Industry Focus

Energy Storage Technologies

An exclusive collection featuring top-tier articles, visionary experts, and essential industry insights

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Foreword

Welcome to the latest edition of our Industry Focus eBook, where we explore the rapidly evolving world of energy storage technologies. As global demand for efficient, sustainable, and high-performance energy solutions continues to grow, breakthroughs in battery production, materials, and recycling are shaping the future of the industry.

In this edition, we examine cutting-edge advancements driving energy storage forward. From precision monitoring in battery electrode manufacturing to the game-changing potential of mass profilometry, innovation is redefining production quality and efficiency. We also explore the latest trends in the global lithium battery market, highlighting key factors influencing growth and sustainability.

Solid-state battery technology remains a focal point of research, with new developments pushing the boundaries of performance and safety. Meanwhile, alternative battery chemistries—such as cost-effective aluminum-ion solutions—are paving the way for environmentally friendly energy storage. As industries seek cleaner and more efficient solutions, recycling plays a crucial role in reducing the environmental impact of battery production compared to traditional mining.

Beyond the realm of batteries, novel approaches like nanofluids and turbulators are unlocking new possibilities for sustainable energy applications. And in the automotive sector, we look ahead to 2025, analyzing what's next for electric vehicles and energy storage in transportation.

This eBook captures the essence of progress in energy storage, bringing together expert insights and emerging trends that will shape the future of energy solutions. We hope these articles inspire fresh ideas and foster meaningful discussions in this exciting field.

Lexie Corner
Editor

AZO NETWORK

The Global Lithium Battery Market: Growth and Trends

Li-ion (Li-ion) batteries can be used in multiple products, including electronics, battery-powered industrial equipment, wireless headphones, household appliances, and energy storage systems. Innovative Li-ion battery manufacturing and recycling techniques are being commercialized rapidly, significantly increasing global demand.[1]

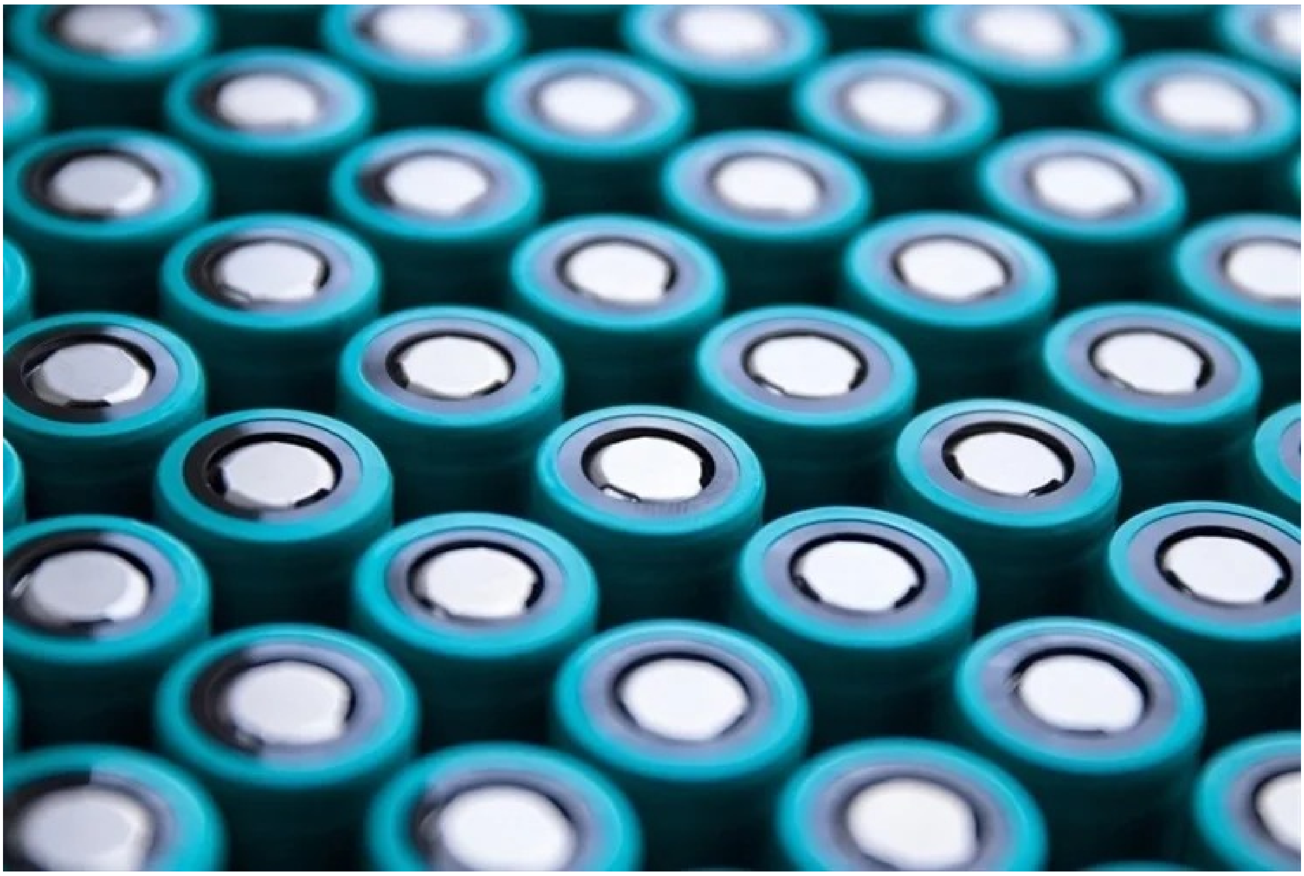


Image Credit: P5h/Shutterstock.com

Li-Ion Batteries: Current Market Dynamics

Over the past ten years, Li-ion batteries have gained popularity in domestic and industrial applications. Their superior charge density and ability to store electric energy are the core reasons for their success.

Their superior energy density means these batteries can store much higher energy than traditional products, using much less material and in a much smaller volume. This makes them a popular choice for small, wearable, and portable products.

The market value of the Li-ion battery industry was about 54.4 billion U.S. dollars in 2023. With the enhanced demand for lithium batteries, experts predict this market will grow steadily, with a compound annual growth rate (CAGR) of around 20.3 % from 2024-2030.[2]

The automotive sector is the primary client of Lio-ion batteries and holds the most development potential. Thanks to the improved capabilities and low cost of Lio-ion batteries, electric vehicle (EV) registrations are expected to expand exponentially worldwide.

The U.S. is at the forefront of this market, with increasing EV sales driven by favorable regulations and numerous private operators. By 2030, 64 % of total lightweight vehicles in the U.S. are expected to be powered using LIBs.[3]

Among the major Lio-ion battery manufacturing companies, Albemarle Corporation (ALB) generates the highest profit, with a market value of 18.1 billion U.S. dollars.[4] Other key players, such as LG Energy Solutions from South Korea, Japan-based industrial giant Toshiba Corporation, and Arcadium Lithium PLC, are the frontrunners in Lio-ion battery development worldwide.

Technological Advancements: More Efficient and Powerful Li-Ion Batteries

Novel types of lithium batteries are emerging every month, with lithium-iron-phosphate (LFP) batteries currently dominating the market. China is the leading manufacturer of LFP batteries, producing nearly 95 % of those installed in light-duty vehicles (LDVs).

Supply chains for sodium-ion batteries, which do not contain lithium, are also being established, with over 100 GWh of manufacturing capacity operating or announced (primarily in China).[5]

With its dominance in LFP battery chemistries, China's CATL produces the majority of truck batteries. LFP batteries' durability and lower cost make them the most preferred alternative to conventional Li-ion batteries.

All-solid-state lithium batteries (ASSLBs), which rely on solid electrolytes, are also gaining popularity as they are much safer to operate. Most manufacturers utilize sulfide electrolytes with high ionic conductivity for their highly efficient operational capability.

However, the significant electronic conductivities of sulfide electrolytes (approximately 10^{-8} S cm^{-1}) facilitate smooth electron transport through the electrolyte pellets, leading to the direct deposition of lithium dendrites at the grain boundaries (GBs) and causing serious self-discharge.

Researchers have recently introduced a grain-boundary electronic insulation (GBEI) strategy to prevent electron transport across grain boundaries (GBs).[6] This approach enables Li–Li symmetric cells to exhibit thirty times longer cycling lives. It also gives the full cells a self-discharging rate three times lower than pristine sulfide electrolytes.

The Li–$LiCoO_2$ ASSLBs demonstrate high-capacity retention of 80 % after 650 cycles and maintain stable cycling performance for over 2600 cycles at a current density of 0.5 mA cm^{-2}.

Challenges and Future Innovations in Lithium Batteries

While lithium batteries offer impressive functionality, they are not without limitations. Lithium extraction poses significant environmental risks, such as depleting underground water levels.[7] Lio-ion batteries also pose fire safety hazards, underscoring the need for prompt solutions to facilitate their swift commercialization.[8]

Recent innovations are expected to shape the future of lithium batteries, with the integration of new materials playing a crucial role in enhancing energy density and reducing raw material expenses, thereby lowering cell and pack costs.

Among these innovations, novel electrolyte chemistries are top of the list. These formulations are vital for developing next-generation negative and positive electrode active materials for lithium battery manufacturing.

Academic and industrial researchers are developing customized liquid electrolyte formulations, including fluorinated solvents, to promote efficient lithium metal cycling.[9] Companies are also investing in novel and efficient lithium extraction techniques that significantly reduce costs and meet progressing performance requirements.

Considering the advancements in lithium battery development, the increasing trend in their utilization is expected to grow exponentially.

References and Further Reading

[1] U.S. Environment Protection Agency. (2023). *Know the Facts: Lithium-Ion Batteries*. [Online] E.P.A. Available at: https://www.epa.gov/system/files/documents/2023-09/Lithium-Ion-Batteries-Fact-Sheet-8-2023.pdf (Accessed on May 02, 2024).

[2] Grand View Research. (2023). *Lithium-ion Battery Market Size & Trends*. [Online] Grand View Research. Available at: https://www.grandviewresearch.com/industry-analysis/lithium-ion-battery-market (Accessed on May 02, 2024).

[3] Eftekhari, Ali. (2019). Lithium batteries for electric vehicles: from economy to research strategy. *ACS Sustainable Chem. Eng.* doi.org/10.1021/acssuschemeng.8b01494

[4] Reeves, J. (2024). *7 Best Lithium Stocks Of May 2024*. [Online] Forbes. Available at: https://www.forbes.com/advisor/investing/best-lithium-stocks/ (Accessed on May 03, 2024).

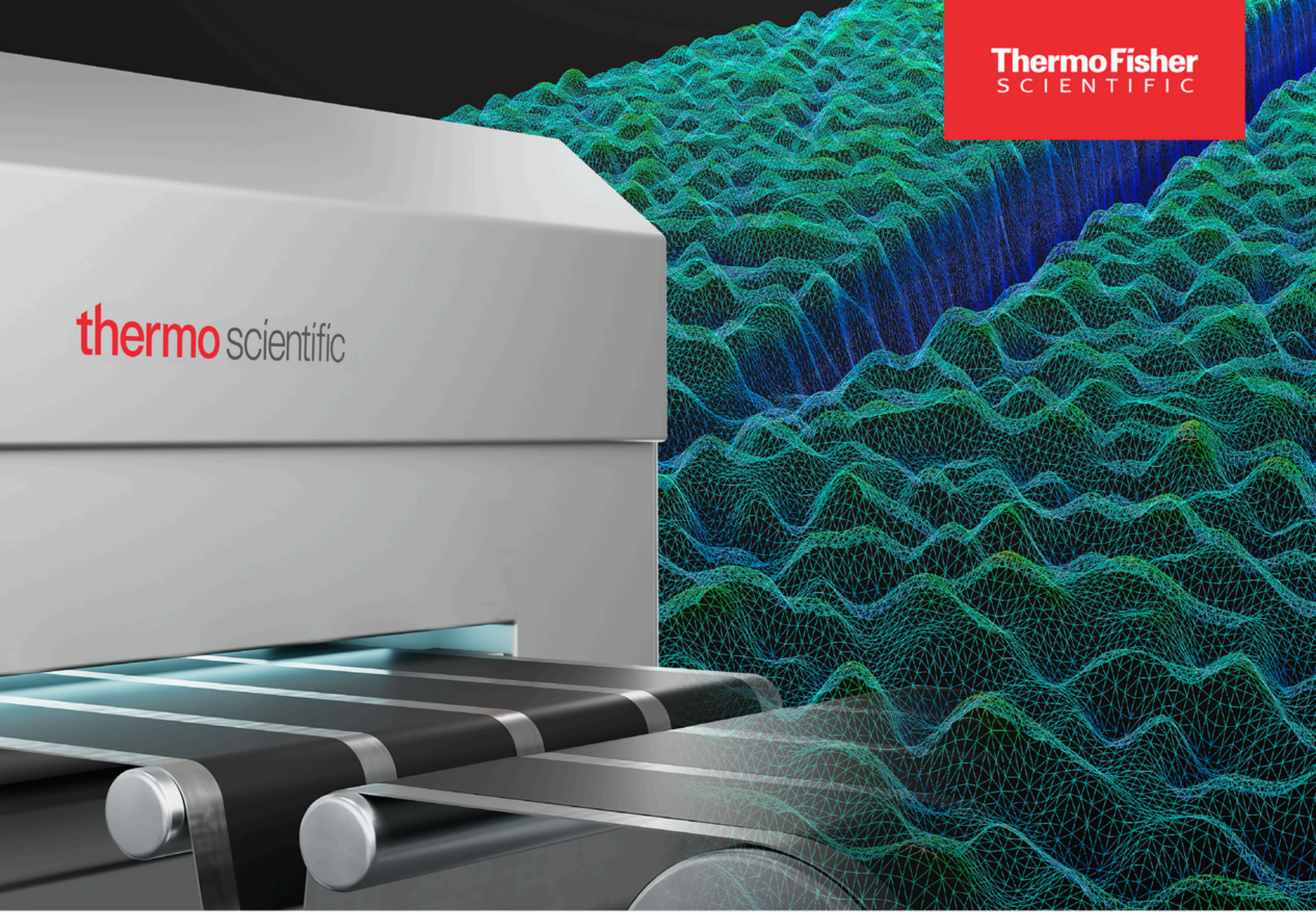
[5] International Energy Agency. (2023). Global EV Outlook 2023: Catching up with climate ambitions. (Online). Available on: https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf (Accessed on May 03, 2024).

[6] Yang, X., *et al.* (2023). Grain boundary electronic insulation for high-performance all-solid-state lithium batteries. *Angewandte Chemie*. doi.org/10.1002/ange.202215680

[7] Anderson, K. (2023). *The Harmful Effects of our Lithium Batteries*. [Online]. Greenly. (Online). Available at: https://greenly.earth/en-us/blog/ecology-news/the-harmful-effects-of-our-lithium-batteries (Accessed on May 04, 2024).

[8] American Society of Safety Professionals. (2024). *Lithium-Ion Batteries: How to Overcome Current and Future Safety Challenges*. [Online] American Society of Safety Professionals. Available at: https://www.assp.org/news-and-articles/lithium-ion-batteries-how-to-overcome-current-and-future-safety-challenges (Accessed on May 04, 2024).

[9] Frith, J, *et al.* (2023). A non-academic perspective on the future of lithium-based batteries. *Nat Commun*. doi.org/10.1038/s41467-023-35933-2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Boost Production Quality by Monitoring Key Parameters in Battery Electrode Processes

The growing demand for Lithium-ion (Li-ion) batteries, driven by applications such as electric vehicles and long-duration energy storage, has increased the pressure on battery manufacturers to enhance both product quality and process efficiency.

Electrode production plays a critical role in the battery supply chain, with an expanding range of options available for monitoring the electrode coating process.

Thermo Fisher Scientific's Thermo Scientific™ LInspector™ Edge In-line Mass Profilometer is an innovative tool that determines the critical parameter of electrode coating weight. With its high resolution, the LInspector Edge In-line Mass Profilometer can efficiently and accurately detect manufacturing defects, ensuring real-time coating quality assurance.

This article explores the measurable metrics, their applications, and the opportunities they present for advanced process control.

A Foundation for Modern Manufacturing

For battery manufacturers, achieving smart manufacturing, digital transformation, and Industry 4.0 relies on adopting innovative solutions for process monitoring. Tools that deliver advanced analytics, real-time data, and interconnectivity are essential to enable decentralized and fully automated decision-making.

The LInspector Edge Inline Mass Profilometer utilizes novel metrology—in-line mass profilometry—to measure the entire surface of coated electrodes in real time, providing coating weight profiles within milliseconds. This generates a rich stream of information that aids in efforts to:

- Assertively classify defects during coating and develop appropriate remedial and management strategies to minimize their impact.
- Improve process control.
- Establish robust end-to-end traceability for every battery.
- Develop multi-physics and data-driven models to facilitate more predictive design and electrode manufacturing processes.
- Build digital twins capable of forecasting the outcomes of various operational strategies, enabling advanced process optimization.

In-line mass profilometry can help battery manufacturers overcome issues such as scrap rates —currently estimated at around 5 % and 30 %—and relatively high levels of unexpected downtime while enhancing battery quality and safety.

Figure 1. *LInspector Edge In-line Mass Profilometer. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

Data Analysis 1: Coating Weight Uniformity

Figure 2 illustrates a two-dimensional heat map of coating weight uniformity in the cross direction (CD) and machine direction (MD).

This live graphical representation of coating weight data employs color coding to depict the magnitude of various values across the coated surface. The traces displayed below and to the right of the heat map highlight the numerical variability for each emerging electrode.

In-line mass profilometry delivers 100 % coating weight measurement, a statistically significant real-time dataflow for responsive decision-making.

Providing complete surface inspection at full production speed, it eliminates the limitations of scanning gauges and other traversing frame technology, which can miss significant areas of the coating, especially at high production speeds.

The straightforward design of the heat map enables process engineers, production managers, and analysts to quickly identify and examine defective regions. For instance, it allows engineers to detect low or high spots, which can then be analyzed in detail to observe the magnitude of individual values and evaluate the degree of variability across the electrode.

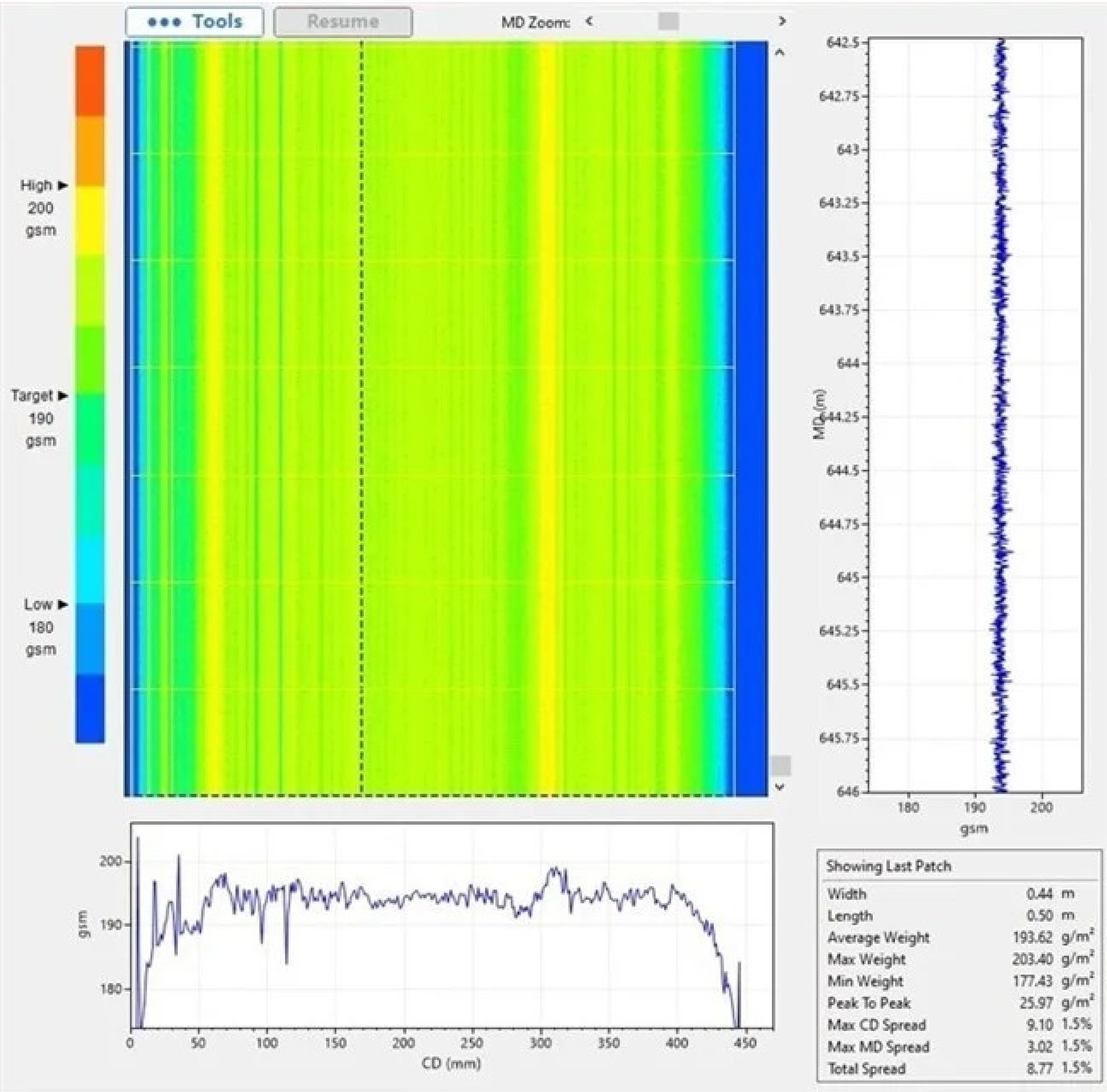

***Figure 2.** 2D heat map, high-resolution CD and MD profiles. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

Data Analysis 2: Defect Detection and Tracking

At higher magnifications, heat maps are particularly effective in revealing defects, as illustrated in Figure 3. Small red areas indicate localized patches of excess coating, which may result from issues such as agglomerates or bubbles. In contrast, broader blue striations across the surface suggest a general lack of loading uniformity across the sample.

Battery manufacturers must address a variety of defect types, including:

- Coating weight defects relating to either average weight or high/low points
- Uniformity defects such as CD spread, MD spread, total spread, Cp and CpK
- Dimensional defects – width or length
- Edge faults, including shallow edge slopes or high edge slopes (bunny ear) on any edge
- Scratches/streaks
- Voids/bubbles
- Agglomerates
- Contaminants
- Chatter/ribbing

Defects can either extend across the full width of the electrode roll, affecting a specific length or be localized to a small, confined area.

Figure 4 presents a heat map stripe profile display, emphasizing edge defects (marked in red).

To enhance visibility and facilitate assessment, stripe edge zoom profiles for these samples are shown in Figure 5. These profiles highlight the side edges of coated stripes across CD web profiles.

Together, these figures demonstrate key features of the system software for defect monitoring, including the ability to:

- Display a minimum of 4 stripe profiles per page and up to 16 scrollable stripes or full-width profiles.
- See coated (white) and uncoated (light blue) zones in real-time.
- Set-up sub-zoom windows for the left and right edges of each stripe for up to 16 stripes.

Statistical values and setup options for the chart display can be customized to suit specific processing requirements. For instance, in the sub-zoom window, users can adjust the X-axis edge zoom display size (in mm) and zoom width (as a percentage) with a 75/25 % bias toward the coating near the target edge position. Similar modifications can also be made to the Y-axis.

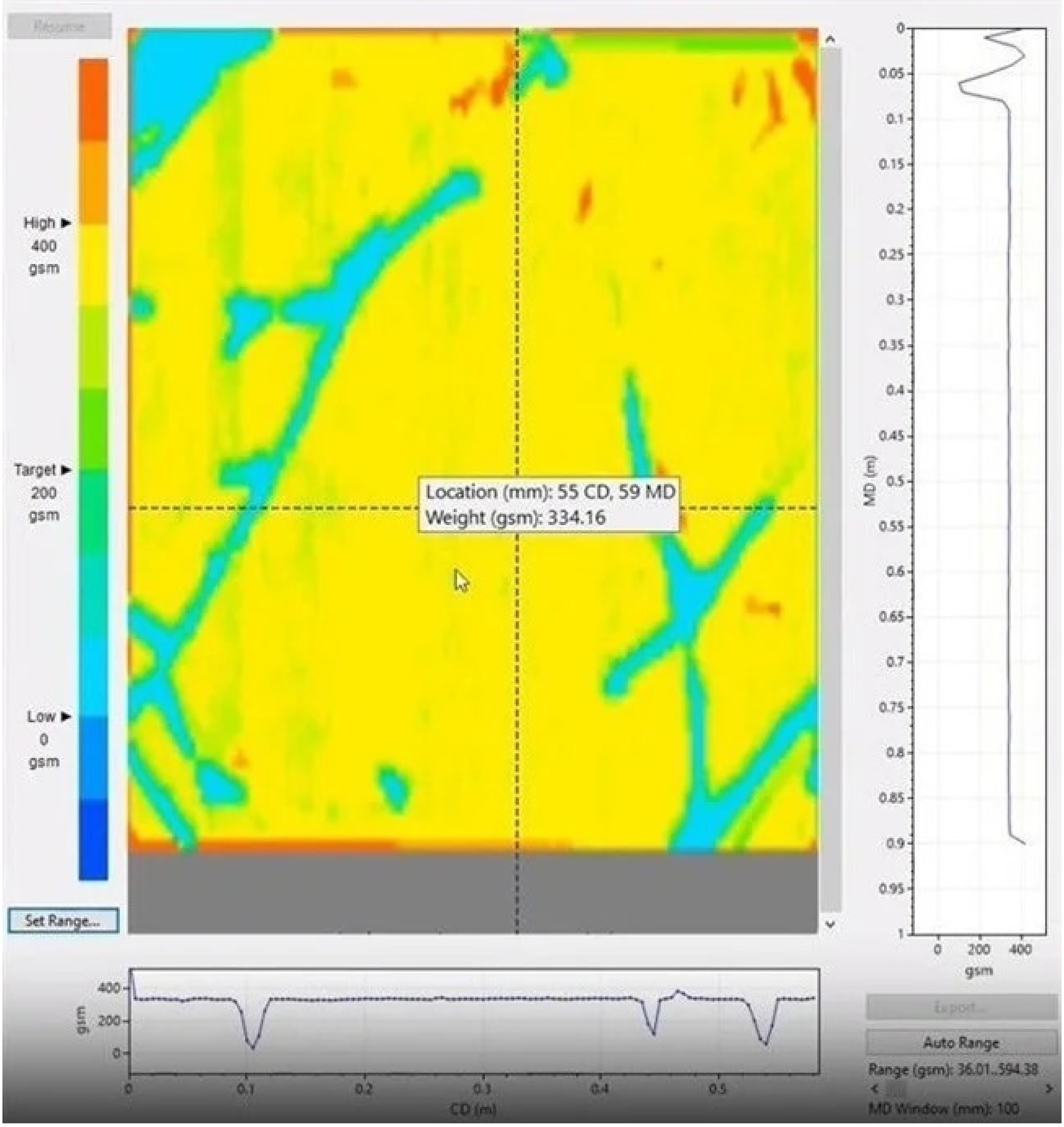

__Figure 3.__ 2D birds eye view, high dimensional CD and MD data and defect identification. Image Credit: Thermo Fisher Scientific – Production Process & Analytics

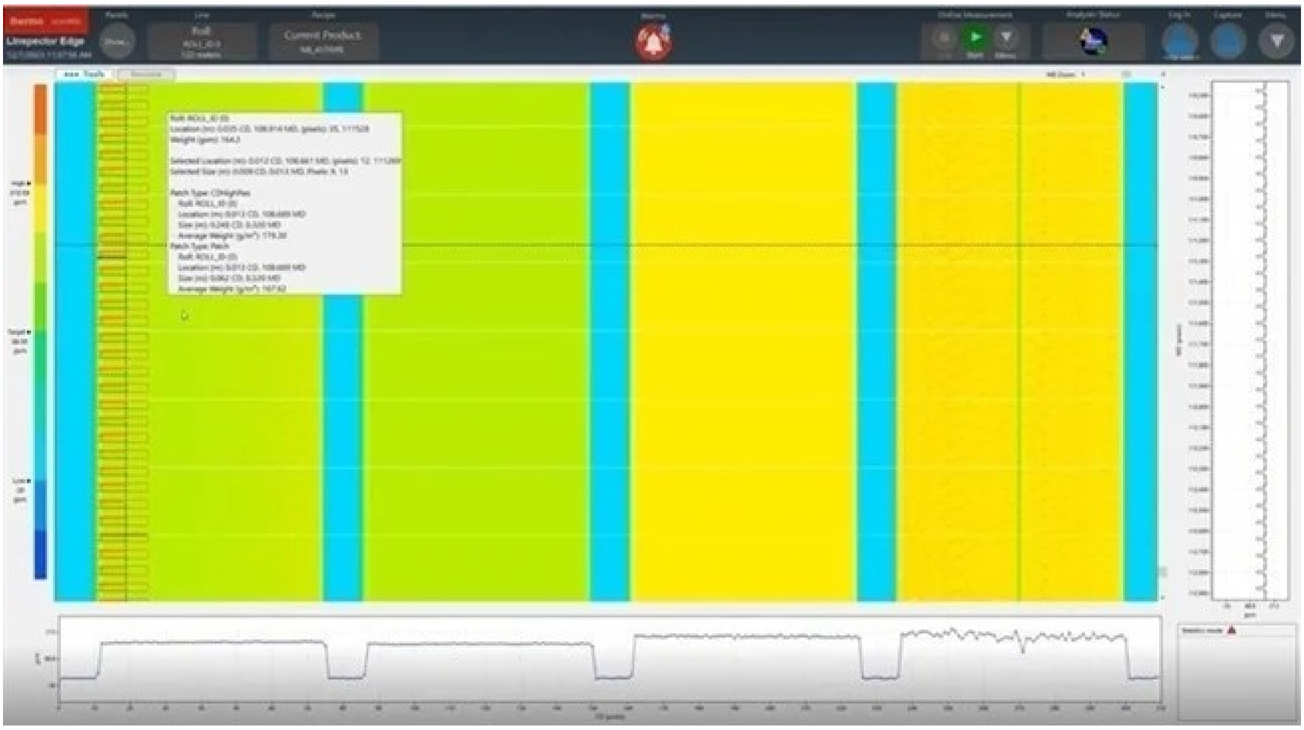

Figure 4. *Heat map view with edge defect identification. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

Figure 5. *CD stripe edge zoom profiles showing sub-zoom windows for each edge (lower half of the image). Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

The red areas in the image above indicate that the coating has deviated from the defined specifications, triggering remedial actions to minimize the amount of coated electrode lost to scrap.

In contrast, conventional scanning technology is slower and more prone to missing substandard areas of the electrode, resulting in a greater volume of out-of-specification product before corrective measures can be taken.

Importantly, all the data presented not only facilitates easier manual decision-making but also provides a robust foundation for advanced, automated process control.

Looking Ahead

Battery manufacturers must strengthen their understanding of production and employ advanced process control to create smart, highly effective processes and meet increasingly strict levels of product quality.

The LInspector Edge In-line Mass Profilometer captures high-resolution data at unprecedented speeds, offering a versatile toolset for analysis and establishing a strong foundation for achieving this goal.

Coating quality is assessed by measuring variations in loading, while rapid, high-sensitivity measurements enhance the ability to detect and identify defects. This valuable data enables the prediction and mitigation of potential issues, helping to minimize their impact.

Defect-free electrodes are essential for producing high-quality Li-ion batteries, requiring thorough and comprehensive quality inspection at all production speeds to achieve higher productivity and quality standards.

With its capability to assess product quality across all types of electrode coatings, this advanced technology plays a crucial role in promoting resource and cost efficiency during production while identifying opportunities for continuous improvement.

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What Are the Latest Innovations in Solid-State Battery Technologies?

Novel battery technology is surpassing current standards. A significant development in this area is the emergence of solid-state batteries (SSBs). These batteries, which use a solid electrolyte, are an improvement over traditional lithium-ion batteries (LIBs) and offer enhanced safety features.

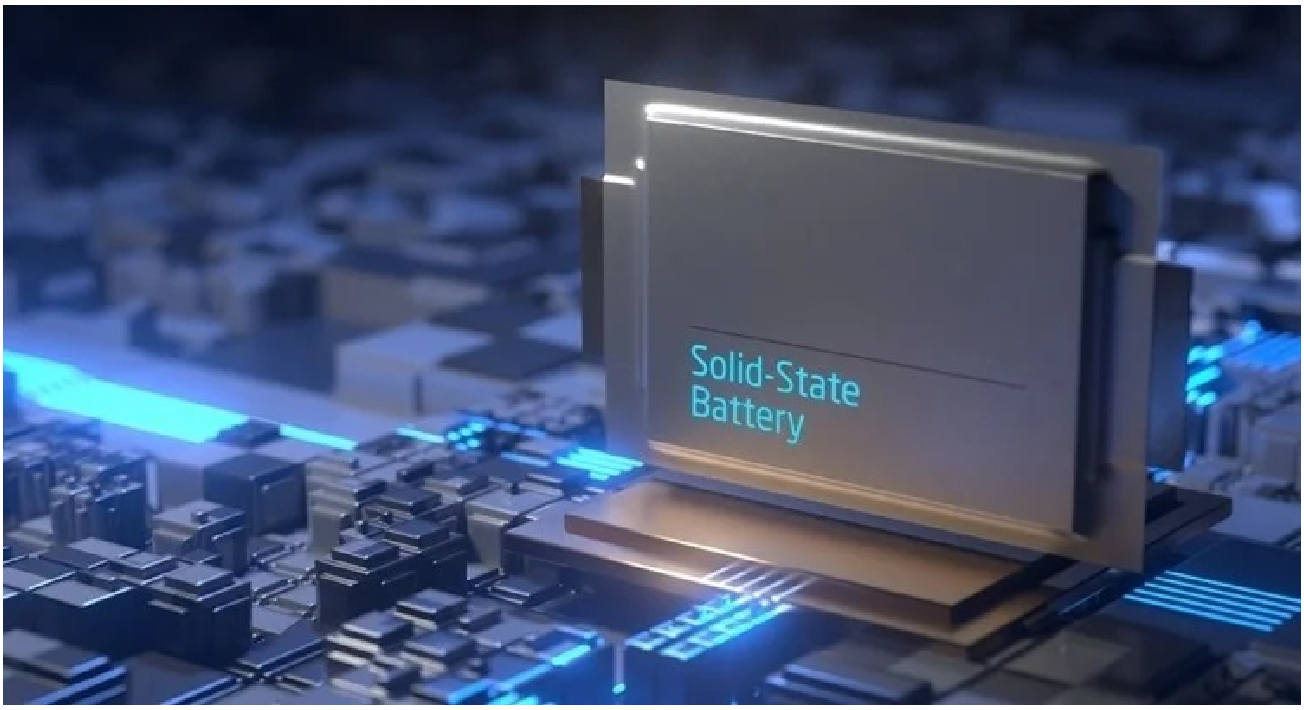


Image Credit: JLStock/Shutterstock.com

Researchers in material science are actively working to advance SSB technology. This article explores some of the latest breakthroughs in this innovative field.

Overview of Solid-State Batteries

SSBs use solid electrolytes, unlike LIBs, which use a liquid electrolyte. An advantage of SSBs is enhanced safety, as solid electrolytes remove the risk of thermal runaway and electrolyte leakage.[1] Solid-state batteries also offer higher energy densities, allowing them to store more energy within a smaller footprint.

Portable devices, electric vehicles (EVs), and grid-scale energy storage systems rely on electrochemical power sources like LIBs. However, the commercial LIBs currently in use pose significant safety risks when overcharged since they contain flammable liquid electrolytes.

The energy density of traditional LIBs is also very close to its physiochemical limit. Therefore, the development of technologies with high energy density and intrinsic safety is crucial for large-scale energy-storage systems. As a result, SSBs have seen a resurgence recently for their improved safety and higher energy density.

The transition to SSBs is also promising for addressing challenges in renewable energy storage and EV adoption. By leveraging solid electrolytes, these batteries can withstand extreme temperatures and harsh operating conditions, making them ideal for use in EVs operating in diverse climates.[2]

Key Innovations in Solid-State Battery Technology

Advancements in SSB technology have focused on enhancing the ionic conductivity and stability of solid electrolytes for safer and more efficient energy storage solutions.

Recently, a group of researchers identified high ionic conductivity in pyrochlore-type oxyfluoride, which remained stable in air.[3] This compound exhibited a remarkable bulk ionic conductivity of 7.0 mS cm–1 and a total ionic conductivity of 3.9 mS cm–1 at room temperature (approximately 298 K), surpassing any previously reported oxide solid electrolytes.

The conduction mechanism within this structure involves the sequential movement of Li ions along with changes in bonds with F ions. This discovery not only resulted in the synthesis of a highly conductive and stable solid electrolyte but also introduced a new class of superionic conductors based on pyrochlore-type oxyfluorides.

Considerable efforts have been made to improve polyethylene's low ionic conductivity at ambient temperature. Techniques such as incorporating inorganic fillers to reduce polymer crystallization have been explored.

Since poly(ethylene oxide)(PEO) can coordinate its numerous oxygen atoms with Li-ions, it efficiently facilitates ion conduction within the matrix, making it the most researched polymer in this context. The polymer chains in PEO's amorphous regions are the primary means of ion transport and are crucial for the material's mechanical qualities and conductivity.

The electrochemical properties of PEO have been significantly enhanced by modifying the amount of two distinct liquid crystalline monomers, each with a different length of methylene chain connected to a stiff core and terminal acrylate groups.[4] This modification enhances the structural integrity and ion conductivity of the porous polymer network by forming effective ion transport channels.

Due to their solid-state construction, SSBs have less overall weight and volume, eliminating the need for separators and thermal management systems necessary for liquid electrolyte LIBs (LE-LIBs).[5] This compactness is particularly beneficial for EVs, helping them save weight and space.

Solid electrolytes in SSBs also have a longer lifespan and a slower rate of capacity reduction over time because they are more stable and degrade less under cycling circumstances. Studies in this area have produced materials whose ionic conductivities are either as high as or higher than those of their liquid equivalents.[6]

Compared to liquid electrolytes, which tend to degrade over time and under heat stress, solid electrolytes found in supercapacitors are less susceptible to degradation. Researchers have found that the inherent stability of solid electrolytes helps SSBs last longer, which lowers the need for frequent battery replacements and, over time, lessens the environmental and economic impacts of battery disposal.[7]

Since SSBs have no liquid components, more design flexibility is available. This enables the production of batteries in sizes and configurations that were previously impossible, creating new opportunities for integrating batteries into various products and applications, from wearable electronics to renewable energy sources.[8]

Challenges to Commercialization

Despite the many benefits SSBs provide, several challenges must be addressed before they can be produced on a large scale.

Firstly, the production of SSBs involves complex manufacturing processes that are currently difficult to scale. It requires precise engineering and management to fabricate tiny, flawless layers of solid electrolyte and ensure ideal contact with the electrodes. A major challenge for making SSBs commercially viable is scaling these techniques to mass production while maintaining quality and consistency.

Additionally, the thermal management of SSBs remains a challenge despite their inherent safety and stability at high temperatures, particularly in high-power applications such as electric vehicles. Compared to liquid electrolytes, solid electrolytes have a less effective heat-dissipation capacity. For SSBs to function correctly and have a long lifespan, heat management during fast charge and discharge cycles must be carefully considered in the design.

Lastly, many solid electrolytes, especially those made of ceramic, are brittle, making them difficult to handle and more prone to failure. It is imperative to develop solid electrolytes with sufficient mechanical strength to endure these shocks.

Future Outlook for Solid-State Batteries

As research endeavors persist in pushing the boundaries of ingenuity, addressing pivotal challenges such as manufacturing scalability, thermal regulation, and mechanical resilience, SSBs are set to significantly impact the transition toward cleaner and more sustainable energy systems.

With continual strides in materials science, battery architecture, and production methodologies, SSBs are anticipated to increasingly rival conventional LIBs, offering enhanced safety profiles, augmented energy densities, and protracted operational lifespans.

As collaborative efforts within the sector increase, the widespread commercialization of SSBs holds the potential to drive significant advances toward a more eco-friendly and efficacious energy landscape.

References and Further Readings

[1] Wang, C., *et al.* (2023). The Promise of Solid-State Batteries for Safe and Reliable Energy Storage. *Engineering*. doi.org/10.1016/j.eng.2022.10.008.

[2] Machín, A., *et al.* (2024). Advancements and Challenges in Solid-State Battery Technology: An In-Depth Review of Solid Electrolytes and Anode Innovations. *Batteries*. doi.org/10.3390/batteries10010029.

[3] Aimi, A., *et al.* (2024). High Li-ion conductivity in pyrochlore-type solid electrolyte Li2-xLa(1+x)/3M2O6F. *Chemistry of Materials*. doi.org/10.1021/acs.chemmater.3c03288

[4] Wang, M., *et al.* (2023). Accelerated ion transportation in liquid crystalline polymer networks for superior solid-state lithium metal batteries. *Chem. Eng.* doi.org/10.1016/j.cej.2023.146658.

[5] Janek, J., *et al.* (2023). Challenges in speeding up solid-state battery development. *Nat. Energy*. doi.org/10.1038/s41560-023-01208-9.

[6] Xu, L., *et al*. (2022). Recent advances of composite electrolytes for solid-state Li batteries. *J. Energy Chem*. doi.org/ 10.1016/j.jechem.2021.10.038.

[7] Waidha, A., *et al*. (2023). Recycling of All-Solid-State Li-ion Batteries: A Case Study of the Separation of Individual Components Within a System Composed of LTO, LLZTO and NMC. ChemSusChem. doi.org/10.1002/cssc.202202361

[8] Pandey, G., *et al*. (2022). Architectural Design for Flexible Solid-State Batteries. *Solid State Batteries*. doi.org/ 10.1021/bk-2022-1414.ch013.

Reimagining Electrode Loading Analysis

The rapid shift to electric vehicles has created an unprecedented demand for batteries that prioritize safety, reliability, faster charging, extended lifespan, increased power, and cost efficiency.

Electrode loading uniformity—evenly distributing active materials in the coating—is a performance-defining quality for batteries and upgrades are crucial to meet these requirements.

Detecting non-uniformity and defects such as blisters, pinholes, folds, and streaks early is critical for implementing cost-efficient remedial actions. However, current quality control measures often fall short, as electrodes are typically fully evaluated only after the final cell is assembled.

If a substandard cell makes it into a vehicle, the consequences can be severe, including reputational damage and, in the worst-case scenario, catastrophic thermal runaway and fire. Failures in the field are not only costly but also potentially dangerous.

To achieve higher performance levels, battery manufacturers are innovating with advanced cathode and anode materials while simultaneously seeking to enhance cost-efficiency.

Real-time quality assurance is essential to support these advancements, providing a solid foundation for continuous improvement. To fully realize these goals, more effective solutions are required to:

- Identify progressively small inconsistencies and size miscalculations
- Enable battery manufacturers to balance anode and cathode mass loadings consistently
- Detect issues more rapidly to decrease waste and reduce downtime
- Deliver complete assurance and traceability
- Facilitate reactive, enhanced process control

Current electrode mass loading measurement technology falls short of meeting these demands, highlighting the need for new, innovative solutions.

Designed specifically for the battery industry, in-line mass profilometry provides simultaneous monitoring across the full width of the electrode, delivering complete edge-to-edge coating profiles in milliseconds.

The Thermo Scientific™ LInspector Edge™ In-line Mass Profilometer builds on a legacy of real-time metrology, utilizing this innovative technique to set new standards in measurement speed, precision, resolution, and coverage. It empowers manufacturers to detect even the smallest defects with confidence, ensuring exceptional coating uniformity, enhancing process understanding, and accelerating the development of new battery technologies.

Image Credit: Thermo Fisher Scientific – Production Process & Analytics

Technology Comparison

Traditional in-line gauges rely on a single-point scanning sensor to measure the cross-width electrode profile. Typically, only 2-3 % of the total surface area is assessed, and several meters of electrode can be produced in the time it takes to complete a single profile scan.

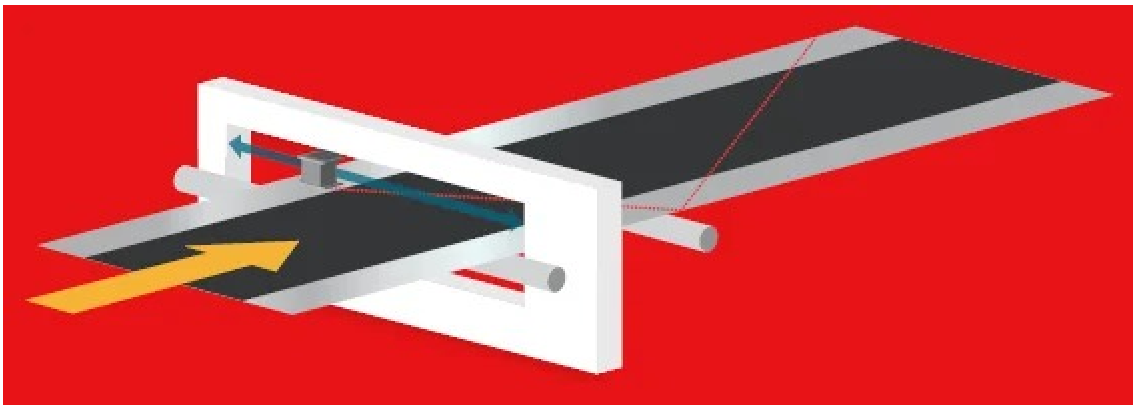


Image Credit: Thermo Fisher Scientific – Production Process & Analytics

The LInspector Edge In-line Mass Profilometer's features include:

- Full width basis weight and profile uniformity analysis in one system
- Orders of magnitude–1000X–more mass loading data than conventional gauges. Complete high-resolution coating images in place of spot measurements.
- Excellent spatial resolution for superior mass loading defect detection

The LInspector Edge In-line Mass Profilometer establishes a new benchmark for electrode coating analysis, delivering faster, more comprehensive, and more precise measurements than any other in-line technology.

The LInspector Edge In-line Mass Profilometer stands apart by providing precise, complete, edge-to-edge electrode coating analysis in milliseconds—without the need for scanning.

Image Credit: Thermo Fisher Scientific – Production Process & Analytics

The breakthrough performance of the LInspector Edge In-line Mass Profilometer brings significant value by allowing manufacturers to:

- **Identify faults quicker:** Edge-to-edge measurement, entire area coverage, and high data acquisition rates enable quick and thorough fault identification. Utilize information-rich data and high-resolution visualization to capture small defects—wrinkles, thick edges ("bunny ears"), and streaks—early in the process and make corrections promptly.
- **Increase production yields:** Quicker feedback means faster, better-informed, and more precise control decisions. Instant start-up and accelerated product transitions decrease scrap and improve throughput.
- **Accomplish full traceability:** Complete coating uniformity measurements for the whole production run with high-resolution images, enabling full traceability of the electrode roll. Record data for every patch on the surface and export measurements and statistics

to the Manufacturing Execution System to enhance visibility and drive optimization.

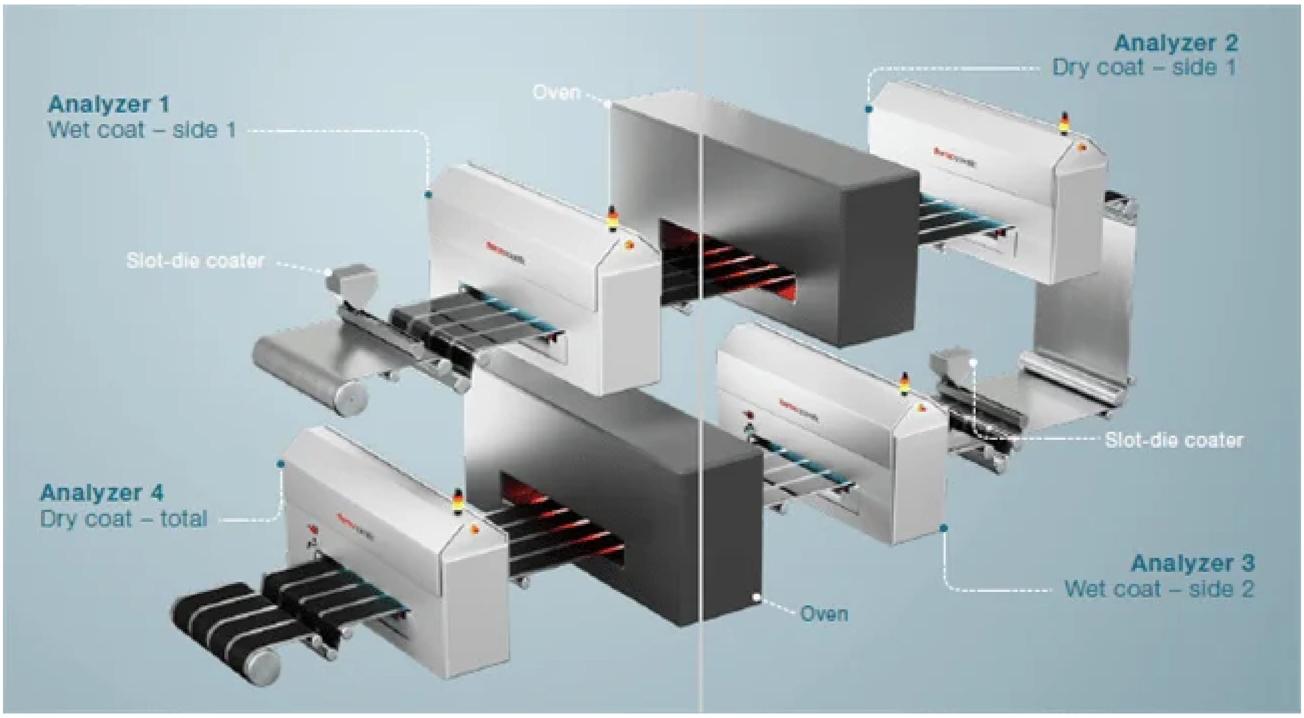
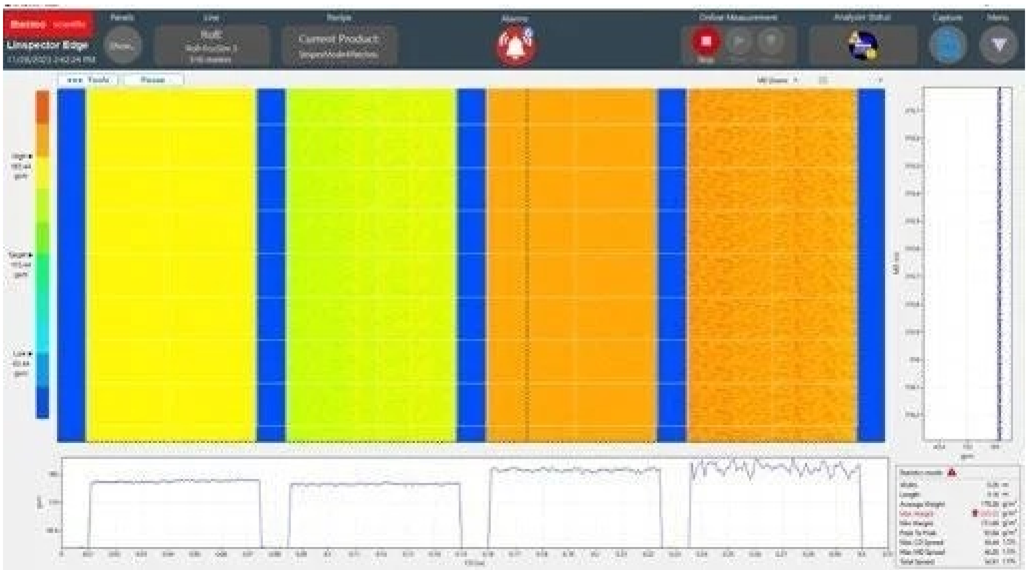


Image Credit: Thermo Fisher Scientific – Production Process & Analytics



The heat map provides high-resolution visualization of electrode loading and coating weight defects in real-time, while the stripe profile display provides a cross section view with statistics for each stripe. Real-time availability of information-rich data allows operators to make process control decisions faster, and ensure that optimal electrode loading uniformity and coat weight are maintained. Image Credit: Thermo Fisher Scientific – Production Process & Analytics

The LInspector Edge In-line Mass Profilometer provides the data that battery manufacturers need for success, to make safer, higher performance batteries, confidently and cost-efficiently.

A Future Investment

Source: Thermo Fisher Scientific – Production Process & Analytics

Criteria	Scanning gauge	Vision inspection systems	LInspector Edge In-line Mass Profilometer
Measured area coverage	2 – 3%	100%	100%
Mass loading measurement [gsm]	Yes	No	Yes (entire electrode)
Loading uniformity profile	Yes	No	Yes (entire electrode)
Defect detection	Limited to measured area	Optical surface only	Mass loading variations (entire electrode)
Measurement frequency	3 – 5 seconds	10 – 1000s frames per second (fps)	1 millisecond
Data visualization	Profile	Image	Image (heat map)

To quantify the potential impact of the LInspector Edge In-Line Mass Profilometer, let's compare the performance with traditional measurement technology.

These benefits improve understanding, monitoring, and control of electrode coating processes, resulting in operational savings that deliver a return on investment (ROI) through:

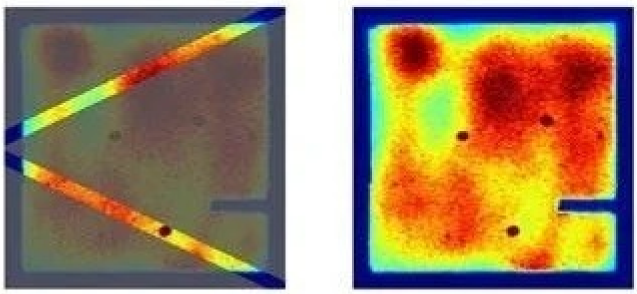
- **Condensed start-up/transition times:** Setpoints can be quickly reached with millisecond data acquisition, creating more marketable products.
- **Reduced scrap:** The longer it takes to identify out-of-specification products, the more scrap is produced. With quicker feedback, scrap can be dramatically decreased, facilitating lesser disposal or recycling expenses and higher throughput.
- **Improved line speeds:** Coating line throughput can be pushed to the maximum during well-controlled operations. Even small speed gains can significantly impact the bottom line at no financial expense.

These substantial gains can easily justify the investment. Equally important, however, are the advantages derived from reliable and timely quality assurance.

Utilizing the LInspector Edge In-line Mass Profilometer:

- Decreases end-of-line testing dependence
- Lowers the chance of sub-standard electrodes slipping into the completed cell
- Reduces the possibility of making poor-quality battery packs

When evaluating the investment in the LInspector Edge In-line Mass Profilometer, consider the costs of a single safety issue, product recall, or brand-damaging event.



In these images, a small section has flaked off this coated sample. The traditional gauge (left) misses the defect because of its zig zag scanning pattern; LInspector Edge In-line Mass Profilometer clearly captures it (right). Image Credit: Thermo Fisher Scientific – Production Process & Analytics

A Comprehensive Package for Long-Term Profitability

The inherently robust, state-of-the-art design of the LInspector Edge In-line Mass Profilometer provides exceptional performance, reliability, and serviceability.

However, its value extends far beyond the product itself. Comprehensive service plans are tailored to align with specific operational strategies, offering a proactive partnership aimed at optimizing performance throughout the equipment's lifetime. This approach ensures maximum return on investment for customers.

All service plan levels include:

- Secure global supply chains for affordable, high-quality upgrades and spares
- International engineers to deliver specialist support and responsive service from project launch through commissioning, and for the product's lifetime through custom service contracts.
- Remote technical support team, available to answer any queries and share their knowledge.
- Comprehensive, relevant application support customized to battery industry requirements.
- Education and training programs to promote enhanced performance and team growth.

The LInspector Edge In-line Mass Profilometer is a future-proof, economically sound solution to the problems that many battery manufacturers face.

ThermoFisher SCIENTIFIC

This information has been sourced, reviewed and adapted from materials provided by Thermo Fisher Scientific – Production Process & Analytics.

For more information on this source, please visit Thermo Fisher Scientific – Production Process & Analytics.

Recycling Batteries Reduces Environmental Impact Compared to Mining

A recent Stanford University study published in *Nature Communications* demonstrates that recycling batteries offers substantial environmental benefits, including significant reductions in greenhouse gas emissions, energy use, and water usage, compared to mining for new metals.

Stanford Assistant Professor William Tarpeh and Ph.D student Samantha Bunke in the Tarpeh lab. Image Credit: Bill Rivard/Precourt Institute for Energy

Recycling lithium-ion batteries to recover their critical metals has substantially less of an environmental impact than mining virgin metals. Recycling may, for the most part, alleviate the long-term supply insecurity of vital battery minerals, both physically and geopolitically.

Lithium-ion battery recyclers source materials from two main streams: defective scrap from battery manufacturers and "dead batteries," primarily collected from workplaces. Lithium, nickel, cobalt, copper, manganese, and aluminum are extracted from these sources during recycling.

The study measured the environmental impact of this recycling process and discovered that it uses roughly one-fourth of the water and energy required to mine new metals and emits fewer than half the greenhouse gases (GHGs) of traditional mining and refinement of these metals.

The environmental benefits are even greater for the scrap stream, which makes up roughly 90% of the recycled supply under study. It accounts for 11% of energy use, 12% of water use, and 19% of mining and processing-related GHG emissions. Although not measured explicitly, lower energy consumption is also associated with lower levels of air pollutants such as sulfur and soot.

> *Recently, I was in an Uber electric vehicle. The driver asked me if EVs really are 'good' for the environment because he recently had read that maybe they aren't. All he knew was that I was faculty at Stanford.*
>
> *William Tarpeh, Assistant Professor and Study Senior Author, Chemical Engineering, School of Engineering, Stanford University*

"I told him that EVs definitely are good for the environment, and we're now finding new ways to make them even more so. This study, I think, tells us that we can design the future of battery recycling to optimize the environmental benefits. We can write the script," said Tarpeh.

Location, Location

The location of the processing facility and the source of electricity significantly impact the environmental effects of battery recycling.

> *A battery recycling plant in regions that rely heavily on electricity generated by burning coal would see a diminished climate advantage.*
>
> *Samantha Bunke, PhD Student and Study Lead Investigator, Stanford University*

"On the other hand, fresh-water shortages in regions with cleaner electricity are a great concern," added Bunke.

Redwood Materials in Nevada, North America's largest industrial-scale lithium-ion battery recycling facility, provided most of the study's battery recycling data. Redwood benefits from the cleaner energy mix in the western US, which consists of solar, geothermal, and hydropower.

Another important consideration is transportation. For instance, the Democratic Republic of the Congo is where 80% of the world's cobalt supply is mined and processed. Afterward, 75% of the cobalt used in batteries is transported to China for refinement via land, air, and sea. In the meantime, Australia and Chile mine most of the world's lithium supply. The majority of that supply also ends up in China. Gathering used batteries and scrap, which need to be delivered to the recycler, is the analogous procedure for battery recycling.

> *We determined that the total transport distance for conventional mining and refining of just the active metals in a battery averages about 35,000 miles (57,000 kilometers). That's like going around the world one and a half times.*
>
> *Michael Machala, Ph.D '17, and Study Lead Author, Stanford University*

"Our estimated total transport of used batteries from your cell phone or an EV to a hypothetical refinement facility in California was around 140 miles (225 km)," added Machala, who was a Postdoctoral Scholar at Stanford's Precourt Institute for Energy at the time of research and is now a Staff Scientist for the Toyota Research Institute.

This distance was based on presumed optimal locations for future refining facilities amid ample US recyclable batteries.

Academia/Industry Cooperation

Based on information from an industrial-scale recycling facility, this study is the first lifecycle analysis of lithium-ion battery recycling that is known to exist.

"We are grateful for the data supplied by Redwood Materials from the largest industrial-scale lithium-ion battery recycling facility in North America, which was needed for this research," said William Tarpeh.

Redwood was among the first to incorporate the project's lessons into their own operations and environmental impact; they have since started construction on a new facility in South

Carolina.

"The insights of this research have played a key role in refining Redwood's battery recycling processes," said JB Straubel, Company Founder and Chief Executive. Straubel earned his undergraduate and graduate degrees from Stanford.

"Thanks to the researchers' observations, we have further reduced our environmental footprint, while also advancing both resource efficiency and process scalability," said Straubel.

Patent Advantage

The environmental results of Redwood do not accurately reflect the environmental performance of the fledgling battery recycling sector as a whole. A crucial step in the refining process, conventional pyrometallurgy uses a lot of energy and typically requires temperatures above 2,550 ℉ (1,400 ℃).

However, Redwood has patented a method known as "reductive calcination," which produces more lithium than traditional techniques, does not use fossil fuels, and requires much lower temperatures.

"Other pyrometallurgical processes similar to Redwood's are emerging in labs that also operate at moderate temperatures and don't burn fossil fuels," said Xi Chen, the third lead author and Postdoctoral Scholar at Stanford during the time of research and now an Assistant Professor at the City University of Hong Kong.

"Every time we spoke about our research, companies would ask us questions and incorporate what we were finding into more efficient practices. This study can inform the scale-up of battery recycling companies, like the importance of picking good locations for new facilities. California doesn't have a monopoly on aging lithium-ion batteries from cell phones and EVs," added Chen.

Looking Ahead

Senior author Tarpeh says that although industrial-scale battery recycling is expanding, it is not happening fast enough.

"We're forecast to run out of new cobalt, nickel, and lithium in the next decade. We'll probably just mine lower-grade minerals for a while, but 2050 and the goals we have for that year are not far away," said Tarpeh.

The United States has successfully recycled 99% of lead-acid batteries for decades but currently only recycles around 50% of lithium-ion batteries. According to Tarpeh, the opportunity is substantial because used lithium-ion batteries contain materials that have an economic value that is up to ten times higher.

"For a future with a greatly increased supply of used batteries, we need to design and prepare a recycling system today from collection to processing back into new batteries with minimal environmental impact. Hopefully, battery manufacturers will consider recyclability more in their future designs, too," said Tarpeh.

Journal Reference:

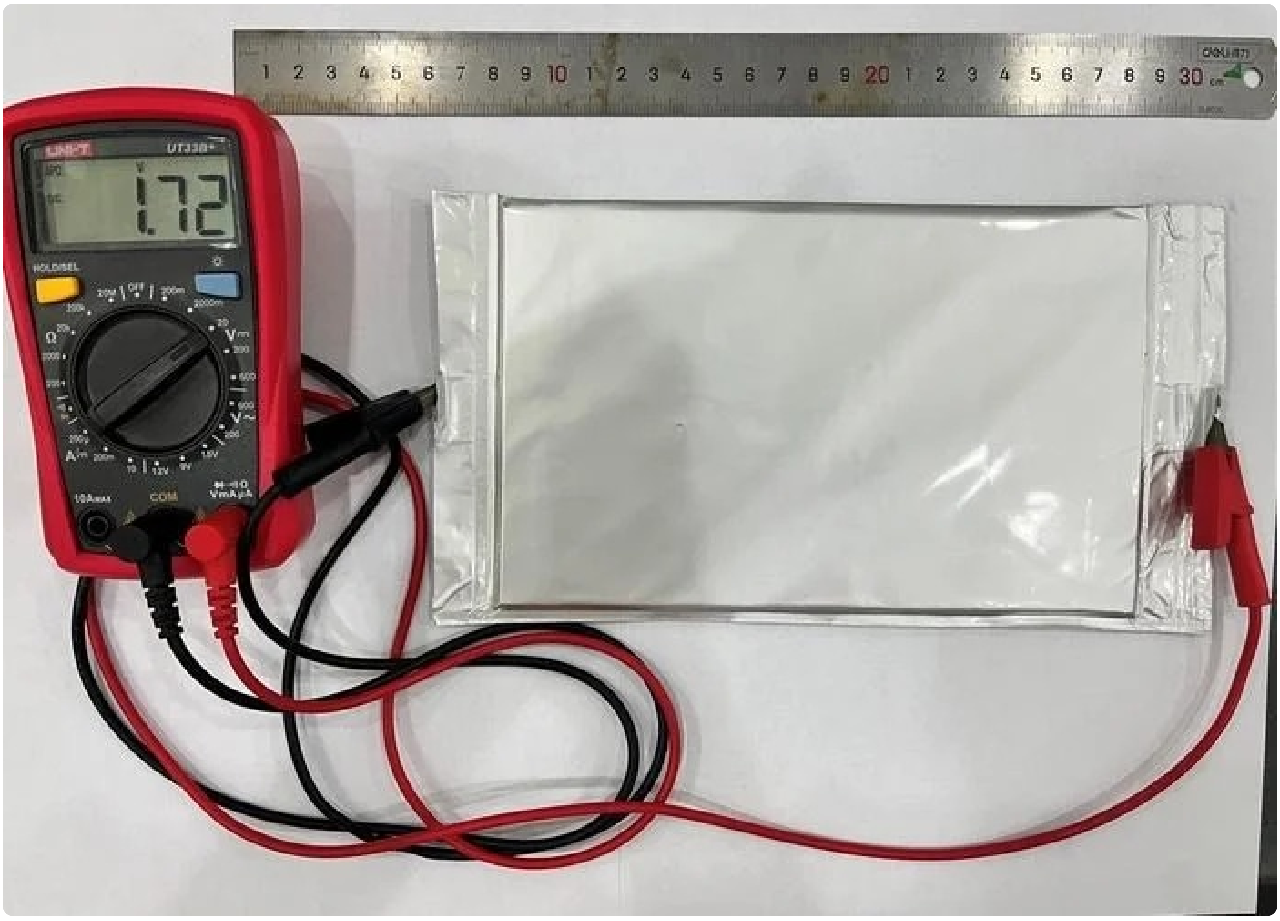
Chen, X., *et al.* (2025) Life cycle comparison of industrial-scale lithium-ion battery recycling and mining supply chains. *Nature Communications.* doi.org/10.1038/s41467-025-56063-x

Source:

Stanford University

Cost-Effective and Environmentally Benign Aluminum-Ion Battery

Researchers have developed an aluminum-ion (Al-ion) battery that is cost-effective and environmentally sustainable, as reported in *ACS Central Science*.



A porous salt produces a solid-state electrolyte that facilitates the smooth movement of aluminum ions, improving this Al-ion battery's performance and longevity. Image Credit: ACS Central Science 2024, DOI: 10.1021/acscentsci.4c01615

Large-scale energy storage solutions are essential for integrating renewable sources like solar and wind power into the United States' energy grid. However, existing battery technologies are either too expensive or lack the necessary safety and reliability for such applications.

Lithium-ion (Li-ion) batteries, commonly used in consumer electronics and electric vehicles, offer high energy density but are unsuitable for large-scale energy storage due to their high cost and flammability, which poses safety concerns.

Al-ion batteries are a promising alternative for long-term energy storage. However, the most commonly used electrolyte, liquid aluminum chloride, corrodes the aluminum anode and is highly sensitive to moisture, leading to instability and reduced performance. To address these limitations, Wei Wang, Shuqiang Jiao, and their team developed an improved Al-ion battery design.

The researchers incorporated an inert aluminum fluoride salt into the Al-ion electrolyte, which solidified the electrolyte and provided a three-dimensional porous structure. This enhanced aluminum ion mobility, improving conductivity.

Additionally, the team used fluoroethylene carbonate as an interface additive, forming a thin, solid coating on the electrodes. This coating prevented the formation of aluminum crystals, which degrade battery performance.

The resulting solid-state Al-ion battery demonstrated enhanced stability, including resistance to moisture, high thermal tolerance up to 392 °F, and durability against physical impacts like punctures.

The battery also exhibited an extended lifespan, retaining over 99 % of its initial capacity after 10,000 charge-discharge cycles. The aluminum fluoride used in the electrolyte could be easily washed and recycled, enabling reuse with minimal performance reduction.

This advancement in Al-ion battery design improves its practicality for large-scale energy storage by reducing production costs, enhancing durability, and supporting recyclability.

> “*This new Al-ion battery design shows the potential for a long-lasting, cost-effective, and high-safety energy storage system. The ability to recover and recycle key materials makes the technology more sustainable.*
>
> *Wei Wang, Associate Professor, University of Science and Technology*

The researchers note that further improvements in energy density and lifecycle performance are necessary before the battery can be commercialized.

This study was supported by the Beijing Nova Program, the University of Science and

Technology Beijing's Interdisciplinary Research Project for Young Teachers, and the National Natural Science Foundation of China.

Journal Reference:

Guo, K., *et. al.* (2025) A Recyclable Inert Inorganic Framework Assisted Solid-State Electrolyte for Long-Life Aluminum Ion Batteries. *ACS Central Science*. doi.org/10.1021/acscentsci.4c01615

Source:

American Chemical Society

How Mass Profilometry Revolutionizes Battery Electrode Production

Early electrode and cell manufacturing leaders have scaled up their volume of production by duplicating existing production lines to meet the increasing demand for batteries in electric vehicles. As a result, in some instances, yield has been sacrificed to reduce time to market or increase the number of battery cells supplied.

End-of-line electrical cycle testing of completed cells offers partial assurance of the safety and performance of the final product. However, it is not a foolproof solution. With the increasing adoption of electric vehicles worldwide, the number of product recalls due to battery failures has also risen.

As market competition intensifies, maximizing yield is becoming essential for long-term profitability. However, failure rates of 5 % to 30 % are commonly observed, particularly during the early stages of production scale-up. The electrode coating process is especially challenging and often accounts for the most significant yield losses.

This article introduces a novel metrology technique, in-line mass profilometry, which has the potential to significantly enhance electrode coating quality and improve process yield.

Industrial Metrology

Before the mid-1900s, the thickness or basis weight (mass per unit area) of flat sheet materials produced on an industrial scale could only be measured through destructive contact methods performed after production.

However, as physicists began exploring the applications of X-ray, radioisotope, and other electromagnetic energy-based sensors, manufacturers across various industries gained access to non-contact, non-destructive measurement instruments. (See Figure 1.)

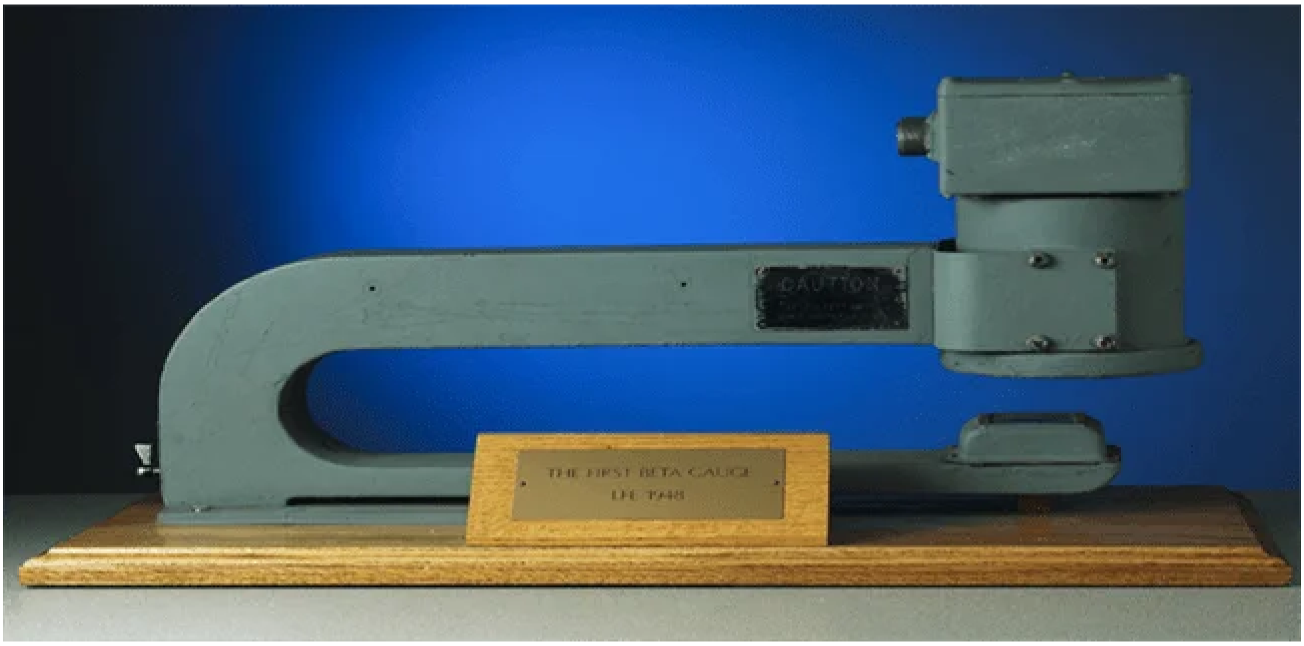


Figure 1. *Early beta-ray basis weight gauge. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

The functionality and features of these early instruments evolved as process engineers demanded more real-time data on the mass profile and dimensional properties of the materials being produced.

To obtain thickness data across the sheet, a sensor was mounted on a frame equipped with a motor to drive the measurement head from one edge of the strip to the other (see Figure 2). This fundamental approach remains in use today on manufacturing lines for all types of flat sheet materials, including battery electrodes.

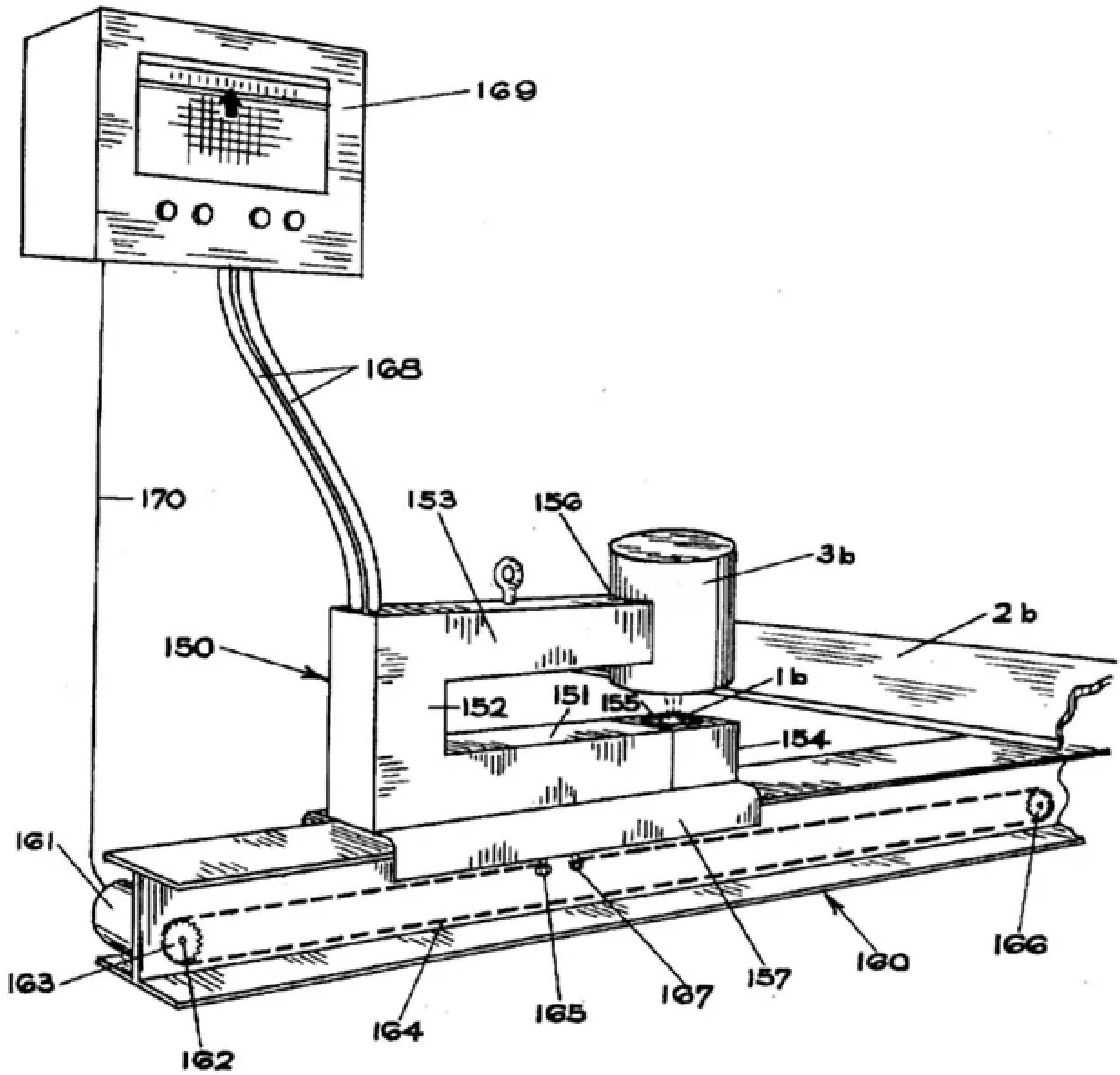


Figure 2. *1952 patent for profile thickness gauge. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

Battery Electrode Production

Modern gigafactory electrode manufacturing lines are optimized for continuous mass production. Ideally, slot-die coaters operating at carefully controlled flow rates deposit precise amounts of active electrode material, suspended in a slurry, onto metal foil substrates. The wet coating is then passed through a long oven to dry the slurry.

Once the top side of the sheet is coated and dried, it is directed through a second coating station, where the same application process is performed on the bottom side. (See Figure 3.)

This process results in a coated electrode "mother roll," which is then slit into narrower formats to be combined with its opposing electrode and a separator film, eventually forming the stacked or rolled final cell.

Traditionally, during the electrode coating process, the mass per unit area of active material—commonly referred to as mass loading—is monitored using a multi-frame gauging system.

In this setup, each frame is equipped with a single-point sensor that moves across the sheet in a synchronized motion, following the measurement path of the previous sensor.

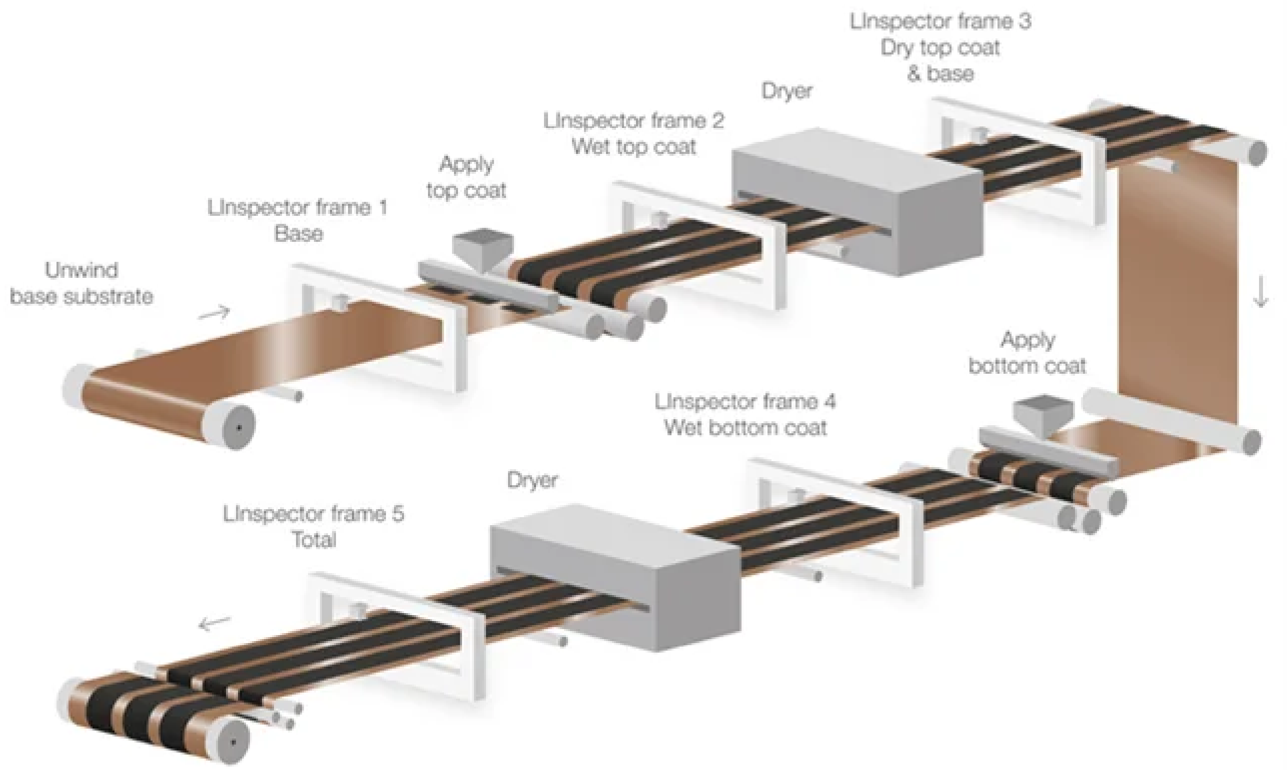


Figure 3. *Typical double-sided electrode coating line. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

This synchronized movement enables the system software to determine a differential measurement of the top or bottom layer separately. This information is beneficial to line operators for observing the slot die gap and slurry pump flow. From a quality viewpoint, it only presents calculation data on 2–4 % of the electrode material. (see Figure 4)

Scaling high-volume production has been instrumental in reducing the cost per kilowatt-hour (kWh). However, there is an increasing need to enhance yield while maintaining uncompromising standards of battery cell quality, safety, and performance.

Innovations in in-line metrology provide manufacturers and cell development teams with new insights into the electrode coating process. Real-time analysis of mass loading across the entire electrode at full production speeds is also revolutionizing quality assurance, enabling faster process qualification and development while elevating production standards.

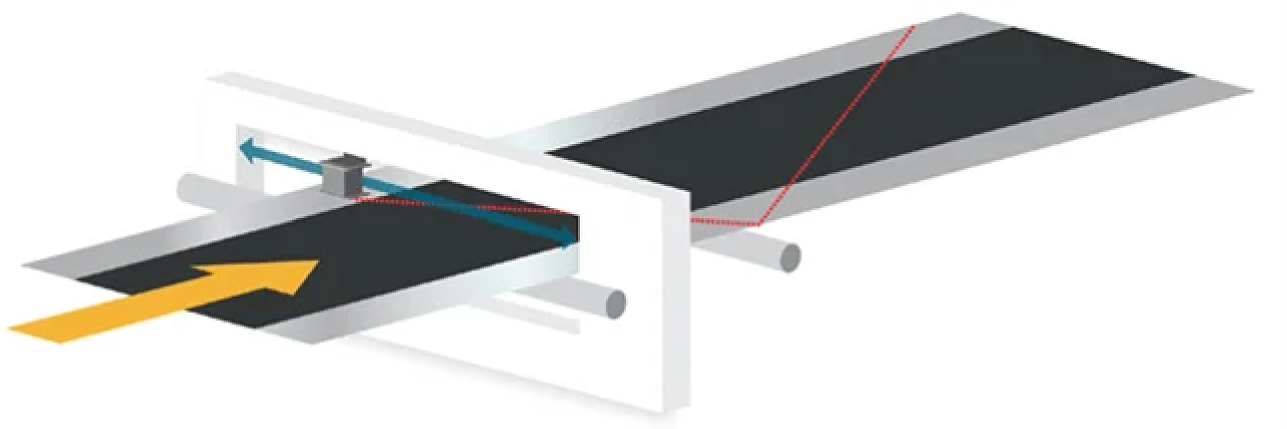


Figure 4. *Traversing single point sensors only measure 2% to 4% of the electrode material (note red trace of measurement spot). Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

Mass Profilometry

The term mass profilometry represents a new paradigm in in-line metrology, accurately reflecting the capability of an advanced analyzer to deliver real-time mass loading data across the full width of the electrode sheet.

By providing an instantaneous measurement profile, 100 % of the electrode material is monitored. This equips line operators with a comprehensive data set for precise control of coating stations and offers process engineers valuable insights for optimizing process parameters and conducting design studies.

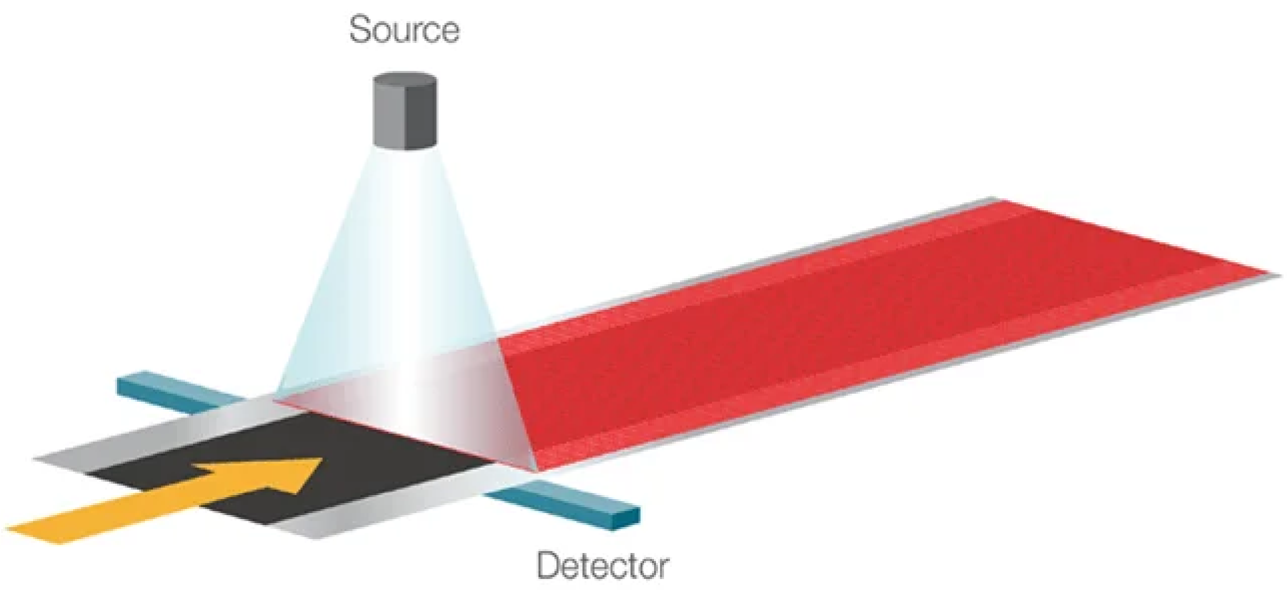


Figure 5. *Mass profilometry measurement. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

From a quality and traceability standpoint, the mass profilometer surpasses single-point sensors by detecting loading defects that might otherwise go unnoticed. With its high-resolution, high-speed capabilities, it can identify defects in-line that previously required time-consuming offline destructive analysis.

Issues such as high-frequency oscillations in the coating application, excess coating, scratches, and high edges can all affect the localized loading of active electrode materials, potentially disrupting the critical anode-to-cathode balance.

The example of visualized mass profilometry data in Figure 6 provides a full mapping of an electrode patch, clearly highlighting high-edge defects (indicated by orange and red along the left and right edges) and coating streaks. Pass/fail thresholds and alarm parameters can be customized to notify operators of any changes in process conditions

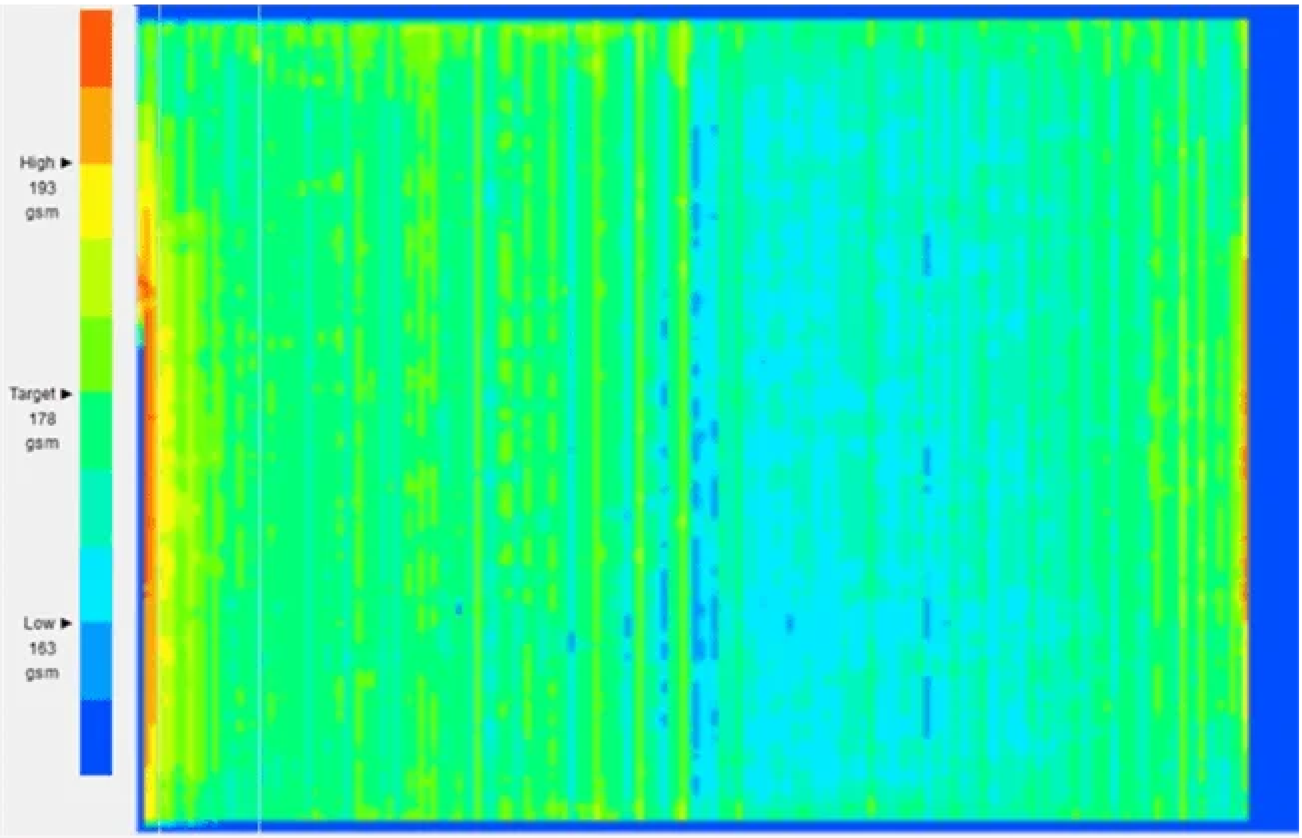


Figure 6. *Mass loading heatmap of a cathode patch. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

By presenting the loading uniformity (or lack thereof), the mass profilometer segregates out-of-tolerance material or coating parts with high or low spots.

Detecting these faults early in cell production is cost-effective in downstream processes, including slitting, stacking, and electrical testing.

Additionally, sections of the electrode that slightly deviate from the target loading can be paired with similarly loaded areas of the opposite electrode material, helping to maintain the ideal anode-to-cathode ratio for optimal battery cell performance.

Compared to the time and length of material that goes under a traversing scanner before a complete edge-to-edge profile measurement is accessible, the immediate profile data from the mass profilometer allows users to drastically decrease the time to target when initiating a new production run.

Summary

Existing single-point gauges utilized for electrode mass loading measurement only measure

2–4 % of the electrode material.

This technology has been in use for many decades and has now reached its peak, making it difficult to achieve the meaningful improvements required by the rapidly evolving battery manufacturing industry to enhance overall yield and meet the reliability and performance levels demanded by consumers.

In-line mass profilometry provides effective, real-time quality assurance, allowing for improvement in the areas of:

- Identifying small non-uniformities and dimensional errors
- Reliable balancing of anode and cathode mass loadings
- Faster identification to lower scrap and reduce downtime
- Complete data traceability and failure analysis
- Responsive and advanced process control

With access to extensive loading data, pilot plants and gigafactories can meet production targets while ensuring optimal cell quality and safety.

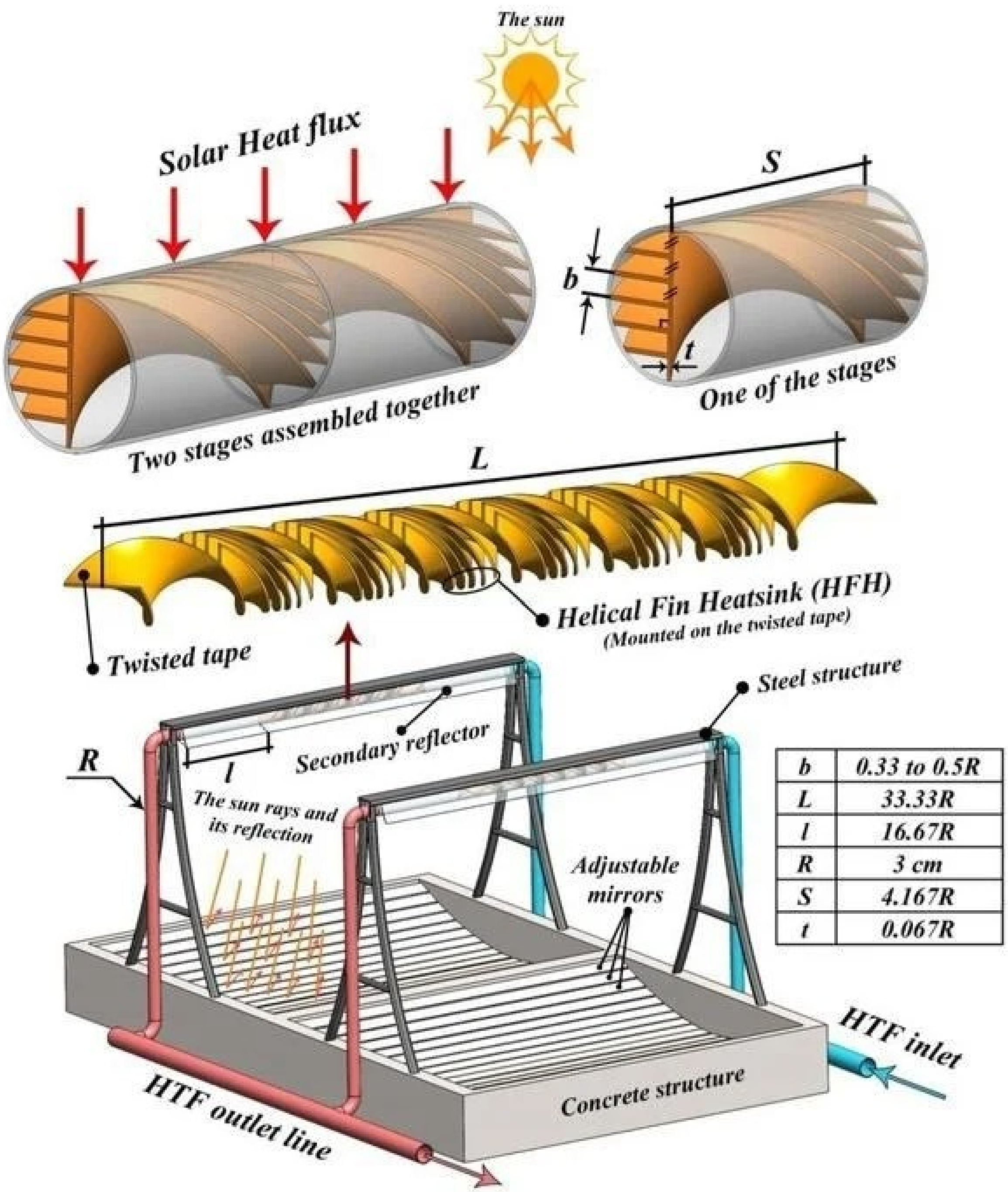
ThermoFisher SCIENTIFIC

This information has been sourced, reviewed and adapted from materials provided by Thermo Fisher Scientific – Production Process & Analytics.

For more information on this source, please visit Thermo Fisher Scientific – Production Process & Analytics.

Combining Nanofluids and Turbulators for Sustainable Energy

Scientists from the University of Sharjah, in a study published in *Applied Thermal Engineering*, highlighted the potential of nanofluids and turbulators to enhance thermal conductivity, improve heat transfer efficiency, lower energy costs, and reduce dependence on fossil fuels.



Hybrid nanofluid turbulent transportation through a tube with an innovative twisted tape combined with helical fins heat sink. Image Credit: Sustainable Energy Technologies and

Assessments.

While turbulators, typically made of stainless steel, consist of coiled wire or small metal baffles, nanofluids are fluids containing nanoparticles as small as a few nanometers.

Recent advancements have focused on using nanofluids and turbulators to improve cooling systems, enhance heat transfer rates, and support renewable energy applications.

The researchers' key finding demonstrates that combining nanofluids and turbulators to optimize their functions can significantly enhance energy transfer, cooling, and heating efficiency.

Heating and cooling systems account for nearly half of global energy consumption and contribute to over 40 % of energy-related carbon dioxide emissions. With air conditioning demand projected to increase by 45 % by 2050, this issue is expected to worsen.

The researchers emphasized the urgency of transitioning to renewable energy: *"to turn to the broader utilization of renewable energies instead of fossil fuels to effectively tackle this widely recognized challenge of transition to sustainable energy*."

Their study includes *"the design of a roadmap that integrates advanced (nanofluid and turbulator-based) technologies into sustainable energy systems*." They identified "*huge potential in these technologies to make considerable contributions towards the global transition towards renewable energy sources*."

The automotive, aerospace, and renewable energy sectors are showing increasing interest in this research and related fields of study.

The study was conducted in collaboration between researchers from five universities: the University of Sharjah in the UAE, Lancaster University in the UK, King Fahd University of Petroleum and Minerals in Saudi Arabia, the National Technical University of Athens in Greece, and Sunway University in Malaysia.

Dr. Zafar Said, lead author and Associate Professor at the University of Sharjah's College of Engineering, explained that the study addresses the need for sustainable energy solutions and helps pave the way for energy systems with improved performance and reduced environmental impact.

> *This can notably improve the efficiency of renewable energy technologies, besides contributing to a shift away from fossil fuel economies. New materials, such as phase-change materials and hybrid nanofluids, were introduced, holding much promise for more efficient energy storage and transportation.*
>
> *Dr. Zafar Said, Study Lead author and Associate Professor, University of Sharjah*

According to Dr. Said, whose research focuses on heat transfer, nanofluids, and sustainable energy, he and his colleagues are developing new technologies that, if implemented, would *"enhance the heat transfer processes, which are crucial in energy applications, focusing on nanofluids, turbulators, and new working fluids to investigate their potential and efficiency improvement in solar collectors and heat exchangers."*

> *Our research emphasizes environmental sustainability, answering the modern goals for clean energy and low carbon emissions. It looks at how these advanced technologies would be incorporated into large-scale applications and points toward a roadmap for transition toward renewable energy systems.*
>
> *Dr. Zafar Said, Study Lead author and Associate Professor, University of Sharjah*

However, the authors acknowledge that the method they used in their study still "*requires careful consideration of potential drawbacks, such as increased nanoparticle deposition, which may reduce system efficiency. This holistic approach considers economic, environmental, and social factors, ensuring compliance with global sustainability benchmarks and contributing to energy system sustainability research."*

Dr. Said remains optimistic, highlighting the enhanced thermal conductivity and efficiency of turbulators and nanofluids, along with their significant potential for application in cooling systems and renewable energy devices.

> *Our research highlights the transformative potential of nanofluids and turbulators in shaping the future of energy systems. Integrating these advanced materials into everyday applications can bridge the gap between energy efficiency and environmental sustainability.*
>
> *Dr. Zafar Said, Study Lead author and Associate Professor, University of Sharjah*

While the researchers show how turbulators and nanofluids can be combined to maximize cooling and heating device efficiency in terms of volume, cost, and environment, they also highlight some upcoming difficulties, especially regarding stability and scalability.

"These practical techniques thus illustrate that modern heat transfer systems can be feasible and usable in reality. Translating theory into practice becomes easier in this respect."

Dr. Said points out that their findings "*directly apply to efficient systems design in HVAC, transportation, and renewable energy industries, further showing the scalability and systems economics at larger sizes*."

HVAC, short for Heating, Ventilation, and Air Conditioning, refers to a system that utilizes various technologies to control temperature, humidity, and air quality in enclosed spaces, ensuring comfort and sustainability.

The authors note, "*The future energy systems are going to be designed based on the principles of efficiency and the usage of new materials. Some of the major challenges in research involve developing new materials and combinations to achieve cost reductions and enhancement of heat transfer using turbulators and special fluids*."

"This paper has highlighted the importance of efficient energy consumption by combining different new methods with renewable and alternative energy sources. It is urgent to turn to the broader utilization of renewable energies instead of fossil fuels to effectively tackle this widely recognized challenge of transition to sustainable energy."

The researchers describe their research as "visionary," highlighting how it identifies "*key hurdles to be conquered if such technologies significantly impact future sustainable energy systems*." They provide guidelines for addressing the remaining technological challenges.

"*These are inclusively outlined as novel material development, performance enhancement, long-term stability, life cycle methodology, and cost reduction in implementing innovative technologies into large-scale industrial applications*," they added.

The authors also emphasize the need for achieving industrial-scale technologies, further cost reductions, and sustainable scalability and material compatibility as key challenges for future research.

The researchers noted, "*The realization of the technology, cost, scalability, and material compatibility are key factors to consider. These technologies can also be applied to many disciplines, like those concerned with automotive and aerospace engineering, where the control of heat is very much an issue*."

Despite these challenges, the authors remain optimistic about the future of "*nanofluids, turbulators, and new working fluids [which] are expected to become the keys to revolutionizing heat transfer. Advancements in these fields will have an impact on automotive and aerospace engineering, which would greatly benefit from improved thermal management*."

"*Moreover, applying heat transfer enhancement techniques can lead to a higher pressure drop in the flow, which increases the unit's operational cost, especially in the cases with turbulators. However, the proper design of the enhanced units can minimize the increase in the pumping work demand, and finally, the overall designs can effectively enhance the global system performance*," they added.

The researchers stress the importance of advancing cooling systems for automobiles and airplanes and bridging the gap between theory and practical applications of nanofluids, turbulators, and new working fluids.

"*Nanofluids can be used to enhance the heat transfer inside car cooling systems. This will provide improved performance and better fuel economy for automobiles. Specific case studies can be done on this*," the authors highlighted in their study.

They also encourage using machine learning to optimize devices and technologies that incorporate turbulators and nanofluids. This approach "*leverages AI and machine learning to tune a system to the most optimal configuration for business. It greatly reduces experimentation and accelerates the dissemination of technologies*."

Journal Reference:

Said, Z., *et al*. (2024) Nanofluids, turbulators, and novel working fluids for heat transfer processes and energy applications: Current status and prospective. *Applied Thermal Engineering*. doi.org/10.1016/j.applthermaleng.2024.124478.

Source:

University of Sharjah

What's Next for the Automotive Market in 2025?

The automotive industry is at a defining point, shaped by rapid technological advancements and evolving consumer needs. As we enter 2025, key trends like the growth of electric vehicles (EVs), progress in autonomous driving, and an increasing focus on sustainability are transforming the market.[1,2]

Image Credit: Volodymyr TVERDOKHLIB/Shutterstock.com

Key Trends

The Growth of Electric Vehicles

The EV market is expanding rapidly, driven by breakthroughs in battery technology, the rollout of charging infrastructure, and supportive government policies. Fully electric vehicles dominate the sector and provide a zero-emission alternative to traditional internal combustion engines. However, challenges such as range anxiety, long charging times, and high battery costs remain significant barriers to widespread adoption.

Solid-state batteries are a significant development in energy storage. They offer higher energy density, improved thermal stability, faster charging capabilities, and reduced reliance on liquid electrolytes compared to lithium-ion batteries.[3] Companies like Toyota and QuantumScape are leading efforts to commercialize these batteries, with the goal of increasing EV range, safety, and efficiency.

Emerging technologies are addressing key challenges in EV adoption by improving convenience and efficiency. Wireless charging systems, such as those developed by Plugless Power and Qualcomm Halo™, provide a streamlined charging process, while dynamic wireless charging concepts enable vehicles to recharge while in motion.[4-6]

Additionally, vehicle-to-grid (V2G) systems and advancements in power distribution are optimizing energy usage.[4-6] Governments are supporting these developments with subsidies, tax incentives, and infrastructure investments, with countries like Norway aiming to phase out internal combustion engine (ICE) vehicles by 2025.[5]

Role of Autonomous Driving

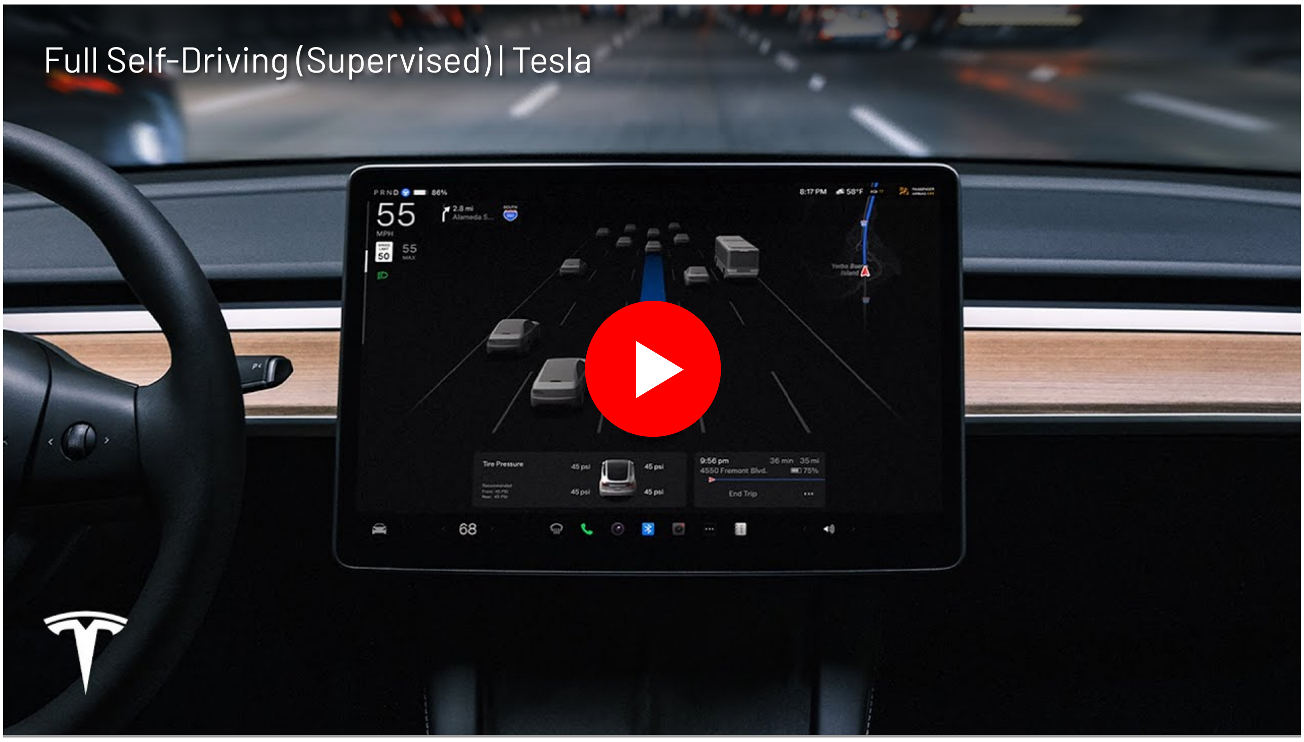
Developments in artificial intelligence (AI), sensors, and vehicle-to-everything (V2X) communication are enabling autonomous vehicles to operate more safely and efficiently.

Autonomous vehicles use a combination of LiDAR, radar, and cameras to navigate and make decisions in real time. AI and deep learning algorithms enhance object detection and decision-making, improving safety and efficiency.[2,4]

Vehicle connectivity is also undergoing rapid advancements, driven by technologies such as advanced driver-assistance systems (ADAS) and V2X communication. ADAS technologies use integrated sensors and real-time data to optimize driving safety, while V2X systems facilitate communication between vehicles and surrounding infrastructure to enhance traffic management and reduce congestion.[2,7]

The integration of 5G technology is further advancing these capabilities by enabling ultra-reliable, low-latency communication for autonomous and connected vehicles. Concurrently, cybersecurity measures, including blockchain for secure data transfer and virtual private networks, are critical to ensuring system integrity and resilience against cyber threats.[8]

Companies such as Waymo, Tesla, and NVIDIA are leading efforts to implement these technologies in personal and commercial vehicles.[2] Autonomous electric vehicles (AEVs) are also gaining attention, as they combine the environmental benefits of EVs with the operational advantages of automation.[4]



Sustainable Practices and Manufacturing Innovations

Sustainability is increasingly embedded in automotive design and production, with significant progress in recycling methods, material engineering, and second-life applications. Recycling initiatives, particularly for EV batteries, address the environmental challenges of battery end-of-life disposal.[7] These processes recover critical materials such as lithium, cobalt, and nickel, which are essential for producing new batteries.

Companies like Renault and BMW are also repurposing spent batteries for stationary energy storage solutions, contributing to a circular economy and extending the lifecycle of valuable resources.[2]

Lightweight composites, such as advanced aluminum alloys and carbon fiber, are being incorporated into vehicle designs to reduce weight and improve energy efficiency. These materials are integral to achieving lower emissions and enhancing the operational range of EVs.[2]

In manufacturing, the integration of advanced robotics, AI, and digital twin technology is enhancing production efficiency and precision. Digital twins—virtual replicas of physical assets—allow manufacturers to simulate and optimize production processes, reducing waste and improving resource allocation. These advancements are enabling agile manufacturing systems capable of adapting to demand shifts while supporting sustainable practices.[3]

Additionally, innovative policies and business models are supporting the development of centralized recycling hubs and scalable second-life battery applications.[7] These initiatives address supply chain vulnerabilities and reduce dependency on raw material extraction by creating efficient pathways for material reuse, aligning with long-term environmental and economic goals.

Challenges and Future Outlook

The evolution of the automotive market is accompanied by several challenges, including regulatory inconsistencies, supply chain disruptions, and gaps in infrastructure development.

Regulatory frameworks differ significantly across regions, complicating efforts to standardize production processes and deploy technologies on a global scale. Additionally, compliance with stringent emissions regulations necessitates continuous innovation, requiring manufacturers to develop vehicles that meet low-carbon requirements without compromising performance or cost efficiency.[5]

Supply chain vulnerabilities, particularly in securing critical materials such as lithium, cobalt, and rare earth elements for EV batteries, pose another significant challenge. These materials are essential for EV production, and disruptions—exacerbated by global events—can lead to delays and increased costs.[9] Addressing these issues will require enhanced recycling methods, diversified supply sources, and more resilient procurement strategies.

Infrastructure development remains a critical bottleneck, particularly in regions with limited access to EV charging networks. Many areas, especially rural and underserved communities, lack the fast and widely accessible charging infrastructure needed to support large-scale EV adoption.[9]

Expanding charging networks, including those powered by renewable energy, is essential to meeting future demand. Research, such as that by Alrubaie *et al.*, highlights the potential of integrating solar photovoltaic systems into grid-connected EV charging infrastructure, offering both economic and environmental benefits for sustainable mobility.[10]

As the automotive market evolves, collaboration between governments, industries, and researchers will be essential. Advances in battery technologies, autonomous systems, and sustainable practices will drive progress, creating a transportation ecosystem that prioritizes environmental stewardship while meeting the needs of consumers. By 2025, the automotive industry is set to deliver smarter, cleaner, and more efficient mobility solutions for the future.

Reference and Further Readings

1. Kovačić, M.; Mutavdžija, M.; Buntak, K. (2022). New Paradigm of Sustainable Urban Mobility: Electric and Autonomous Vehicles—a Review and Bibliometric Analysis. *Sustainability*. https://www.mdpi.com/2071-1050/14/15/9525

2. Trovão, JP. (2023). Exploring Current Automotive Industry Trends [Automotive Electronics].

IEEE Vehicular Technology Magazine. https://ieeexplore.ieee.org/abstract/document/10375860

3. Trovão, JP. (2023). Future Vehicles May Arrive Soon [Automotive Electronics]. *IEEE Vehicular Technology Magazine*. https://ieeexplore.ieee.org/abstract/document/10058075

4. Mo, T.; Li, Y.; Lau, K.-t.; Poon, CK.; Wu, Y.; Luo, Y. (2022). Trends and Emerging Technologies for the Development of Electric Vehicles. *Energies*. https://www.mdpi.com/1996-1073/15/17/6271

5. Sanguesa, JA.; Torres-Sanz, V.; Garrido, P.; Martinez, FJ.; Marquez-Barja, J. M. (2021). A Review on Electric Vehicles: Technologies and Challenges. *Smart Cities*. https://www.mdpi.com/2624-6511/4/1/22

6. Alam, B.; Islam, N.; Subhan, I.; Sarfraz, M. (2022). Analysis and Modelling of Basic Wireless Power Transfer Compensation Topology: A Review. *Intelligent Data Analytics for Power and Energy Systems*. https://link.springer.com/chapter/10.1007/978-981-16-6081-8_25

7. Manzolli, JA.; Trovao, P.; Antunes, CH. (2022). A Review of Electric Bus Vehicles Research Topics–Methods and Trends. *Renewable and Sustainable Energy Reviews.* https://www.sciencedirect.com/science/article/pii/S1364032122001344

8. Tahir, MN.; Katz, M. (2022). Performance Evaluation of Ieee 802.11 P, Lte and 5g in Connected Vehicles for Cooperative Awareness. *Engineering Reports*. https://onlinelibrary.wiley.com/doi/full/10.1002/eng2.12467

9. Romare, M.; Dahllöf, L. (2017). *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries*. [Online] IVL Svenska Miljöinstitutet. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1549706&dswid=-2827

10. Alrubaie, AJ.; Salem, M.; Yahya, K.; Mohamed, M.; Kamarol, M. (2023). A Comprehensive Review of Electric Vehicle Charging Stations with Solar Photovoltaic System Considering Market, Technical Requirements, Network Implications, and Future Challenges. *Sustainability*. https://www.mdpi.com/2071-1050/15/10/8122