A Review on Solid State Batteries in Electric Vehicles

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***Abstract*—Solid-state batteries (SSBs) replace liquid electrolytes with solid ones, improving EV safety by eliminating leakage, flammability, and thermal runaway risks. They also offer higher energy density, faster charging, longer range, better thermal stability, and extended lifespan. However, high cost, low room-temperature ionic conductivity, and interface issues limit large-scale use. Ongoing research aims to overcome these challenges, making SSBs a strong candidate for safer and more efficient next-generation EVs.**

***Index Terms*—Electric Vehicle, Battery System, Renewable Energy, Lithium Ion Battery, Solid State Battery, Cost, Environmentally Friendly.**

I. INTRODUCTION

Solid-state batteries (SSBs), including all-solid-state batteries (ASSBs), are emerging EV energy storage systems that replace liquid electrolytes with solid ones, improving safety by reducing leakage, fire, and thermal runaway risks.

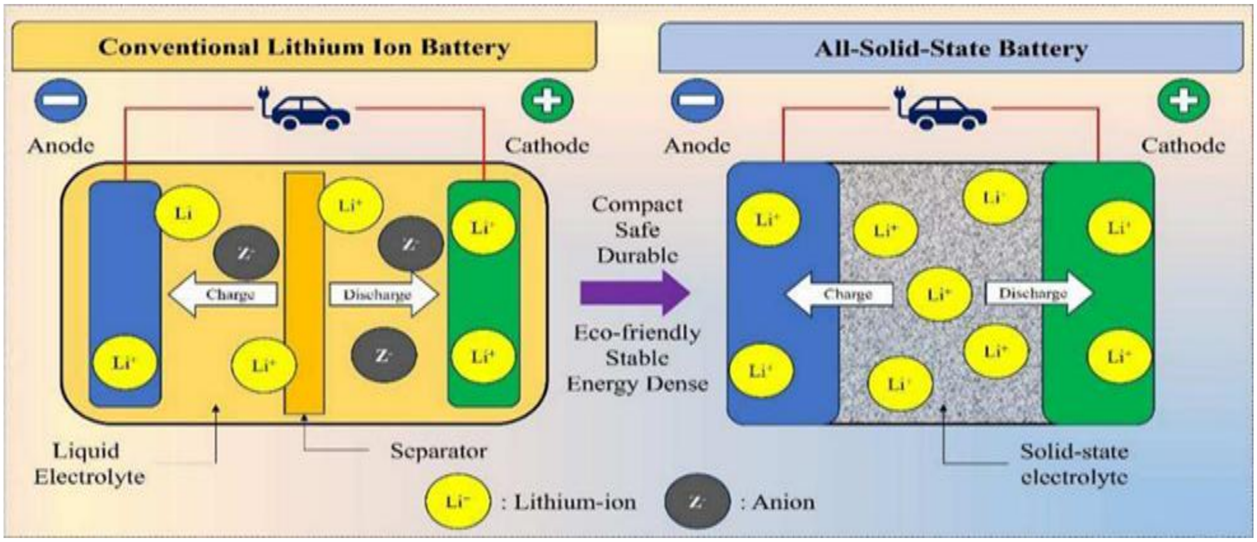


Fig 1 Comparison of conventional and all-solid-state battery

SSBs provide higher energy density for longer range, faster charging, better thermal stability, and improved reliability. They also offer longer lifespan due to reduced degradation, enhancing durability and sustainability in EVs.

However, challenges such as high production costs, low ionic conductivity at room temperature, and difficulties in maintaining stable interfaces still need to be addressed.

Overall, solid-state batteries are a promising solution for safer and more efficient EV energy storage. Solid-state materials gained prominence in the 1920s, with early focus on lithium compounds. Over time, the development of new materials has significantly advanced solid-state battery (SSB) technology.

This design offers higher energy density, longer lifespan, improved safety, and better environmental compatibility. Electrode materials (anode, cathode, and interfaces) are critical for performance, particularly the cathode–electrolyte interface, which affects ion transport. Solid electrolytes also provide better thermal stability and durability, though their properties depend on conditions like temperature and pressure, making material selection application-specific.

II. MATERIALS

Material selection is crucial in solid-state batteries as it defines structure, interfacial behavior, and ionic/electronic conductivity. It also depends on cost, performance, and safety, and includes anode, cathode, electrolyte, and interfacial materials.

A. Anode

Lithium (Li) metal is an ideal anode due to its high capacity (3860 mAh g^{-1}) and low potential (−3.04 V), but dendrite formation, volume expansion, and low coulombic efficiency limit its safety and durability. Graphite is used as an alternative, offering better stability and cycling performance but lower capacity.

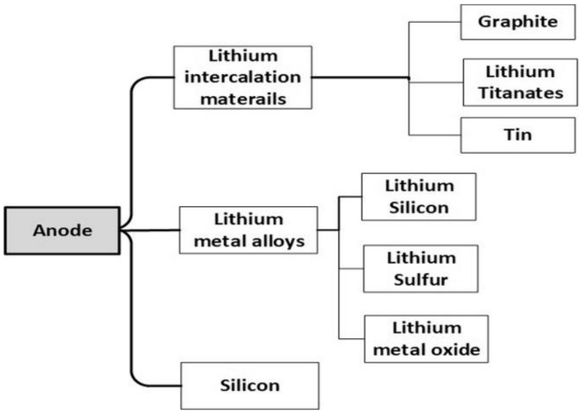


Fig 2. Classification of Anode Materials in SSB.

Tin (Sn)-based anodes provide higher capacity than graphite but face large volume expansion and poor stability. Alloy anodes such as Li–Si, Li–Sn, and $Li_4Ti_5O_{12}$ offer improved capacities; Li–Si has very high capacity with severe volume changes, while Li–Sn is more stable but with lower capacity.

Conversion-type anodes (e.g., $LiCoO_2$, $LiAlH_4$) offer high capacity but suffer from structural instability, while sodium (Na) metal is a low-cost alternative with reasonable performance but limited by dendrite formation and poor cycling stability. Recent approaches include graphite surface patterning to enhance ion transport and reduce polarization, and anodeless designs where metal is deposited in situ to improve energy density and SSB performance.

B. Cathode

All-solid-state batteries (SSBs) use high-energy, long-life cathodes such as LCO, NCA, NMC, LMO, and LFP, classified as spinel, layered, olivine, and tavorite types. NMC provides high capacity (>200 mAh g^{-1}) but is less effective in ASSBs, while advanced materials like LMNC offer improved capacities (200–290 mAh g^{-1}), enabling next-generation high-energy-density ASSBs (~1000 Wh L^{-1}, 400 Wh kg^{-1}).

Sulfur is a low-cost, high-capacity cathode (~1145.9 mAh g^{-1}) with good retention when combined with nitrogen-doped carbon. In sodium ASSBs, glass-ceramic cathodes are preferred due to safety, low cost, and fast Na^+ diffusion.

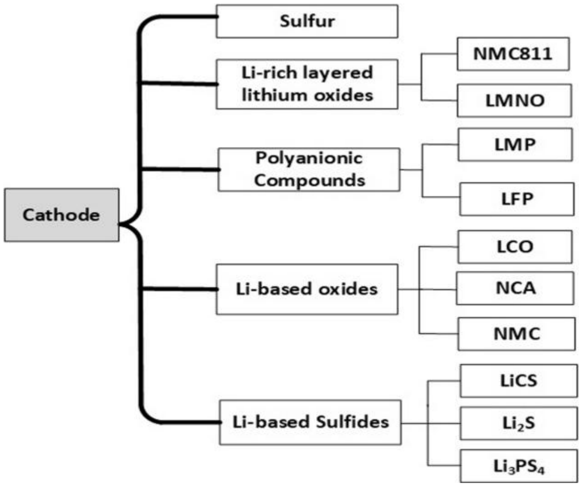


Fig 3. Classification of Cathode Materials in SSBs

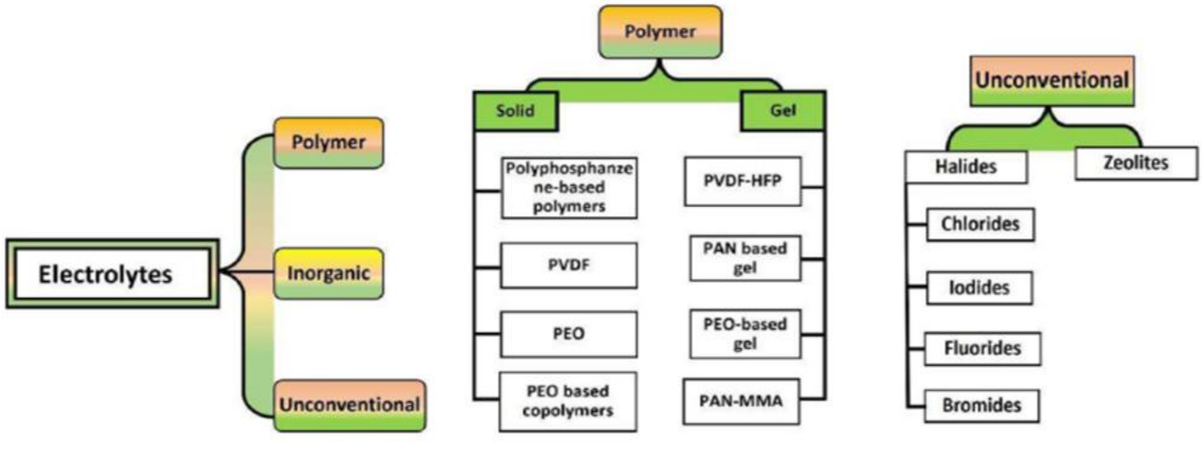
Performance is improved using coatings such as LiPON, Al_2O_3-coated LNMO, and $LiFePO_4$ with polymer electrolytes, enhancing conductivity and buffering volume changes. Li-rich Li_2RuO_3 also provides high stability and good capacity retention.

C. Electrolytes

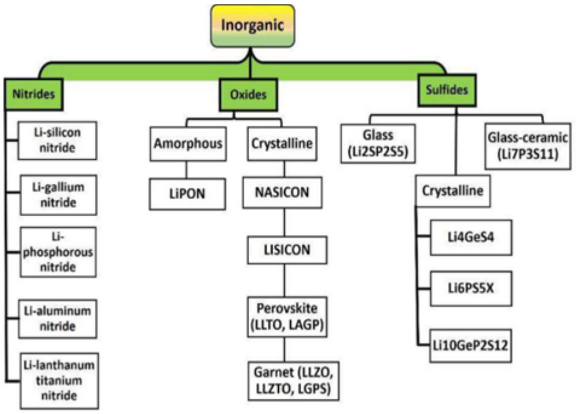
Electrolytes are essential in batteries; in SSBs, solid electrolytes replace liquid ones, offering better thermal stability, lower flammability, improved durability, and simpler design, but typically lower room-temperature ionic conductivity.

Solid electrolytes are classified into polymer, inorganic, and unconventional types. Polymer electrolytes (e.g., PEO, PVDF) offer flexibility and good electrode contact but have lower ionic conductivity and safety concerns; gel types can reduce dendrites but may increase interfacial resistance. Inorganic electrolytes (oxides, sulfides, halides) provide higher ionic conductivity (1–10 mS cm^{-1}) and better Li^+ transport than polymers.

Oxide electrolytes include amorphous (LiPON) and crystalline types such as garnet, perovskite, NASICON, and LISICON.



(a) (b) (c)



(d)

Fig 4. (a) Classification of Electrolyte Materials in SSBs (b)Polymer, (c) Unconventional, (d) Inorganic.

Garnet-based LLZO offers high stability but is prone to dendrite formation and sensitivity to CO_2/moisture. Sulfide electrolytes provide very high conductivity but have interfacial instability issues.

Unconventional electrolytes such as halides and zeolites offer good conductivity, air stability, and scalability but need buffer layers for metal anodes and better low-temperature performance. Hybrid electrolytes (e.g., DOL, PEGDMA) are also explored to improve ion transport and overall performance.

Electrolyte selection strongly affects battery performance, and optimizing anode, cathode, and electrolyte combinations is essential to improve thermal stability, conductivity, and durability.

Electrolytes are evaluated based on chemical stability, ion selectivity, mechanical strength, and cost. Ceramics have high elastic modulus, making them suitable for rigid, high-temperature systems, while polymers have lower modulus, enabling flexibility and lower-cost, easier processing.

III. WORKING OF SOLID-STATE BATTERY

Current flow in solid-state batteries is similar to conventional batteries (anode to cathode) but uses a solid electrolyte instead of liquid. Solid electrolytes provide longer life and better durability due to lower reactivity. However, SSBs are currently limited to low-power use, with ongoing research focused on improving capacity and ionic conductivity to match lithium-ion batteries.

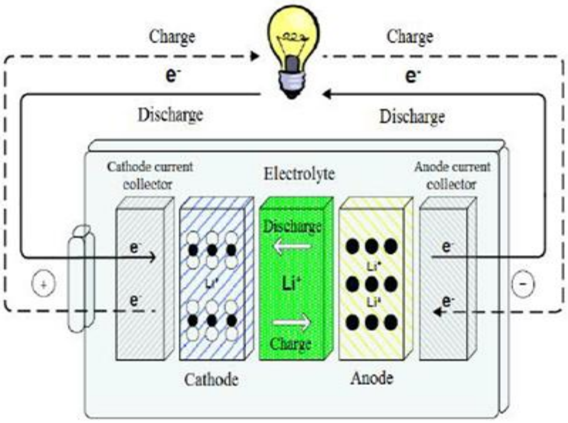


Fig.5 Schematic Diagram of all Solid-State Batteries

Advanced materials and manufacturing can address solid electrolyte limitations. Currently, SSBs are used in small devices like smartphones and tablets, offering fast charging, longer life, and high safety. Research aims to extend these advantages to high-power applications like electric vehicles and energy-intensive systems.

IV. SELECTION CRITERIA FOR SOLID POLYMER ELECTROLYTES

Electrolytes are crucial for battery performance, with over 25 types of solid-state electrolytes available, including oxides, sulfides, phosphates, and various polymer systems. Among them, polyether- and LiPON-based electrolytes are most commonly used in SSBs.

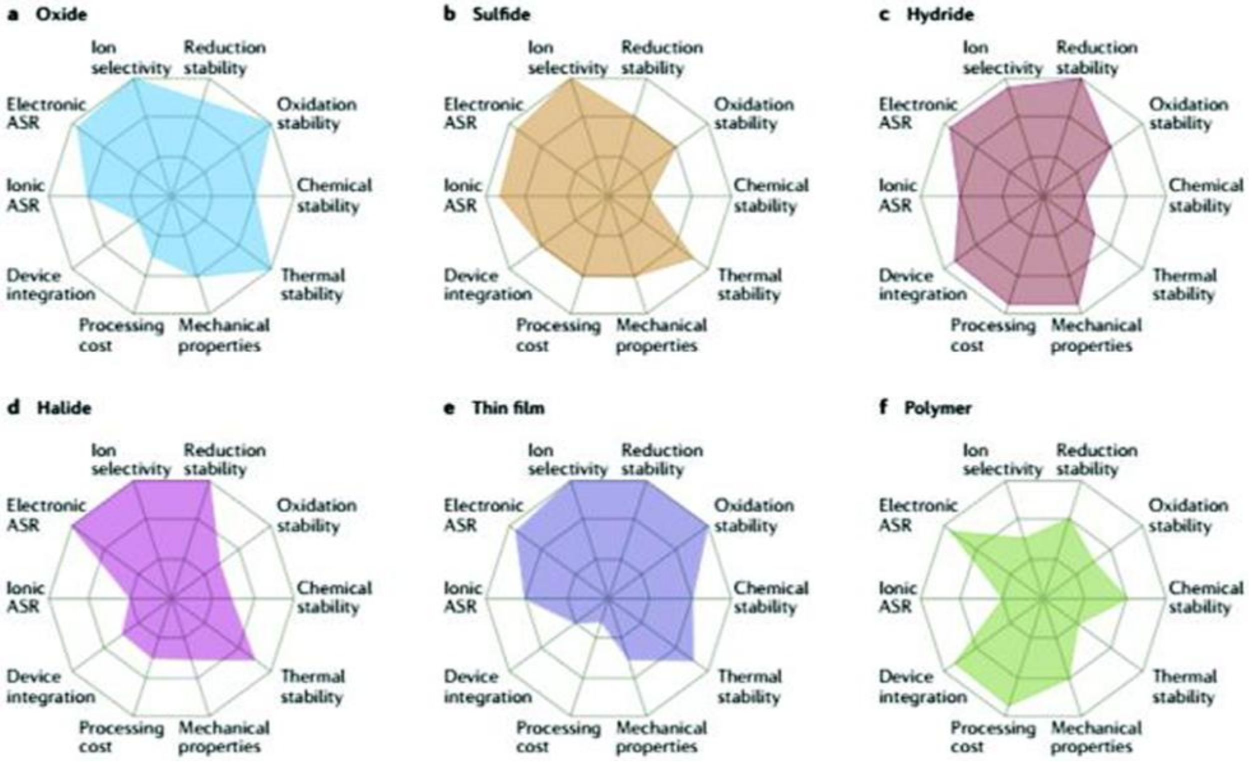
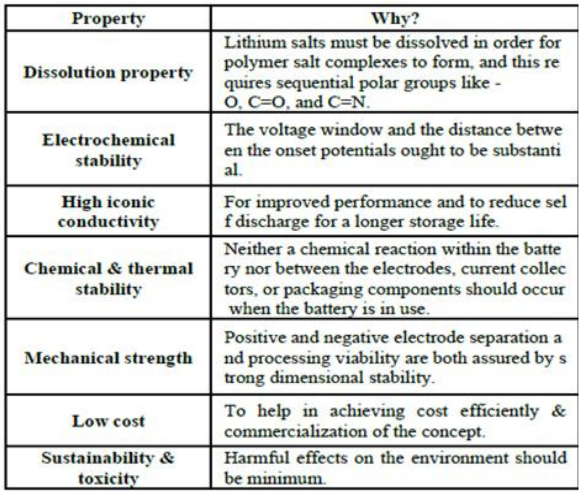


Fig 6. Performance analysis of different solid electrolyte materials

Table.1 SSB Electrolyte Properties for Selection Criteria



Property	Why?
Dissolution property	Lithium salts must be dissolved in order for polymer salt complexes to form, and this requires sequential polar groups like -O, C=O, and C=N.
Electrochemical stability	The voltage window and the distance between the onset potentials ought to be substantial.
High iconic conductivity	For improved performance and to reduce self discharge for a longer storage life.
Chemical & thermal stability	Neither a chemical reaction within the battery nor between the electrodes, current collectors, or packaging components should occur when the battery is in use.
Mechanical strength	Positive and negative electrode separation and processing viability are both assured by strong dimensional stability.
Low cost	To help in achieving cost efficiently & commercialization of the concept.
Sustainability & toxicity	Harmful effects on the environment should be minimum.

V.TYPES OF SOLID-STATE BATTERIES

Solid-state batteries (SSBs) in EVs are classified by solid electrolyte type and cell design, with each offering different trade-offs in performance, safety, and scalability

The main types of solid-state batteries used in EVs are:
1)Oxide-based solid-state batteries
2)Sulfide-based solid-state batteries
3)Polymer-based solid-state batteries
4)Hallide/ Chloride solid state batteries
5) Composite (hybrid) solid-state batteries
6)Thin-film solid-state batteries

A. Oxide-based Solid-State Batteries

Oxide-based SSBs use ceramic electrolytes like garnet-type LLZO ($Li_7La_3Zr_2O_{12}$) and offer high safety, non-flammability, high energy density, wide electrochemical window, and good compatibility with high-voltage cathodes, along with strong stability against lithium metal. These batteries offer better safety and thermal stability than liquid systems but suffer from low ionic conductivity, high-temperature processing needs, brittleness, and high interfacial resistance due to poor electrode–electrolyte contact.

B. Sulfide-based Solid-State Batteries

Sulfide-based SSBs offer high energy density, fast charging (5–10 min), and improved safety. Sulfide electrolytes (e.g., lithium phosphorus sulfide) provide very high ionic conductivity and good flexibility for better electrode contact. Key advantages incionic conductivity comparable to liquid electrolytes and mechanical ductility that maintains interface contact during volume changes. They are classified as amorphous (glassy), glass-ceramic, and crystalline types. However, they suffer from poor air stability, moisture sensitivity, and possible release of toxic hydrogen sulfide gas, requiring careful handling.

C. Polymer-based Solid-State Batteries

Polymer-based SSBs use solid polymer electrolytes (e.g., PEO) instead of flammable liquids, improving safety, flexibility, and energy density with lithium metal anodes. They reduce dendrite growth and leakage but typically require higher operating temperatures due to low room-temperature ionic conductivity. They provide good safety (non-flammable), flexibility, easy processing, and strong electrode contact, making them suitable for wearables. They are also lightweight and enable smaller battery size by removing liquid components.

D. Halide/Chloride Solid-State Batteries

Halide/chloride SSEs are emerging alternatives to sulfide and oxide electrolytes, offering high ionic conductivity and strong high-voltage stability for lithium and sodium solid-state batteries. They offer high room-temperature ionic conductivity ($\sim10^{-3}$–10^{-2} S/cm), a wide electrochemical stability window (>4 V), and good compatibility with high-voltage cathodes (e.g., NCM811), while forming stable cathode interfaces that reduce coating needs. Their softer, more deformable nature improves electrode contact at lower pressure and supports scalable, cost-effective production (e.g., ball milling). Some chlorides like Li_3InCl_6 also show better moisture stability than sulfides.

E. Composite (Hybrid) Solid-State Batteries

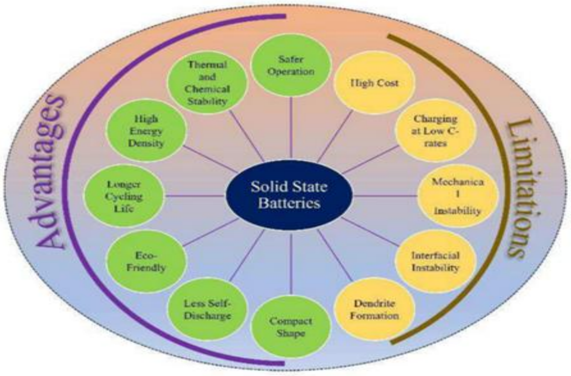
Hybrid (composite) SSBs combine ceramic electrolytes with polymers, offering mechanical strength and good electrode contact, improving interfacial stability, safety, and performance, and enabling faster charging and high energy density (~400 Wh/kg) for EVs. They combine polymers (PEO, PVDF-HFP) with ceramic fillers (LLZO) to balance conductivity and flexibility. The ceramic blocks dendrites while the polymer improves contact. They are non-flammable, operate over wide temperatures, and can be made using modified lithium-ion manufacturing methods.

F. Thin-film solid-state batteries

Thin-film batteries (TFBs) are compact solid-state devices with layered materials and solid electrolytes, offering ultra-thin flexible design, high safety, fast charging (<15 min), long cycle life (10,000+ cycles), wide temperature range (−40°C to +125°C), and high energy density (300–450 Wh/L). They use solid electrolytes, eliminating leakage and separators, and are made via vacuum or sputter deposition. TFBs offer low self-discharge, reliable operation in harsh conditions, and fast charging due to efficient ionic transport.

VI. ADVANTAGES OF SSBS

Rising energy demand, emission reduction goals, and reduced fossil-fuel dependence are driving solid-state battery (SSB) development. They enable efficient renewable energy storage and EV adoption for sustainability. Despite issues like high cost, interfacial instability, and dendrites, SSBs offer clear advantages over conventional lithium-ion batteries in EVs.



A. Increased Energy Density:
Higher energy density enables longer driving range.

B. Faster Charging:
Reduced charging time improves convenience.

C. Improved Safety:
No flammable liquid electrolytes, lowering fire risk.

D. Longer Lifespan:
Lower degradation extends battery life and reduces cost.

E. Better Extreme Performance:
Operates efficiently at high and low temperatures.

F. Cost Potential:
Currently expensive, but may become cost-competitive with scaling.
Despite these benefits, large-scale adoption is limited by high costs and production challenges.

VII. CONCLUSION

Solid-state batteries (SSBs) are set to transform energy storage for EVs, grids, and wearables through safer, efficient, and sustainable solutions. Replacing flammable liquid electrolytes improves safety, thermal stability, and eliminates leakage. By 2026, they target ~400–500 Wh/kg energy density and ultra-fast charging, potentially doubling EV range. Sulfides lead in performance, oxides offer stability, and hybrids balance conductivity, safety, and scalability. Key challenges include interfacial instability, dendrites, high cost, and scalable manufacturing. Early commercialization is expected in 2026, with mass production and cost parity by 2028–2030.

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