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Energy Storage Technologies

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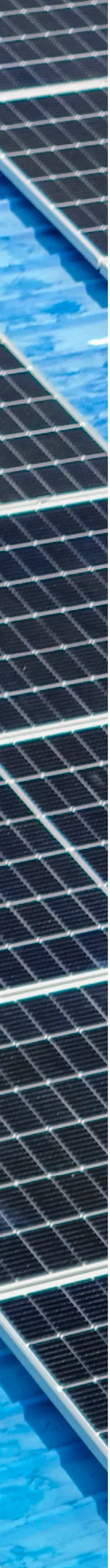

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Foreword

Welcome to the latest edition of our Industry Focus eBook, where we explore the rapidly evolving world of energy storage technologies. As the global push for cleaner energy and decarbonized infrastructure gains momentum, advanced storage solutions are proving to be not just supportive but essential to the future of sustainable power systems.

In this edition, we examine the wide spectrum of technologies shaping the energy storage landscape today, from the next generation of lithium-ion batteries to emerging concepts inspired by nature. From novel manufacturing techniques to strategic policy shifts, each article offers valuable insight into where the field is headed and what it will take to get there.

We begin with **Boost Production Quality by Monitoring Key Parameters in Battery Electrode Processes**, which highlights how greater process control can enhance efficiency and consistency in electrode manufacturing. A deeper look at production methods continues in **How Mass Profilometry Revolutionizes Battery Electrode Production and Reimagining Electrode Loading Analysis**, where innovative characterization tools are optimizing battery design from the ground up.

In **What is Superconducting Energy Storage Technology?**, we unpack a futuristic approach that may dramatically enhance energy transmission and storage efficiency. Meanwhile, **Why Vanadium Batteries Haven't Taken Over Yet: A Reality Check on Commercialization** explores the hurdles facing this promising but underutilized technology.

Our clean technology coverage includes **Charging While We Drive: How Do Sweden's Electric Roads Work?**, offering a glimpse into groundbreaking infrastructure, and **The Future of Graphene Batteries in Electric Vehicles**, which discusses how this supermaterial could reshape the EV landscape.

We also examine the policy and sustainability angle with **What the Battery Passport Means for Researchers and Material Suppliers**, and explore bio-inspired innovation in **Are Biomimetic Batteries the Future of Energy Storage?**.

Together, these features provide a comprehensive view of the challenges, innovations, and breakthroughs defining the future of energy storage. We hope this eBook sparks ideas, informs your perspective, and inspires progress.

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.

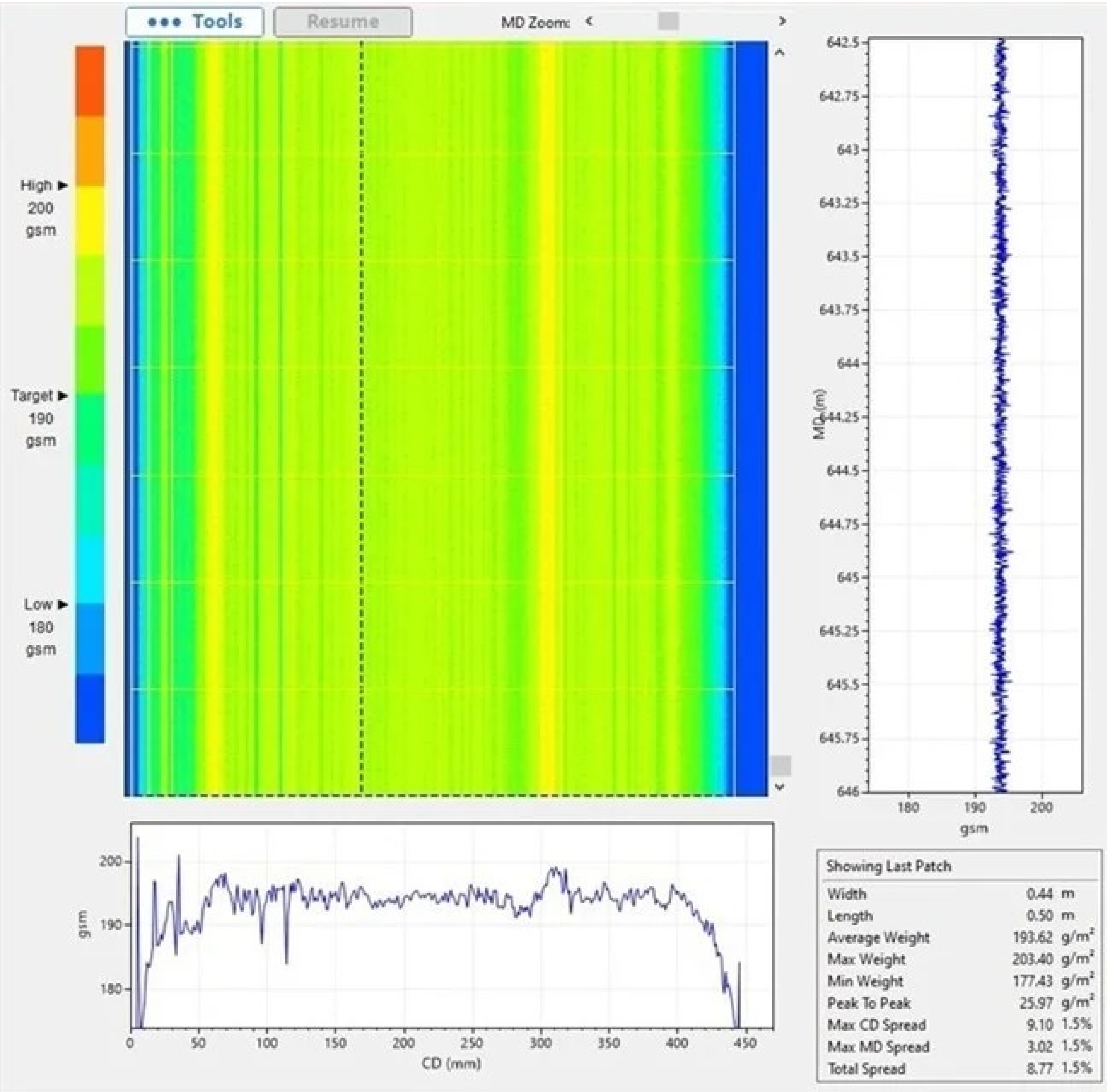

Figure 2. *2D heat map, high-resolution CD and MD profiles. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

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.

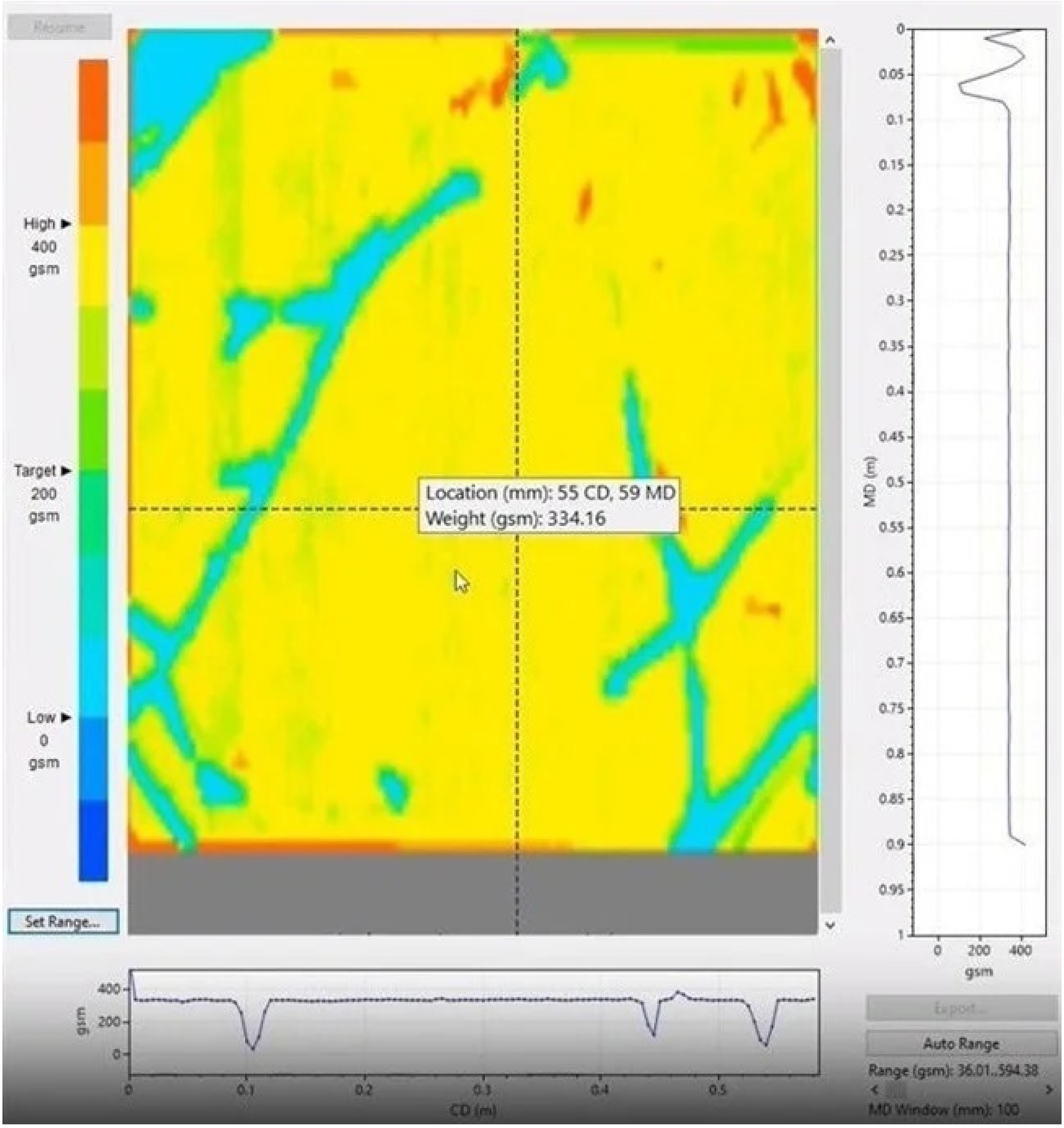

__Figure 3.__ 2D birds eye view, high dimensional CD and MD data and defect identification. Image Credit: Thermo Fisher Scientific – Production Process & Analytics

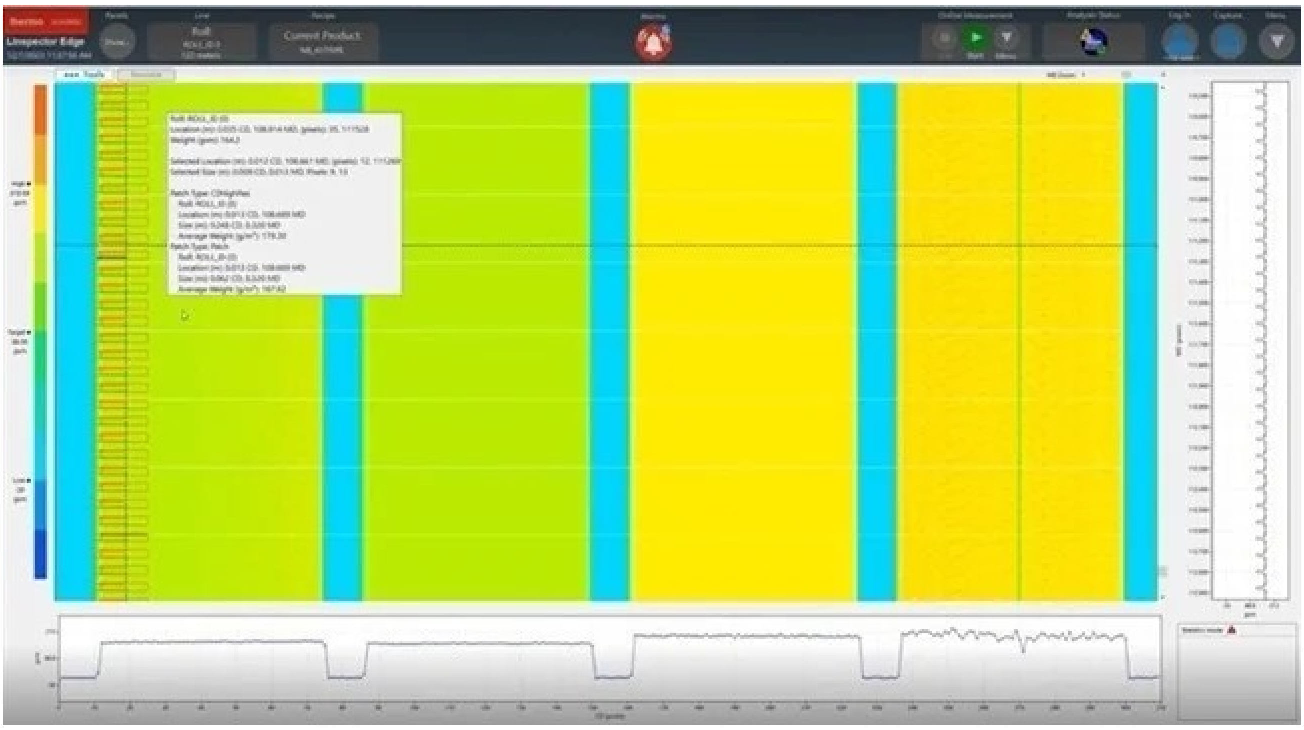

Figure 4. Heat map view with edge defect identification. Image Credit: Thermo Fisher Scientific – Production Process & Analytics

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 is Superconducting Energy Storage Technology?

Superconducting energy storage systems store energy using the principles of superconductivity. This is where electrical current can flow without resistance at very low temperatures.

Image Credit: Anamaria Mejia/Shutterstock.com

These systems offer high-efficiency, fast-response energy storage, and are gaining attention for grid stabilization, high-power applications, and renewable energy integration.

The concept is not new. As early as the 1960s and 70s, researchers like Boom and Peterson outlined superconducting energy systems as the future of energy due to their extremely low power losses.

Over time, this vision has evolved into two main technological pathways: Superconducting Magnetic Energy Storage (SMES) and superconducting flywheel energy storage systems. Both use superconducting materials but store energy in different physical forms (magnetic fields versus rotational motion).

How Superconducting Energy Storage Works

Superconducting Magnetic Energy Storage

SMES stores energy in a persistent direct current flowing through a superconducting coil, producing a magnetic field.

The concept was first proposed by Ferrier in 1969 and realized shortly thereafter by researchers at the University of Wisconsin. The technology advanced further in the 1990s with the introduction of high-temperature superconductors, and by 1997, a grid-connected SMES unit was demonstrated in Germany.

A standard SMES system comprises a vacuum-insulated cryogenic chamber that houses the superconducting coil, a cooling system (using liquid helium or nitrogen), a power conditioning system (PCS), and a control and protection system.

The PCS manages the conversion between AC and DC power, enabling fast charge and discharge cycles. Once current is induced in the superconducting coil, it continues to flow indefinitely without loss, thanks to the zero electrical resistance at cryogenic temperatures.

SMES coils can maintain this current even when the voltage source is removed. Variations in the current create changes in the surrounding magnetic field, and this energy can be efficiently recovered.

Discharge efficiencies of up to 95 % are possible, with system lifetimes exceeding 30 years. SMES systems are also known for their rapid response times, making them suitable for stabilizing power grids and handling high-frequency power fluctuations.

Recent developments in SMES include efforts to improve power system stability using artificial intelligence. Techniques such as fuzzy logic controllers (FLCs) and artificial neural networks (ANNs) are being tested to optimize real-time decision-making and fault tolerance.

However, despite the technological maturity (SMES are considered to have reached Technology Readiness Level 7), widespread industrial deployment remains limited. Future research is expected to focus on integrating SMES into live grid environments, where long-term performance and cost-effectiveness can be validated under real-world conditions.

Superconducting Flywheel Energy Storage

In contrast to SMES, superconducting flywheel energy storage systems store energy in the form of kinetic energy. The system uses a motor to spin a rotor at high speed, converting electrical energy into rotational energy. When energy is needed, the motor acts as a generator, converting the rotor's kinetic energy back into electricity.

These systems first gained attention in the 1960s and 70s, particularly in aerospace applications. NASA, in collaboration with the United States Flywheel Systems (USFS), explored flywheel batteries as a power backup solution for deep space missions and electric vehicles. Early designs used fiber-composite rotors, and while initial systems lacked long-term durability, they laid the foundation for current high-efficiency flywheel storage technologies.

A modern flywheel system typically includes power electronics, a tachometer for rotational monitoring, analog-to-digital converters, and a real-time control computer. These components regulate motor speed and conversion efficiency, ensuring the flywheel operates safely and reliably across load cycles. The amount of energy stored is proportional to the flywheel's moment of inertia and the square of its angular velocity.

There are two main configurations in high-temperature superconducting flywheel systems. One design uses axial superconducting magnetic bearings (SMBs) to support the rotor's thrust, with passive magnetic bearings (PMBs) and active magnetic bearings (AMBs) providing radial stabilization and vibration control. These components operate in a vacuum chamber to minimize friction and energy loss.

The second design adopts a radial configuration, where radial SMBs carry the weight of the rotor and both radial and thrust AMBs ensure stability. These systems allow for high rotational speeds and can deliver quick bursts of energy.

While early flywheel batteries suffered from material fatigue and limited energy density, advances in magnetic bearing technology and control systems have renewed interest in flywheels, particularly for applications requiring rapid discharge and high cyclability.

The Future of Superconducting Energy Storage Tech

Superconducting energy storage technologies have demonstrated strong potential for high-efficiency, low-loss energy management. Among these, SMES stands out for its rapid charge-discharge response, high cycle life, and minimal environmental impact.

However, deployment at an industrial scale remains limited. Bridging the gap between laboratory success and real-world application is a key priority. Ongoing research is expected to focus on optimizing cost, expanding thermal management strategies, and validating system performance under live grid conditions.

As clean energy targets drive demand for more sustainable storage solutions, superconducting technologies are well-positioned to support future high-performance power systems.

References and Further Reading

1. Boom, R. et. al. (2003). Superconductive energy storage for power systems. IEEE Transactions on Magnetics. 8(3). 701-703. Available at: https://doi.org/10.1109/TMAG.1972.1067425
2. Bitterly, J. et. al. (1998). Flywheel technology: past, present, and 21st century projections. IEEE Aerospace and Electronic Systems Magazine, 13(8), 13-16. Available at: https://doi.org/10.1109/62.707557
3. Kwon, K. (2021). Flywheels Turn Superconducting to Reinvigorate Grid Storage Potential: Energy losses defeated previous-gen flywheels as viable big batteries; so new ones levitate more efficiently. IEEE Spectrum. [Online]. Available at: https://spectrum.ieee.org/superconducting-flywheel-grid-energy-storage [Accessed on: March 04, 2025].
4. Tang, J. et. al. (2010). Superconducting energy storage flywheel—An attractive technology for energy storage. Journal of Shanghai Jiaotong University (Science). 15. 76-83. Available at: https://doi.org/10.1007/s12204-010-7151-9
5. Gandolfi, C. et. al. (2018). Study of a universal power SMES compensator for LV distribution grid. In 2018 AEIT International Annual Conference (pp. 1-6). IEEE. Available at: https://doi.org/10.23919/AEIT.2018.8577335
6. Buckles, W. et. al. (2000). Superconducting magnetic energy storage. IEEE Power Engineering Review, 20(5), 16-20. Available at: https://doi.org/10.1109/39.841345
7. European Energy Research Alliance (EERA) Joint Program SP5-Superconducting

Magnetic Energy Storage. (2019). Fact Sheet 1. [Online]. Available at: https://www.eera-energystorage.eu/component/attachments/?task=download&id=566:EERA_JPES_SP5_Factsheet_final [Accessed on: March 05, 2025].

8. Adetokun, B. et. al. (2022). Superconducting magnetic energy storage systems: Prospects and challenges for renewable energy applications. Journal of Energy Storage, 55, 105663. Available at: https://doi.org/10.1016/j.est.2022.105663
9. Khaleel, M. et. al. (2023). Technical challenges and optimization of superconducting magnetic energy storage in electrical power systems. e-Prime-Advances in Electrical Engineering, Electronics and Energy, 5, 100223. Available at: https://doi.org/10.1016/j.prime.2023.100223

Why Vanadium Batteries Haven't Taken Over Yet: A Reality Check on Commercialization

Over the past decade, efforts to achieve carbon-neutral operations have emphasized renewable and sustainable energy sources. These sources, however, often produce power inconsistently, making it challenging to integrate them into existing energy grids.

Energy storage systems are used to regulate this power supply, and Vanadium redox flow batteries (VRFBs) have been proposed as one such method to support grid integration.

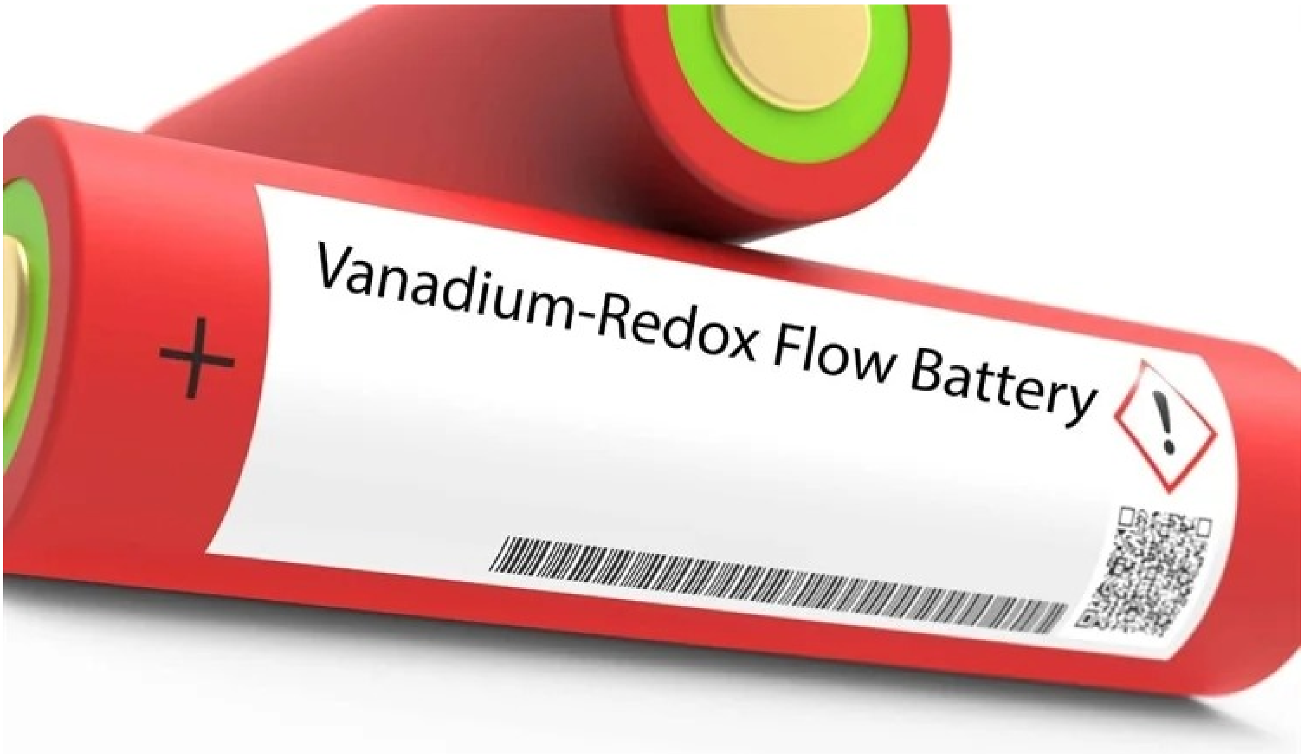


Image Credit: luchschenF/Shutterstock.com

Core Components of Vanadium Redox Flow Batteries

VRFBs include an electrolyte, membrane, bipolar plate, collector plate, pumps, storage tanks, and electrodes. Typically, there are two storage tanks containing vanadium ions in four oxidation states: V^{2+}, V^{3+}, VO^{2+} (V^{4+}), and VO_2^+ (V^{5+}).

Each tank contains a different redox couple.[1] The positive side of the battery connects to the electrolyte and electrode associated with V^{4+} and V^{5+} ions.

Electrolyte Composition and Performance Characteristics

The use of the same active species on both sides minimizes capacity losses from cross-contamination. A standard VRFB can store about 20–30 Wh/L of electrolyte, with the output voltage typically around 1.3V.[2]

The electrolyte concentration determines how much is used. V_2O_5 is considered cost-effective for electrolyte production, while $VOSO_4$ offers more flexibility for adjusting concentrations.

How VRFBs Work: Operating Principle and Cell Reactions

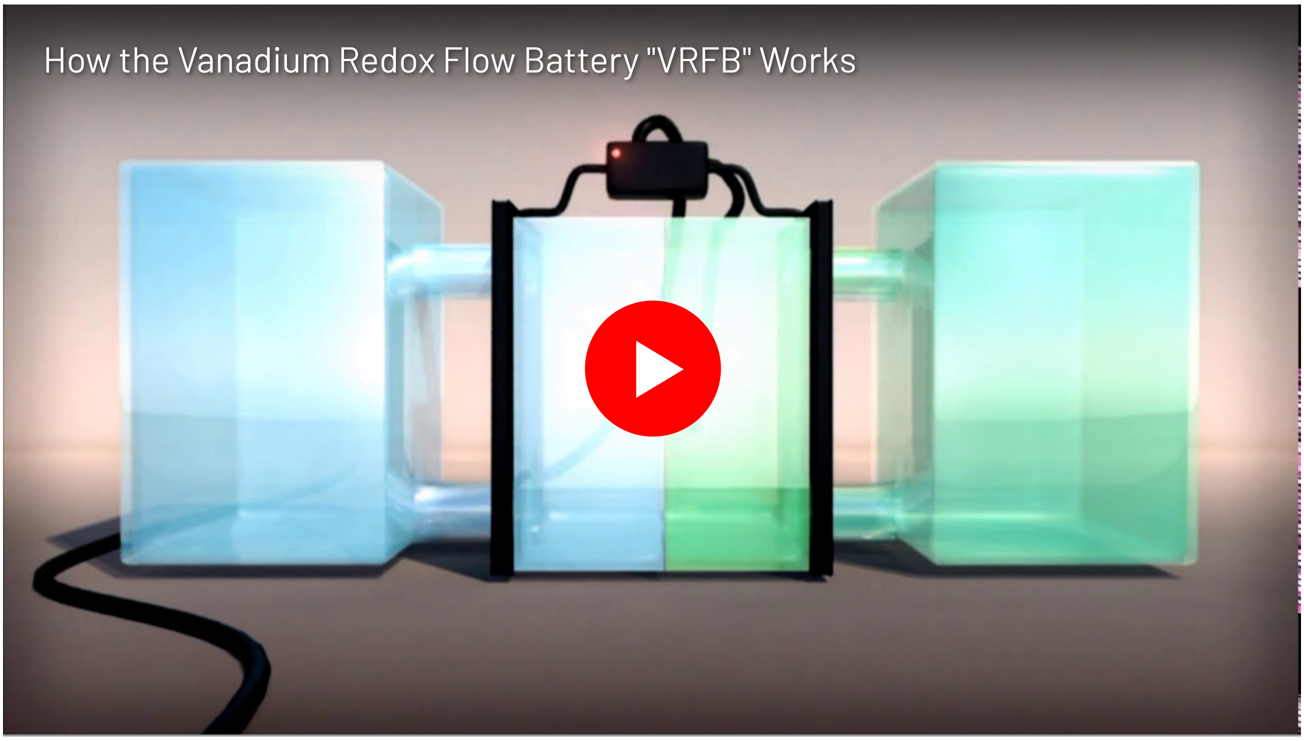
Electrolytes are pumped through two separate half-cells and returned to the storage tanks. Each half-cell consists of an electrode and a bipolar plate, separated by a membrane that allows selective ion exchange. This arrangement forms a single cell, and several cells are stacked using shared bipolar plates.

At the positive half-cell, VO^{2+} reacts with H^+ and an electron to produce VO_2^+ and water. At the negative half-cell, V^{2+} is oxidized to V^{3+}, releasing an electron. The overall reaction is:

$$\mathbf{VO_2^+ + V^{2+} + 2H^+ \rightleftharpoons VO^{2+} + V^{3+} + H_2O}$$

Multiple stacks of VRFBs are connected electrochemically to enable energy storage for large-scale applications. In a typical setup, the stacks and cells receive a continuous supply of electrolyte in parallel, which helps maintain a stable concentration of redox-active ions across the system.

During charging, electrons move through the bipolar plates from the positive to the negative side, while hydrogen ions (H^+) pass through the membrane in the same direction.[3] This electrochemical process allows VRFBs to support energy needs in both industrial and residential settings.



VRFBs: The Good, the Bad, and the Practical

VRFBs provide design flexibility due to the use of liquid electrolytes, which can be stored in tanks of various shapes and sizes. The separation of power and energy capacity allows for independent scaling, which can be useful in industrial applications.

These batteries also tend to have a longer cycle life than conventional batteries, as the liquid electrolytes degrade more slowly over time, even with some degree of crossover. The separation of the energy storage (tanks) and power generation (cell stacks) components enables more flexible system layouts.

For example, tanks can be installed in underground or less space-constrained areas, while cell stacks can be located where heat management is more efficient. This arrangement can simplify cooling system design and potentially reduce associated costs.[4]

However, despite these design advantages, VRFBs also face notable limitations, particularly when it comes to mobile applications. Their relatively low power and energy densities make them less practical in compact or portable systems. Power densities are typically around 15 W/cm^2 in the cells, 100 W/cm^2 in the stack, and approximately 25 Wh/kg in the electrolyte solutions.

These characteristics often necessitate the use of large electrolyte tanks, limiting their application in compact or mobile systems. Additionally, electrical efficiency can be reduced by the presence of shunt currents within the battery system.[5]

Another challenge is the unintended transfer of vanadium ions and water across the membrane, including diffusive and electro-osmotic crossover effects. Water imbalance between the battery compartments can result in the precipitation of vanadium salts, which negatively affects performance.

Managing this imbalance requires careful system control. The relatively high viscosity and flow requirements of the electrolyte also contribute to increased pressure drops and higher pumping power, which impacts overall system efficiency.[6]

Vanadium, the key active material in VRFBs, is primarily used in the steel and chemical industries. For example, in Germany, about 90 % of vanadium consumption is for steel production. This demand limits the availability of vanadium for battery production and contributes to higher material costs.

Additionally, the number of vanadium mines is smaller than resources such as lithium, resulting in supply constraints. There are also concerns related to vanadium toxicity, and health, safety, and environmental (HSE) regulations can restrict its handling and usage.[7]

These technical and material challenges, combined with regulatory hurdles, initially limited industry interest in VRFBs. At the same time, lithium-ion batteries (LIBs) gained market traction and became the dominant technology for energy storage in consumer electronics and electric vehicles, further slowing the commercial adoption of VRFBs.

How VRFBs Are Being Used

Redox flow batteries, including VRFBs, are well-suited for stationary energy storage applications where power output and energy capacity are designed to remain in a fixed ratio. Their operational safety, modular scalability, and high cycle life make them a viable option for such use cases.[8]

VRFBs can support the integration of renewable energy sources into large power grids by helping to stabilize supply, manage peak loads (peak shaving), and contribute to grid reliability.

In wind and hydroelectric systems, VRFBs can assist with power smoothing by absorbing short-term fluctuations in output without significantly impacting the overall performance of the generation system. This helps ensure more stable power delivery to the grid.

Additionally, VRFBs can be integrated with the DC link in systems such as wound rotor synchronous generator (WRSG)-based wind turbines. This configuration may improve the system's ability to handle low-voltage events, thereby enhancing grid stability during voltage disturbances.[9]

What's Next for VRFBs?

For VRFBs to become more viable for large-scale commercial applications, key technical challenges must be addressed, particularly those related to membrane and electrode performance.

Developing low-resistance membranes and more efficient electrodes can help reduce cell resistance and improve overall system efficiency. Additionally, reducing the frequency of regeneration cycles (e.g., from once per year to once every five years) could lower maintenance costs.

Projections suggest that increasing round-trip efficiency from approximately 75 % to 85 %, and extending battery life to around 14,600 cycles (equivalent to 40 years), could significantly improve the commercial feasibility of VRFBs in long-duration energy storage (LDES) projects.[10]

Progress in areas such as advanced materials research, cost optimization, supportive policy frameworks, and targeted government incentives may contribute to the broader adoption of VRFBs in the energy storage sector over the coming decade.

References and Further Reading

1. Gundlapalli, R. et. al. (2018). Stack design considerations for vanadium redox flow battery. INAE Letters, 3(3), 149-157. Available at: http://dx.doi.org/10.1007/s41403-018-0044-1
2. Zhang, H. et. al. (2017). Redox flow batteries: fundamentals and applications. CRC Press. Available at: https://www.doi.org/10.5772/intechopen.68752
3. Lourenssen, K. et. al. (2019). Vanadium redox flow batteries: A comprehensive review. Journal of Energy Storage, 25, 100844. Available at:

https://doi.org/10.1016/j.est.2019.100844
4. Cunha, Á. et. al. (2015). Vanadium redox flow batteries: a technology review. International Journal of Energy Research, 39(7), 889-918. Available at: https://doi.org/10.1002/er.3260
5. Olabi, A. et. al. (2023). Redox Flow Batteries: Recent Development in Main Components, Emerging Technologies, Diagnostic Techniques, Large-Scale Applications, and Challenges and Barriers. Batteries. 9(8). 409. Available at: https://doi.org/10.3390/batteries9080409
6. Guarnieri, M. et. al.(2016). Vanadium redox flow batteries: Potentials and challenges of an emerging storage technology. IEEE Industrial Electronics Magazine. 10(4). 20-31. Available at: https://doi.org/10.1109/MIE.2016.2611760
7. Ciotola, A. et. al. (2021). The potential supply risk of vanadium for the renewable energy transition in Germany. Journal of Energy Storage, 33, p.102094. Available at: https://doi.org/10.1016/j.est.2020.102094
8. Girschik, J. et. al. (2021). Redox flow batteries: stationary energy storages with potential. Chemie Ingenieur Technik, 93(4), pp.523-533. Available at: https://doi.org/10.1002/cite.202100001
9. Aluko, A. et. al. (2023). A review on vanadium redox flow battery storage systems for large-scale power systems application. IEEE Access, 11, 13773-13793. Available at: https://doi.org/10.1109/ACCESS.2023.3243800
10. Poli, N. et. al. (2024). Techno-economic assessment of future vanadium flow batteries based on real device/market parameters. Applied Energy, 362, 122954. Available at: https://doi.org/10.1016/j.apenergy.2024.122954

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[TM] LInspector Edge[TM] 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.

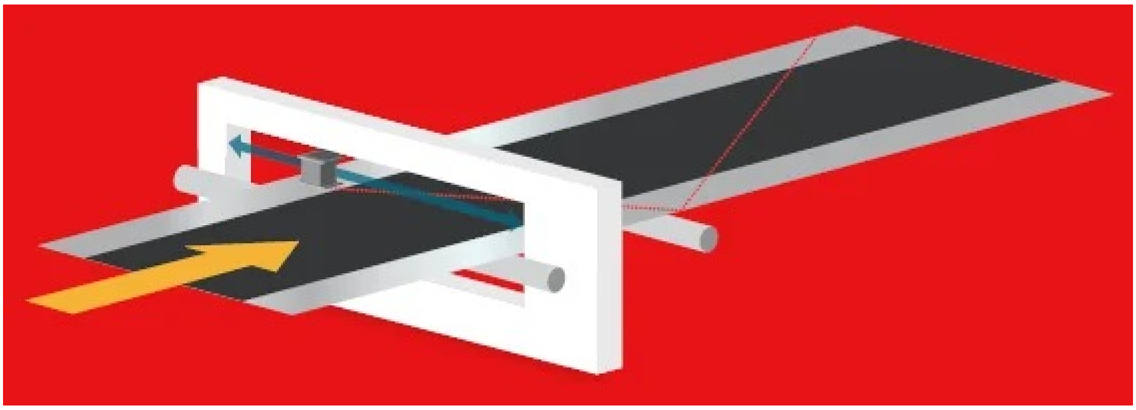


Image Credit: Thermo Fisher Scientific – Production Process & Analytics

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.

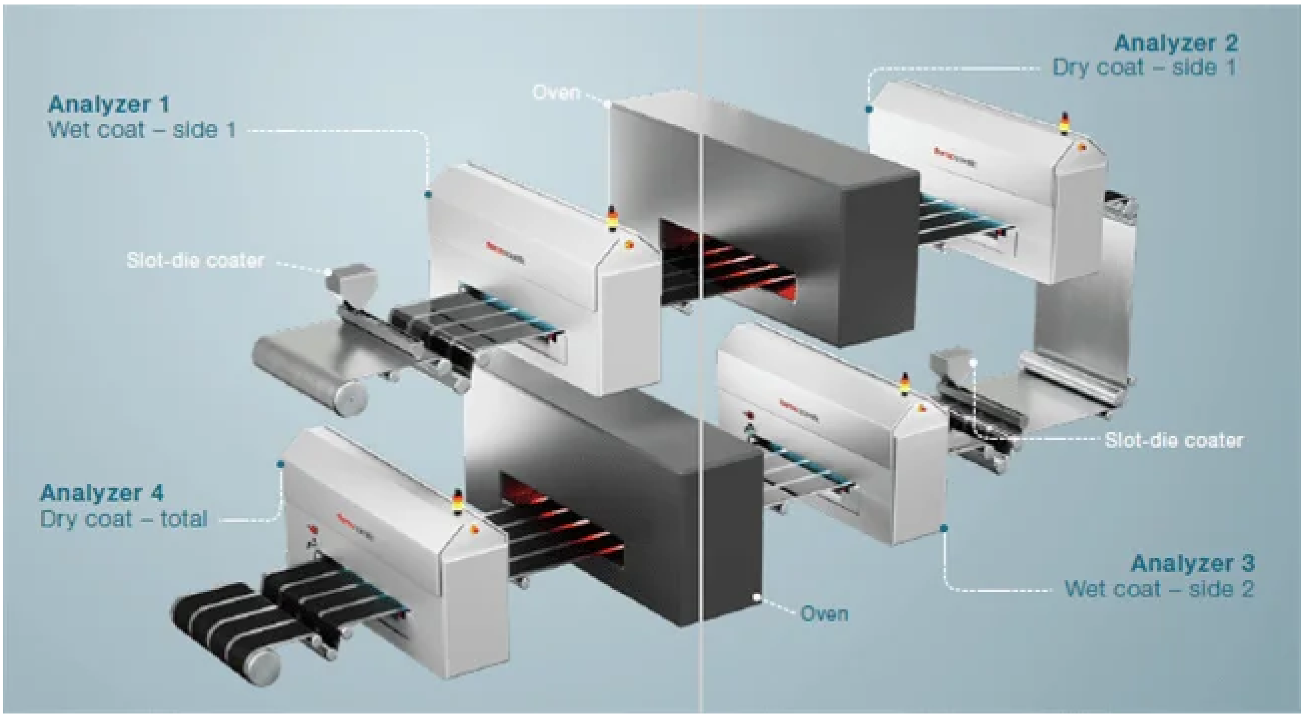
The LInspector Edge In-line Mass Profilometer stands apart by providing precise, complete, edge-to-edge electrode coating analysis in milliseconds—without the need for scanning.

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.



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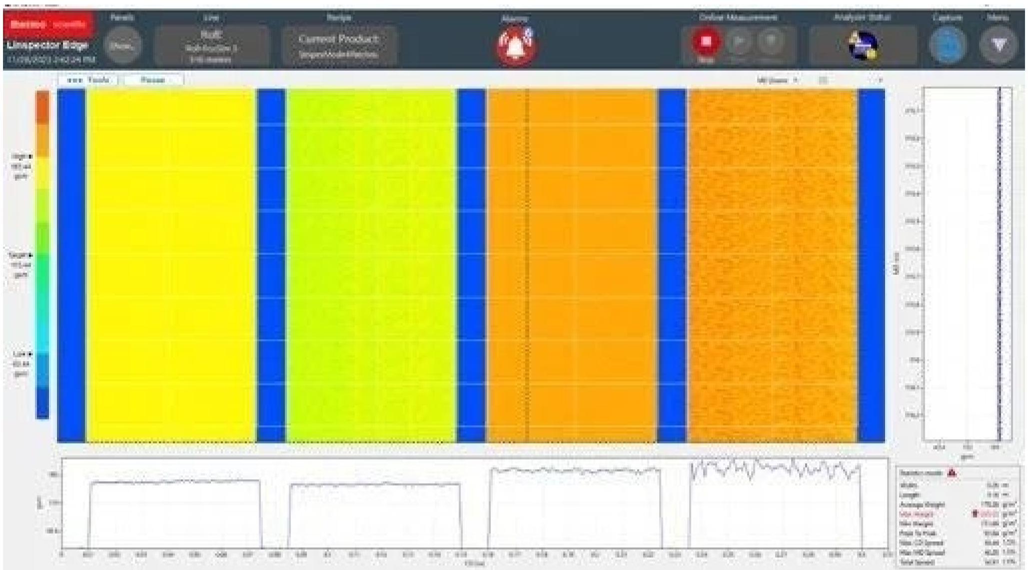


The heat map provides high-resolution visualization of electrode loading and coating weight defects in real-time, while the stripe profile display provides a cross section view with statistics for each stripe. Real-time availability of information-rich data allows operators to make process control decisions 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:

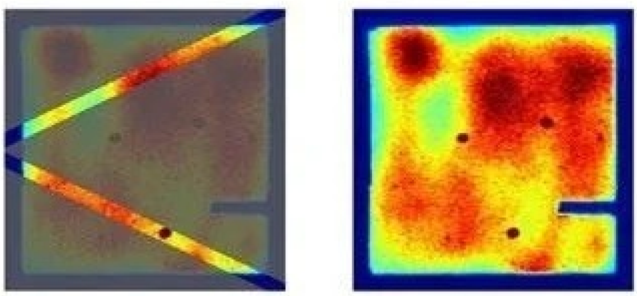
- **Condensed start-up/transition times:** Setpoints can be quickly reached with millisecond data acquisition, creating more marketable products.
- **Reduced scrap:** The longer it takes to identify out-of-specification products, the more scrap is produced. With quicker feedback, scrap can be dramatically 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.

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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.

Charging While We Drive: How Do Sweden's Electric Roads Work?

Sweden is redefining transportation with its electric roads, or e-roads. This system allows vehicles to charge their batteries while they drive and helps solve range anxiety, a major issue for electric vehicle (EV) users. By integrating charging infrastructure directly into highways, Sweden aims to reduce the need for frequent stops at charging stations.

This effort lowers dependence on fossil fuels and supports Sweden's goal of reaching net-zero emissions by 2045. The world's first permanent electrified highway is being built on the E20 route. This technology could change how countries look at sustainable travel.[1,2]

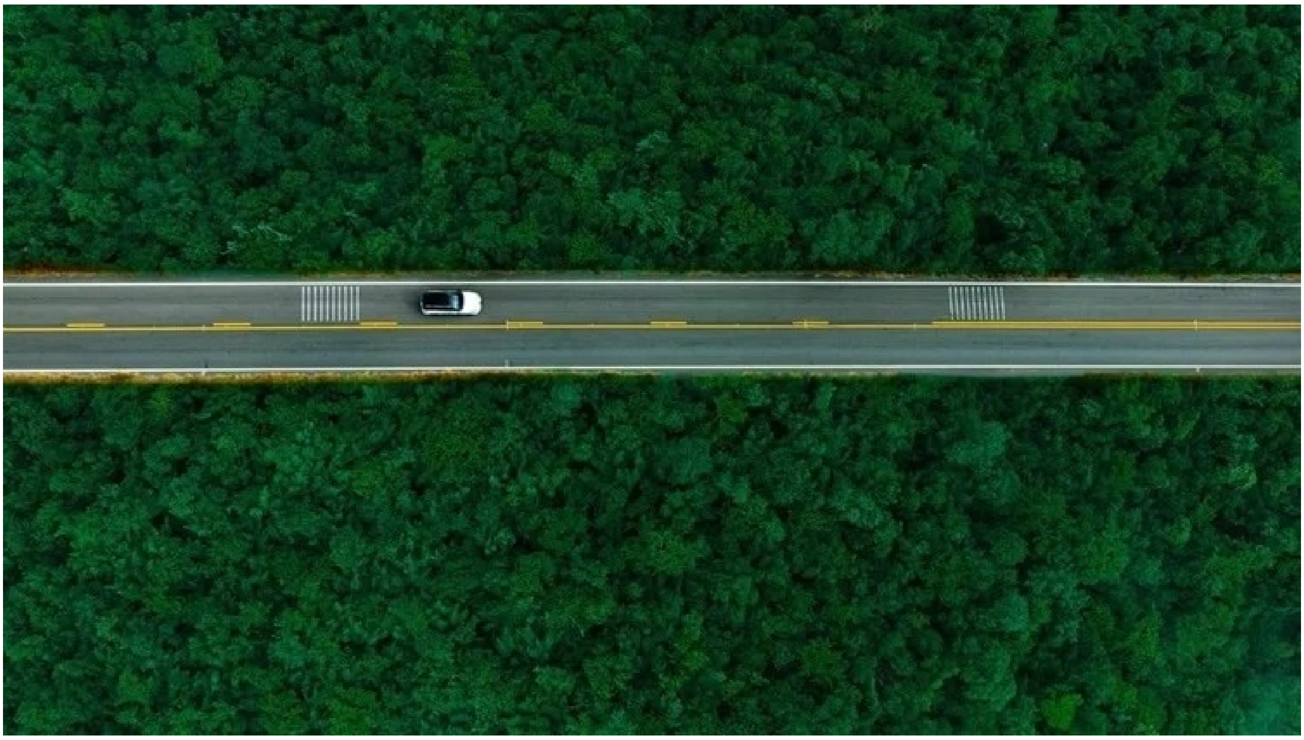

Image Credit: Me dia/Shutterstock.com

What are Electric Roads?

Sweden aims to create a smooth charging experience where EVs can recharge their batteries without stopping.

E-roads are highways that deliver electricity to moving vehicles. This takes place through physical contact, known as conductive technology, or by using wireless electromagnetic fields, called inductive technology.[2,3]

The idea comes from many years of research, beginning with tests on trolleybuses and trams. Today, e-roads can serve various vehicles, from personal cars to heavy trucks.

For many years, Sweden's Transport Administration, Trafikverket, has tested different technologies, including overhead wires, conductive rails, and inductive coils, to find the best solution that can be used widely. The goal is to establish a standard system supporting city and long-distance travel while keeping infrastructure costs low.[1,2]

How Do E-Roads Work?

Conductive charging

Sweden's e-roads primarily use two charging methods. The first is called conductive charging. This method requires the vehicle to make physical contact with an electrified rail or overhead wire. For example, the eRoadArlanda pilot project near Stockholm has a two-kilometer rail that charges trucks using a retractable arm. When a truck drives over the rail, the arm lowers and connects, providing up to 200 kW of power. This is enough to support long-distance freight transport. While this method is energy-efficient, it needs precise alignment and special lanes.[3,4]

Inductive charging

The second method is inductive charging. This system uses coils placed under the road surface to create electromagnetic fields. Vehicles with receiver coils can turn this energy into electricity, charging their batteries without wires. Sweden tested this technology on Gotland Island, where electric buses and trucks charged while driving along a 2.5-mile section. Although inductive charging reduces wear and tear, it provides less power and faces issues with energy loss and alignment.[4,5]

Video Credit: Interesting Engineering/YouTube.com

Why has Sweden Developed Electric Roads?

Sweden is focusing on e-roads to reduce emissions, upgrade infrastructure, and achieve climate goals with transport solutions that can grow and adapt in the future.

Tackling transportation emissions

Transportation accounts for 30% of Sweden's carbon emissions, with road traffic being the largest contributor. To meet climate goals, Sweden needs to reduce emissions from long-haul freight and personal travel.

Traditional charging stations don't work well because heavy trucks have limited battery life and long charging times. E-roads solve this problem by allowing vehicles to use smaller, lighter batteries, reducing waiting time. This makes EVs more practical for deliveries and everyday travel.[1,6]

A strategic infrastructure investment

Sweden's geography, with its long highways linking major cities like Stockholm, Gothenburg, and Malmö, is perfect for testing new ideas.

The E20 highway, an important route for freight, was picked as the first permanent electric road. By electrifying this 13-mile section, Sweden hopes to show that dynamic charging can work while also collecting data on traffic and energy needs. This project supports European Union goals for zero-emission vehicle sales by 2035 and helps position Sweden as a leader in sustainable transportation.[3,5]

What are the Benefits of E-Roads?

E-roads offer significant benefits in terms of sustainability, economic efficiency, and accessibility, making them a promising alternative to traditional transport systems.

Environmental and economic advantages

E-roads could cut heavy truck emissions by one-third in Sweden. Smaller batteries, up to 50–80% smaller, can lower manufacturing costs and use fewer resources. Dynamic charging means drivers won't worry about running out of power and will save money since electricity costs less than diesel.[7,8]

Infrastructure efficiency

Sweden is placing charging systems directly into its existing roads. This approach saves land and avoids the clutter of traditional charging stations. It also helps rural areas that have few charging options, promoting fair access to EVs. These e-roads could create jobs in green technology and attract international investment, boosting the economy.[1,6]

What are the Challenges and Limitations of E-Roads?

Building e-roads requires a significant upfront investment. The E20 project alone is estimated to cost approximately 30 million SEK per kilometer, plus ongoing expenses for maintenance and upgrades.

Inductive systems are less noticeable but need expensive underground installations and regular repairs because of weather damage. Conductive rails are more durable but wear down from friction and need special lanes, which makes traffic flow more complicated.[9,4]

For e-roads to succeed, vehicles and infrastructure must adhere to universal standards. Sweden is working with Germany and France to align technologies, but they still have disagreements. For example, France prefers conductive rails for heavy trucks, while Sweden is exploring inductive options for wider adoption. If these systems cannot work together, cross-border transport could face problems.

Advancements in battery technology also pose a challenge; if EVs can go longer distances independently, e-roads might not be needed anymore.[10]

What are the Alternatives to E-Roads?

Static charging and battery swapping

Static fast-charging stations offer quicker refuels and require less infrastructure investment. Battery-swapping stations replace depleted packs in minutes, eliminating charging waits. However, both solutions still depend on large batteries and frequent stops, which e-roads aim to avoid.[6,7]

Hydrogen fuel cells

Hydrogen-powered vehicles emit only water and offer ranges comparable to gasoline cars. Sweden already operates hydrogen buses in Trelleborg, but production costs remain high and infrastructure is sparse. While hydrogen is suitable for long-haul transport, e-roads provide a more immediate solution for mixed traffic.[11]

What Does the Future Hold for E-Roads?

Sweden plans to expand its e-road network to 3,000 kilometers by 2045, focusing on major highways and urban corridors. There is increasing international interest, with countries like the United States and India also investing in the development of electric roads. However, widespread adoption hinges on cost reductions. Researchers suggest prioritizing high-traffic routes to maximize return on investment, as electrifying 25% of roads could suffice for most journeys.[2,7]

Sweden's e-roads are a significant step toward making transportation cleaner. Although there are challenges, such as costs and the need for standard rules, the benefits could be substantial, including lower emissions, economic growth, and improved mobility.

As countries work toward achieving their climate goals, Sweden's experiments offer valuable lessons on balancing ambition and feasibility. Whether e-roads become widely adopted or serve as a temporary solution, they emphasize the need to rethink infrastructure for a more sustainable future.

References and Further Reading

1. Harrison, J. (2025). Sweden's Groundbreaking Electric Road: A Leap Toward Sustainable Transportation. *Engineerine.com*. https://engineerine.com/swedens-groundbreaking-

electric-road-a-leap-toward-sustainable-transportation/

2. Sweden is building the world's first permanent electrified road for EVs to charge while driving. *euronews.* https://www.euronews.com/next/2023/05/09/sweden-is-building-the-worlds-first-permanent-electrified-road-for-evs-to-charge-while-dri
3. Sweden's e-highway revolution: the world's first dynamic charging roadway in Stockholm. *Techarenan News.* https://www.techarenan.news/2024/04/30/sweden-s-e-highway-revolution-the-world-s-first-dynamic-charging-roadway-in-stockholm/
4. Pei, Y., Chen, F., Ma, T., & Gu, G. (2024). A comparative review study on the electrified road structures: Performances, sustainability, and prospects. *Structures*, *62*, 106185. DOI:10.1016/j.istruc.2024.106185. https://www.sciencedirect.com/science/article/pii/S2352012424003370
5. Sweden will build the world's first EV charging road. (2023). *TopGear.* https://www.topgear.com/car-news/electric/sweden-will-build-worlds-first-ev-charging-road
6. Considering Greener Roadways: The Sweden Electric Road. *Environment Co.* https://environment.co/sweden-electric-road/
7. Börjesson, M., Johansson, M., & Kågeson, P. (2021). The economics of electric roads. *Transportation Research Part C: Emerging Technologies*, *125*, 102990. DOI:10.1016/j.trc.2021.102990. https://www.sciencedirect.com/science/article/pii/S0968090X21000255
8. *Evolution Road – the Next Generation Electric Roads.* News - Smart City Sweden. https://smartcitysweden.com/best-practice/412/evolution-road-the-next-generation-electric-road/
9. Postponed – that's why the cost of Sweden's first permanent electric road skyrocketed. *Ny Teknik.* https://www.nyteknik.se/fordon/skjuts-upp-darfor-skenade-kostnaden-for-sveriges-forsta-permanenta-elvag/4189641
10. CHOOSING ERS TECHNOLOGY FOR EUROPE. (2024). *Webarchive.org.* https://web.archive.org/web/20240310135018/https://electric-road-systems.eu/e-r-systems-wAssets/docs/publications/CollERS-Choosing-ERS-Technology-for-Europe.pdf
11. Sweden Expands Hydrogen Transport to Cut Emissions and Reach 2045 Goal. *Smiley Movement.* https://smileymovement.org/news/sweden-hydrogen-buses

What the Battery Passport Means for Researchers and Material Suppliers

The battery passport creates a digital record that mirrors the physical battery's lifecycle, capturing data on material sourcing, manufacturing history, and sustainability metrics.

It aims to increase transparency across the global battery value chain by standardizing the collection and exchange of reliable data among stakeholders.

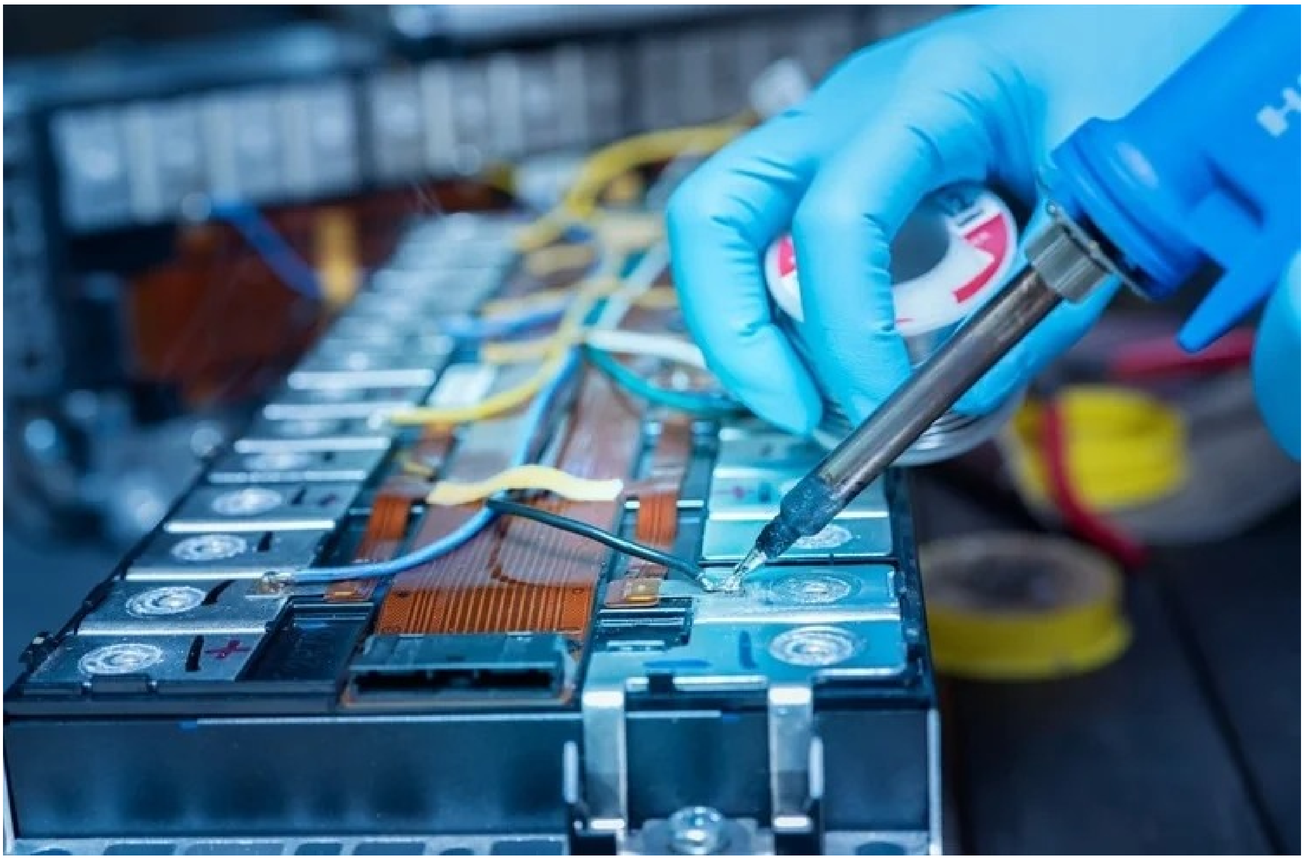

Image Credit: Fahroni/Shutterstock.com

Developed as part of a broader push toward responsible and circular battery production, the battery passport provides a foundation for traceable, auditable, and comparable information. Ultimately, it functions as a quality seal based on sustainability criteria agreed upon by industry, academia, regulators, and civil society.

Achieving this vision requires coordination across a broad ecosystem—auditors, manufacturers, regulators, IT providers, and public institutions—to create an infrastructure that is both scalable and interoperable.[1]

Regulatory Drivers

Global regulations focused on circular economy and sustainability are accelerating the implementation of battery passports [2-4]

In the European Union (EU), the battery passport is a core component of Regulation 2023/1542, which took effect on February 18, 2024.[2]

This regulation applies to all batteries sold in the EU, including those in electric vehicles (EVs), industrial systems, and light means of transport (LMT). It mandates that, starting February 18, 2027, all industrial batteries over 2 kWh and all LMT and EV batteries must be accompanied by a digital battery passport.[2]

The passport must include specific data: a unique identifier, basic technical specifications (such as production date, model, and chemical composition), and updated performance and durability records over the battery's lifespan, including during repair or repurposing.[2]

These requirements apply across the battery supply chain, from raw material suppliers and cell manufacturers to automotive OEMs and battery recyclers. The regulation aims to increase accountability, traceability, and sustainability throughout the lifecycle.[2]

In the United States, similar goals are being addressed through regulatory incentives. The Inflation Reduction Act (IRA), particularly Section 45X, includes provisions such as the Advanced Manufacturing Production Credit. To qualify for the $7,500 EV tax credit, manufacturers must show that critical minerals are sourced or processed in the U.S. or in countries with free trade agreements, or recycled in North America.[3]

At least 50 % of the value added for each mineral must come from qualifying sources. These provisions are already in effect and apply to eligible EV models, including the Tesla Model Y, Tesla Model 3 Long Range, Tesla Model X (2025), Chevrolet Equinox EV (2024), Chevrolet Blazer EV (2024), and Ford F-150 Lightning (2022–2025). While the U.S. does not currently mandate a formal battery passport, development efforts are underway.[4]

Importance for Researchers

Battery passports offer researchers access to standardized, traceable data across the battery lifecycle. This supports work on recyclability, lifecycle assessment, and ethical sourcing of materials. The structured data environment created by battery passports enables faster validation of new technologies and materials.

The increased transparency also encourages interdisciplinary collaboration (particularly between materials science, policy, and sustainability research) and provides a practical framework for addressing key challenges in battery innovation.[5,6]

For example, researchers could use battery passport data to study how different chemistries degrade under real-world use, model cradle-to-grave CO_2 emissions, or assess the impact of material sourcing choices on lifecycle sustainability.

Impact on Material Suppliers

Battery passports place new demands on material suppliers to provide verified, traceable, and low-carbon inputs. With the EU set to require digital passports for EV and industrial batteries by 2027, suppliers must adapt to stricter documentation standards, including carbon footprint disclosures and proof of responsible sourcing.[7]

This is especially important for suppliers of critical materials like lithium and cobalt, which face growing scrutiny over environmental and ethical concerns.

For instance, a lithium producer aiming to comply with EU passport requirements might need to implement on-site emissions tracking, secure third-party certifications, and digitize sourcing documentation to align with carbon disclosure rules. Non-compliance could result in production delays, regulatory penalties, or reputational damage.

At the same time, these requirements present an opportunity. Suppliers that can meet or exceed sustainability standards may differentiate themselves in the market, build stronger relationships with OEMs, and play a larger role in the shift toward responsible battery supply chains.[7]

From Compliance to Opportunity: Navigating Battery Passport Implementation

Implementing battery passports introduces both technical and operational challenges for stakeholders across the battery value chain.

A major hurdle is adapting to evolving regulatory standards, such as the EU Batteries Regulation. Many companies will face high initial costs due to inconsistent data standards and the difficulty of collecting and consolidating information from multiple sources.

There are also concerns about data confidentiality and system interoperability. Companies must ensure that sensitive information is protected and that only authorized parties can access it.[8]

Despite these obstacles, early adopters may benefit from increased trust and market differentiation. Battery passports can reduce procurement costs by 2–10 % and lower pre-treatment and recycling costs by up to 20 %. In the EU, they could help cut carbon emissions by as much as 1.3 million metric tons annually.

The system also empowers consumers to make informed choices and creates new business models in reuse, repurposing, and remanufacturing, supporting a more circular and sustainable battery economy.[7,9]

So, the battery passport is more than just a regulatory tool. For researchers, it enables new opportunities in material innovation and lifecycle analysis. For material suppliers and manufacturers, it creates both pressure and incentive to adopt more responsible and traceable practices. By engaging early, stakeholders can stay ahead of regulatory demands and help shape a more transparent and resilient battery supply chain.

To understand how this regulation is being implemented and what it means for automakers and consumers, watch:

To learn more about how battery materials are recovered, reused, and repurposed across the supply chain, explore these articles:

- What Is Black Mass Recycling?
- Sustainable Battery Recycling: How Watercycle Technologies is Closing the Loop
- Second Life Batteries: Benefits and Drawbacks of Recycling Lithium-Ion EV Batteries
- Enhancing EV Battery Recycling Through Multi-Robot Collaboration

References and Further Reading

1. Battery Passport [Online] Available at https://www.globalbattery.org/battery-passport/ (Accessed on 14 May 2025)
2. Document 32023R1542 [Online] Available at https://eur-lex.europa.eu/eli/reg/2023/1542/oj (Accessed on 14 May 2025)
3. H.R.5376 - Inflation Reduction Act of 2022 [Online] Available at https://www.congress.gov/bill/117th-congress/house-bill/5376/text (Accessed on 14 May 2025)
4. Battery Passports Around the World: Key Battery Regulatory Developments and Trends [Online] Available at https://www.openbatterypassport.com/global-battery-passport-regulations (Accessed on 14 May 2025)
5. Berger, K., Schöggl, J., Baumgartner, R. J. (2022). Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. *Journal of Cleaner Production*, 353, 131492. DOI: 10.1016/j.jclepro.2022.131492,

https://www.sciencedirect.com/science/article/pii/S0959652622011131

6. Berger, K., Baumgartner, R. J., Weinzerl, M., Bachler, J., Preston, K., & Schöggl, J. (2023). Data requirements and availabilities for a digital battery passport – A value chain actor perspective. *Cleaner Production Letters*, 4, 100032. DOI: 10.1016/j.clpl.2023.100032, https://www.sciencedirect.com/science/article/pii/S2666791623000052
7. Bellomo, A., & Castro Maestre, J. A. (2022). Impact assessment of the introduction of Digital Product Passport in the Battery Eco-System by Agent-Based Modeling Simulation. https://www.politesi.polimi.it/handle/10589/215677
8. Rizos, V., & Urban, P. (2024). Barriers and policy challenges in developing circularity approaches in the EU battery sector: An assessment. *Resources, Conservation and Recycling*, 209, 107800. DOI: 10.1016/j.resconrec.2024.107800, https://www.sciencedirect.com/science/article/pii/S092134492400394X
9. Holman, J. (2024) Battery Pass consortium analysis reveals benefits, challenges of European Battery Passport [Online] Available at https://www.spglobal.com/commodity-insights/en/news-research/latest-news/metals/041124-battery-pass-consortium-analysis-reveals-benefits-challenges-of-european-battery-passport (Accessed on 14 May 2025)

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.)

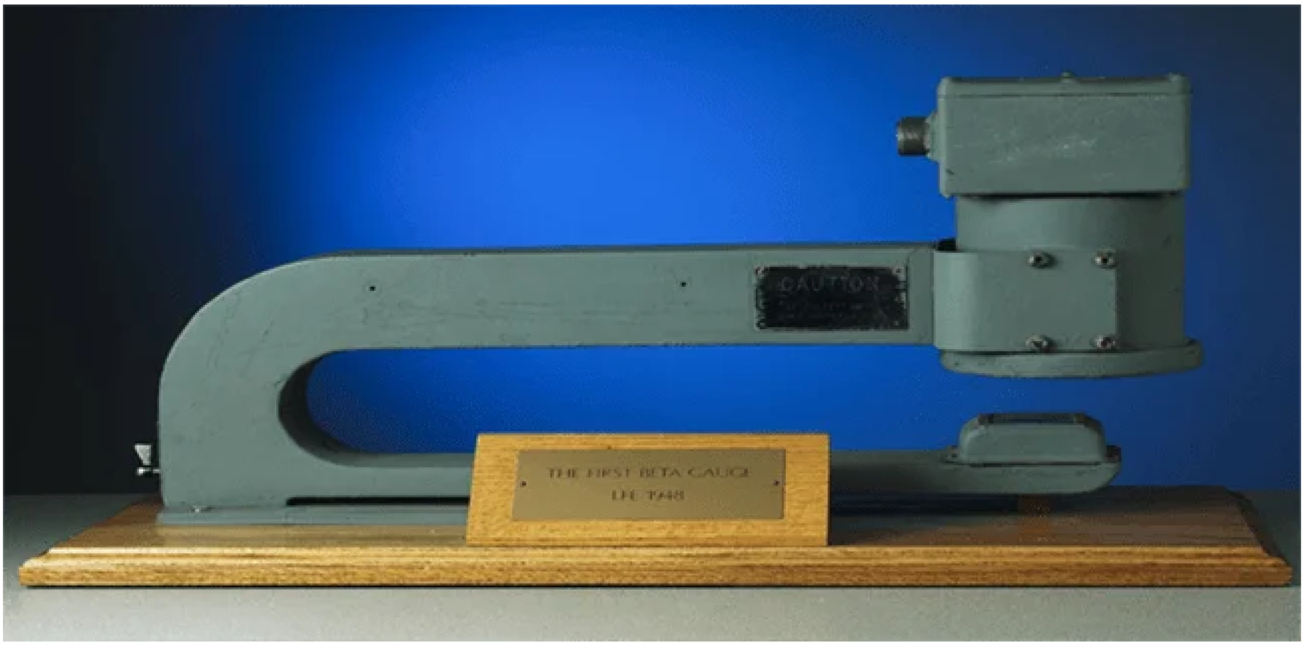

Figure 1. *Early beta-ray basis weight gauge. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

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.

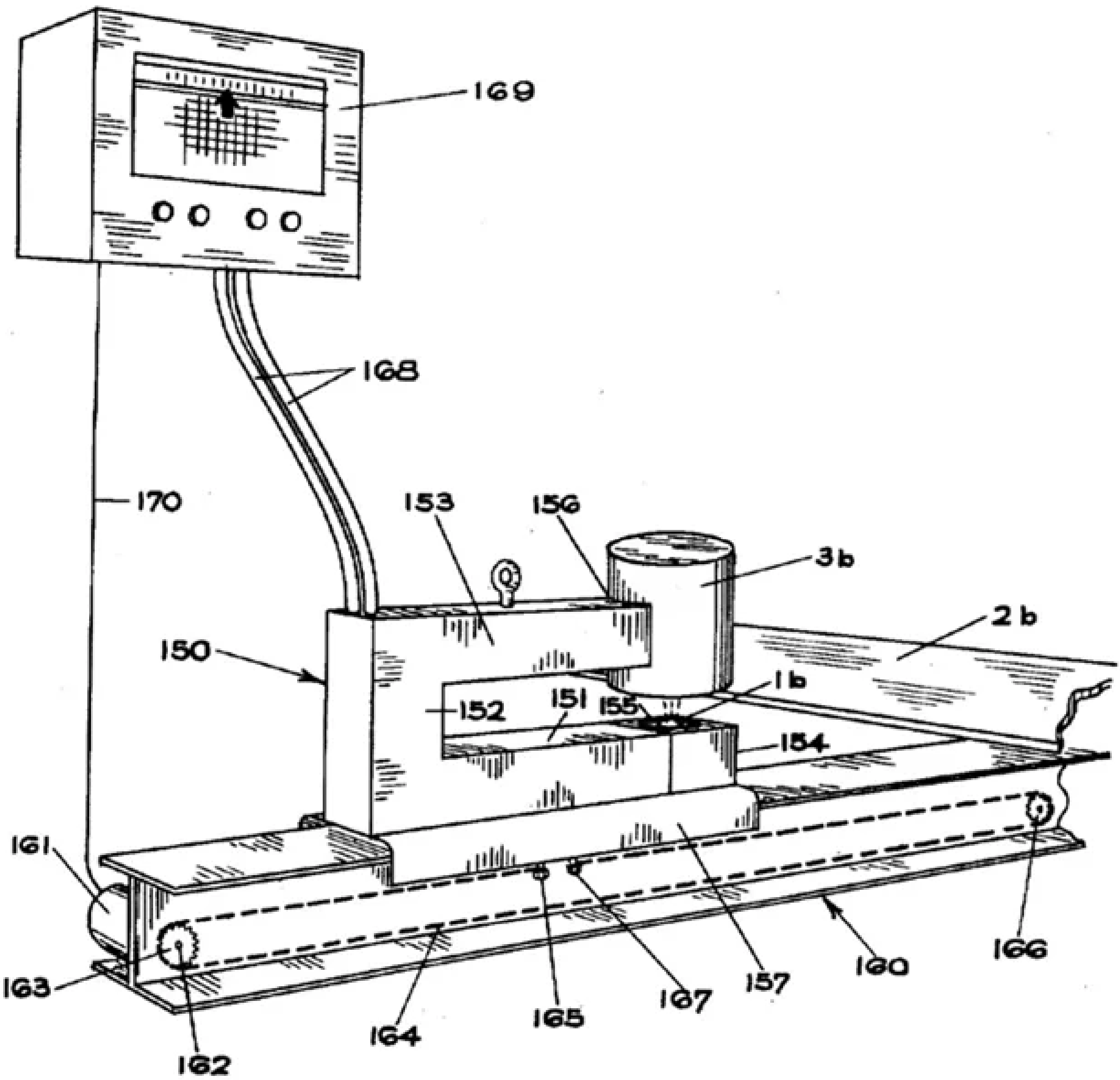

Figure 2. *1952 patent for profile thickness gauge. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

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.

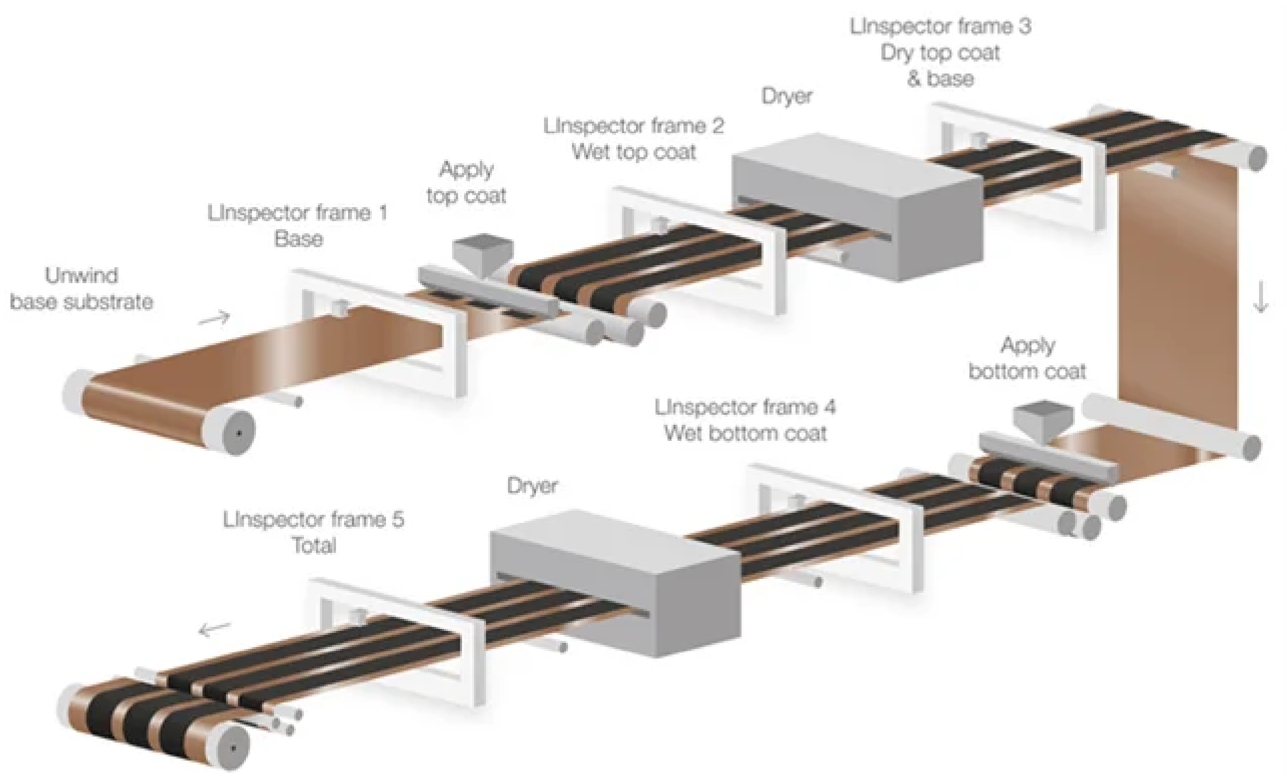

Figure 3. *Typical double-sided electrode coating line. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

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.

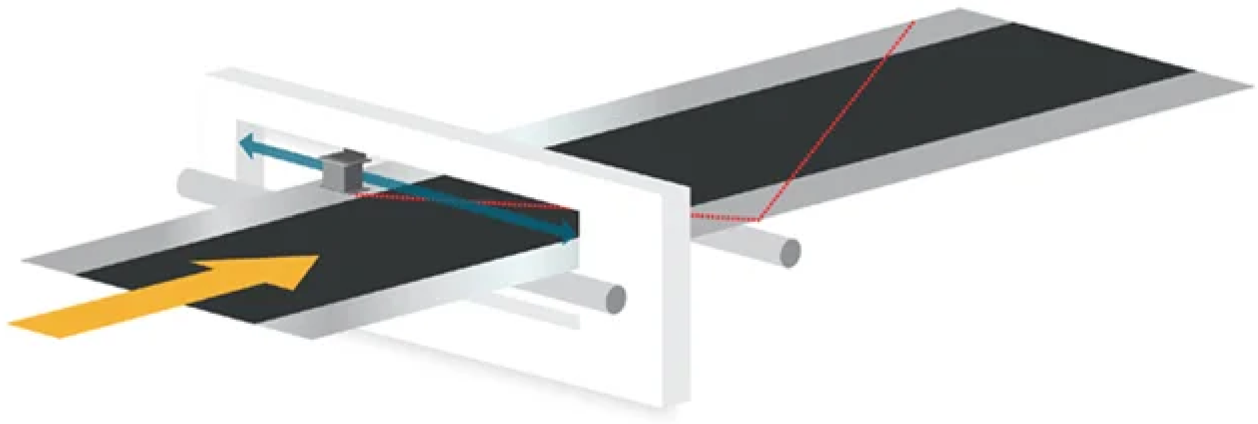

Figure 4. *Traversing single point sensors only measure 2% to 4% of the electrode material (note red trace of measurement spot). Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

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.

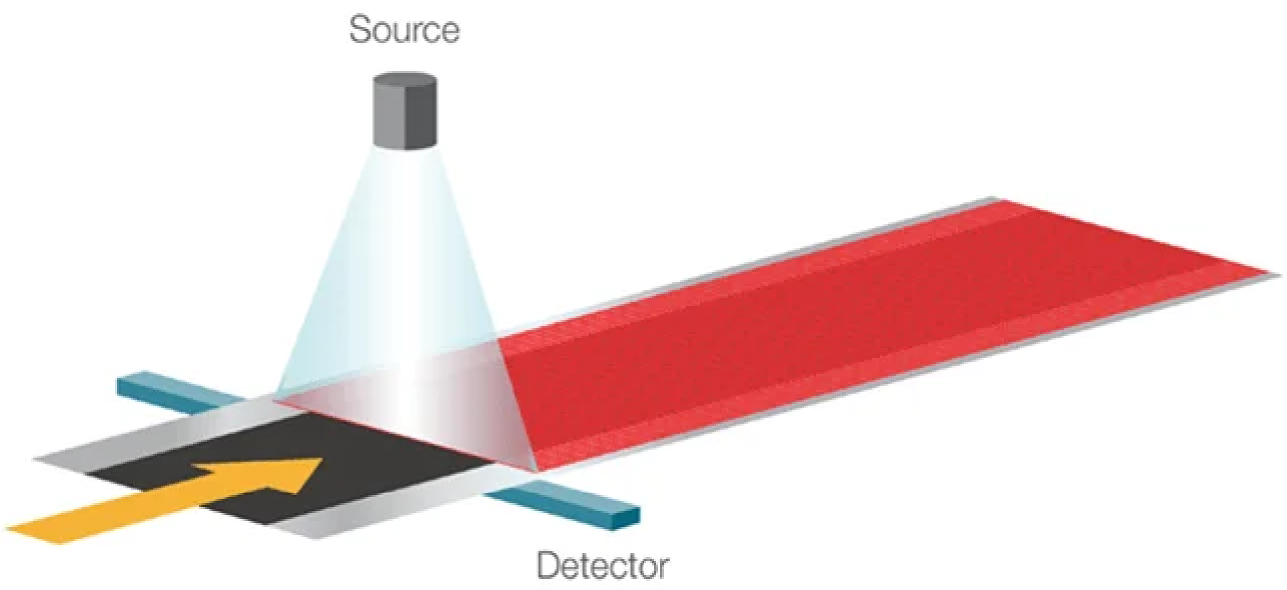

Figure 5. *Mass profilometry measurement. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

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

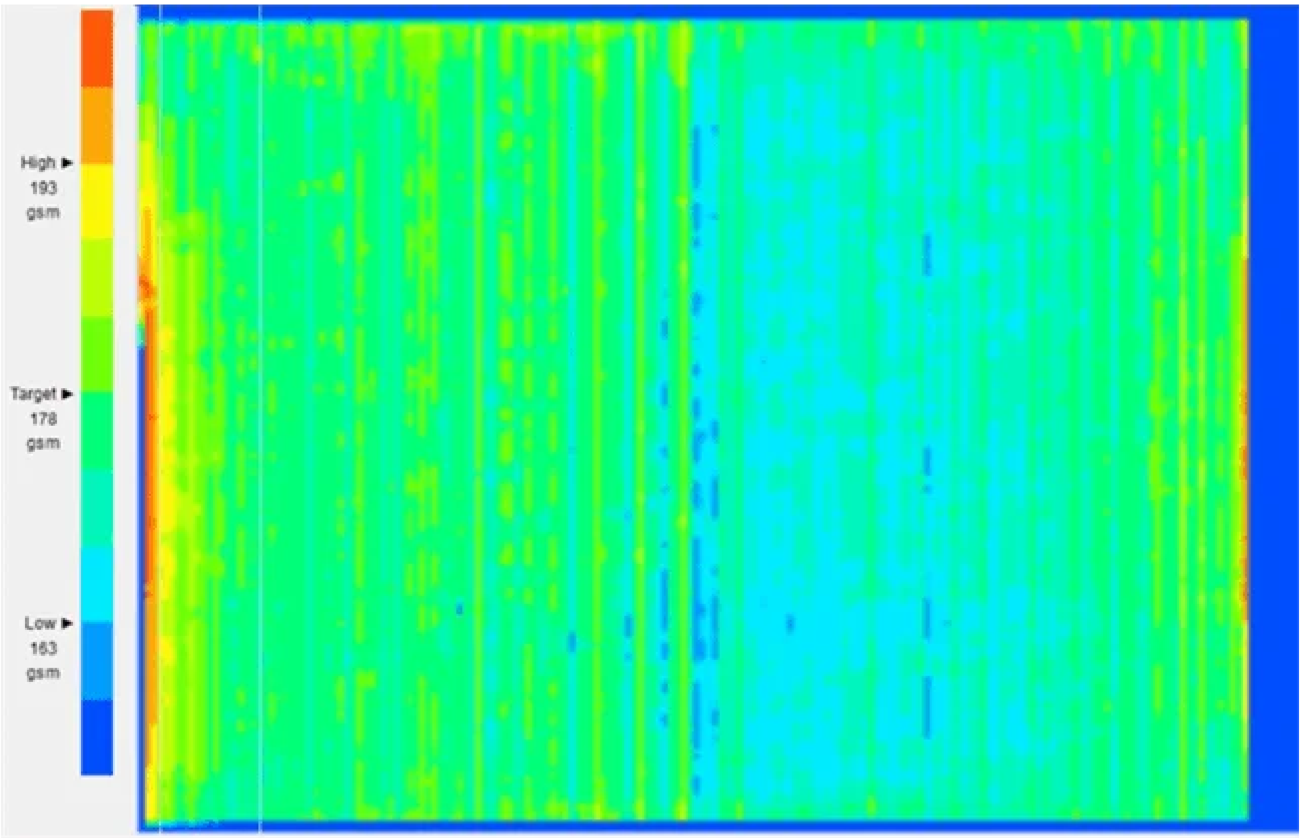

Figure 6. *Mass loading heatmap of a cathode patch. Image Credit: Thermo Fisher Scientific – Production Process & Analytics*

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.

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Are Biomimetic Batteries the Future of Energy Storage?

As the world becomes increasingly reliant on electricity, more stable, versatile, and efficient battery technologies are needed to help the world transition to a post-fossil fuel economy and society. Biomimetic batteries could be the future.

Image Credit: Fahkamram/Shutterstock.com

What are Biomimetic Batteries?

Designing better batteries isn't just about squeezing in more power. It's also about cutting costs, improving efficiency, and shrinking their environmental footprint. Yet despite decades of refinement, conventional lithium-ion technology still falls short of meeting the world's growing sustainability demands.

Biomimetic batteries present an interesting solution. Inspired by nature, they mimic the elegant chemical and structural properties found in living organisms. This emerging approach promises to tackle some of the toughest challenges in energy storage, offering a new version of sustainable power.

The field of biomimetic batteries encompasses a range of innovations, from bio-inspired materials and structural designs to smarter modules and management systems that emulate the efficiency of natural processes.[1]

Management systems and modules based on nature are enhancing the adaptability and flexibility of emerging advanced energy storage systems, whilst bio and bio-inspired materials are providing breakthroughs in rechargeable batteries.[1]

Overcoming Cycle Life Issues with an Innovative Biomimetic Solution

A central issue with current conventional battery technologies is their relatively short life cycles. In lithium-sulfur batteries, for example, dendrite growth and lithium polysulfide (LPS) diffusion can reduce the cycle life of batteries, requiring regular replacement and potentially causing stability and safety issues.

One solution, published in *Nature Communications*, is to use biomimetic aramid nanofiber membranes inspired by cartilage. These self-assembling bio-inspired membranes prevent LPS transport by facilitating the formation of a negative charge surface. This surface is formed on the nanoscale pores present in the biomimetic material.[2]

The results of this study were positive. The battery exhibited a capacity close to the theoretical maximum, with a cycle life of over 3,500 cycles and vastly improved discharge rates. Moreover, the green synthesis methods used mean that this biomimetic battery technology is more sustainable, and the membranes are also safer due to their high thermal resilience.

Biomimetic Thermogalvanic Cells Offer High-Efficiency Waste Heat Recovery

Researchers are exploring ways to harvest waste heat directly within energy storage devices, turning thermal losses into usable energy. While some approaches have shown promise, they still face significant challenges, such as ion pairing, which limits ion concentration gradients and results in less-than-desirable conversion efficiencies.

Thermogalvanic cells have emerged as a particularly promising technology for this purpose, but there are still challenges that stand in the way of their success. Battery designs based on natural structures have the potential to overcome these issues.

A new paper has presented a bio-inspired thermogalvanic cell with a double-layered structure inspired by electric eels. This cell provides improved separation of redox pairs, overcoming ion pairing issues.

The study demonstrates that engineered ionic gradients are possible using this biomimetic energy storage technology.[3] The extent of the device's capabilities was shown using a modular thermoelectric generator that could power commercial electronic displays and LEDs.

Engineering Seamless Interfaces With a Biomimetic Hydrogel

Wearable tech and human/machine interfaces are two areas developing rapidly in tech. However, they require flexibility and durability, which is difficult to achieve. Aqueous batteries show promise here, but current technologies are somewhat limited due to issues such as low strength and potential parasitic reactions.

A new energy storage solution is needed, one that can overcome these limitations and better use wasted energy.

Bio-inspired hydrogel structures could be the way forward. A 2025 paper published in *Energy & Environmental Science* presents one such technology based on bone and mammalian joint structures. This biomimetic hydrogel is extremely dense and ultra-robust, mimicking the interactions between bone and collagen, as well as collagen with synovial fluid.[4]

The hydrogel presented in the study exhibits exceptional mechanical properties and enhanced ion transfer by disrupting unwanted crystallization. The researchers demonstrated that the hydrogel has potential for use as an electrolyte/electrode interface as well as a suitable technology for use in seamless human/machine interfaces in areas such as health monitoring. [4]

Toward the Future: How Can Biomimetic Battery Technologies Help Solve Current Energy Storage Challenges?

Whilst technology has made significant strides toward a more sustainable future in recent years, more work needs to be done to realize the potential of the solutions presented above in environmental energy storage.

Biomimetic devices are potentially game-changing energy storage technologies. However, they need to be scalable and cost-effective to be considered commercially viable.

The increasing interest and focus on these bio-inspired battery technologies is positive, and if governments and the commercial sector are to meet internationally agreed limits on carbon emissions and climate change, more investment and collaboration between academia and industry will be needed.

Biomimetic batteries could well be the future of energy storage, or at least play a noteworthy role in its future.

Further Reading and More Information

1. Zhang, N *et al.* (2025) Learning from nature: Biomimicry in secondary batteries *Materials Today* 82 pp. 223-250 [online] ScienceDirect. Available at: https://www.sciencedirect.com/science/article/abs/pii/S136970212400258X (Accessed on 28 June 2025)
2. Wang, M *et al.* (2022) Multifactorial engineering of biomimetic membranes for batteries with multiple high-performance parameters *Nature Communications* 13, 278 [online] Nature. Available at: https://www.nature.com/articles/s41467-021-27861-w (Accessed on 28 June 2025)
3. Chi, C *et al.* (2025) Bioinspired Double-Layer Thermogalvanic Cells with Engineered Ionic Gradients for High-Efficiency Waste Heat Recovery *Nano Energy* 142 Part A [online] ScienceDirect. Available at: https://doi.org/10.1016/j.nanoen.2025.111189 (Accessed on 28 June 2025)
4. Yao, L *et al.* (2025) Biomimetic bone hydrogel enables a seamless interface for aqueous battery and human/machine interaction *Energy & Environmental Science* 18 pp. 2524-2535 [online] Royal Society of Chemistry. Available at: https://pubs.rsc.org/en/content/articlelanding/2025/ee/d4ee05066e (Accessed on 28 June 2025)

The Future of Graphene Batteries in Electric Vehicles

The rapid growth of electric vehicles (EVs) is pushing the demand for more efficient, durable, and sustainable battery technologies. While lithium-ion (Li-ion) batteries have dominated the EV landscape, they have several limitations, including long charging times, degradation over multiple cycles, and safety concerns.

Graphene, a groundbreaking material known for its exceptional electrical and thermal properties, is emerging as a game-changer in battery technology. By integrating graphene into energy storage solutions, researchers and companies aim to significantly improve battery performance. This article examines graphene batteries' advantages, research progress, commercialization challenges, and impact on EVs.

Image Credit: Aliaksei Kaponia/Shutterstock.com

What is Graphene?

Graphene is a single layer of carbon atoms arranged in a hexagonal lattice, making it the thinnest yet one of the strongest materials known to science. Its remarkable properties include exceptional electrical conductivity, superior mechanical strength, and high thermal conductivity.

Graphene is 200 times stronger than steel while being incredibly lightweight, enabling innovative applications in various industries, from electronics to aerospace.[1]

Due to its high electron mobility, graphene enables faster charge and discharge rates in batteries, enhancing efficiency and performance beyond traditional Li-ion technology.

Since its discovery, extensive research has focused on unlocking its potential for improving energy storage—especially in EV batteries, where it could enhance range, charging speed, and lifespan.[1]

Advantages of Graphene Batteries Over Li-Ion Batteries

Graphene-based batteries offer several advantages over conventional Li-ion batteries, making them highly promising for the EV industry.

- **Faster Charging:** Graphene enables rapid electron movement, significantly reducing charging times. While Li-ion batteries take 30–60 minutes for a full charge, graphene batteries could potentially charge within a few minutes.[1,2]
- **Higher Energy Density:** Li-ion batteries have a limited energy storage capacity. With their high surface area and superior conductivity, graphene batteries can store more energy in the same volume, extending the EV range.[1,2]
- **Longer Lifespan:** Traditional batteries degrade with repeated charge cycles. Graphene batteries exhibit less wear and tear, resulting in a longer operational life and reducing the need for frequent replacements.[1,2]
- **Improved Efficiency:** Graphene enhances ion transport, reducing energy losses during charging and discharging. This leads to better overall battery performance and improved vehicle efficiency.[1,2]
- **Enhanced Safety:** Overheating and thermal runaway are common issues with Li-ion batteries. Graphene's superior thermal conductivity dissipates heat efficiently, minimizing the risk of fires and explosions.[1,2]

Video Credit: Enkoretech/YouTube.com

Current Research and Development of Graphene Batteries

Several companies are actively developing graphene-based battery technology to bring it to commercial viability. For example, Nanotech Energy is working on commercializing graphene batteries with high energy density.

Samsung Advanced Institute of Technology (SAIT) is enhancing Li-ion batteries with graphene for faster charging, while Huawei focuses on graphene for improved heat management, boosting battery efficiency and longevity in EVs.[1]

Similarly, research institutions and universities are also leading efforts in optimizing graphene battery applications for EVs.

A recent study published in *Applied Surface Science* investigated copper-doped graphene as a high-performance anode material for Li-ion batteries using first-principles computational methods.

Copper doping enhanced active sites, significantly increasing theoretical capacities to 1651.8 mAh/g for Li-ion. This material also exhibited low diffusion barriers, minimal lattice changes (<1%), and excellent conductivity, making it a promising anode material for next-generation energy storage solutions.[3]

Another notable study published in the *Journal of Power Sources* introduced a high-energy-density graphene-based anode using a polyethersulfone (PES) sheet and laser-induced graphene (LIG) techniques for Li-ion batteries.

The hexagonal porous structure enhanced lithiation, improving battery lifespan. This binder-free, non-hazardous anode retained 80.7% capacity from 710 mAh/g at 0.1C and achieved 99% coulombic efficiency over 200 cycles, offering a scalable solution for next-generation Li-ion batteries in portable devices and EVs.[4]

The Benefits of Graphene Batteries

Graphene batteries have the potential to significantly enhance EV performance across several key aspects.

Vehicle performance

In the near future, the higher energy density of graphene batteries is expected to enable EVs to achieve significantly longer driving ranges on a single charge, making them more viable for extended journeys. As graphene technology advances, improved power output will likely enhance acceleration and overall efficiency, pushing EVs closer to the capabilities of high-performance sports cars.[1,5]

Furthermore, graphene's superior conductivity is anticipated to ensure consistent energy delivery, reduce performance fluctuations, and optimize power management for a smoother and more reliable driving experience.

Charging times

The ultra-fast charging capability of graphene batteries is one of their most significant advantages. With the ability to charge in minutes rather than hours, EV owners could experience a level of convenience comparable to refueling a traditional gasoline vehicle. This rapid charging would also reduce demand on charging infrastructure, improving accessibility and efficiency in EV networks.[1,5]

Sustainability

Graphene-based batteries could contribute to a more sustainable EV ecosystem. Their longer lifespan reduces battery waste, and they contain fewer environmentally harmful materials than Li-ion batteries. Graphene can also be derived from abundant carbon sources, potentially reducing reliance on rare earth metals and minimizing the environmental impact of battery production.[1,5]

Challenges and Limitations of Graphene Batteries

Despite its potential, several challenges hinder the widespread adoption of graphene batteries in EVs.

• **Manufacturing Costs:** Producing high-quality graphene remains costly, making large-scale manufacturing a significant challenge.[1]
• **Scalability Issues:** Scaling up graphene battery production to meet the demands of the EV industry requires major improvements in fabrication techniques.[1]
• **Integration into Existing Systems:** Most current EVs are built around lithium-ion batteries. Shifting to graphene-based systems would require battery management systems and charging infrastructure updates.[1]
• **Supply Chain Constraints:** Graphene production relies on specialized materials and processes. A sudden spike in demand could strain the supply chain.[1]
• **Commercialization Timeline:** Although research is advancing, it may still take several years before graphene batteries are ready for mass-market adoption, primarily due to the need for further testing and cost reduction.[1]

The Future Outlook of Graphene for Battery Production

The path to commercializing graphene batteries in EVs centers on overcoming technical and economic hurdles. Analysts suggest that over the next decade, graphene-enhanced batteries may begin to appear in high-end EV models, with wider adoption expected as production becomes more cost-effective.[1]

Looking further ahead, graphene technology could play a key role in accelerating EV adoption by addressing key concerns such as range anxiety and charging limitations. As manufacturing processes mature, graphene-based batteries may also support sustainability efforts by reducing dependence on rare earth materials and extending battery life—helping to lower the overall environmental footprint.[1]

Conclusion

Graphene batteries offer strong potential to reshape the EV landscape with faster charging, better performance, and greater durability. While there are still hurdles to clear, ongoing research and investment point to a promising trajectory. As technological progress reduces costs, graphene-based batteries could become a crucial driver of more efficient and sustainable electric mobility.

References and Further Reading

1. de Bortoli, B. *et al.* (2023). Graphene: an overview of technology in the electric vehicles of the future. SAE *Technical Paper 2022-36-0100, 2023*. DOI:10.4271/2022-36-0100. https://www.sae.org/publications/technical-papers/content/2022-36-0100/
2. Wang, X. *et al.* (2021). Research progress on graphene-based materials for high-performance lithium-metal batteries. *New Carbon Materials*, *36*(4), 711-728. DOI:10.1016/S1872-5805(21)60081-1. https://www.sciencedirect.com/science/article/abs/pii/S1872580521600811
3. Hu, J. *et al.* (2025). Cu-doped graphene Cu/N2OG: A high-performance alkaline metal ion battery anode with record-theoretical capacity. *Applied Surface Science*, *682*, 161752. DOI:10.1016/j.apsusc.2024.161752. https://www.sciencedirect.com/science/article/abs/pii/S0169433224024681
4. Rahman, M. M. *et al.* (2025). Polyethersulfone-based thick polymer-supported graphene sheet for high energy density lithium-ion battery. *Journal of Power Sources*, *626*, 235774. DOI:10.1016/j.jpowsour.2024.235774. https://www.sciencedirect.com/science/article/abs/pii/S0378775324017269
5. Chang, H. *et al.* (2021). Graphene-Enhanced Battery Components in Rechargeable Lithium-Ion and Lithium Metal Batteries. *C*, *7*(3), 65. DOI:10.3390/c7030065. https://www.mdpi.com/2311-5629/7/3/65