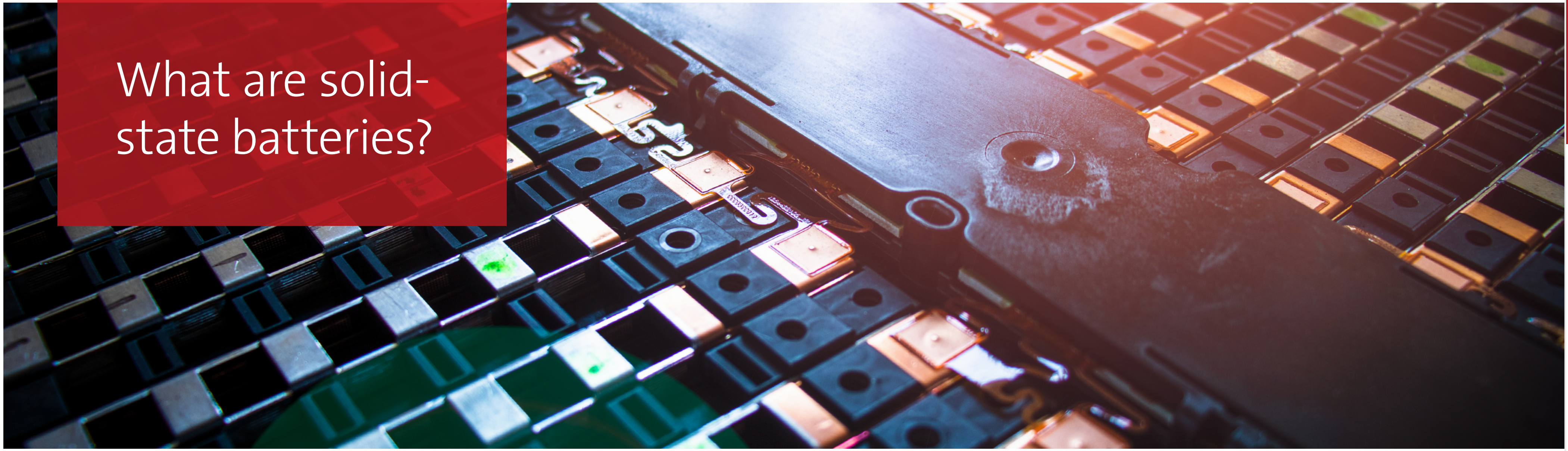
The solid foundation of solid-state batteries

Stakeholders in the solid-state battery supply chain can benefit from the latest testing and certification methodology from UL Solutions

UL Solutions

Safety. Science. Transformation.™



What are solid-state batteries?

Batteries that use a solid-state electrolyte (SSE) as their ionic conductor between the anode and cathode are called solid-state batteries (SSBs). SSBs can conduct different types of ions, such as lithium-ion, aluminum-ion or sodium-ion. However, lithium-ion is the most popular as it features the highest theoretic energy density due to it having the smallest atomic size and lightest weight.

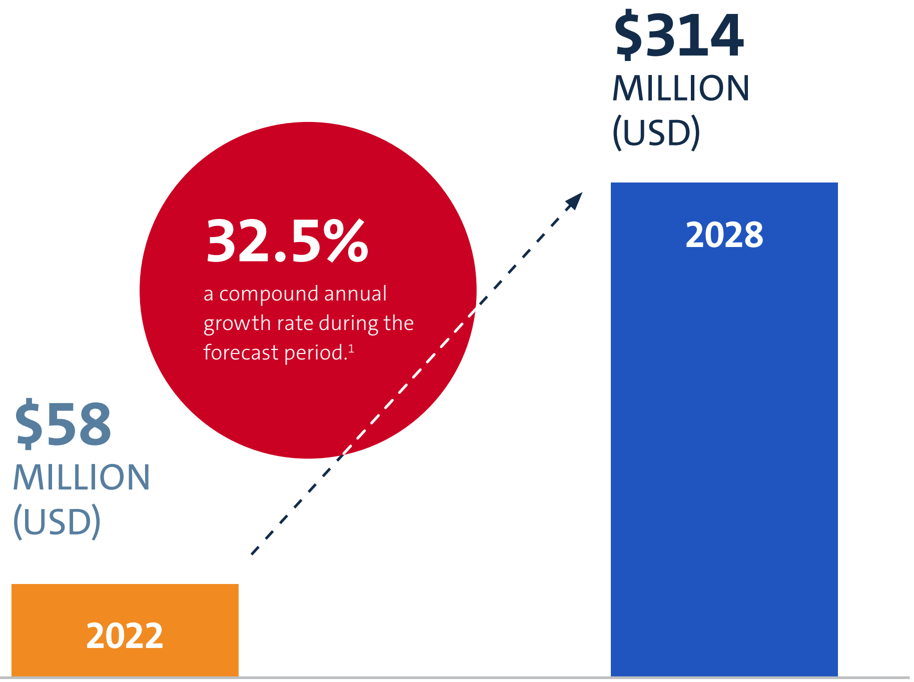
This bullish growth rate forecast ***INDICATES***

GROWING

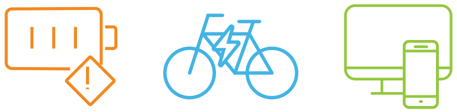
CONFIDENCE

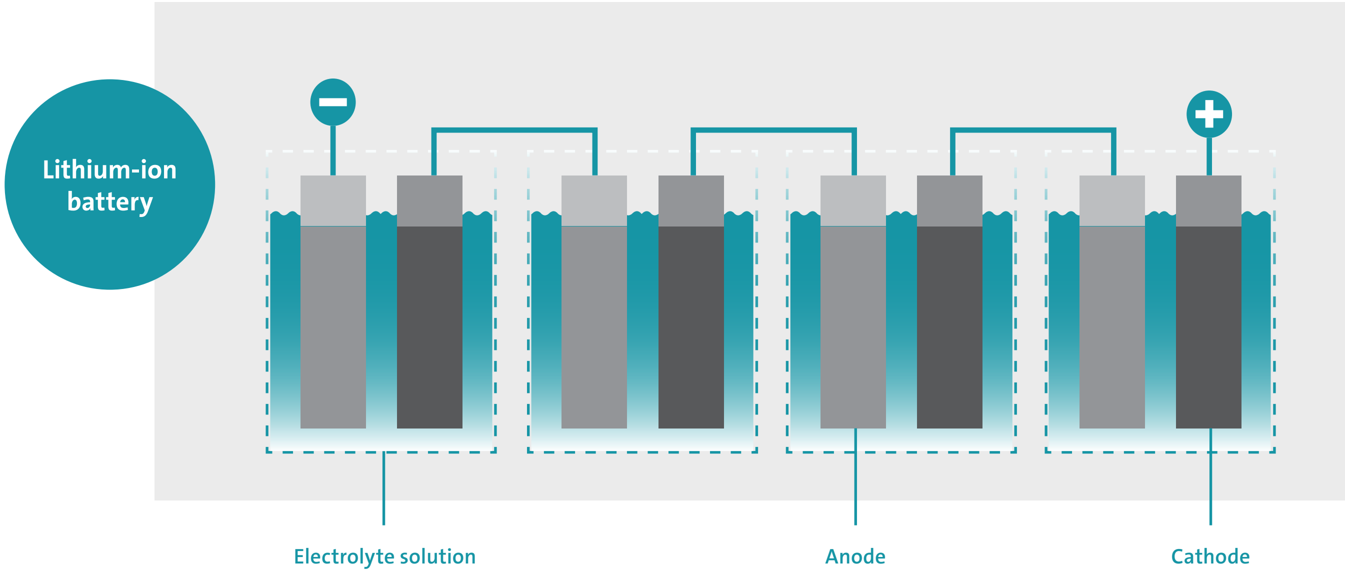
of this battery technology.

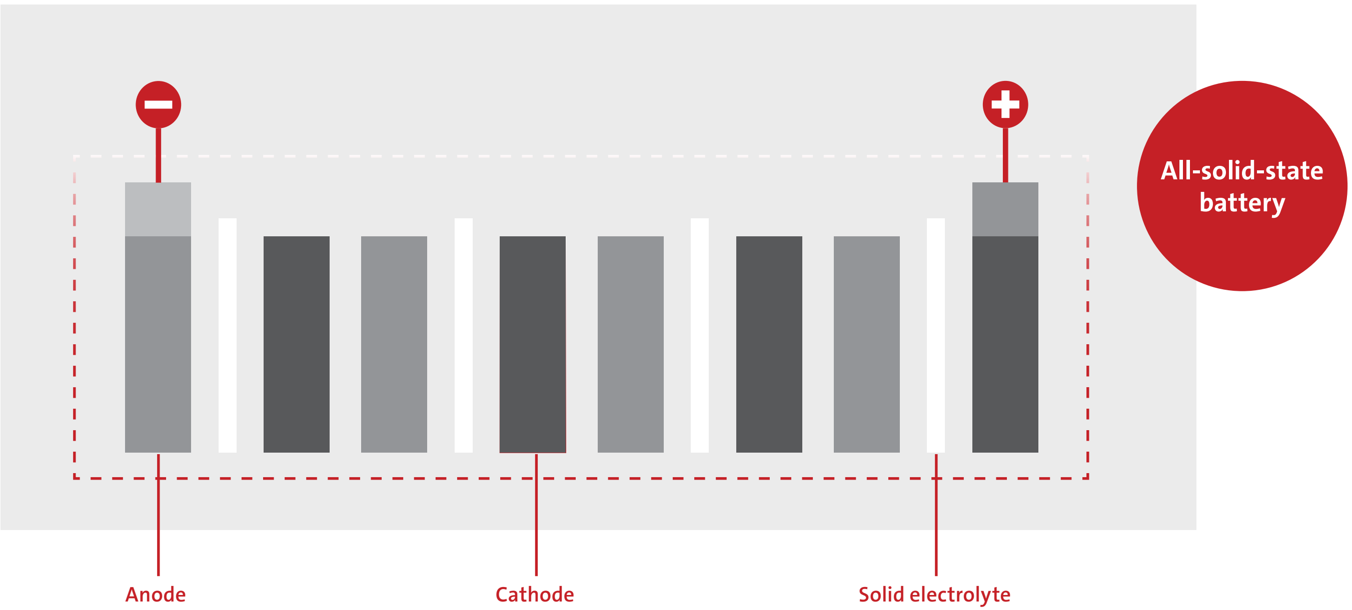
The global solid-state battery market size is estimated to grow from



As conventional lithium-ion battery technology has shown its limitations with energy density and safety concerns, SSBs are considered the most promising next-generation battery. They offer high performance and possibility of improved safety at a low cost. Generally, in controlled lab environments, SSBs have lower flammability, higher electrochemical stability, higher potential cathodes and higher energy density as compared to liquid electrolyte batteries.[2]







Developing an SSB is not just replacing the liquid electrolyte and separator in lithium-ion batteries with an SSE, additional advancements such as changing the anode or cathode materials should be taken into consideration. On the cathode side, conventional cathode materials such as lithium cobalt oxide can be replaced by high-voltage cathode materials, such as lithium-sulfur or lithium-air, to increase the working voltage or accommodate more lithium ions. To improve energy density and capacity on the anode side, changes may include replacing the graphite anode with a silicon-graphite compound, silicon or lithium metal. Lithium metal anodes offer an advantage because no space or weight for the host material is wasted. Lithium ions can be stored in the form of solid metal in the anode. Most all-solid-state batteries (ASSBs) use lithium metal as the anode to maximize energy density, a key benefit of SSB technology.

The advantages and growing use case for SSBs

With decades of development and evolution, lithium-ion batteries are popular today and used in a wide range of applications, such as portable electronics, grid-energy storage systems and electric vehicles. However, most of the lithium-ion batteries in the market now use liquid electrolytes, a mixture of multiple organic compounds that are inherently flammable and unstable under raised temperatures. In recent years, dangerous incidents involving personal injuries and property damage have occurred in products such as earbuds, cell phones, electric vehicles (EVs) and battery energy storage systems.

Factors such as the rising requirement of solid-state batteries in EVs, the increasing trend toward the miniaturization of consumer electronics, and growing R&D activities by major companies are driving the growth of the solid-state battery market.[3] Solid-state batteries support advanced consumer electronics such as mobile devices and laptops, are being adopted more in emerging applications such as energy harvesting and wearable devices and could be a game-changer for EVs.[4]

The most desirable advantage of an SSB is the high volumetric and gravimetric energy density. **SSBs offer several advantages over conventional lithium-ion batteries because they:**

are more
environmentally friendly
as SSBs do not leak toxic organic fluids and have non-volatility properties.

are more
tolerant
to working and storage temperature ranges, especially at low-temperature storage and high-temperature operation.

are more
stable
mechanically and thermally

are more
efficient
and have faster charging rates, using a lithium metal anode.

represent a higher possibility of
sustainability and recyclability
currently missing with today's lithium-ion technology.

Another benefit of SSBs is that when compared to conventional organic electrolytes, SSEs can still exist under much higher working voltage, which makes the application of high-voltage cathode materials feasible. For instance, using fluorides as solid electrolytes can easily lift the voltage to over 5V or even 6V, and no major decomposition can be triggered on the solid-state electrolyte.[5] In contrast, conventional organic electrolytes are prone to decompose at higher voltage conditions, so the maximum charging voltage is normally limited to around 4.2V. A higher working voltage indicates more power can be delivered from the battery. As a result, SSB adopting high working voltage can provide high power density than conventional lithium-ion batteries. Also, the battery charging current can either be lowered, reducing heat buildup which results in battery degradation, or kept the same, reducing time to reach full charge when comparing same capacity batteries between lithium-ion and solid-state batteries.

Applications of solid-state batteries span multiple industries, including:

Energy storage | Consumer electronics | Automotive | Industrial | Aerospace

Due to ultra-high energy density and fast charging capabilities, SSBs are more desirable for EVs applications as they can allow EVs to achieve better performance to meet or even exceed user expectations over conventional gasoline vehicles. Most automotive companies are investing in batteries and racing to patent critical next-generation battery technologies and battery management systems.

Advantages and challenges of liquid lithium-ion batteries versus solid-state batteries[6]

Liquid lithium-ion battery

Advantages

- Low processing cost
- Flexible separators can withstand high mechanical stress
- High ionic conductivity only at room temperature

Challenges

- Self-discharge may reduce shelf life
- Electrolytes used are flammable; it can cause combustion in EVs
- Solid-electrolyte Interfacial (SEI) layer formation affects life cycle
- Limited choice of cathode materials due to electrolyte reaction
- Poor thermal stability
- Sensitive to overcharge

Solid-state lithium-ion battery

Advantages

- Excellent thermal stability
- Comparatively less self-discharge
- High ionic conductivity over a broad range of temperatures
- Electrolyte used is non-volatile
- Electrolytes are non-flammable, and thus, safe
- High energy density
- High tolerance
- No SEI layer formation, and thus, a longer life cycle

Challenges

- Ceramic separator used is rigid and it may break with additional stress

Challenges and safety concerns of SSBs

Currently available SSBs face a challenge in terms of their approximate three years of operating life.[7] But research and development is currently underway to solve this issue.

An ideal SSB should have these attributes:

- **A thick composite positive electrode layer** with high active mass loading
- **A lithium metal anode** with or without a thin extra lithium layer for plating lithium
- **A thin, solid electrolyte layer** to achieve target energy and power performance

However, there are some challenges to achieving such SSBs, including:

- **Interfacial problems**
- **Dendrite growth**
- **Low ionic conductivity of the SSE**
- **Poor electrochemical stability**
- **Poor mechanical stability**
- **Lack of feasibility for large-scale production.**

These problems can cause poor performance and limit their application scope. Among all the key problems mentioned in the list above, interfacial problems and dendrite growth can cause significant impacts on performance and safety.

Similar to the solid-liquid interface of conventional lithium-ion batteries, electrochemical reactions that occur at the solid-state electrolyte/electrode interface in SSBs can also cause some issues. In SSBs, lithium ions conduct from electrolyte to electrode and perform redox reactions with active materials and electrons at the electrolyte-electrode interfacial region.

Repeated interfacial stress variations caused by repeated volume changes of the cathode and anode materials during battery cycling can worsen the connection issues. This problem can become worse in the batteries with lithium metal anodes because the lithium plating/stripping behavior will result in a bigger scale of volume change.

Dendrites are metallic microstructures that form during the charging process. Dendrite formation at the anode surface is a significant challenge related to safety and cyclability for high-energy-density lithium batteries and many other battery types. Because of the heterogeneity between electrolyte and anode, dendrites can form at the anode-electrolyte interface during the charging/discharging process. If the current distribution on the anode surface is uneven, the formation of dendrites becomes more severe. Dendrites can continuously grow and cause internal short-circuits in cells, leading to cells overheating or even catching fire.

Theoretically, the probability of an SSB causing thermal runaway is lower than a lithium-ion battery due to the higher trigger temperature and due to the lack of liquid electrolyte reactions. In practice it will need to be proven depending on the SSB's composition, physical configuration and application/use-case. An SSB with a lithium metal anode contains more lithium than conventional lithium-ion batteries, so the hazard of thermal runaway can be more severe if all the lithium is reacted.

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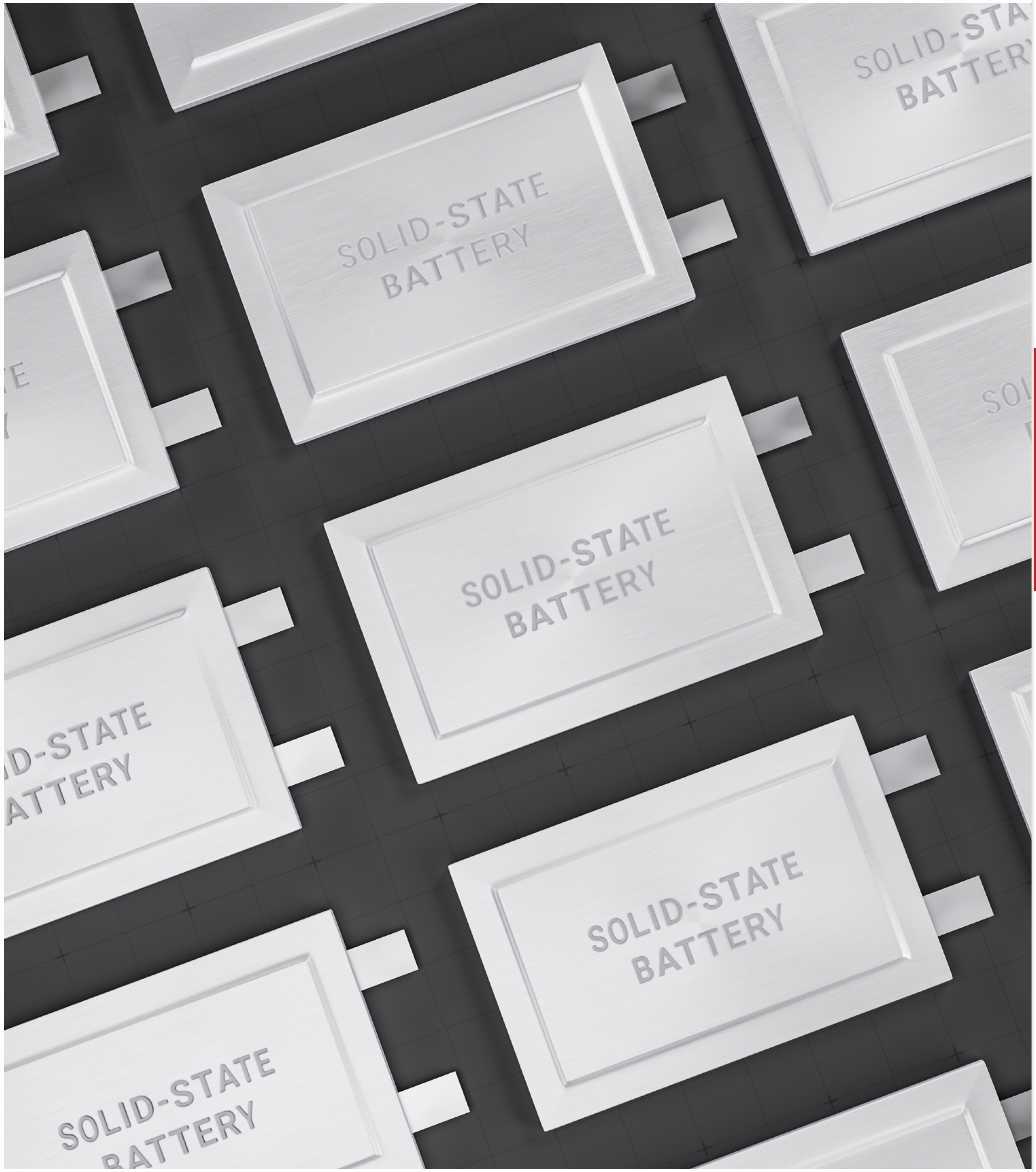


Mitigating SSB risks

By using a risk assessment approach to SSB design and manufacturing, stakeholders can assess the safety risks associated with battery technologies and identify the need for additional testing. Further, other tests may be required to address application-specific requirements or jurisdictional regulations applicable to battery technologies.

These complexities can result in a seemingly exhaustive array of testing to assess the safety of a given battery technology, device or product. UL Solutions can help manufacturers develop a comprehensive strategy at the outset of the product development process to reduce overall expenditures, save time and help avoid unanticipated safety and performance issues that could delay market introduction. At a minimum, the process of developing a comprehensive strategy for batteries should include the following steps:

Step 1

Risk assessment

- Evaluate potential safety risks and hazards associated with the power source.
- Identify necessary design changes to address risks and hazards.
- Pinpoint other safety evaluation and testing criteria that may be required.

Step 2

Understand the regulatory landscape

- Identify target markets and relevant regulations in each geographic location.
- Investigate and outline baseline requirements.
- Map evaluation, testing and certification plans based on regulatory requirements.

Step 3

Consider marketplace requirements and customer expectations

- Identify requirements or measures that could result in competitive advantage.
- Map any evaluations, tests and certifications required to meet regulations, validate product claims, enhance consumer product acceptance or differentiate offerings.

Step 4

Seek expert advice and counsel

- Identify independent accredited ISO 17065 certification organizations to facilitate planning.
- Outline cost-effective evaluation, testing and certification strategies for long-term savings.
- Ask questions about international requirements.

How UL Solutions can help

UL Solutions, a global safety science leader, supports the advancement of battery technologies by helping to drive confidence in innovation. We can test and certify battery products, including solid-state battery cells as well as battery cells and packs, chargers and adapters, and battery-operated end products, to key international, regional and national standards and certification schemes, including:

UL 1642	the Standard for Lithium Batteries (including SSBs)
UL 1973	the Standard for Batteries for Use in Stationary and Motive Auxiliary Power Applications
UL 2054	the Standard for Household and Commercial Batteries
UL 2271	the Standard for Batteries for Use In Light Electric Vehicle (LEV) Applications
UL 2580	the Standard for Batteries for Use In Electric Vehicles
IEC/EN 60086 series	non-rechargeable cells and packs
IEC/EN 61960 series	rechargeable cells and packs - performance
IEC/EN/UL 62133-2	rechargeable lithium cells and packs - safety
IEC/EN/UL 62368-1	audio/video, communication, IT incorporating batteries
IEEE 1625/1725	addressing CTIA Wireless Assoc. requirements for tablets and mobile phones
Other regional and country-specific performance and safety standards	

With continued growth and innovation in SSB technology, OEMs, suppliers, and manufacturers of batteries and battery-operated end products should seek the support of knowledgeable and trusted third-party laboratories to help enhance safety and performance, reduce development cycles and increase speed-to-market.

UL Solutions offers comprehensive testing and certification services for battery technologies. Our capabilities span electrochemical properties, environmental, mechanical and electrical reliability to help you to manage safety risks and product quality, improve performance and demonstrate compliance for market access.

At UL Solutions, we're constantly looking at how technology will impact safety to stay on pace with market developments and work closely with consumer advocacy, trade associations and user groups to shape standards designed to identify and mitigate risk.

We offer a comprehensive battery safety program for manufacturers that can help reduce the likelihood of safety issues:

Recognized expertise

We offer more than 40 years of experience in battery evaluation and testing. By demonstrating compliance to applicable standards, thousands of products have earned UL certification, a key driver of brand reputation and public trust.

Supplier selection

Success often rests on the caliber of partners involved in a project. The UL Prospector® and UL Product iQ® databases help manufacturers identify suppliers that fit their needs by properties, applications, safety data, performance characteristics and more.

System approach to safety

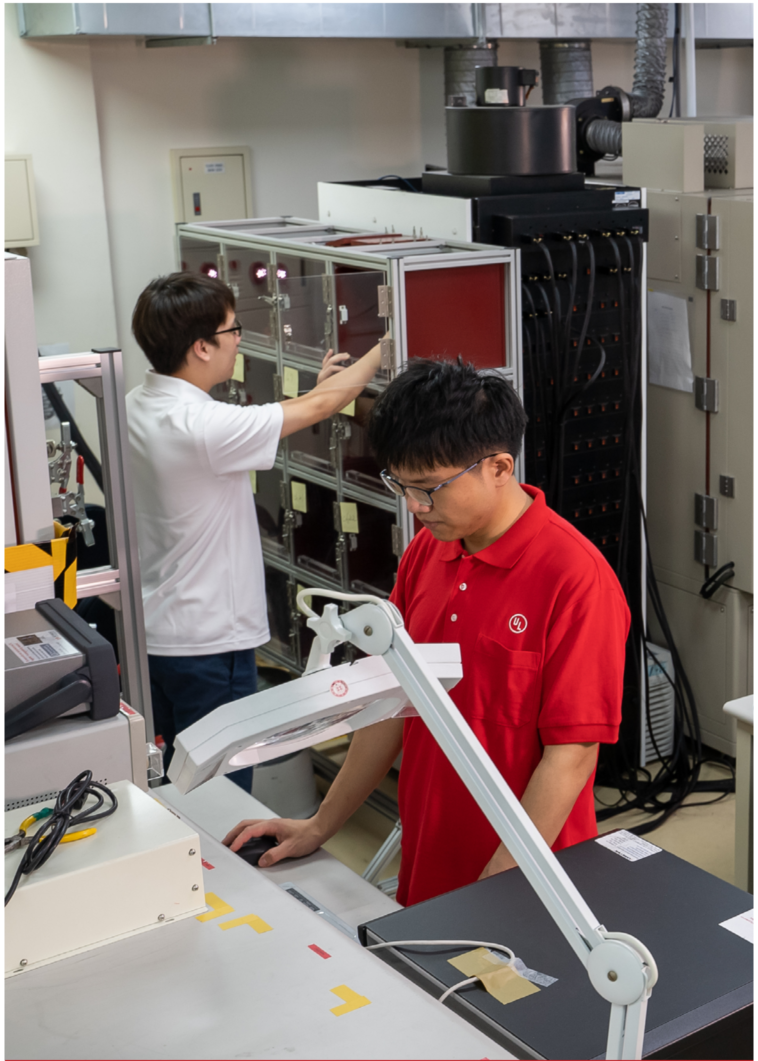
We take a systems approach to safety and analyze ancillary products consumers depend on, such as replacement batteries and chargers.

Failure analysis and audits

Some of the best information about product safety comes when we push products to the limit and identify areas of vulnerability, using methods such as simulation, physical testing and fault tree analysis.

Continual education

We offer self-paced training to research and development, compliance, factory, assembly, maintenance, transportation and shipment workers across the entire battery value chain, as well as informative webinars that help navigate the regulatory landscape.



To learn more about our battery testing and certification services, visit us at UL.com/batt or contact us at UL.com/contact-us

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