 LCOS Framework 1 – Redox Flow Batteries

This LCOS model is developed to assess the techno-economic performance of Vanadium Redox Flow Batteries (VRFBs) by including capacity fade, recovery mechanisms, and operational costs [13]. It assesses the cost of storing and delivering energy by considering all associated expenses over the system's lifetime. The LCOS equation, in this model, is expressed as (1):

$$\text{LCOS} = \frac{\sum_{t=0}^{n}\frac{I(t)+L(t)+T(t)}{(1+r)^{\wedge}t} + \sum_{t=0}^{k}\frac{O\&M(t)+C(t)}{(1+r)^{\wedge}t}}{\sum_{t=0}^{k}\frac{E(t)}{(1+r)^{\wedge}t}} \quad \ldots\ldots\ldots\ldots\ldots \ (1)$$

The LCOS formula evaluates the initial investment costs (I(t)), labor costs (L(t)), taxes (T(t)), Operation and Maintenance costs (O&M(t)), and capital replacement costs (C(t)), all discounted to present value using the rate r. It divides these costs by the total discounted energy discharged (E(t)) over the system's lifetime. This comprehensive approach captures both recurring and operational factors for an accurate economic assessment. The LCOS model for VRFBs includes capacity fade and recovery mechanisms, using rebalancing strategies such as electrolyte mixing, to address reversible decay. These strategies are not applicable to SSBs due to their solid electrolytes, which lack the liquid medium required for such processes. Maintenance costs for liquid management in VRFBs do not apply to SSBs, where degradation stems from lithium dendrite formation, interfacial delamination, and solid electrolyte degradation. Parameters like ion crossover and membrane selectivity in VRFBs must be replaced with considerations specific to SSB failure mechanisms. Charging costs related to liquid flow inefficiencies must also be recalibrated to account for energy losses, caused by thermal management and mechanical stress in SSBs. Key parameters that remain unchanged include capital expenditure, which captures initial investment costs, and the discount rate. These are essential for economic evaluation. Operating and maintenance costs remain applicable but differ in their specific components. Capacity fade and irreversible losses are also retained, though their underlying mechanisms vary between the technologies. Adapting the LCOS model to address SSB-specific characteristics while retaining core economic principles enables accurate cost assessments and supports their commercial viability.

3.2 LCOS Framework 2 – General Electrochemical Storage

This LCOS model is developed to evaluate the lifetime costs of different electrochemical energy storage (EES) technologies, focusing on key economic and technical parameters [11]. By analyzing sensitivity factors such as round-trip efficiency, storage duration, and unit investment costs, the model provides insights for stakeholders to optimize technology deployment and promote cost-effective energy storage solutions in various applications. The LCOS equation, in this model, is expressed as (2):

$$\text{LCOS} = \frac{Capex + \sum_{n=1}^{N}\frac{Opex(n)}{(1+r)^{\wedge}n} + \sum_{n=1}^{N}\frac{Tax(n)}{(1+r)^{\wedge}n} + \sum_{n=1}^{N}\frac{Charging(n)}{(1+r)^{\wedge}n} + Crep + Crec}{\sum_{n=1}^{N}\frac{E\,(Discharged)}{(1+r)^{\wedge}n}} \ldots \ (2)$$

The LCOS model evaluates storage economics using key parameters: CapEx for initial investment, OpEx (n) for annual operation and maintenance costs, Tax (n) for yearly taxes, and Charging (n) for energy input costs. It also includes C_rep, the discounted battery replacement cost, and C_rec, the residual value of the system. E (discharged) measures total discharged energy, while N represents the system's service lifetime. Together, these factors provide a comprehensive assessment of lifetime storage costs. When adapting this LCOS model for SSBs, parameters such as Capex, OpEx, Tax, Charging, C_rep, and E_discharge should be retained, as they are fundamental to assessing lifetime storage costs. However, considerations specific to technologies with liquid electrolytes, such as rebalancing strategies and maintenance costs related to electrolyte management, should be excluded. Instead, SSB-specific parameters like costs related to mitigating lithium dendrite formation, interfacial degradation, and thermal management must be included. Adjustments are also needed for C_rep, focusing on degradation mechanisms unique to SSBs, rather than electrolyte replacement. This ensures the model captures the distinct operational and economic dynamics of solid-state battery systems.

3.3 LCOS Framework 3 – Second-Life Lithium-ion Battery Energy Storage

This LCOS model is developed to evaluate the cost-effectiveness of utility-scale second-life lithium-ion battery energy storage systems (SLBESS), by comparing them to new battery energy storage systems (BESS) [15]. The model includes economic factors like capital costs, operating expenses, charging costs, and end-of-life costs. It also accounts for parameters unique to second-life systems, such as repurposing and degradation rates. In this LCOS model, n is the project year, N the project lifetime, and r the discount rate for adjusting costs and outputs. O&M represents annual operation and maintenance costs, EOL, the end-of-life costs, Elec (D), the annual electricity discharged, and charging (n) the annual charging costs. These parameters collectively assess lifetime storage costs and efficiency. The LCOS equation, in this model, is expressed as (3):

$$\text{LCOS} = \frac{TCC + \sum_{n}^{N}\frac{O\&M}{(1+r)^{n}} + \sum_{n}^{N}\frac{Charging}{(1+r)^{n}} + \frac{EOL}{(1+r)^{N+1}}}{\sum_{n}^{N}\frac{Elec\,(D)}{(1+r)^{n}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

For SSBs, parameters such as Total Capital Costs (TCC, O&M, Charging, EOL, Elec (D), and the discount rate (r) should be retained, as they are critical for assessing lifetime costs. However, elements unique to second-life systems, such as repurposing costs, should not be included, as SSBs are new systems. Instead, SSB-specific degradation factors, such as costs associated with lithium dendrite formation and thermal management, should be incorporated to accurately reflect their operational dynamics.

3.4 Proposed Framework – LCOS Model for SSB

The LCOS model for SSBs includes specific variables to account for their characteristics and cost factors. TCC represents high upfront costs, due to advanced solid electrolyte manufacturing, similar to Lithium-ion Batteries. O&M (n) is included for periodic checks on thermal stability and structural integrity, though SSBs have reduced maintenance needs, compared to liquid-based systems. Charging (n) reflects infrastructure costs, such as ultra-fast chargers required for high energy-density systems. EOL and Recycling explicitly capture the high and immature costs of solid electrolyte recycling and end-of-life recovery processes. Manufacturing (n) addresses the advanced, costly production processes specific to SSBs. E (discharged) shows their higher energy densities and discharge efficiencies, critical for LCOS performance. Finally, the discount rate (r) accounts for the time value of money, a standard parameter in all LCOS evaluations. The LCOS equation, in the proposed framework is given by (4):

$$\text{LCOS} = \frac{TCC + \sum_{n=1}^{N}\frac{O\&M(n)+Charging(n)+Manufacturin\ \ (n)}{(1+r)^{n}} + \frac{EOL+Recycli}{(1+r)\text{^}(N+1)}}{\sum_{n=1}^{N}\frac{E\,(Discharged)}{(1+r)\text{^}n}} \quad (4)$$

The proposed model captures the advantages of SSBs (e.g., high energy density, low maintenance) while accounting for challenges (e.g., high manufacturing and recycling costs).

4. Results

The proposed SSB LCOS model is applied to analyze and compare the LCOS values of three different car brands, KIA (EV3 Long Range/EV6 Long Range 2WD), Hyundai (Kona Electric/Ionic 5 AWD), and Audi (Q4-e-tron-35/Q6-etron), each with 400V/800V powertrain architectures. A number of observations are made. As seen in Figure 2, the energy discharge of 800V systems is superior to that of 400V systems due to the inherent advantages of high-voltage operation in EVs. The higher energy discharge observed in 800V systems compared to 400V systems can be attributed to the improved efficiency of electric motor operation at higher voltages. In electric drivetrains, the motor's performance is influenced by the voltage applied to its windings. Higher voltages in 800V systems enable the motor to operate at lower current levels for the same power output, reducing magnetic saturation in the motor windings. This improves the use of the motor's electromagnetic field. It also allows the motor to achieve higher torque output and efficiency, leading to more effective energy-to-motion conversion. Additionally, higher voltage systems can maintain optimal inverter operation, across a broader range of motor speeds, ensuring a more consistent energy discharge profile over various driving conditions. This enhanced motor control and efficiency directly contribute to the increased total energy discharge observed in 800V systems. There is also the slightly higher energy consumption observed in 800V systems compared to 400V systems. This is also attributed to the higher operating voltage, which requires the use of power electronics, with wider voltage margins and increased switching frequencies. In an 800V system, components such as inverters and DC-DC converters, are designed to handle higher voltages. This often leads to greater switching and control losses inherent to wide-bandgap semiconductor devices, such as silicon carbide (SiC) MOSFETs. While SiC devices are highly efficient and enable the operation of 800V architectures, their increased switching speeds can introduce higher dynamic losses during operation, especially under high power delivery demands. The 800V configuration, also, typically requires more complex voltage balancing and insulation mechanisms, which can introduce additional parasitic losses in the overall system, contributing to the slightly higher energy consumption. Additionally, the higher efficiency in power transfer within 800V systems minimizes energy losses, allowing for greater use of stored energy. This results in more energy being available for propulsion and auxiliary systems, thereby increasing the total discharged energy compared to 400V counterparts.

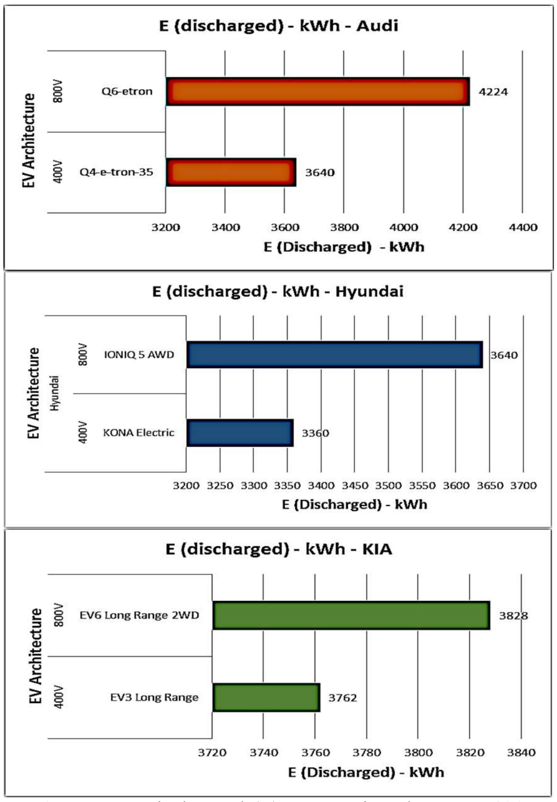

Figure 2. Energy Discharged (E) Comparison between 400V and 800V EV Architectures

Table 2 indicates key cost parameters required for the computation of final LCOS values, comparing 400V and 800V EV architectures. It is observed that most cost components, such as charging and manufacturing costs, are higher for 800V systems, except for O&M costs, which are notably lower. The reduced O&M costs for 800V systems is due to their improved electric efficiency and reduced current levels. This minimizes wear on components such as cables, connectors, and power electronics, thereby lowering maintenance requirements over the system's lifecycle.

Table 2. Cost Comparison of 400V and 800V Electric Vehicles across Lifecycle Stages. Source:[16][17]

	400V EV	800V EV
Charging Costs per year (EUR)	1700	1900
Manufacturing Costs (EUR)	1700	1900
End-of-Life Costs (EUR) - one time	15000	12000
Recycling Costs (EUR) - one time	10000	7000
O&M Costs per year (EUR)	1500	1000

In contrast, EOL and recycling costs are significantly lower for 800V systems. This reduction is explained by the enhanced potential of 800V batteries for second-life applications, such as integration into stationary energy storage systems. The higher energy density, superior thermal stability, and overall performance characteristics of 800V batteries increase their residual value and make them more viable for repurposing after their primary automotive use. This additional revenue potential offsets the EOL and recycling costs, resulting in a more favorable lifecycle economic profile. These characteristics underline the technical and economic advantages of 800V systems in achieving reduced LCOS compared to 400V architectures. Figure 3 presents the final LCOS values for 400V and 800V EV architectures across the three auto brands. It is observed that 800V systems consistently exhibit low LCOS compared to their 400V counterparts, indicating improved lifecycle cost efficiency, as seen in Figure 3. A low LCOS indicates a more cost-effective energy storage solution over the vehicle's operational lifetime, which can be attributed to factors such as optimized energy discharge capability, better scalability of battery configurations, and increased use of system components. The slightly high LCOS values observed for 400V systems, suggest relatively lower energy output and a higher per-unit cost of energy delivered over the same operational lifecycle. The use of SSBs in 800V systems is therefore better, for both manufacturers and consumers, with regards to cost, compared to 400V systems, as 800V EVs enable more efficient energy usage and better system performance.

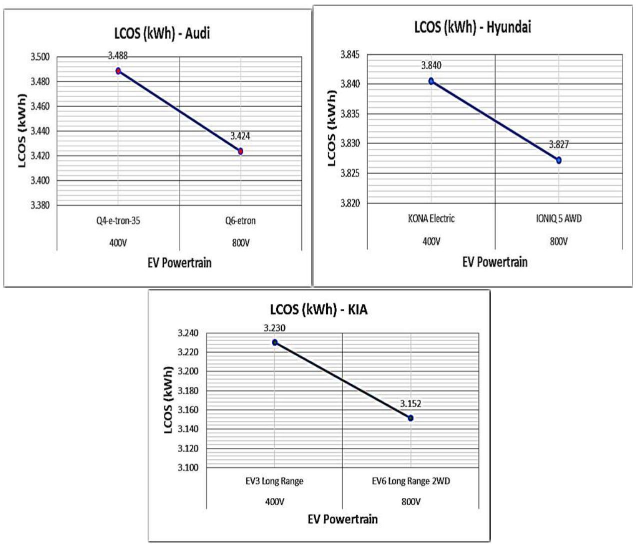

Figure 3. LCOS Comparison between 400V and 800V EV Architectures

5. Conclusion

This paper shows the economic and technical advantages of integrating SSBs into 800V EV powertrains, compared to 400V systems. Analysis reveals that 800V architectures consistently achieve low LCOS values, driven by higher energy discharge and improved system efficiency. 800V systems exhibits approximately 15–20% lower LCOS than their 400V counterparts, proving their cost-effectiveness. The reduced LCOS is due to lower current requirements in 800V systems, minimizing resistive losses and extending the lifespan of components such as cables, connectors, and inverters. Additionally, the higher energy density of SSBs allows 800V systems to integrate larger battery capacities, leading to greater total energy discharged over their lifetime, up to 10% higher than in 400V systems. Further benefits include reduced end-of-life (EOL) and recycling costs in 800V EVs. EOL costs are approximately 20% lower in 800V systems, due to the higher residual value of SSBs, which are well-suited for second-life applications such as grid storage. Conversely, 400V systems exhibits slightly higher LCOS due to lower energy output and greater operational inefficiencies. Despite the higher upfront costs of 800V systems, their superior lifecycle performance and cost distribution provide long-term economic advantages. These findings show the potential of 800V systems with SSBs, to transform EV powertrain architectures, offering scalable, efficient, and cost-effective energy storage solutions. Future LCOS analyses could avoid generalizing across all SSB models, as variations in structural and electrolyte classifications can impact performance and cost metrics. Structurally, SSBs include All-Solid-State Batteries (All SSBs), Almost-Solid-State Batteries (Almost SSBs), and Semi-Solid-State Batteries (Semi-SSBs). Electrolyte classifications also include organic polymer electrolytes, such as polyethylene oxide (PEO) doped with lithium salts, and inorganic electrolytes, such as sulfides ($Li_7P_3S_{11}$) and oxides ($Li_7La_3Zr_2O_{12}$, LLZO). It is recommended to develop specific LCOS models for each structural and electrolyte type, reflecting their unique characteristics, challenges, and application demands for more precise evaluations.

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