The Road to 2030

New software capabilities will be required for battery manufacturers to scale efficiency, throughput, and circularity.

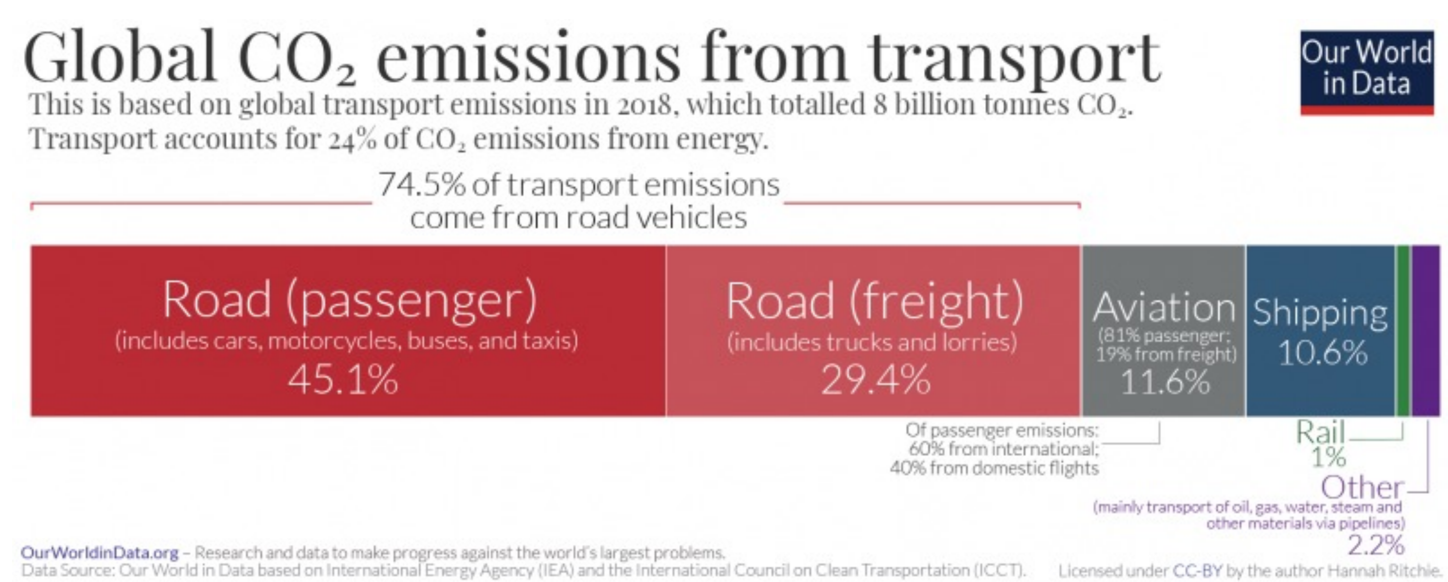
Battery production capacity is needed to support the emerging EV Market

A five-fold increase in electric vehicle (EV) battery production capacity is expected by 2030. Decarbonization of the transportation sector cannot be achieved without this massive build-out of EV battery production capacity. Governments worldwide are encouraging domestic production to attract jobs and promote long-term economic security, while simultaneously striving to mitigate long-term geopolitical and supply chain risks.

After the recent enactment of laws mandating local production to be eligible for rebates, political leaders in both the European Union and North America now realize what China recognized a decade ago: The significance of battery technology and production capacity in the future global economy will be equivalent to that of oil production in the past century. If EV batteries are the “new oil,” then battery factories are the refineries of the future.

It is anticipated that China, and Asia in general, will continue to maintain its leadership in production capacity. However, battery production is expected to shift toward the EV assembly plants being constructed worldwide, often near each other. Governments worldwide are promoting domestic production as a means of achieving long-term economic stability, mitigating climate change, and creating more employment opportunities in the manufacturing sector.

Transportation accounts for 24% of global CO2 with more than 74% coming from road vehicle emissions



In 2022, 13% of new vehicles sold in the U.S. were EVs.[1] A recent Bloomberg NEF study estimates that just over half of passenger cars sold in the U.S. will be electric vehicles by 2030, thanks in part to consumer incentives and the passage of the landmark climate action plan within the U.S. Inflation Reduction Act (IRA).

To meet increasing consumer demand, car manufacturers have announced that more than 60 new EV models will be available within the next five years. Battery and automotive manufacturers have been announcing new plants on what feels like a weekly basis. Global investments in EV assembly and battery plants are expected to reach $860 billion by 2030. Of this, $210 billion is expected to be invested in the United States alone.[2] Barriers to entry have come down, enabling new players like Rivian, Lucid, and Foxconn to enter the market.

This decade will witness the emergence of companies that efficiently expand their production and operations to meet ever-increasing demand projections. These companies will develop capabilities to adeptly handle the constantly evolving impacts associated with battery chemistries, material costs, quality, safety, and genealogy.

The ability to cost-effectively scale EV battery production will be the single most important variable impacting the pace of decarbonization.

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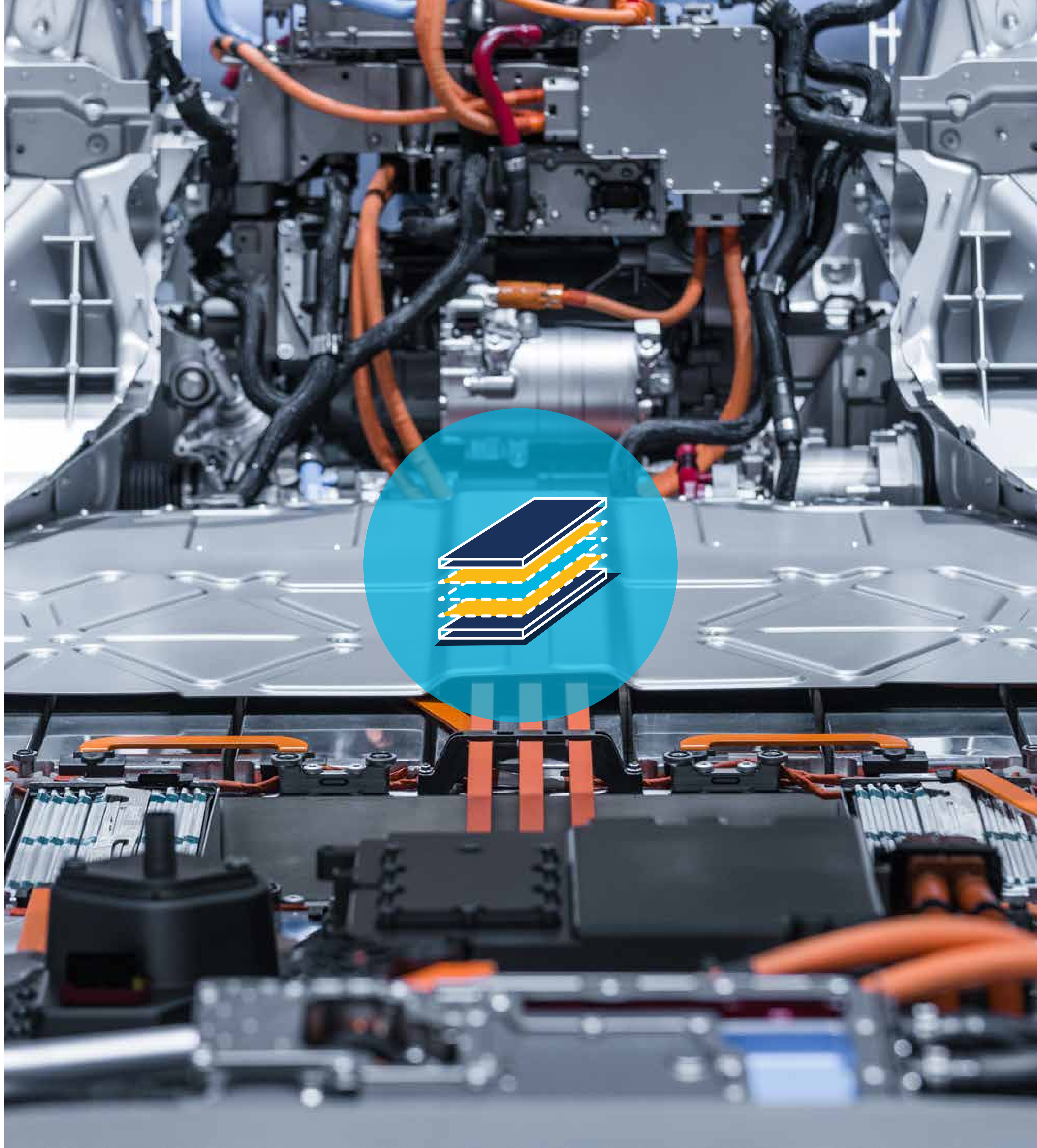
1 The International Energy Agency (IEA) Electric Vehicle Tracking Report (Sept. 2022)

2 Atlas Public Policy Research (January 2023)



Challenges on the Road to 2030

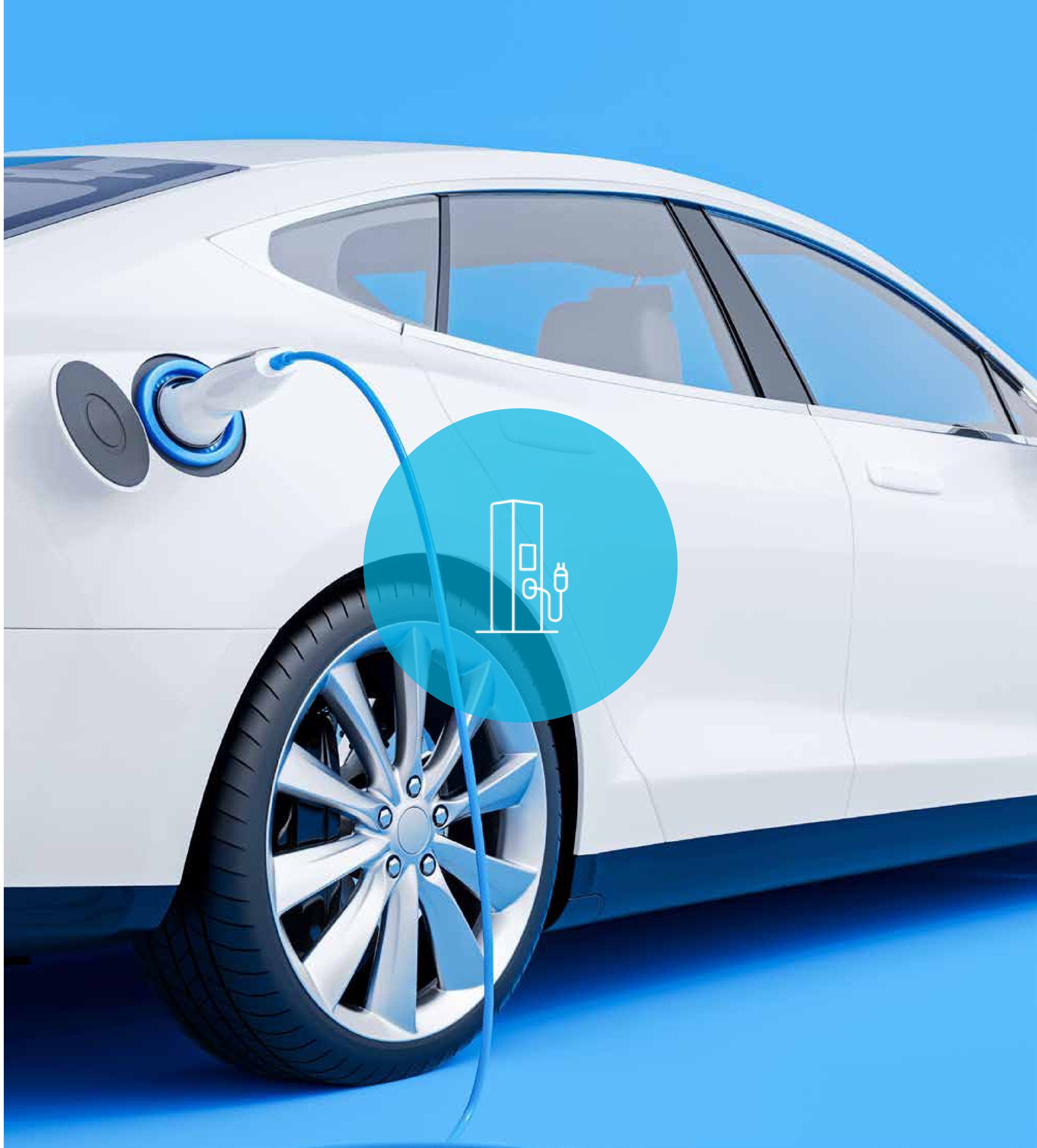
Automakers understand the significance of battery technology in shaping their future. Automakers are currently engaged in either developing their own battery manufacturing capabilities or establishing strong partnerships with established battery manufacturers.

The race to 2030 is just the beginning of a multi-decade build-out of the battery production capacity required to decarbonize the transportation sector. Undoubtedly, every decade will produce new winners and losers, but this decade will establish the foundation of the industry for the years ahead. In 2030, China is expected to still lead the world in EV battery capacity. However, we will see the emergence of new EV battery plants in Europe and North America. Over the next seven years, manufacturers will be competing to increase their production capacity while simultaneously reducing their production costs.

Top challenges for EV battery manufacturers will include:

1. Managing complex, interconnected processes
2. Scaling production capacity
3. Enterprise visibility & optimization
4. Transition from linear to circular supply chains

This white paper will explore each of these challenges in detail and illustrate how GE Digital's Smart Factory Software can help manufacturers tackle these challenges.



Challenge #1:

Managing Complex, Interconnected Processes

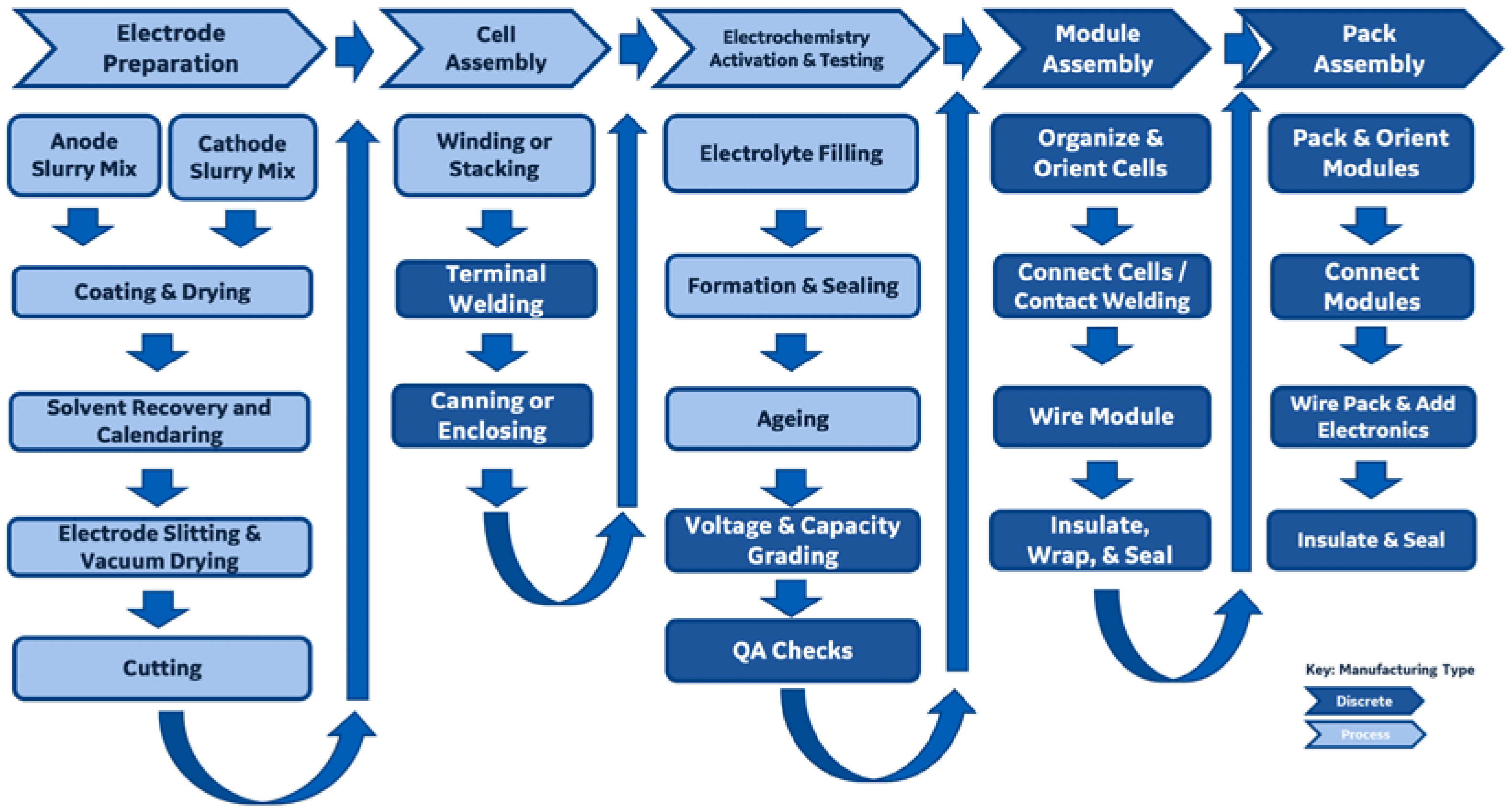
EV battery pack production cannot be accomplished through a single process. It necessitates various intricate and interrelated procedures, each presenting its own challenge, production rate, and quality consideration. The end-to-end manufacturing process encompasses both process-based and discrete-based production activities. The process of making electrodes and cells largely follows continuous process manufacturing steps, while the assembly of modules and packs is discrete.

A lithium-ion cell commonly utilized in EV applications can be manufactured through two distinct methods: wet or dry.

- The wet method uses anode and cathode electrodes in a slurry form and applied as a coating onto a thin foil, which is then rolled into a cell.
- The dry process involves a powder mixture of the electrode directly applied onto the foil, obviating the necessity for drying wet components.

Typically, there is less processing involved in comparison to the overall process. After the material has been rolled, it is enclosed in a cell casing and subjected to testing. The next step involves assembling the battery cells into a module, which can then be integrated into a battery pack suitable for the intended application, such as an EV.

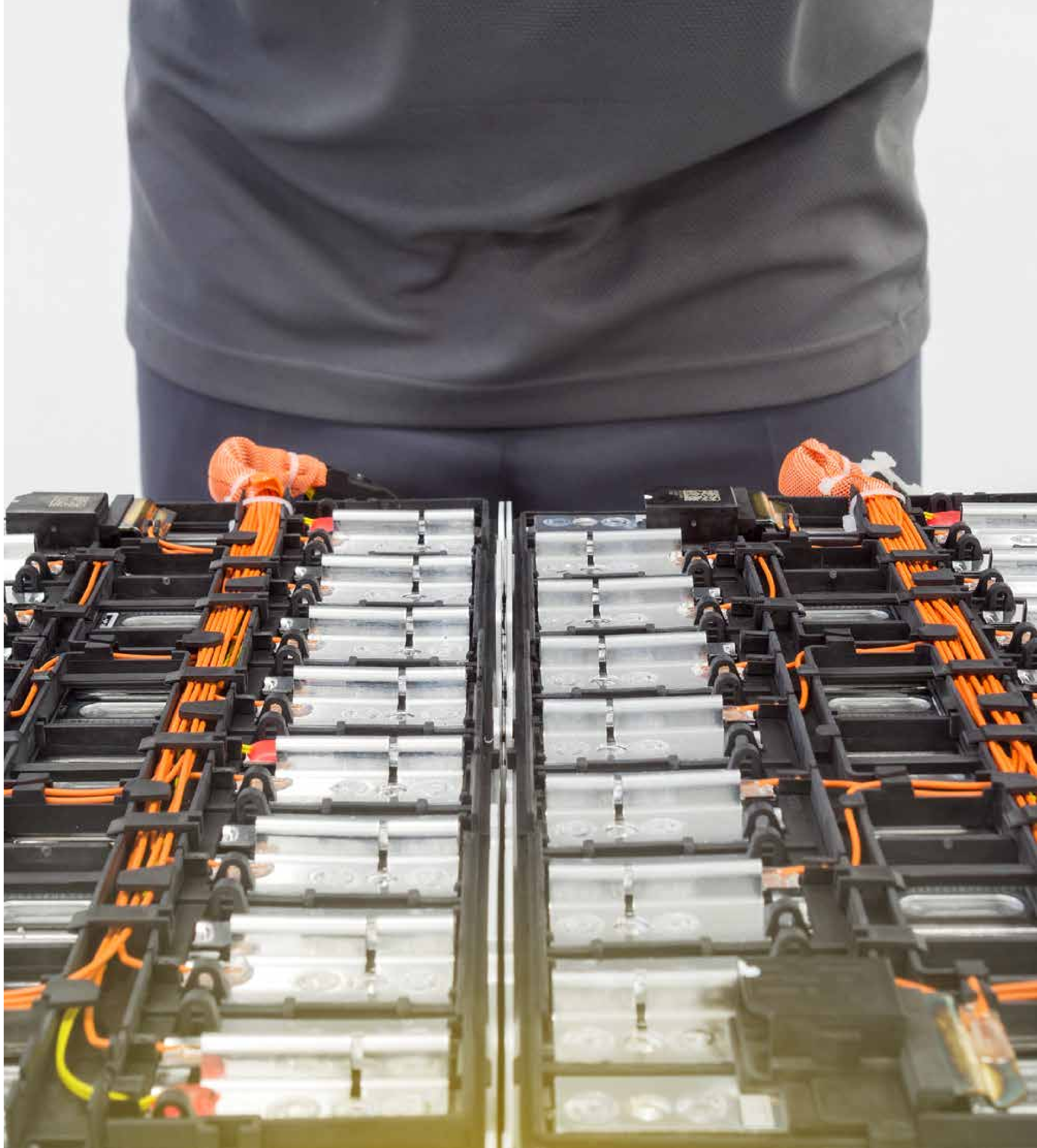
Figure 1: Representative EV Battery Production Processes



As part of the cell production process, it is imperative to balance the cell's energy density and power density. Energy density is the battery's capacity of retaining an electric charge, whereas power density is the ability of the battery to release the stored charge. For a process engineer, the goal is to maintain equilibrium between these two critical cell characteristics. Attempting to optimize one at the expense of the other results in battery performance problems.

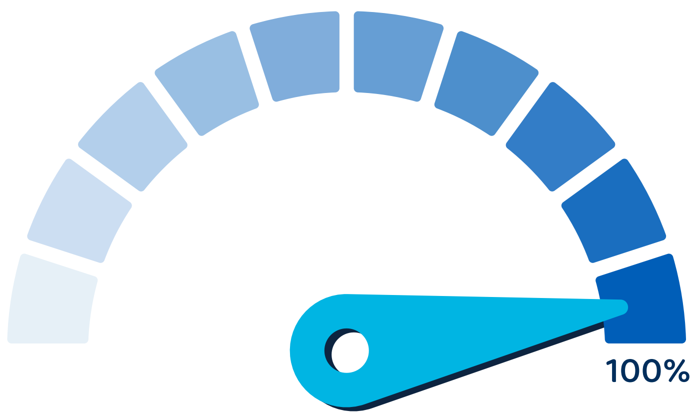
The cell manufacturing process is influenced by several factors, including but not limited to the choice of materials, equipment, and process conditions. To attain optimal cell performance in a consistent manner, it is imperative for a process engineer to exercise control over the entire process, be it wet or dry, to ensure uniform application of the electrode material.

Utilizing statistical process control and advanced analytics is crucial to achieve the goal of optimizing production processes.



Challenge #2: Scaling Production Capacity

The software used to startup the plant may not scale as production capability expands. The ability to supervise and control manufacturing floor processes and production line operation in real time is essential for efficient production scaling. Manufacturing execution systems (MES) can be effectively leveraged on a large scale, while maintaining cost efficiency. Most MES vendors must use two separate and distinct MES systems to support EV battery production, as they often cannot support mixed-mode manufacturing (i.e. supporting both continuous process and discrete manufacturing activities in a single platform).



Mixed-mode manufacturing: *The ability to manage high-volume, process and discrete, manufacturing operations – under one roof – in a single MES solution*

If we revisit the overall battery manufacturing process end-to-end, from the manufacturing of a single cell to a module to the battery pack in its entirety (which eventually goes into the end application like an EV), the processes cover batch/continuous style manufacturing and a discrete assembly process. This poses a unique challenge, as typically most MES systems are designed to support only one of these manufacturing types, not both.

The second dimension of complexity in the production of batteries for electric vehicles concerns the attributes of the cell manufacturing process which involve high volume, high speed, and high variability of data. For instance, the process of cell manufacturing can be compared to a continuous production line, such as paper manufacturing, which feeds into a packaging line, akin to bottling.

The equipment is not the same, but the challenges are similar. A single “bad” cell used as input to a battery pack could impact the overall battery performance. To identify the underlying cause of a faulty cell, it is necessary to trace the pack back to the module and then to the manufacturing processes, material states, and sources. This requires a comprehensive traceability system that can track the various production stages and the origin of the materials used.

The EV battery manufacturing environment presents a unique challenge of addressing shop floor operational efficiency in mixed-mode manufacturing, while ensuring traceability of products in a high-volume line. A solution to this challenge is necessary.

The process of manufacturing batteries is intricate and demanding. Mixed-mode MES, catering to both process and discrete manufacturing, offers a viable solution to this complex manufacturing environment. These solutions provide manufacturers with comprehensive production visibility, which is essential in surmounting the challenges associated with battery production and achieving success.

A well-implemented MES can reduce process variability and optimize performance metrics such as throughput, yield, and quality. Additionally, MES can effectively decrease downtime, material waste, emissions, water consumption, and energy usage. By monitoring these parameters, MES offers users valuable insights into process variations and underlying root causes of process deviations. The observations noted above can subsequently be used to identify anomalies, predict malfunctions, and propose modifications to enhance process parameters or implement closed-loop process controls.

With a tight Go Live schedule, a major Lithium-ion battery manufacturer sought an MES provider with proven software for mixed manufacturing (process/batch and discrete) along with services to support solution design and implementation.

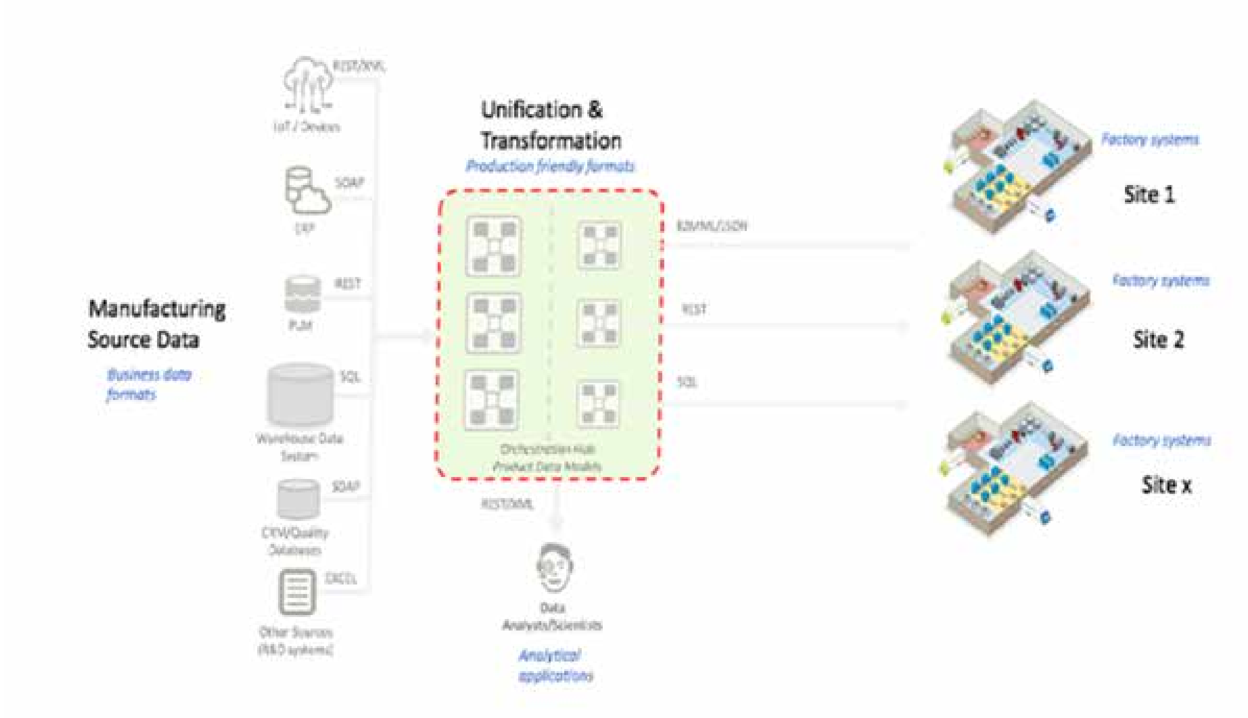
> **Recipe management:** The ability to rapidly bring new chemistries to production, while capturing production and quality records for each manufacturing run while maintaining production and quality records associated with unique chemistries.

EV transition success depends on manufacturers' abilities to make batteries the "tech of the future." Similar to Moore's Law for semiconductors, battery chemistries and technologies will need to exponentially improve energy density and increase vehicle range while reducing charging time.

According to the U.S. Department of Energy (DOE) Vehicle Technologies Office, there was an eightfold increase in battery energy density between 2008 and 2020 (from 55 to 450 Wh/L). This trend is expected to continue and most likely accelerate, driven by new battery chemistries and technological advancements. Some advancements focused on reducing or eliminating dependencies on scarce materials, like cobalt, often sourced from places such as the Democratic Republic of the Congo. For example, there is a shift to lower-cost lithium iron phosphate (LFP) batteries, which contain no nickel or cobalt.

Battery manufacturers will need capabilities to manage these chemistries similarly to those used in process industries like Pulp & Paper, Food & Beverage, Life Sciences, and Chemicals. These capabilities are referred to as recipe management, and include the formulas, standards, and controls. While the end products may be quite different, many of the production steps involved in making a battery are remarkably similar from a process standpoint. Battery manufacturers will need these capabilities to manage versions of recipes based on changes in chemistry. As manufacturers are working to develop the highest energy density cell possible with chemistries such as LiFePO and $LiCoO_2$, the resulting formulas must be managed. Given the constant recipe evolution in this market, the production process must be flexible and adaptable to accommodate the changes and continue to deliver consistent quality and production volume.

Recipe management enables the process to adapt to changes in ingredients, volumes, times, and equipment capacity while maintaining the highest levels of quality. This capability can be used to scale the recipe by updating setpoints in the automation controls to correct for process variability. GE Digital's Recipe Management capabilities reduce the time required to move new chemistries from the lab to the plant. Software solutions like Orchestration Hub (discussed in more detail below) can be use to help deploy recipes across multiple lines or sites.



Genealogy and traceability – The ability to capture the end-to-end production history of the finished product

The production and quality records capture the key data required for genealogy and traceability.

1. The production record captures all variables associated with the production run, including specific materials used, production conditions, recipe version, production date and time, and run-time.

2. The quality record documents test samples and results from specific production runs. Issues can be identified and addressed throughout the manufacturing process before they impact the final product.

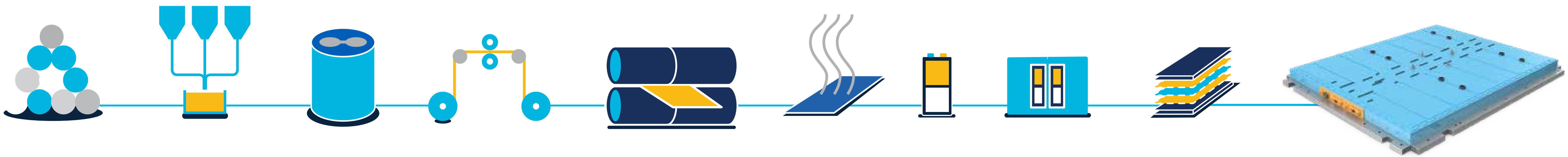
EV batteries must be optimized for safety, durability, and performance. Maintaining the characteristics of battery cell quality and performance is of utmost importance.

Material factors that affect cell quality and performance include:

- Inbound receiving inspection for material purity, grain size, viscosity, etc.
- Anode/cathode material thickness inconsistency
- Anode/cathode laser weld (preparation, fixture, and weld quality)
- Cell-wetting consistency

Because of these influences, materials management protocols must include:

- No cross-contamination between anode and cathode materials
- Storing anode materials in an anode room
- Storing cathode materials in a cathode room
- Using separate equipment for anode and cathode mixing in material transportation
- Treating each operation room as a clean room

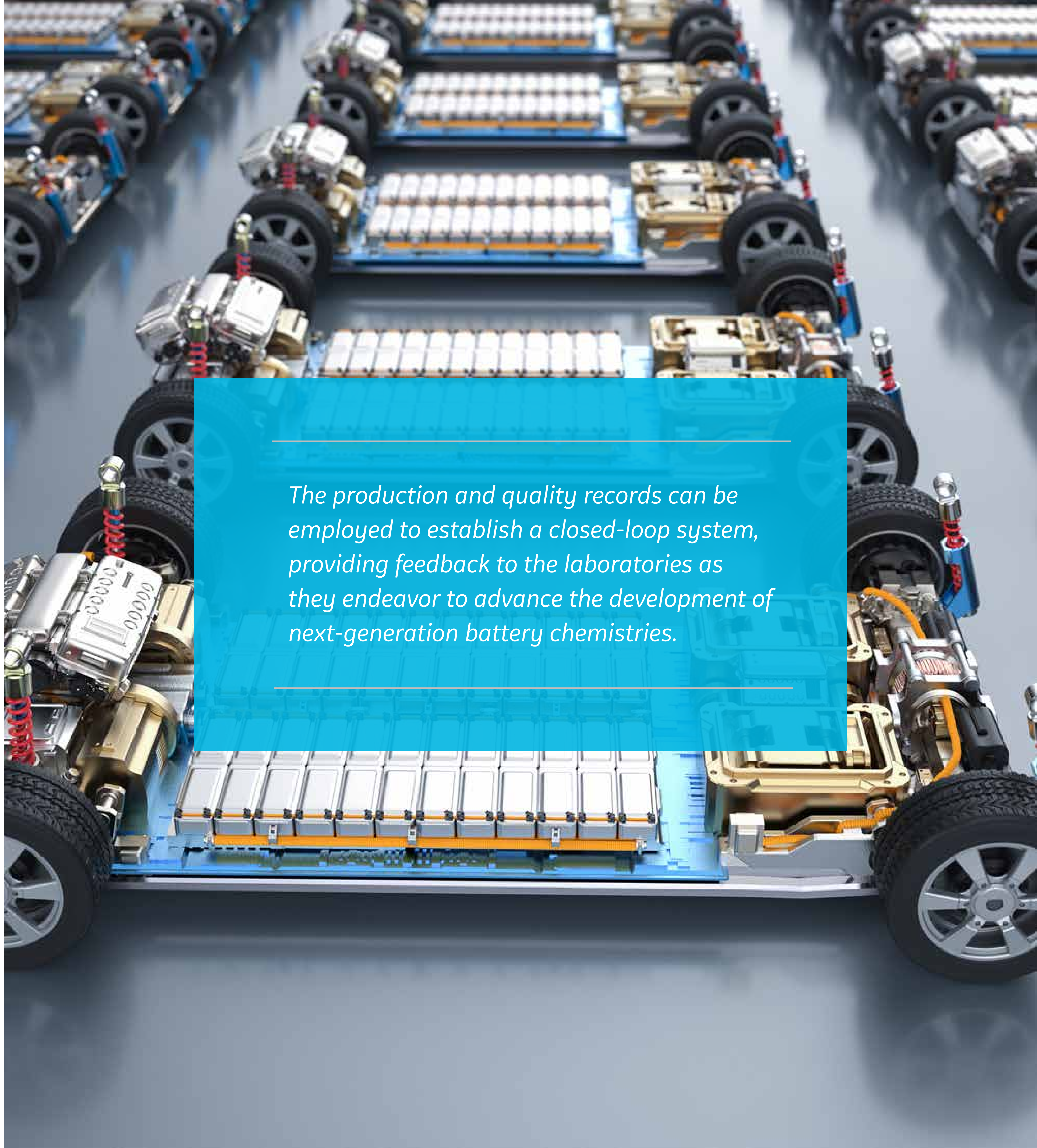


Beyond the material factors, there are further dynamics that affect battery quality and performance, including battery formation factors such as:

- Charge current and voltage
- Charge/discharge time
- Temperature profile
- Form factor
- Packaging type

The factors involved in battery formation must be thoroughly documented to ensure traceability and accompanied by quality tests that are both crucial and appropriately designed. Furthermore, in the case of EVs, it is imperative to retain the lineage of cells and packs throughout the lifespan of the vehicle, or for a minimum of 10 years. The genealogical information should be accessible and accompanied by high-quality linked data for every cell or pack. If a repair is required, documentation should be added to the replacement cell pack, along with any modifications made at the customer's request during the vehicle purchase. In case of a production problem, expenses linked to recalls or services can be considerably minimized if battery and automotive manufacturers are able to trace the issue back to specific production batches.

The appropriate collection and retention of battery production history, quality data, and operational performance records will allow battery manufacturers to comply with regulatory obligations for reporting and traceability. Additionally, this will offer the possibility to realize advancements in chemistry and processes.



The production and quality records can be employed to establish a closed-loop system, providing feedback to the laboratories as they endeavor to advance the development of next-generation battery chemistries.

Challenge #3:
Enterprise Visibility & Optimization

Battery manufacturers require solutions that optimize plant and enterprise production. The solutions must integrate workers, production processes, and the factories across the enterprise. Organizations that possess a unified and comprehensive perspective of their operational procedures and data can make well-informed decisions in a timely manner, leading to superior outcomes.

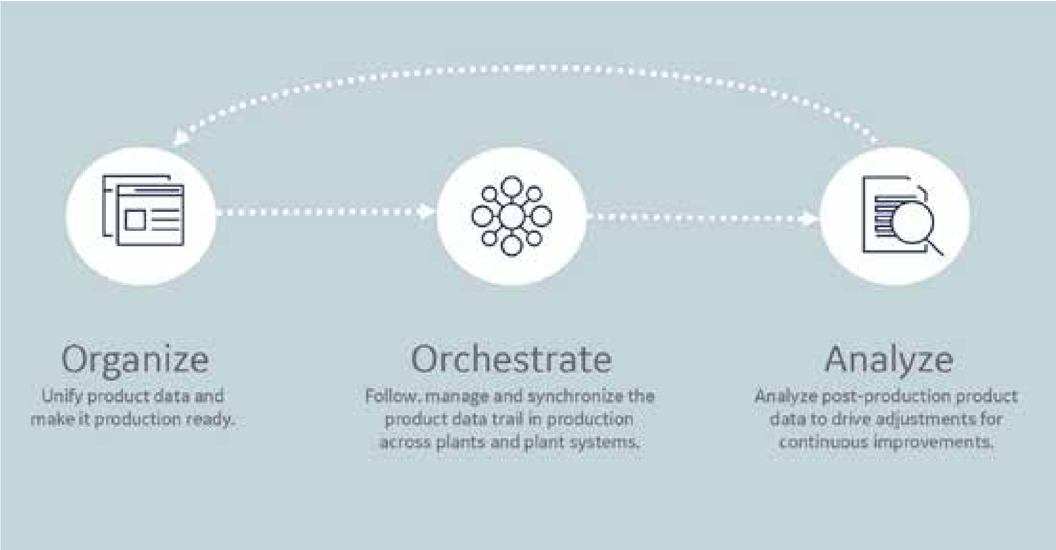
A decade ago, tackling the enterprise challenge required substantial infrastructure to transfer data from the plant floor and store it in a cost-efficient and logical manner in a data center. This would enable data scientists and process engineers to analyze the data and tackle issues on a large scale. The emergence of cloud-based technologies such as Infrastructure-as-a-Service (IaaS) and Software-as-a-Service (SaaS) has made this endeavor economically viable and capable of swift deployment.

In the manufacturing industry, cloud technology has facilitated the democratization of data, enabling process engineers and data scientists to effortlessly retrieve data, construct diagnostic and predictive analytics, and implement these tools on a large scale throughout the enterprise. Time series data, which typically constitutes most of the data analyzed, can now be conveniently stored and accessed in cloud-native historians such as Proficy Historian.

This allows for efficient management and analysis of raw data. MES data, such as critical to quality (CTQ) indicators that are associated with product specifications, equipment availability, order performance, and traceability data, can be stored along with their contextual models. This enables convenient accessibility and query-ability. This means that a process engineer is not required to possess knowledge of intricate data models. Rather, they only need to comprehend the context and utilize pre-existing data models to scrutinize the data.

In recent years, GE Digital has launched a tool known as the Orchestration Hub that consolidates product data for MES systems and all related components. Orchestration Hub facilitates the integration of corporate Product Lifecycle Management (PLM) and/or Laboratory Information Management System (LIMS) data with the MES on the plant floor. Frequently, product information is dispersed and confined within different systems or distributed among remote databases or Excel spreadsheets. Orchestration Hub consolidates all product data, establishing a singular source that facilitates consistent production across one or multiple manufacturing facilities.

Orchestration Hub utilizes cloud computing to facilitate advanced analytics, including the application of machine learning algorithms to factory data. This enables the prediction of machine downtime, uptime, and system health. Additionally, Orchestration Hub integrates cloud-based data with analytics tools to provide the necessary insights for optimizing operational efficiency.



Challenge #4:
Transition from Linear to Circular Supply Chains

Automotive manufacturers have numerous incentives to optimize their operations and minimize their material usage. To enhance sustainability and mitigate the volatility of material costs, obtaining real-time information is crucial for decision-making in an often-dynamic production environment. This is particularly relevant for those seeking to reduce the resource intensity of their vehicles. For instance, the crucial components used in EV batteries have experienced a significant cost surge, or at the very least, exhibited remarkable instability. According to data sourced from S&P Global, the nickel market experienced a significant surge of 150% between June 2021 and March 2022. Similarly, the cost per ton of lithium witnessed a staggering year-over-year increase of 600% in 2022 and displays no indication of abating.

One of the most significant obstacles is accessing essential materials necessary for contemporary battery production. Nickel, cobalt, lithium, and manganese are indispensable elements for cathode production for most batteries currently available in the market. The chemistry of the cathode plays a critical role in ensuring the reliability, high performance, and extended range of EVs. Cobalt offers stability to the cathode, prolonging the number of charge-discharge cycles that a battery can undergo before experiencing any degradation in performance. In the context of long-range EV applications, the role of nickel is particularly crucial in achieving a high-energy density within the battery. This, in turn, directly correlates with an extended driving range. The scarcity of these materials presents a significant risk to the advancement of the EV industry. The potential unavailability of these materials in the future poses a legitimate threat to impeding progress.

Automakers are endeavoring to mitigate supply chain vulnerabilities through diverse means. Efficient production and resource utilization are long-standing strategies adopted by prominent manufacturers. Certain manufacturers are strategically advancing their position in the value chain by establishing partnerships with mining and extraction companies. These manufacturers are entering into long-term contracts with their vendors to secure future access to crucial raw materials. Battery chemistry innovations are currently being investigated to achieve a balance between performance and the availability of materials. Although the previously mentioned strategies prioritize upstream supply, effective management of end-of-life or end-of-use stages is equally crucial, if not more so, in guaranteeing future supply.

Some automotive manufacturers are starting to vertically integrate material recovery processes by incorporating recycling capabilities to include secondary material streams in battery production.

Current state of battery reuse & recycling

Today, top battery recyclers can use a blend of mechanical and chemical recycling techniques to attain a material recovery rate of more than 95%. During the mechanical recycling procedures, the battery constituents are rendered inactive, disintegrated, and sorted to produce a combination of copper, aluminum, and black mass (the remaining lithium, cobalt, nickel, and manganese from the cathode of the battery). The black mass is subjected to pyrometallurgical and/or hydrometallurgical techniques to refine it into high-quality and battery-grade metals. These metals are subsequently used as secondary inputs in the battery production.

Recycling represents the outermost layer of a circular supply chain. However, it should be noted that recycling alone does not guarantee circularity. Merely investing in recycling infrastructure will not suffice in creating the necessary systems to effectively manage global inventories of these materials. The recycling techniques used for extraction and purification of metals from batteries are highly energy intensive. To fully realize the potential benefits and optimize the efficiency of EV batteries, it is essential to maintain a tighter supply chain loop within the economy. This involves prioritizing activities such as maintenance and lifetime extension, reuse, repair, remanufacturing, and, as a last resort, material recovery through recycling when other processes are not feasible.

Blockchain will enable manufacturers to create digital product passports that can be utilized throughout the life-cycle of an EV battery.

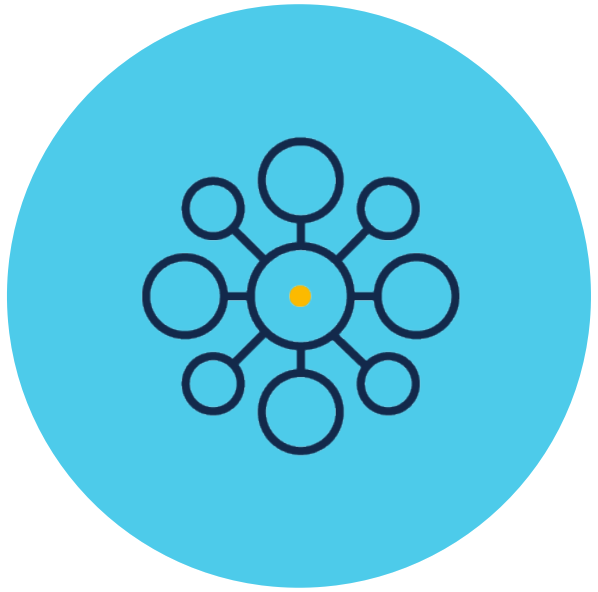
Both private and public entities acknowledge the potential of digital product passports and are taking steps to make them a reality. In March 2022, the European Union introduced a framework for Eco-design of Sustainable Products, which includes a requirement for product passports in several sectors. The Global Battery Alliance endeavors to establish norms regarding digital battery passports. It comprises a diverse range of entities, including corporations, startups, and non-governmental organizations, all of which are invested in various stages of the electric vehicle battery lifecycle.

GE Digital acknowledges the significance of digital passports in the automotive industry's shift from traditional linear supply chains to circular ones. The initial entry in digital passports is the production record. This capability is a distinguishing characteristic of Proficy Smart Factory. GE Digital's solutions offer comprehensive visibility into a product's complete lineage, as well as its manufacturing and sustainability characteristics, such as energy intensity, which can be documented and linked to both products and components. The proficiency to handle these resources proficiently will be pivotal in guaranteeing their sustainable supply as the energy shift progresses.

Conclusion

The next seven years will transform how and where batteries and EV vehicles are manufactured. It will also reward manufacturers who adopt solutions that help them solve the four key challenges:

1. **Managing Complex, Interconnected Processes**
2. **Scaling Production Capacity**
3. **Enterprise Visibility & Optimization**
4. **Transition from Linear to Circular Supply Chains**



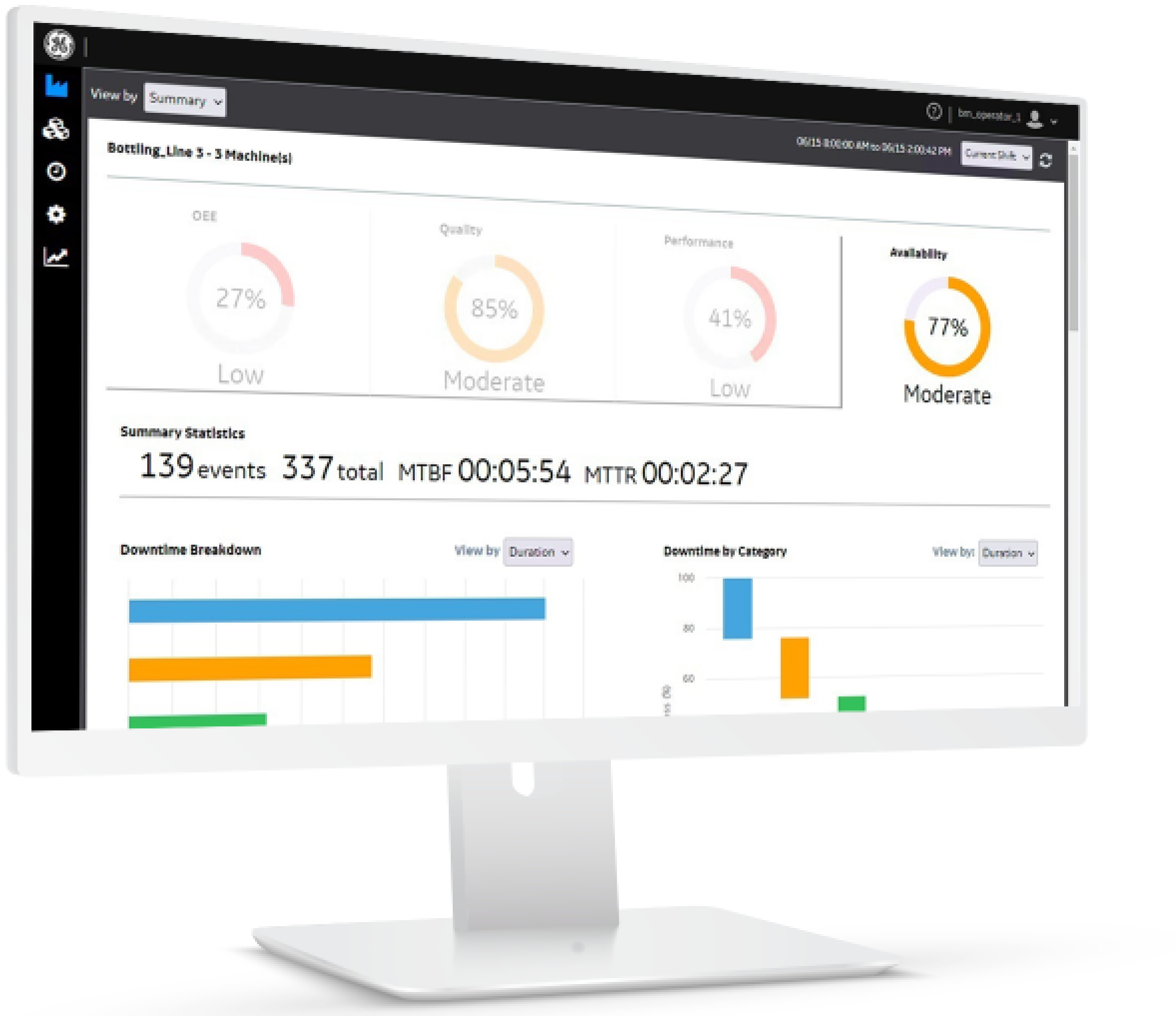
Proficy Smart Factory by GE Digital

Gartner named GE Digital a Leader in the 2023 Magic Quadrant for Manufacturing Execution Systems for its Proficy Smart Factory (MES) software solution. GE Digital was ranked among the top two out of 19 vendors in the Gartner® Critical Capabilities for Manufacturing Execution Systems (MES) report for the following categories:

- Continuous process manufacturing
- Complex discrete manufacturing
- Batch/Continuous flow manufacturing
- Highly regulated industries

GE Digital's technology offers solutions for precision batch mixing, computational track and trace, and big data analysis. Furthermore, GE Digital supports both the cell manufacturing process and the pack assembly process through a single MES. This unique software portfolio provides the analytics tools to enable operations to optimize recipes, machine parameters, and quality testing.

GE Digital software solutions support the capture of end-to-end genealogy from cell production through module/pack assembly enabling material and process traceability. Complex genealogy tracking along with data in context with cell manufacturing will drive the overall performance of the cells within a pack and affect its longevity and power profile, providing an important aspect, as far as, warranty and repair. Proficy Smart Factory can help battery manufacturers achieve efficient and scalable battery production for increased battery production per shift, per hour, or per month.



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