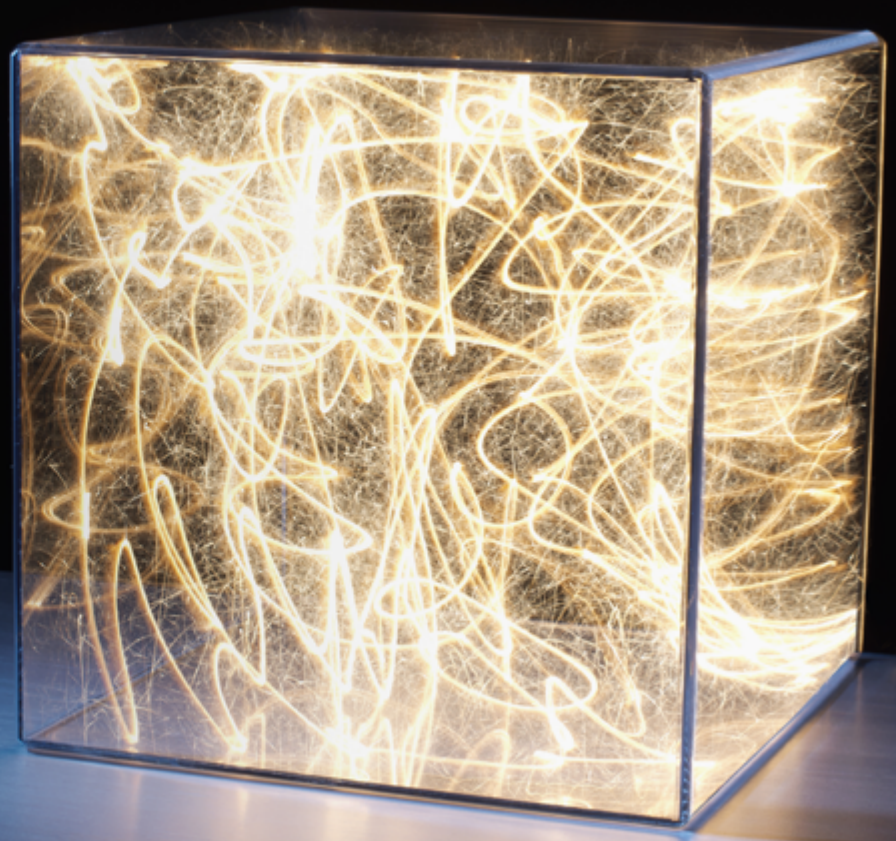
The battery revolution

Shaping tomorrow's mobility and energy



Capgemini RESEARCH INSTITUTE

#GetTheFutureYouWant

Table of contents

04
Who should read this report and why?

06
Executive summary

08
Batteries are powering a sustainable revolution

18
How will batteries transform existing industries?

30
The future of batteries depends on overcoming multiple challenges across the value chain

46
What are the key levers to accelerate the battery industry?

62
Conclusion

64
Research methodology

Who should read this report and why?

We have designed this report for C-suite executives and strategic leaders in critical areas related to battery chemistry, manufacturing, R&D, usage, and end-of-life recycling. The content is relevant to major battery manufacturers, recyclers, and consumers from the energy and utilities sector, and automotive industry.

The report should be of particular interest to leaders involved in the following areas: R&D, innovation, cell technology, engineering, supply chain, procurement, production, digitalization, battery management systems, battery energy storage systems (BESS), energy transition, battery services (such as battery swapping/leasing, sustainability, regulatory affairs and policies), and corporate strategy. We offer comprehensive analysis regarding the growth of the battery industry, next-generation battery chemistry, sustainability measures, and the role of data, technology, and regulations in shaping the future of battery production. We also examine examples of new battery business models such as BaaS, and end-user applications such as EVs and BESS.

The report is based on:

Findings from our global survey of 750 senior executives from large battery, automotive, and energy and utilities organizations across North America, Europe, and APAC.

In-depth interviews with 22 industry leaders to gather their qualitative insights and perspectives.

All the organizations we surveyed are significant players in their respective segments, including battery manufacturers with annual revenue exceeding $50 million; energy and utilities firms with revenue over $1 billion (except those from Sweden and Norway, whose revenue exceeds $500 million); and automotive manufacturers with revenue above $1 billion (excluding two- and three-wheeler original equipment manufacturers [OEMs] with revenue over $300 million). The global survey was conducted in September–October 2024.

Please refer to the methodology section at the end of the report for more details on the research methodology.

Executive summary

Rising demand for electric vehicles (EVs) and energy storage solutions (ESS) is driving investment in battery technology and gigafactories, particularly in the US and Europe.

- As the world transitions toward renewable energy sources, batteries are critical to decarbonizing carbon-intensive sectors.
- China dominates the battery market due to its access to resources such as lithium, cobalt, and nickel, alongside substantial production capacity and government support for R&D.
- Meanwhile, despite resource and infrastructure challenges, the US and Europe are advancing their battery capabilities.
- New technological trends will shape the future of batteries; the industry is actively developing alternative chemistries such as sodium-ion and solid-state batteries (SSBs) for improved performance and longevity.
- However, lithium-ion batteries are expected to dominate the market until alternative technologies become commercially viable.

Advancements in the battery industry benefit multiple applications

Automotive industry: Automotive manufacturers are exploring new business models, including battery swapping, battery-as-a-service (BaaS)[1] to address infrastructure challenges and cost-effectiveness for EVs. The success of these business models depends heavily on the implementation of economies of scale, standardization, battery performance, and supportive regulatory frameworks.

Energy and utilities sector: Growth in renewable-energy generation is driving demand for battery storage capacity to manage the surplus. However, financial viability and the complexity of the existing technologies pose challenges.

Our survey reveals that battery innovation will heavily impact fleet operators, heavy transportation, railways, shipping, manufacturing, and aviation.

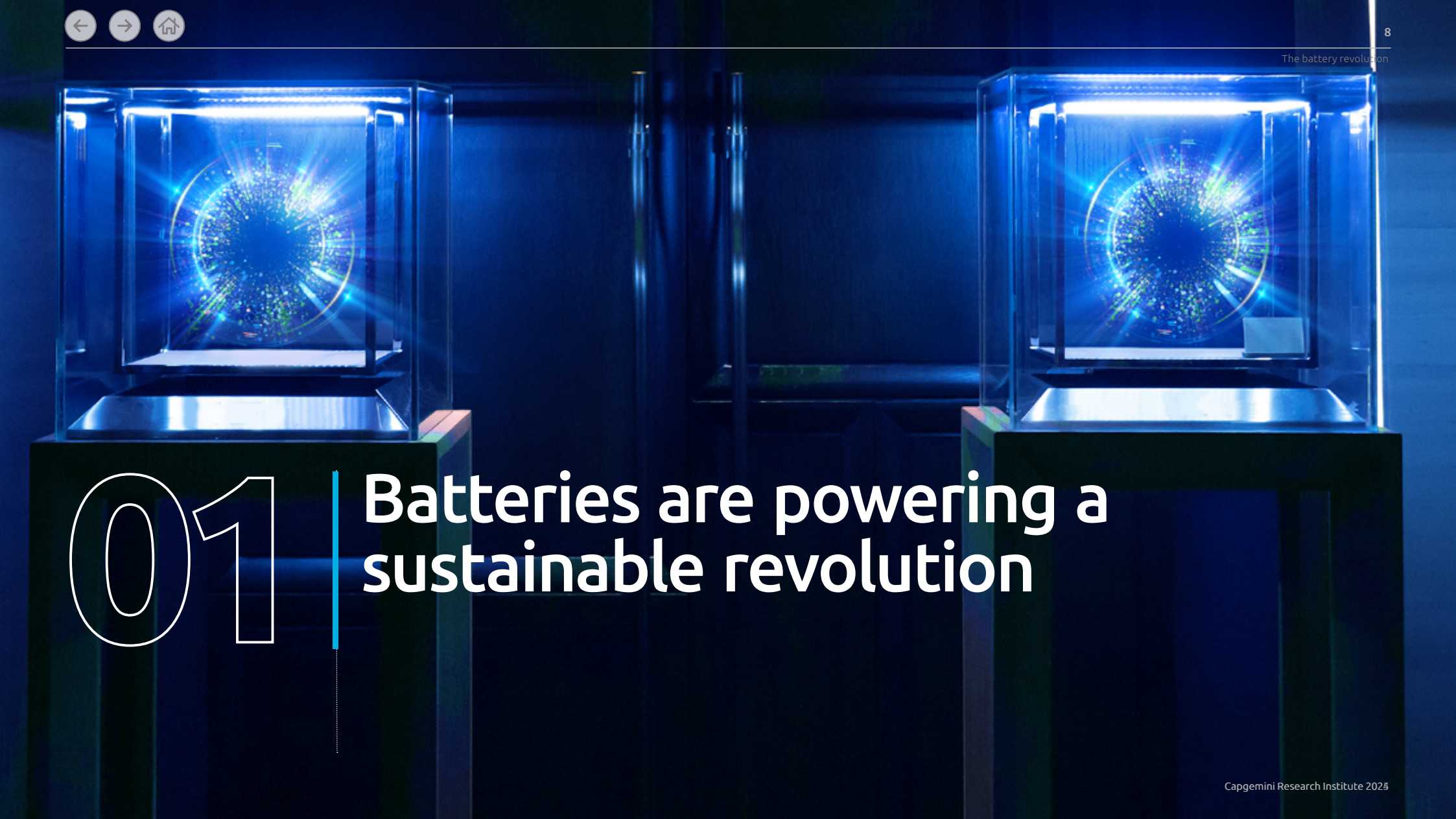
Executive summary

But the future of batteries hinges on the value chain's ability to overcome multiple challenges

- **Economic pressures:** 45% cite economic viability and profitability of battery production.
- **Scaling inefficiencies:** High scrappage rates and quality issues are critical challenges, with 68% of auto organizations reporting difficulty in maintaining standards at scale.
- **Supply chain risks:** Over half (53%) of executives cite difficulties in securing a stable supply chain for battery components and materials as an impediment to scaling production.
- **Skills shortage:** 60% of executives face skills shortages in battery R&D and manufacturing, including thermal management and power electronics.
- **Manufacturing capacity:** Three-quarters of battery manufacturers need to upgrade or build new lines to support production of next-generation cells.
- **Sustainability:** Batteries have significant environmental and social impact. Two-thirds of organizations are still integrating sustainability practices.

How can organizations accelerate to a battery-driven sustainable future?

- Build a scalable digital foundation with a digital first approach and architecture.
- Data-driven acceleration and optimization to accelerate battery chemistry research, optimize production and utilization of equipment, and enable supply chain visibility.
- Accelerate scaling-up of gigafactories with building information modeling, improved product and process maturity, and optimized manufacturing and operations.
- Bridge the talent gap with collaboration between industry, academia, and R&D.
- Incubate efficient market platforms for growth with battery-friendly energy markets and battery marketplaces.



01 Batteries are powering a sustainable revolution

Lithium-ion batteries dominate current global battery production

Batteries are key to decarbonize major emitting sectors and achieving net zero ambitions

Surging demand for EVs and energy storage solutions (ESS) is driving a rise in investment in battery technology, including gigafactories, especially in the US and Europe. Batteries will indeed play a key role in helping the COP28 signatory countries to fulfill their pledges.[2] Achieving these commitments will require to triple global renewable energy capacity to at least 11,000 gigawatts (GW) by 2030.[3]

To support the rapid deployment of solar and wind power necessary to achieve this 11,000-GW ambition, global ESS capacity must increase sixfold, to 1,500 GW, by 2030. Under the Net Zero Emissions by 2050 Scenario (NZE Scenario), batteries are expected to contribute 90% of this, reaching 1,200 GW by 2030. Additionally, in the NZE Scenario, EV sales will rise significantly, leading to a sevenfold increase in demand for EV batteries by 2030, replacing the current need for over eight million barrels of oil per day.[4]

In the NZE Scenario, about 60% of CO2 emissions reductions to be made in the energy sector by 2030 are associated with batteries.[5] As a pivotal force in decarbonization, batteries will drive significant emissions reductions and play a crucial role in accelerating a cleaner, more sustainable energy future.

Battery technology is constantly evolving

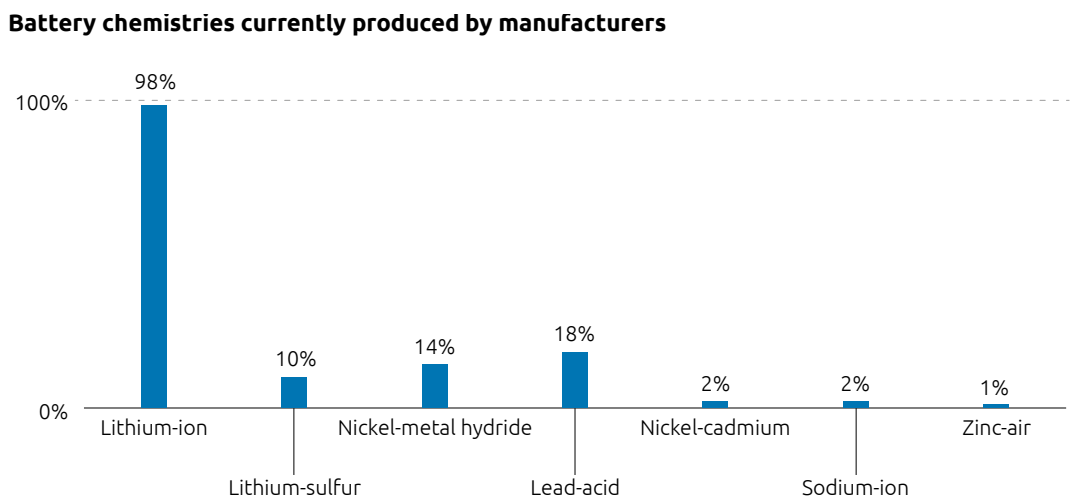
In the coming decades, the battery industry is poised to evolve, driven by the need for higher energy density, faster charging times, improved safety, lower prices, greater sustainability. Currently, lithium iron phosphate (LFP) batteries are the most prevalent chemistry in the Chinese EV market and lithium nickel manganese cobalt oxide (NMC) batteries dominate the European and US markets.[6] We expect new technological trends, such solid state batteries (SSBs), to shape the future of the industry.

Chinese manufacturers such as CATL and BYD have massive production capabilities, supported by substantial government subsidies and investment in R&D, ensuring profitability and competitiveness. BYD, for example, has used vertical integration to secure lower prices for raw material.[7] Likewise, CATL's technological advantage and innovations in battery chemistry, particularly in fast-charging and high-energy-density batteries, have enabled it to maintain a leading position over its competitors, establishing itself as an essential player in the clean energy economy.[8]

Looking ahead, conventional lithium-ion batteries are expected to retain a dominant market share, even as emerging technologies become commercially viable, due to their proven performance, scalability, and well-established supply chains. Aydin Basceken, former Country Director, Germany, at Shenzhen Topband, another Chinese battery manufacturer, comments: *"I foresee lithium iron phosphate and lithium nickel manganese cobalt oxide batteries dominating the market for the next decade. However, solid-state and lithium-sulfur batteries might take over due to their longer lifespans and shorter charging times, despite current high costs."*

Figure 1.

Lithium-ion batteries dominate current global battery production



*Percentage represents share of battery manufacturers currently producing the specified battery chemistry.
Source: Capgemini Research Institute, Future of batteries survey, September–October 2024, N = 338 battery manufacturing executives.

Solid-state batteries answer the need for improved performance

Owing to their potentially higher energy densities, faster charging times, and improved safety compared to traditional lithium-ion batteries, many industry experts see SSBs as a game-changer. These batteries use a solid rather than a liquid electrolyte, reducing the risk of leaks and fires. Almost every EV producer including Toyota, VW, BMW, and Ford are investing heavily in this technology, with commercialization expected by the end of this decade.[9]

Aydin Basceken, former Country Director, Germany, at Shenzhen Topband, states: *"The future is indeed bright for solid-state batteries. Their potential to surpass lithium-ion with improved safety and energy density could revolutionize energy storage and EVs in the long run."* He adds: *"High entry costs are a barrier, but with continued investment and technological advancements, costs should decrease over the next decade."*

SSB technology remains less centralized in China, with developments emerging globally, presenting a strategic opportunity for Western countries to establish dominance in next-generation battery innovation.[10] However, China is rapidly stepping up its efforts, investing over ¥6 billion (approximately $830 million) in SSB R&D through China All-Solid-State Battery Collaborative Innovation Platform (CASIP)', a consortium of leading battery and EV manufacturers intending to maintain its global leadership in battery technology.[11,12] Multiple organizations across the value chain are actively investing in SSB R&D:

- PowerCo, a Volkswagen Group subsidiary, and QuantumScape, an SSB manufacturer, have agreed to mass-produce batteries for Volkswagen's EV lines. QuantumScape will license PowerCo to produce battery cells using its SSB technology.[13] With QuantumScape's technology, PowerCo will manufacture batteries capable of storing up to 40 gigawatt hours (GWh) per year, with additional expansion to 80 GWh, sufficient to power 1 million VW vehicles annually.[14]
- Stellantis and Factorial Energy have partnered to deploy SSBs in next-generation EVs. The partnership was built on a $75 million investment by Stellantis in 2021. Stellantis will deploy the batteries in its new Dodge Charger Daytona vehicles as a demonstration fleet.[15]
- CATL, the world's largest EV maker, aims to produce exclusively EV SSBs by 2027.[16]

Figure 2.
Different types of solid-state battery

	Energy density	Cycle life	Electrolyte technology	Charging speed
CATL Neo battery	200 Wh/kg	More than 3,000 times	Oxide solid electrolyte	80% in 10 minutes
Toyota solid-state battery	400 Wh/kg	More than 1,000 times	Solid-state electrolyte	80% in 10 minutes
Quantum Scape battery	400 Wh/kg	More than 1,000 times	Sulfide solid electrolyte	80% in 15 minutes
Samsung SDI battery	500 Wh/kg	More than 3,200 times	Oxide solid electrolyte	80% in 9 minutes
LG Chem battery	270 Wh/kg	More than 1,000 times	Solid polymer electrolyte	80% in 30 minutes
ProLogium solid-state battery	321 Wh/kg	More than 1,000 times	Ceramic oxide electrolyte	80% in 8.5 minutes
Bollore Blue Solutions solid state battery	450 Wh/kg	More than 1,000 times	Solid polymer electrolyte	80% in 20 minutes
GanFeng Lithium	240 Wh/kg	More than 1,500 times	Solid polymer electrolyte	80% in 20 minutes
Solid Power	390 Wh/kg	More than 1,000 times	Sulfide solid electrolyte	-
Factorial	390 Wh/kg	More than 2,000 times	Solid polymer electrolyte	80% in 18 minutes

Source: Electronic Design, "New long-life solid-state batteries claimed to have highest energy density," August 2024; QuantumScape website, Battery Technology; Batteryline.com, "Solid State battery manufacturing differences than conventional lithium-ion battery," August 2024; Volkswagen Group website, "PowerCo confirms results: QuantumScape's solid-state cell passes first endurance test," March 2024; CATL website, R&D, Innovative Technology, 2023; ProLogium website, "Prologium-technology-presented-its-film-free-2024ssbsummit," September 2024; Blue Solutions Bollore, "Are Solid-State Batteries Ready For Mass-Adoption?," June 2023; Sphere-Energy, "Navigating the Solid-State Battery Hype: An Industry-Driven Assessment of Potential and Limitations," 2023; Sphere, "A 2024 Deep-Dive into the Solid-State Battery Market," 2024; Solid Power, "Solid Power's All-Solid-State Battery Cell Technology," accessed February 2025; Businesswire, "Factorial Unveils 40Ah All-Solid-State Battery Cells with Dry Coating Process," December 2024; The Investor, "Factorial Energy, Hyundai Motor step forward in EV battery development," March 2024.

Sodium-ion batteries offer a low-cost, sustainable alternative

Sodium-ion batteries are gaining attention as a cost-effective alternative to lithium-ion batteries (sodium is more abundant and less expensive than lithium). Companies such as Natron Energy are already making strides in commercializing sodium-ion technology for grid storage and other applications.[17]

Additionally, sodium-ion batteries have already been deployed in EVs within the Chinese market, demonstrating their versatility:

- In 2023, Volkswagen-backed JAC Yiwei EV began mass production of the world's first sodium-ion battery-powered EV, the JAC Yiwei 3, in China. The deliveries began in January 2024.[18]
- In 2024, BYD began construction of a sodium-ion battery plant in Xuzhou City, China, to produce sodium-ion battery cells and battery packs. The factory, in which BYD invested ¥10 billion ($1.4 billion), will be used to power small electric cars and light electric vehicles (LEVs).[19]

Advanced battery management systems (BMS) for optimized battery performance

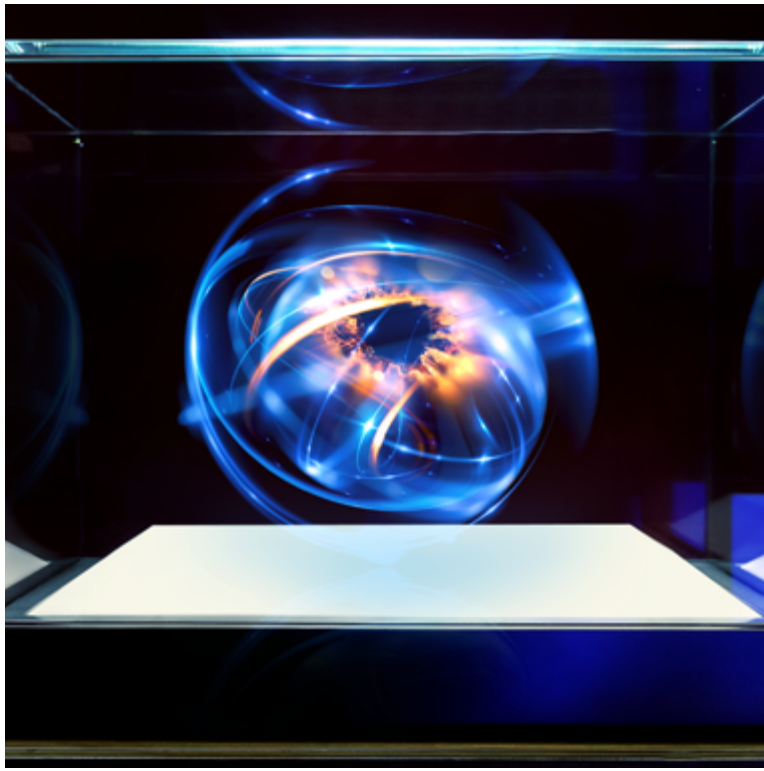
The integration of advanced BMS is crucial for optimizing battery performance, extending lifespan, and ensuring safety. Harnessing AI and machine learning (ML) algorithms, these systems monitor and maintain battery health, implement predictive maintenance, and optimize charging cycles.

Enhanced by digital twins for diagnostics and predictive maintenance, BMS also plays a key role in managing dynamic data such as State of Health (SoH) and State of Charge (SoC).

Features such as active balancing redistribute energy during charge/discharge, and sensorless temperature measurement use current and voltage data to infer comprehensive temperature mapping.

How are batteries positioned in markets across geographies?

US and Europe are making significant strides in the battery industry through substantial investment and policy support. However, they face ongoing challenges, including supply chain constraints and market dependency, which must be addressed to establish a robust and sustainable battery production ecosystem.



"I foresee lithium iron phosphate and lithium nickel manganese cobalt oxide batteries dominating the market for the next decade."

Aydin Basceken
ex-Country Director – Germany
Shenzhen Topband,
a Chinese battery manufacturer

China enjoys global dominance while the US and Europe aim to localize

China accounts for 83% of global battery production.[20] This dominance reflects a strategic blend of security of supply (access to lithium, cobalt, and nickel); vast production capacity that supports economies of scale; and robust government support and investment in R&D.

Since 2020, investments in gigafactories in Europe have surged, reflecting commitment to energy transition and sustainable mobility. Stellantis and CATL's joint investment of up to €4.1 billion in a new LFP battery plant in Spain, is set to begin production by the end of 2026, with a target capacity of 50 GWh.[21]

From 2018 to the first half of 2024, dozens of planned battery factories were canceled in Europe and North America, leading to a projected 72% undersupply of EV demand.[22] Despite these challenges, Europe is expanding its gigafactory capacity, with 38 plants expected to be operational by 2030, including seven in Germany.[23] European policies such as Extended Producer Responsibility (EPR)[24] and digital 'battery passports' emphasize sustainability and circularity, setting high environmental standards for battery production and recycling.

The North American battery industry has grown significantly in recent years. The US has increased its number of battery factories from two in 2019 to more than 62 announced until 2024.[25, 26] Investments are estimated to total approximately $112 billion in domestic cell and module manufacturing, with an annual capacity of nearly 1,200 GWh by 2030.[27] Tesla has built a 5.4 million-square-foot gigafactory in Nevada, with a $6.2 billion investment.[28] Additionally, Natron Energy is investing $1.4 billion in a sodium-ion battery gigafactory in North Carolina. Policy incentives such as that provided by the US Inflation Reduction Act (IRA) and Canada's Clean Technology Investment Tax Credit (ITC) have encouraged organizations to invest in battery-related projects, reducing reliance on China and nurturing localized production and self-sufficiency.

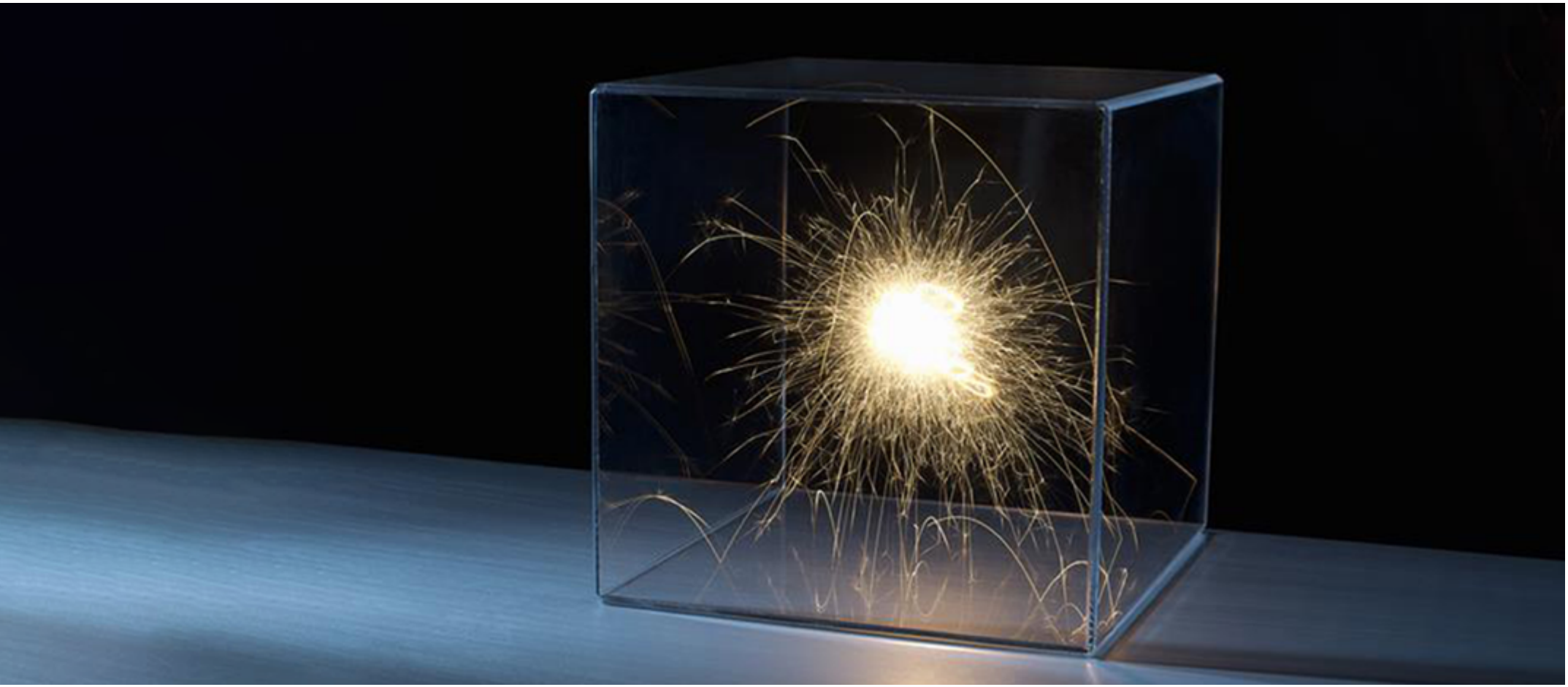
North Africa and Europe see new geographies to emerge as battery hub for Asian players

Hungary and Poland have emerged as battery manufacturing hubs thanks to their strategic location advantages, cheap energy, skilled labor, and favorable governmental policies. SK Innovation and Samsung SDI have established large-scale production facilities in Hungary to serve the European market.[29] LG Chem operates one of Europe's largest EV battery plants in Wrocław, Poland.[30]

In North Africa, Morocco's strategic position as a gateway between Africa and Europe, combined with its vast phosphate reserves, accounting for approximately 70% of the world's total reserves, has positioned the country as a key emerging hub in the global battery value chain.[31] Phosphate is a critical component in lithium iron phosphate (LFP) batteries, which are increasingly favoured by major automakers due to their cost-effectiveness and safety advantages.

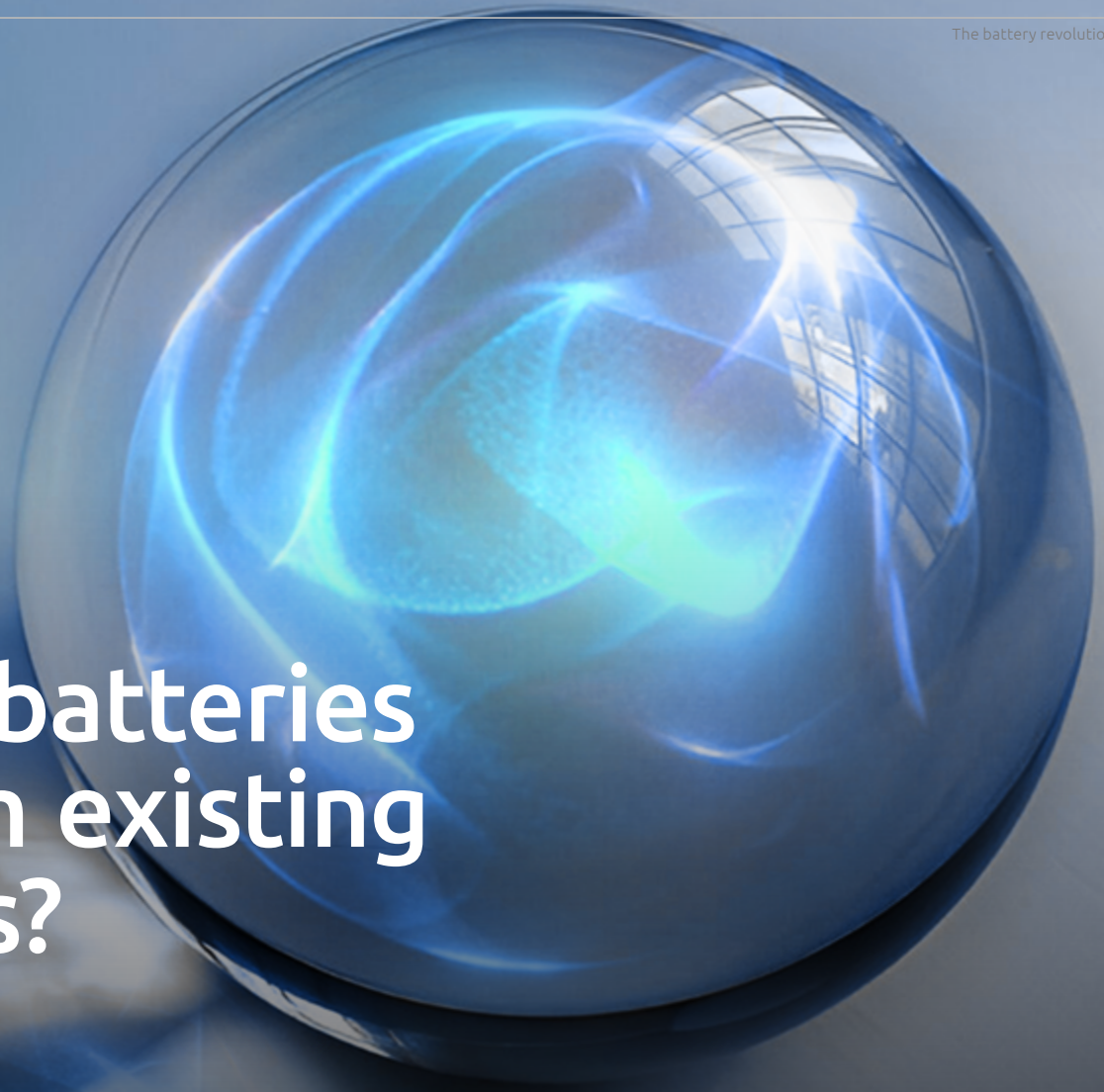
Chinese battery manufacturers have recognized Morocco's unique trade advantages, particularly its free trade agreements (FTAs) with both the US and the EU, which allow products manufactured in Morocco to qualify for tax credits under the US IRA.[32] This has led to significant investments from leading Chinese companies such as Gotion High-Tech, Tinci, and Shinzoom, aiming to establish a strong battery ecosystem in the country. Gotion High-Tech, for instance, is investing $6.4 billion to set up a 100-GWh EV battery gigafactory in Kenitra, Morocco.[33] Additionally, LG Chem and China's Huayou Group are building an LFP cathode materials plant in Morocco, targeting the US market with an annual capacity of 50,000 tons—enough to supply 500,000 entry-level EVs.[34]

Morocco's growing role extends beyond its raw material reserves and FTAs. The country is increasingly integrating into the global supply chain by leveraging its advanced industrial infrastructure, including modern ports, rail links, and a well-established automotive manufacturing base. With the Democratic Republic of Congo (DRC) and Zambia also developing their battery mineral industries, Morocco is strategically positioned to lead a regional battery value chain, capturing greater value from Africa's natural resources while strengthening its position as a critical supply hub for the global EV market.[35]



"We're convinced that as both battery technology and the AI system that control them evolve, we are on the cusp of any energy storage revolution that will accelerate as batteries become even cheaper. Short and medium term duration batteries will play a major role in the energy transition and will revolutionize the generation, distribution and consumption of energy."

James Forrest
Executive Vice President, Global Energy Transition and Utilities Industry Leader, Capgemini



02 How will batteries transform existing industries?

"The choice between opportunity charging and battery swapping ultimately depends on the business model, operational needs, and battery size requirements."

Gopala Rao Uppala
CTO at E-Trio Automobiles, an EV manufacturer in India

EVs are shifting mobility industry

To support widespread adoption, EVs require a robust charging infrastructure, and the most productive future lies in striking a balance between charging and swapping methods. Each has specific advantages and challenges and requires standardization, regulation, and innovative business models to succeed. The integration of these technologies will play a pivotal role in achieving an efficient EV ecosystem.

Batteries are enabling new business models

Vehicle to Grid
The Vehicle-to-Grid (V2G) business model uses the bi-directional flow of electricity to draw power from the grid for charging EVs and to discharge stored energy back into the grid when needed. This interaction helps balance energy production and consumption, especially with the increasing use of renewable energy sources such as wind and solar, which can be intermittent. By participating in V2G, EV owners can earn revenue by providing grid services such as frequency regulation and voltage support. Additionally, this model supports grid stability and can reduce the need for additional energy storage infrastructure.

Battery swapping
Battery swapping facilitates the rapid exchange of discharged batteries for fully charged replacements at designated stations, benefitting two-wheelers and heavy-duty trucks, in particular, in terms of cost and convenience. Around 64% of mobility players are currently exploring the system.

- NIO completed over 40 million battery swaps and is pioneering the scaling of this technology.[36]
- Ample, a San Francisco startup, uses a modular, swappable battery architecture that is compatible with existing car designs and enables EV battery replacement in just five minutes. Hamid Schricker, Director of Product at Ample, comments: *"The whole vision is that we want to provide an experience that is as fast, affordable, and convenient as gas."*[37]

52%

of automotive organizations are exploring new models such as battery-as-a-service, rental, or subscription for EVs

Gopala Rao Uppala, CTO at E-Trio Automobiles, an EV manufacturer in India, adds: *"The choice between opportunity charging and battery swapping ultimately depends on the business model, operational needs, and battery size requirements. Both methods can be viable, depending on the specific use cases and how companies choose to set up their logistics."* We believe battery swapping is not a viable solution for passenger cars. With next-generation batteries enabling ultra-fast charging times of around 15 minutes, the time saved compared with a five-minute battery swap becomes negligible. Additionally, the infrastructure would need to cope with peak demand, such as holiday seasons, while remaining underutilized for much of the year, making it economically unfeasible.

However, battery swapping holds strong potential in specific use cases. It is well-suited to captive fleets, such as company cars, and buses, where battery usage can be strategically planned, enabling optimized asset utilization and infrastructure efficiency. Additionally, it remains relevant for light urban mobility vehicles, where demand fluctuations are more predictable and operational efficiency is key.

Battery-as-a-service

The battery-as-a-service (BaaS) model allows EV owners to lease or rent their batteries, rather than buy them, making EVs accessible to a broader range of consumers. Over half (52%) of automotive organizations are exploring this option to counter EV adoption slowdown amid falling subsidies.

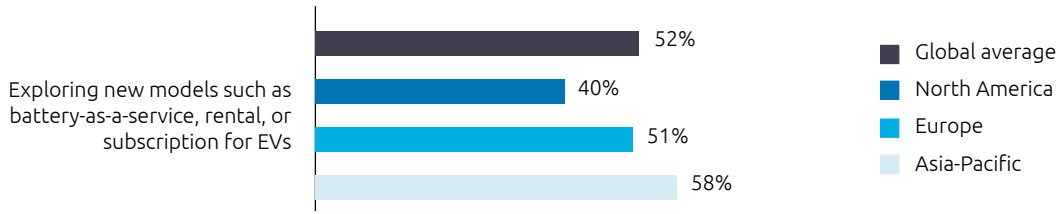
Nearly two in three auto organizations are also exploring battery leasing options. Since Nio launched its BaaS offering, more than 70% of its users have subscribed.[38]

In Germany, the removal of several purchase subsidies resulted in a decrease in the share of EV sales from 30% in 2022 to 25% in 2023, with electric car sales dropping by almost 5% in the first quarter of 2024.[39] The EV registrations in Germany dropped by 27% from 2023, accounting for 13.5% of sales in 2024.[40] Likewise, in 2024 in the US, changes to tax credit eligibility under the IRA have narrowed the range of qualifying EV models from 45 to fewer than 30, potentially limiting consumer options.[41] As financial incentives diminish, consumers may become more inclined to explore BaaS models with lower up-front costs.

Vidyut, an Indian startup specializing in full-stack EV ecosystems, has partnered with JSW MG Motor India to launch a BaaS program for selected EV models. The new BaaS program reduces overall running costs by 40% compared with traditional internal combustion engine (ICE) vehicles.[42]

Figure 3.
Nearly two-thirds of automotive organizations are exploring battery leasing options to make EVs more affordable

Automotive organizations are exploring Battery as a Service model



* Percentages represent the share of automotive executives.
Source: Capgemini Research Institute, Future of batteries research, September–October 2024, N = 292 automotive executives.

Standardizing cells and packs is key to widespread battery adoption

The concept of standardized battery cell and pack, similar to universal EV charging connectors, could revolutionize the industry. However, this would create tensions between battery manufacturers and OEMs. Moreover, automakers may prefer to retain control over the design and integration of their batteries as critical differentiators of their lines. A shift to standardized, universal battery models could generate a more dynamic competitive landscape, but would require significant cooperation among stakeholders, as well as government support.

Trio's Rao Uppala highlights the benefits and challenges of establishing common standards: *"While having a common standard could enhance user convenience and interoperability, it might conflict with manufacturers' interests in differentiating their products. The government's involvement could be critical to establishing industry-wide standards. Left to their own devices, manufacturers might develop unique systems that hinder widespread adoption."*

Currently, the unique nature of each model makes standardizing battery design and specifications nearly impossible. Automakers such as Volkswagen and Audi have made progress by standardizing battery cell designs across their brands, but they still face challenges in normalizing

battery packs across different models. Standardized battery packs could facilitate widespread adoption of Battery-swapping.

As batteries transition to new chemistries like sodium-ion and solid-state, 61% of automotive executives identify shifts in battery weight and size as key challenges. This makes flexible manufacturing systems essential but also complicates the standardization of battery cells and packs. Additionally, 51% of executives highlight compatibility with diverse charging standards and technologies as another major hurdle.

Batteries power the transition to renewable energy

Batteries help to stabilize the grid and aid in renewable integration

Battery energy storage offers a multitude of benefits, including the ability to balance supply and demand, integrate renewable energy sources, and strengthen grid stability. Long-duration (over eight hours) energy storage systems absorb excess renewable energy during times of oversupply for release when demand peaks, reducing the frequency of negative pricing. Globally, 99% of installed storage capacity – excluding pumped hydro storage (PHS)– is short-duration (under eight hours), with 75% discharging for under four hours.[43]

Mark Cavill, Director of Commercial Controlling at E.ON, an international energy company, explains: *"Across countries, we're seeing a strong drive toward renewable energy, but storage hasn't always been prioritized to match. Many nations rely on cross-border interconnectivity to balance supply and demand, but this approach has limitations, especially during peak renewable output periods, when surpluses can build up across regions. The shift to renewables requires an integrated storage strategy to ensure reliability and grid stability for the future."*

Lithium-ion batteries currently account for over 90% of global energy storage capacity, primarily supporting short-duration applications (2–4 hours).[44] Alternative chemistries, such as sodium-sulfur and lead-acid, predate the dominance of lithium-ion. Other technologies are also close to achieving 100-hour energy storage. For example, Form Energy, a US startup, which collaborated with Puget Sound Energy, an electric and gas utility serving organization, to develop a 10-MW system with 1,000-MWh capacity – equivalent to a 100-hour duration. The key ingredients of the battery are iron and air.[45,46]

"The shift to renewables requires an integrated storage strategy to ensure reliability and grid stability for the future."

Mark Cavill
Director of Commercial Controlling
E.ON

Despite these developments, most alternative technology projects are small, reaching only tens of megawatts. A major challenge for these alternatives is the lack of manufacturing scale (in contrast with what lithium-ion has achieved through the EV industry), as well as the lack of robust grid infrastructure or advanced control systems.[47]

Batteries enable new revenue streams for energy and utility companies

Two in five energy and utilities organizations integrate batteries with renewable energy systems to optimize energy storage and usage, with a significant 69% currently offering or planning to offer BaaS. Matt Leckey, Director of Utility Partnerships at NextEra Energy Resources, a US-based energy solutions provider, says: *"Our 'bring-your-own-device' model allows customers to [monetize] their batteries by allowing utilities access to stored energy during periods of high demand or to prevent blackouts. We're exploring various models, including utility-owned batteries installed at customers' homes. This approach not only benefits the grid but also offers customers back-up power during outages, which is a clear win-win."*

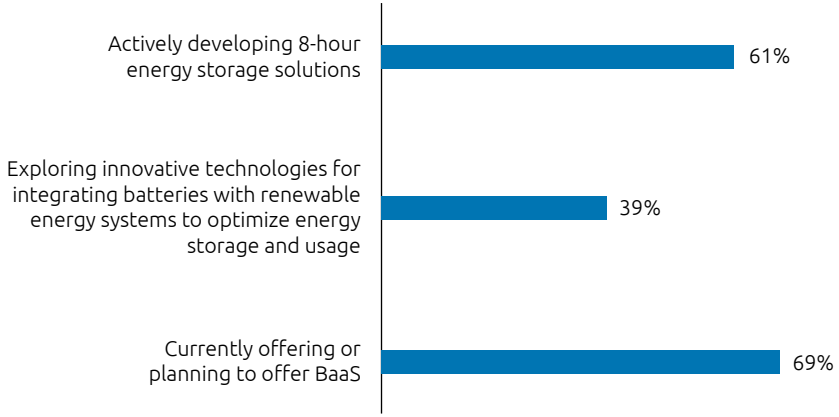
Vicinity Centres, a prominent Australian retail property group, has partnered with Enel X, a division of the Enel Group, to pilot on-site batteries at two of its shopping centers. This initiative expands on Vicinity's Integrated Energy Strategy by integrating battery storage with solar power and automated demand management, advancing sustainability goals by reducing reliance on the electricity grid.[48]

BMW Group, Ford, and Honda formed ChargeScape, which will focus on optimizing EV grid services through a single platform that connects electric utilities, automakers, and EV customers to manage energy usage.[49]

Octopus Energy, a UK-based energy tech firm, offers the country's first vehicle-to-grid (V2G) mass market tariff, Octopus Power Pack. Using V2G technology and its Kraken tech platform, the scheme charges EVs with cheap, green off-peak electricity and discharges stored energy back to the grid when needed.[50,51]

Figure 4.
Most (69%) of energy and utility organizations offer or plan to offer BaaS

Share of organizations that are exploring alternative battery solutions



Source: Capgemini Research Institute, Future of batteries survey, September–October 2024, N = 83 energy and utilities executives.

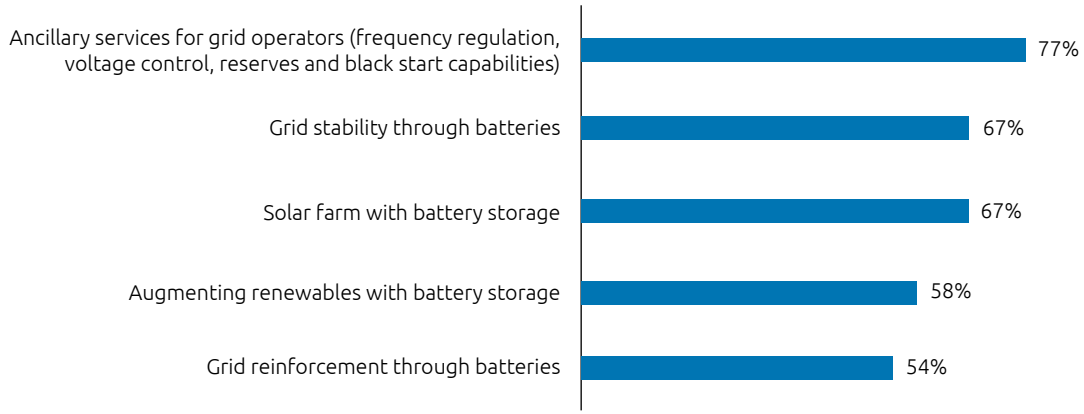
Energy and utilities organizations are exploring multiple options, including grid reinforcement, grid stability, and ancillary services as part of a BaaS model (see **Fig. 5**).

"[...] We're exploring various models, including utility-owned batteries installed at customers' homes. This approach not only benefits the grid but also offers customers back-up power during outages, which is a clear win-win."

Matt Leckey
Director of Utility Partnerships at NextEra Energy Resources, a US-based energy solutions provider

Figure 5.
Almost 80% of organizations offering or intending to offer BaaS also plan to provide ancillary services for grid operators

Share of organizations planning to implement the following, based on market viability



Source: Capgemini Research Institute, Future of batteries survey, September–October 2024, N = 32 energy and utilities executives from organizations that are currently offering or planning to offer BaaS.

Battery adoption in the energy and utility sector faces key challenges

While a battery is considered an expensive asset, the electricity it stores is relatively cheap. For example, a 1-kWh battery might cost $200, but the electricity it can store may only be worth $0.30. To break even with a cost spread of $0.25 per kWh, the battery must cycle 800 times, which would be close to the design life of some batteries, meaning 0% ROI. However, modern commercially available batteries can exceed 2,000 cycles, generating positive returns within eight years and extended lifespan could make use beyond this point highly profitable, albeit requiring patience from investors.[52]

This impact is also reflected in our survey, where a significant 66% of energy and utilities firms are discouraged by the extended payback period. Mark Cavill at E.ON explains: *"Batteries must generate revenue not only through traditional charge/discharge cycles but also by leveraging additional revenue streams. For instance, frequency response services pay for availability, which preserves battery life since these micro-cycles involve minor charge/discharge actions. Batteries may also receive capacity payments for being on standby for emergencies. Essentially, battery operators must treat the asset as a mini power plant, balancing cycles, lifespan, and revenue options to ensure long-term investment viability."*

Developing long- and short-duration storage systems are cited by 55% of energy and utilities firms as their principal challenge,

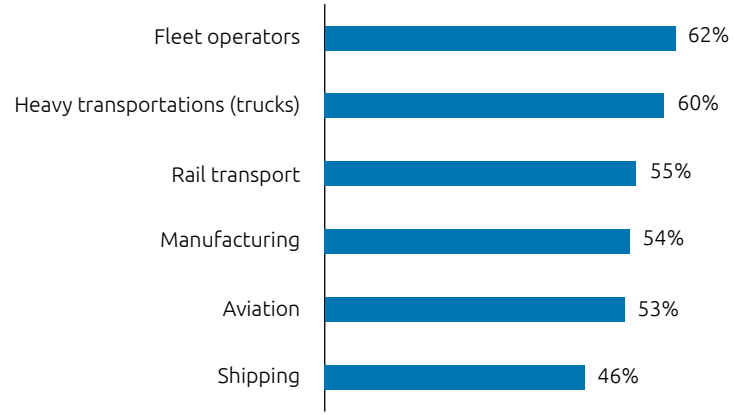
and a lack of robust grid infrastructure and advanced control systems by 65%. Over half (55%) of the energy and utilities organizations in our survey note the lack of standardized market structures limits widespread battery deployment. Furthermore, 59% indicate a need for open performance standards to ensure reliability and transparency, and 61% emphasize the need for multiple battery types to facilitate both short-term and long-term storage solutions . Pablo Collado, Director of Renewable Business Europe at Iberdrola, a Spanish multinational electric utility, sums it up aptly: *"The landscape of battery storage is fraught with technological challenges and the rapid pace of advancements. This makes investment decisions particularly complicated, as we need to match systems needs, state of the technology, and willingness to invest."*

Multiple other industries are incorporating batteries into their operations

Three in five of the battery, automotive, and energy and utilities executives we surveyed indicated that battery innovation will significantly impact fleet operators and heavy transportation. Additionally, nearly half highlighted significant disruption across industries such as rail transport, shipping, manufacturing, and aviation (see **Fig. 6**).

Figure 6.
Fleet services and heavy transportation will see the most disruption

Industries projected to see the most disruption in the next 5–10 years due to battery innovation



* Percentages represent the share of executives who strongly believe that the industry will be disrupted.
Source: Capgemini Research Institute, Future of batteries survey, September–October 2024, N = 751 executives from battery, automotive, energy and utilities.

62%

executives believe that battery innovation will significantly impact fleet operators

Advancements in aerospace: Battery-powered air taxis

In the aerospace domain, manufacturers are developing battery-powered eVTOLs (Electric Vertical Take-Off and Landing), also called air taxis or flying taxis. California-based Joby Aviation, in partnership with Toyota, has developed an eVTOL for urban air mobility, completing a test flight in Japan in November 2024.[53] Ascendance, an aircraft and hybrid electric propulsion manufacturer, has developed two solutions: a patented modular hybrid propulsion system, STERNA, which allows multiple energy sources to be used simultaneously, and a next-generation VTOL aircraft called ATEA, powered by STERNA. Ascendance plans to conduct the first flight of the ATEA prototype in 2025 and plans to scale up in partnership with Capgemini.[54]

Electrified ships: Pioneering sustainable maritime transport

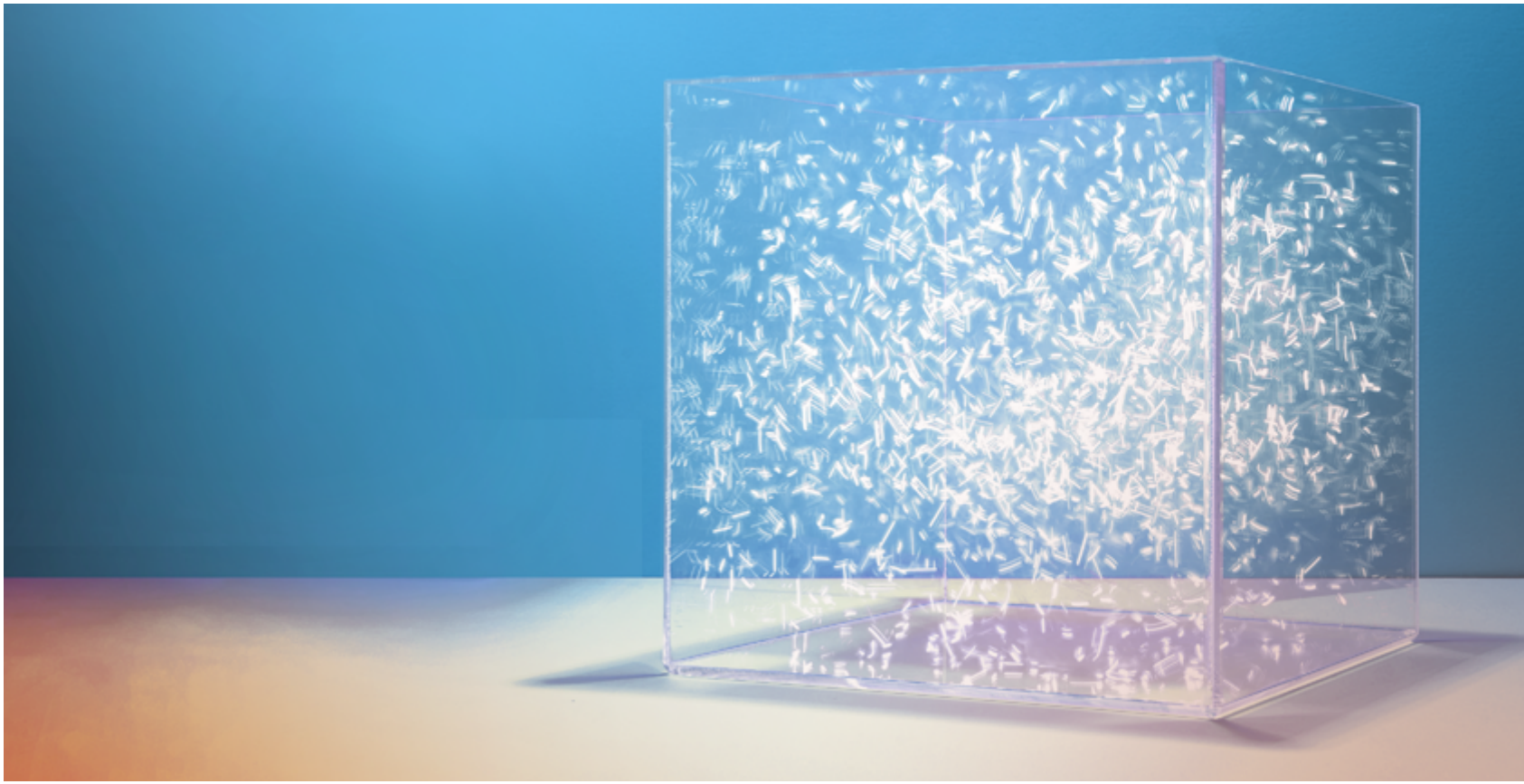
Innovators are also testing prototype electric ships on short sea routes.[55] Yara, a Norwegian chemical company, partnered with technology company Kongsberg to build the world's first fully electric, fully autonomous cargo ship, the Yara Birkeland. The ship uses a 7-MWh battery and can carry over 100 containers. While it carries a $25 million price tag – around three times that of a conventional ship – it is expected to reduce Yara's operational expenses by 90%.[56]

Battery-powered heavy trucks gain traction with new advancements

Traditionally, industries have considered heavy-duty vehicles poor candidates for battery electrification due to the sheer size, weight, and cost of the batteries required. However, advancements in battery technology, charging infrastructure, and government policies are changing this perception. In 2024, the German government launched the Power to the Road project to build a nationwide fast-charging network for heavy-duty vehicles as part of its broader strategy to decarbonize the national transport sector by 2045. This initiative will establish 350 fast-charging sites, covering 95% of Germany's highways, to encourage the adoption of electric trucks, which currently make up just over 2% of the commercial truck fleet.[57]

"The ability to design and build high-quality performance batteries is key to the energy transition and decarbonization of transport. Western countries must ramp up their ambitions and actions if they are to compete with leading players from Asia, secure supply chain sovereignty, and achieve their own sustainability objectives. Today's leaders are not standing still, so it's imperative that late arrivals to the battery game aim high and formulate strategies that go beyond merely 'catching up' and aspire toward long-term leadership."

Laurence Noël
Executive Vice President, Head of Global Automotive Industry, Capgemini



03 The future of batteries depends on overcoming multiple challenges across the value chain

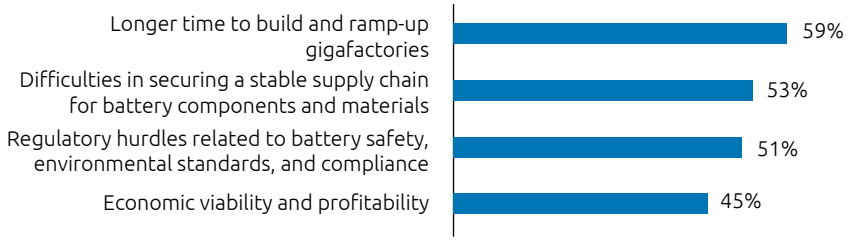
The battery industry must overcome a series of complex challenges across its entire value chain, from securing sustainable raw materials and optimizing manufacturing processes to advancing lifecycle management and recycling capabilities. These challenges apply to a wide range of areas, from gigafactory industrialization and ramp-up, regulatory compliance, economic viability, and supply chain constraints (see **Fig. 7**).

59%

of battery executives cite longer time to build and ramp-up gigafactories as a top challenge

Figure 7.
Challenges battery manufacturers face

Major challenges to battery manufacturers



* Percentages show the proportion of executives who rate the specified challenge as a major hurdle.
Source: Capgemini Research Institute, Future of batteries survey, September–October 2024, N = 338 battery executives.

Gigafactory construction and ramp-up delay

Industrial ramp-up of gigafactory to reach on-time SOP

As the battery industry undergoes a significant transformation, battery manufacturers must evaluate their readiness in key areas, such as plant construction, product quality, and production scalability. Over half (59%) of battery manufacturers cite time required to build gigafactories as a key challenge.

On top of keeping construction time under control, gigafactory actors must also secure a fast ramp-up to avoid what Yann Vincent, CEO of Automotive Cells Company, describes as a "death valley" effect[58] with huge quantities of cash burned to produce cells and modules that will eventually be scrapped for being of insufficient quality.

Optimize process to improve product quality

Another pressing challenge is manufacturing inefficiencies and high scrappage rates during the scale-up phase of battery production. Most (68%) automotive organizations state difficulty in maintaining standards across large-scale production. Based on the experience of Capgemini experts, at initial manufacturing phase, the scrappage rate can be as high as 70%, as 57% of automotive manufacturers struggle to achieve desired battery quality. Over half (54%) of automotive firms report high scrappage rates due to equipment and process variations, fragmented data systems, and lack of real-time monitoring systems, hindering in-line quality inconsistency detection and delaying production process improvement. This underscores the critical need for an IT and data-centric strategy from the early stages of a project, ensuring it can be effectively implemented during scale-up.

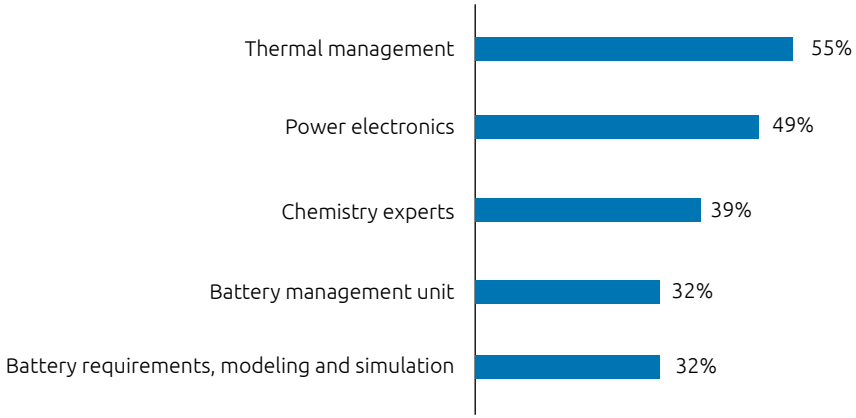
K.V. Ramakrishnan, former Director of Plant Operations (ICE, EV) at Great Wall Motor and General Motors, agrees: *"Variations in chemistry between manufacturers lead to inconsistencies during assembly, while shelf-life constraints cause materials to degrade, contributing to waste. Challenges such as temperature control during transportation further complicate matters, as demand fluctuations can affect battery performance and safety. Even after cells arrive in the host country, rejections during battery pack assembly, along with other repairs, contribute to a persistent 20–30% supply gap, which, without digital tech adoption, could increase as demand rises."*

Workforce shortages and upskilling

As many as 60% of executives face skills shortages in battery technology and manufacturing, particularly in thermal management and power electronics (**Fig. 8**).

Figure 8.
The most significant skills gap is in thermal management

Top five areas with the largest skill shortages



* Percentages represent the share of executives.
Source: Capgemini Research Institute, Future of batteries survey, September–October 2024, N = 751 executives from battery, automotive, energy and utilities.

Among battery manufacturers, 36% report skills gaps in operations and manufacturing capabilities, and 39% identify gaps in multi-disciplinary skills, such as material science expertise combined with data analytics skills. When it comes to battery manufacturing, the most critical skill is electrochemical expertise, required to master the coating processes – which is the key to overall battery quality, performance and safety. However, expertise gaps extend beyond electrochemistry. The industry also faces a shortage of data scientists and manufacturing engineers who can analyze and correlate production data with battery performance, enabling process optimization and defect reduction.

Existing battery production lines are incompatible with next-gen batteries

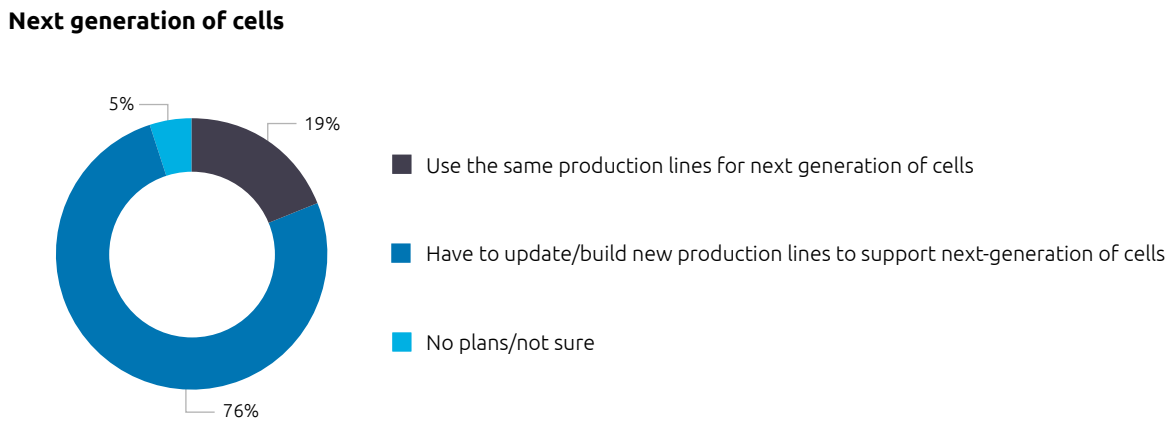
Current NMC battery production lines are not fully compatible with LFP manufacturing. This challenge becomes even more pronounced with next-gen technologies like SSB. The shift to advanced chemistries demands significant modifications or entirely new production lines to meet evolving manufacturing requirements. This is clearly reflected in the survey. Three-quarters (76%) of battery manufacturing executives have highlighted that they will have to build new

production lines to support production of the next generation of cells.[59] Just 19% are planning to use current production lines (**Fig. 9**). Gilles Moreau, Chief Open Innovation and Sustainability Officer at Verkor, a French startup that develops lithium-ion batteries for EVs, adds: *"Each gigafactory is optimized for a specific battery type. Changing over is complex. If we were to produce another type, I'd advocate for a dedicated gigafactory to ensure optimal performance and profitability."*

> ***"The landscape of battery storage is fraught with technological challenges and the rapid pace of advancements."***

Pablo Collado
Director of Renewable Business
Europe
Iberdrola

Figure 9.
Three-quarters of battery manufacturers will need to update/build new production lines to support the next generation of cells



Source: Capgemini Research Institute, Future of Batteries survey, September–October 2024, N = 338 battery executives.

"Electrification presents automotive manufacturers with complex cost, regulatory, and technological challenges. Advances in battery design & engineering, manufacturing & digital continuity, resilience & intelligent supply chain can help resolve these, as well as enabling worthwhile business models. And, along with infrastructure changes, battery evolution could also shape the whole transition to renewable energy."

Emmanuelle Bischoffe-Cluzel
Vice President, Sustainability Lead, Global Automotive Industry, Capgemini

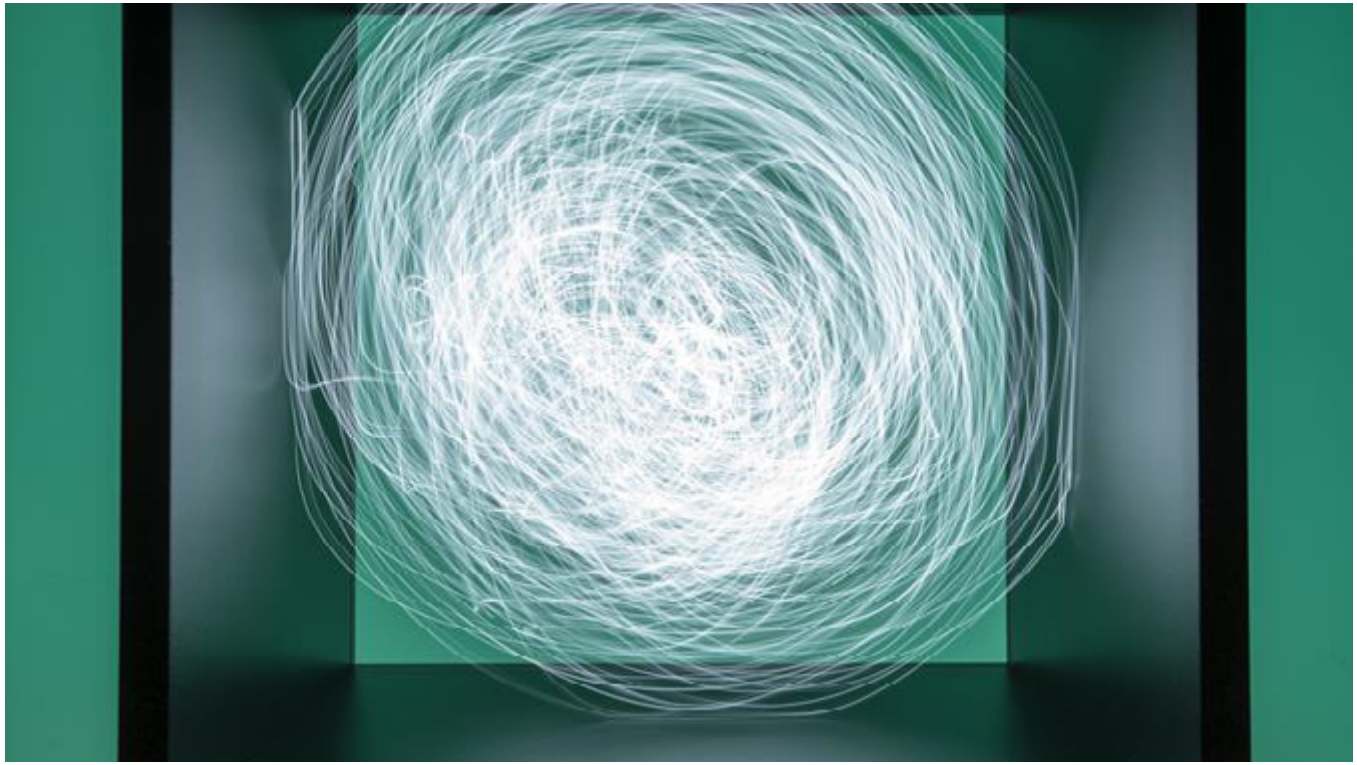
Challenges from supply chain risks and geopolitical factors

Over half (53%) of executives cite difficulties in securing a stable supply chain for battery components and materials as an impediment to scaling production. Limited local availability of raw materials is cited by 65% of executives in North America, 67% in Europe, and 53% in APAC as their principal concern. Europe's progress toward self-sufficiency in critical raw materials faces challenges including lengthy processes to secure permits, opposition from residents regarding lithium production, constraints on cobalt and nickel reserves, and issues related to processing waste, and environmental impacts associated with graphite.[60]

Rising trade tensions and the imposition of export limits or tariffs on raw materials by various countries are driving up costs and incentivizing the US and Europe to build more localized, self-sufficient supply chains. Policy adjustments that accompany changes in government may impact trade relations, incentivizing domestic production.[61],[62] Obtaining planning approval for battery manufacturing facilities in Europe is often a lengthy, complex process, with local variations to negotiate. In Germany, for instance, a two-year timeline for final environmental approval is considered rapid, with projects frequently taking three to five years.[63]

Uncertainty around economic viability and profitability is a challenge

Around 45% of executives cite economic viability and profitability of battery production as key challenges. For instance, the price of a lithium-ion battery pack and cell fell dramatically between 2013 and 2023 as production capacity increased across the battery value chain.[64] Around half (46%) of executives cite the high up-front capital investment required, and 59% cite the extended timeline to build gigafactories and production ramp-up as key challenges to scaling. At least 18 EV and battery startups that have gone public in recent years were in danger of running out of cash by the end of 2024.[65]. Building a first gigafactory requires a massive upfront investment, in both infrastructure and resources. Furthermore, the lengthy scale-up process leads to substantial cash burn, driven by high scrappage rates and inefficiencies in early production. This extends the break-even timeline and delays profitability, making it critical for companies to optimize production ramp-up, minimize waste, and enhance process efficiencies from the outset.



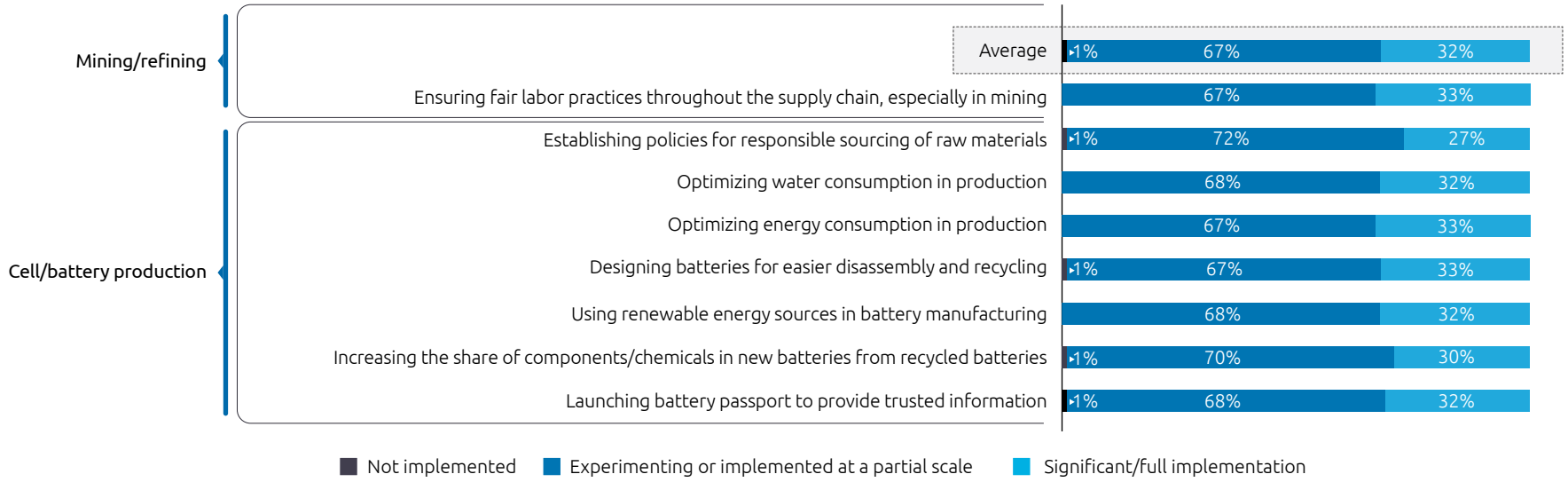
‘Sustainable by design’ is a must

Alongside the exciting benefits, battery production brings significant environmental and social impact. To mitigate this, the industry must adopt end-to-end traceability solutions and a sustainable-by-design approach, ensuring responsible practices from raw materials sourcing to end-of-life management.

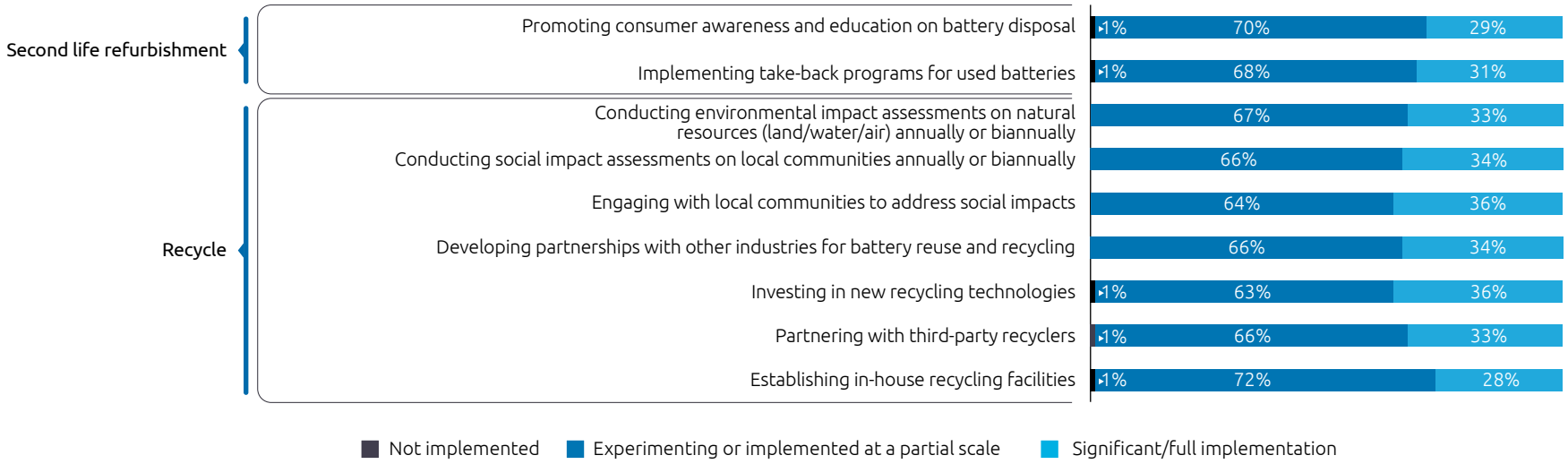
However, two-thirds of organizations are either in the experimentation phase or have partially scaled. Only one in three has taken meaningful steps toward establishing a sustainable circular economy **(Fig. 10)**. This gap underscores a critical challenge. Sustainability efforts across the entire battery lifecycle remain far from where they need to be.

Figure 10.
Two-thirds of organizations are still in the initial phases of sustainability initiatives

Measures taken by organizations to ensure sustainability and circularity



Source: Capgemini Research Institute, Future of Batteries survey, September–October 2024, N = 751 executives from battery, automotive, energy and utilities.


Second life refurbishment
Promoting consumer awareness and education on battery disposal
1%
70%
29%
Implementing take-back programs for used batteries
1%
68%
31%
Recycle
Conducting environmental impact assessments on natural resources (land/water/air) annually or biannually
67%
33%
Conducting social impact assessments on local communities annually or biannually
66%
34%
Engaging with local communities to address social impacts
64%
36%
Developing partnerships with other industries for battery reuse and recycling
66%
34%
Investing in new recycling technologies
1%
63%
36%
Partnering with third-party recyclers
1%
66%
33%
Establishing in-house recycling facilities
1%
72%
28%
Not implemented
Experimenting or implemented at a partial scale
Significant/full implementation

Navigate the regulatory landscape for sustainable solutions

In response to the growing need for sustainable solutions, governments and regulatory bodies worldwide are evolving their frameworks to foster transparency and accountability in environmental practices.

From February 2027, EVs sold within the EU must be equipped with 'battery passports' that provide detailed information on battery composition, including sources of key materials, carbon footprint, and recycled content.

Traceability has become a cornerstone of these initiatives, as demonstrated by the EU Sustainable Batteries Regulation. The regulation imposes ambitious lithium recycling targets, mandating a 50% recovery rate from waste batteries by the end of 2027, increasing to 80% by 2031. Additionally, it sets minimum levels of recycled content for lithium at 6% by August 2031, and 12% by 2036, while for nickel, the targets are 6% by August 2031 and 15% by 2036.[66] Despite these stringent requirements, only around 60% of organizations have made significant strides in enhancing traceability.

A sustainability executive from a multinational automotive organization explains the sustainability regulatory landscape: *"The policy landscape in the EU is more progressive and stringent, often influencing the US. ESG [Environmental, Social, and Governance] pressure in the US comes from consumers and capital markets, rather than regulatory bodies. Regulations such as the IRA, enacted to reduce heavy reliance on China for EV components and battery cells, and the Uyghur Forced Labor Prevention Act (UFLPA), are shaping the dynamics of the battery supply chain by pushing for more ethical sourcing and reducing geopolitical risks."*

In response to these evolving requirements, organizations are launching a variety of sustainability initiatives, not only to comply with regulations but also to use these mandates for business benefits. For example, Automotive Cells Company (ACC) collaborated with UK startup Circulor to verify provenance and embedded carbon emissions of raw materials across ACC's supply chains, expediting proof of responsible sourcing and compliance with global regulations.[67] Rockwell Automation has partnered with Circulor, which will offer advanced traceability solutions that enable manufacturers to meet emerging regulatory requirements.[68]

Capgemini collaborates with Optel to offer a complete end-to-end traceability solution for battery manufacturing. Optel is a key player in ESG traceability and due diligence. Tapping into their expertise and audits of more than 300,000 suppliers, they provide a detailed assessment of batteries raw materials (lithium, cobalt, manganese, etc.) sourcing, in line with battery passport requirements.

By embracing these initiatives, organizations are ensuring compliance with stringent regulations while fostering a more ethical and resilient supply chain.

Mitigating value chain challenges and environmental impact

Raw materials sourcing and impacts

Raw materials sourcing in battery manufacturing presents significant challenges – environmental, geopolitical and social.

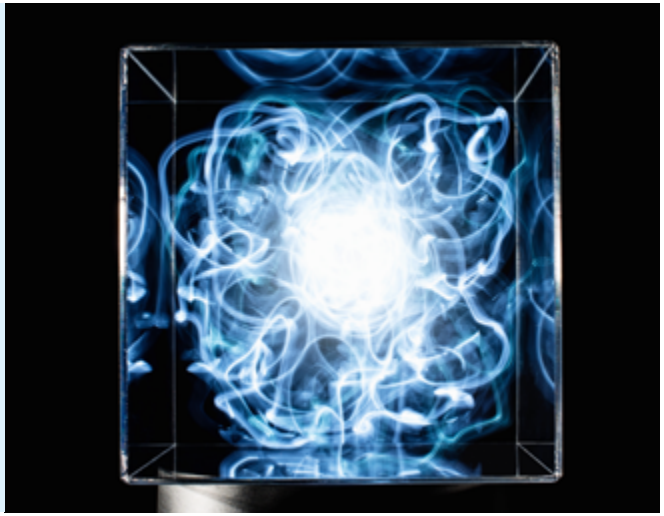
For example, lithium extraction is highly water-intensive, leading to environmental concerns in regions where water is scarce. Mining activities pollute water supplies, contaminate crops, reduce soil fertility, and lead to biodiversity loss.[69] Additionally, the extraction of nickel, another critical battery material, often involves strip mining, which causes deforestation and soil erosion.

Unethical labor practices are another serious issue, particularly in regions with weak labor regulations. Reports indicate that up to 75% of lithium-ion battery supply chains may involve forced or child labor. This exploitation not only violates human rights but also perpetuates poverty and inequality in affected communities.[70]

To build a truly sustainable and ethical battery industry, companies must prioritize responsible sourcing, stronger labor protections, and circular-economy initiatives. Addressing these challenges head-on is not just an environmental or ethical necessity but is also crucial for securing a resilient and future-proof battery supply chain.

"Challenges, such as temperature control during transport, further complicate matters, as demand fluctuations can affect battery performance and safety."

K.V. Ramakrishnan
ex-Director of Plant Operations (ICE, EV)
Great Wall Motor and General Motors



“Batteries play a pivotal role in reducing carbon emissions across various sectors. As new technological advancements emerge, the battery industry is exploring innovative chemistries. Yet, the future success of batteries depends on overcoming significant hurdles in manufacturing capacity, addressing skills shortages, improving scalability, and mitigating supply chain risks”

Pierre Bagnon
Executive Vice-President, Global Head of Intelligent Industry Accelerator, Capgemini

Energy sourcing and production efficiency
Energy sourcing in battery manufacturing significantly impacts both the carbon footprint and costs. The reliance on non-renewable energy sources during production increases greenhouse gas (GHG) emissions, contributing to a larger carbon footprint. For instance, it is estimated that Northvolt and Tesla gigafactories require 50-65 KWh of electricity to manufacture 1 kWh of battery cells and packs. Producing a battery with the French electricity mix (60 gCO2/kWh) instead of the South Korean mix (around 500 gCO2/kWh) avoids the emission of 25 kgCO2 per kWh. For a gigafactory producing 2,000 MWh of batteries per year, this translates to a reduction of 50,000 tonnes of CO_2 annually. This implies that, for a 15-GWh gigafactory, a low-carbon energy mix could lead to ~350kT of CO2 per year.[71]

The fluctuating costs of renewable energy can make it challenging to maintain cost-effective production. Ensuring a stable and sustainable energy supply is essential to reducing environmental impact and controlling manufacturing costs.

Organizations need to develop a circular value chain
The case for battery recycling rests on several pillars: reducing GHG emissions and environmental impacts; securing a steady supply of critical materials; and achieving cost savings. However, this varies depending on the recycling process used (hydrometallurgy, pyrometallurgy, etc.) and overall recycling supply chain complexity

On top of the technical and economic aspects of recycling, battery actors face several other significant challenges. In Europe, more stringent regulations require OEMs to report volume of batteries recycled and how much critical material was recovered.[72,73] EU cell producers are also responsible for recycling their waste and will be required to produce new batteries with an increasing percentage of recycled material. This will require a secure supply, potentially through retake or offtake agreements.[74,75]

In China, regulators are also pushing for higher recovery rates and stricter standards.[76] In the US, while there is no comprehensive federal regulations, state-specific rules are being put in place.

On the other side, recyclers face the challenge of securing feedstock, as batteries last longer than expected,[77] resulting in limited volumes of cells and scrap for recycling. This creates a cyclical problem, with the lack of a clear path to large-scale recycling hampering progress.

A robust battery recycling framework is essential to mitigate environmental concerns and reduce dependency on imported raw materials. A product director at a leading battery manufacturing organization adds: *"Circularity in the battery ecosystem not only alleviates supply chain risks but also positions organizations to meet stringent regulatory requirements. The*

"Each gigafactory is optimized for a specific battery type. Changing over is complex. If we were to produce another type, I'd advocate for a dedicated gigafactory to ensure optimal performance and profitability."

Gilles Moreau
Chief Open Innovation and Sustainability Officer
Verkor

winners will be those that integrate recycling as a core competency."

Currently, organizations recycle only one-third of batteries. According to the International Lead Association (ILA), in Europe and the US 99% of lead batteries are collected at end-of-life and recycled.[78] In 2022, all EU countries achieved the target of 65% recycling efficiency for lead-acid batteries and accumulators, with many achieving recycling efficiencies up to 90%.[79]

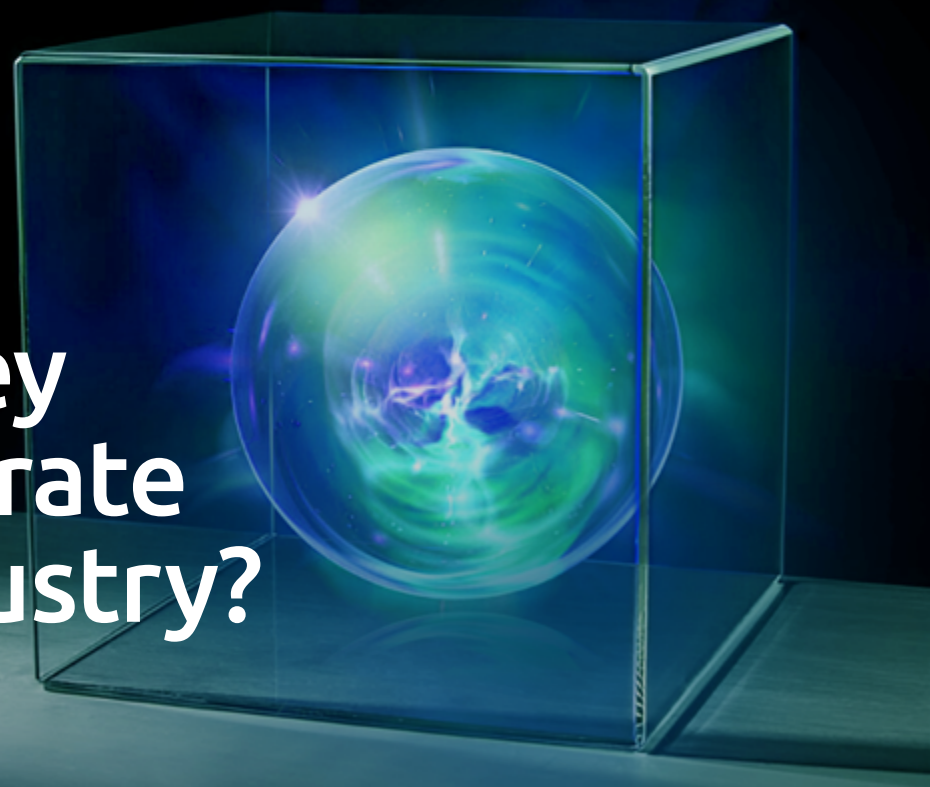
Over half (58%) of executives believe that, with the increase in EV adoption, the focus will shift to optimizing battery recycling and reuse of energy storage systems. As illustrated in Fig. 10, organizations can collaborate with third-party recyclers and other industries for battery reuse and recycling, and/or establish their own in-house recycling facilities.

A product director at a leading battery manufacturer company adds: *"When materials like cobalt and nickel are expensive, the economic viability of recycling increases, with companies often able to profit from retrieving these materials from used batteries. However, when prices drop, recycling becomes less profitable, and we observe a dip in recycling rates, especially for materials with lower intrinsic value, like LFP cells."*

"Optimizing resource use and paving the way for a more sustainable future by minimizing scrap, lowering cost, and enhancing recycling and traceability of batteries is important. Every step taken towards better efficiency and accountability empowers circular economies, and accelerates the transition to cleaner, greener future."

Vincent Charpiot
Executive Vice President, Head of Group
Sustainability Business Accelerator, Capgemini

04 What are the key levers to accelerate the battery industry?

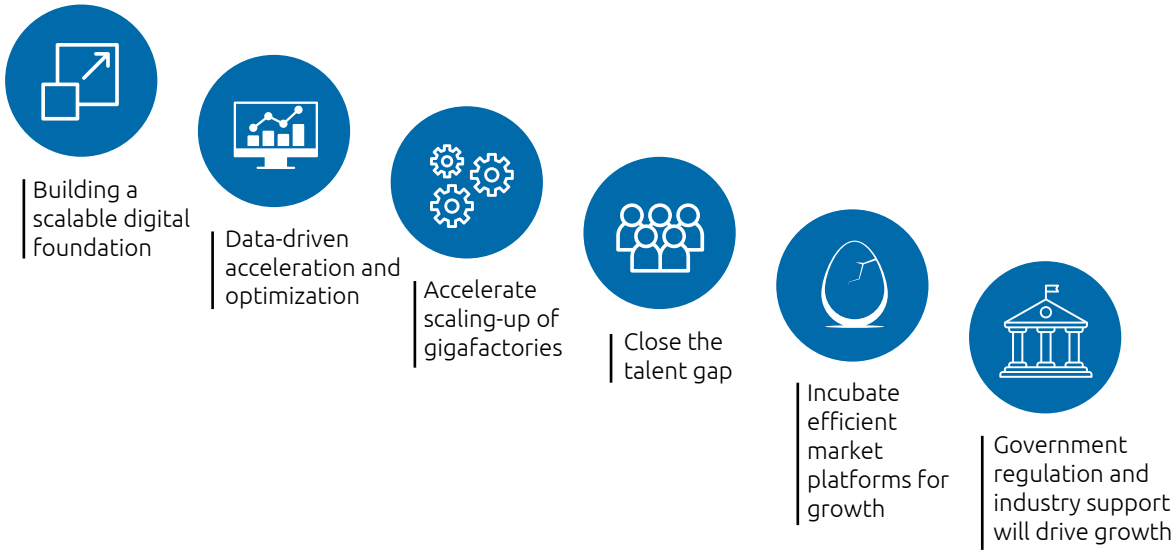


Based on our survey of 750 executives and our interaction with industry experts from battery manufacturers, automotive firms, and energy and utilities organizations, we recommend the following areas of focus.

> *"A massive, anonymized database that companies can tap into for benchmarks and comparisons could revolutionize the industry."*

Jos Theuns
Senior Director Strategy and Partnership for Energy Solutions
EXIDE Technologies

Figure 11.
Core areas of focus for building an efficient battery ecosystem



Source: Capgemini Research Institute analysis.

"Every day, electric vehicles generate millions of data points, and with this data, we have an incredible opportunity to enhance safety, reliability, and sustainability."

Dr. Kai-Philipp Kairies
Founder and CEO
Accure Battery Intelligence

Building a scalable digital foundation

Digital First approach

Unlike in other domains, in the battery value chain digitalization not only facilitates process optimization, but also unlocks fundamental competitive advantages. An essential prerequisite is a comprehensive digital and data foundation, which:

- can be scaled quickly to accommodate a rapid rise in production capacity;
- enforces open and standardized data formats to enable quick integration of software solutions;
- provides accessibility so that data can be utilized not only in individual stages of the value chain, but across domains and even tiers;
- guarantees high semantic quality of data, to achieve a realistic representation of processes and full traceability.

The final aspect can be divided into two levels of maturity:

The first stage concerns documenting the genealogy of the materials used (i.e., the link between input materials, intermediate products, and the final battery). This allows the history of a battery to be traced from the extraction of raw materials to recycling and compliance, to any reporting obligations (e.g., the full battery passport).

In the second stage, in addition to genealogy, organizations store and link the process data from the production steps. This is the key to effective optimization of production processes, allowing the effect of process parameters on end-product performance to be traced and adjusted accordingly.

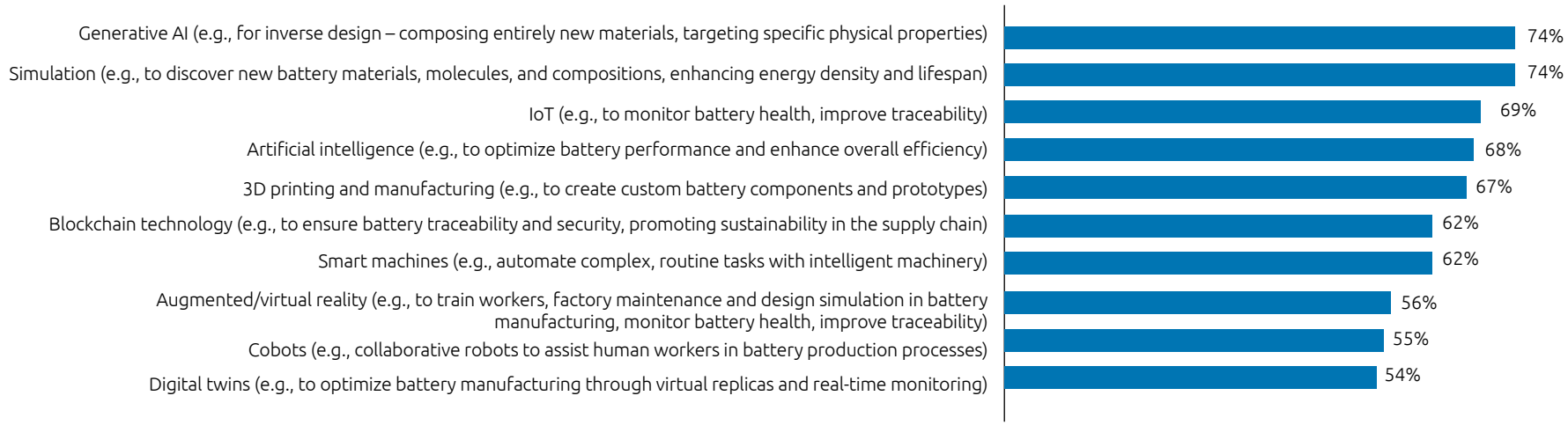
In the case of the battery value chain, some of the production processes involved are still not well established and are executed by machinery for which there are still no standardized, cross-industry data models. Manufacturers, therefore, need to be both innovative and cooperative in collecting, collating, and democratizing data.

IT/OT masterplan

After establishing the appropriate data foundation, organizations should develop an IT/OT (operational technology) masterplan for the successful integration and scaling of data and digital technologies in gigafactories, based on a thorough analysis of the current state of the IT landscape: infrastructure, systems and capabilities, and a strategic vision of the targeted model for IT functions, aligned with overall business objectives and strategic goals. Laying the proper IT and digital architecture foundations is a huge performance enabler through the use of technologies such as ML, Big Data analytics, and digital twin. We believe this transformation will help battery actors improve performance, efficiency, safety, and sustainability.

Figure 12.
Digital technologies can enhance the battery value chain

Potential of digital technologies



* Percentages represent share of executives who believe these digital technologies have the highest potential to enhance battery development, manufacturing, operations, and performance.
Source: Capgemini Research Institute, Future of batteries survey, September–October 2024, N = 338 battery executives.

Digital architecture

Digital architecture should focus on two important aspects. First is the convergence of IT and OT. This can be achieved through structured information models based on industry standards such as OPC UA. In addition, this requires OT/IT governance to enforce those standards for integration of all machines and Internet of Things (IOT) sensors. The second aspect is the integration of all IT systems across the value chain to achieve a single source of truth and seamless data flow across systems such as product lifecycle management (PLM), enterprise resource planning (ERP), and manufacturing execution systems (MES). Scalable hybrid data platforms allow the aggregation and management of data from various sources and ensure data consistency and accessibility.

Achieving both targets is key to accelerating scaling, collection, use, and sharing of data to facilitate real-time monitoring and decision making. Strong governance is essential to ensuring consistency and cybersecurity.

Data-driven acceleration and optimization

Our survey indicates that, while organizations are successfully collecting and distributing data, they lag expectations in terms of effective utilization. For example, we noted data utilization in just 12% of refurbishment or second-life operations and 37% of quality control operations (**Fig. 13**).

These results demonstrate that, on top of the impact already seen across the value chain, battery manufacturers have considerable scope to improve data usage across a diverse range of use cases.

Accelerate battery chemistry research

Aionics, based in Palo Alto, US, uses AI to improve battery electrolyte discovery. It harnesses AI-accelerated quantum mechanics to evaluate 10,000 candidate molecules per second from a database of billions. Its AI model learns over time, enhancing problem-solving and outcome prediction. In 2024, Aionics began using Gen AI models to design new molecules for specific applications, and large language models (LLMs) from OpenAI to help scientists reach viable formulations. Data scientists train these tools on chemistry textbooks and scientific papers to eliminate unsuitable molecules prior to testing.[80] Jos Theuns, Senior Director Strategy and Partnership for Energy Solutions at EXIDE Technologies, a storage battery manufacturing company, confirms the importance of databases: *"A massive, anonymized database that companies can tap into for benchmarks and comparisons could revolutionize the industry. With regular updates and insights, it could help everyone, from manufacturers to end-users, optimize their choices and strategies. This kind of transparency and shared knowledge could push the entire sector forward."*

Optimize production and utilization of equipment

Improve manufacturing quality

As the industry strives to meet demand and comply with regulation, manufacturers must implement rigorous, technologically enhanced process controls and quality assurance measures. This requires advanced process and production maturity. US startup Voltaiq offers an enterprise battery intelligence platform that uses analytics to increase the volume of usable data. Tesla has fine-tuned its manufacturing process through automation and robotic programming.[81] Kai-Philipp Kairies, CEO at Accure Battery Intelligence, a German battery analytics software organization, asserts: *"By using ACCURE's software to detect manufacturing defects already during the formation process, we can improve quality control and significantly reduce scrap rates."*

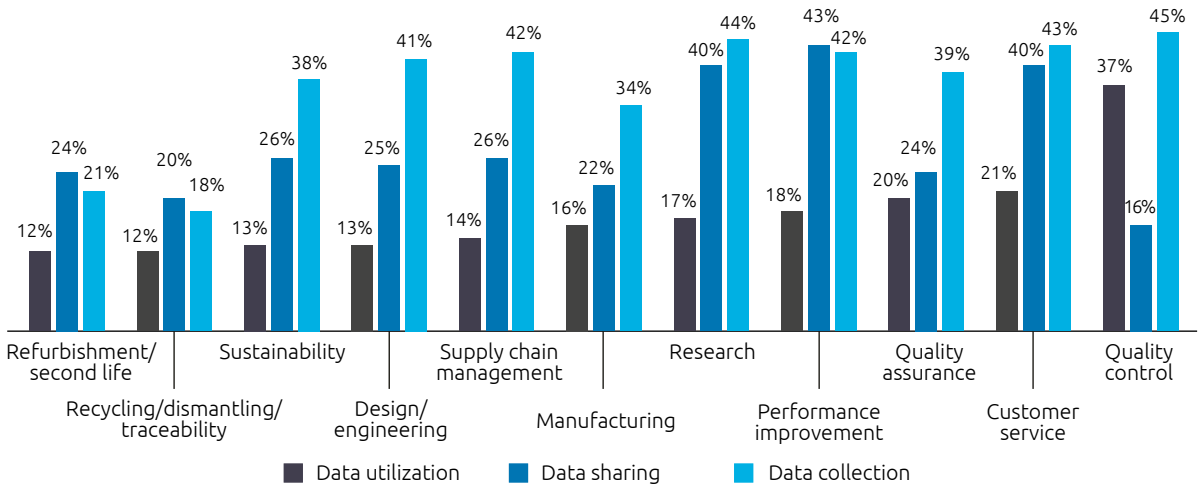
Implement predictive maintenance

Kairies adds: *"Every day, EVs generate millions of data points, and with this data, we have an incredible opportunity to enhance safety, reliability, and sustainability. At Accure, we harness the power of ML and physics-based models in the cloud to unlock the full potential of these vehicles, helping automotive manufacturers extend battery life and ensure safer, more efficient operations."*

Similarly, Bosch has developed 'battery in the cloud:' smart battery management that offers services such as battery performance and lifetime monitoring. It also reduces the probability of unforeseen breakdown.[82] Areas of focus are:

Figure 13.
Data usage is minimal in sustainability-related fields

Data practices by operational area

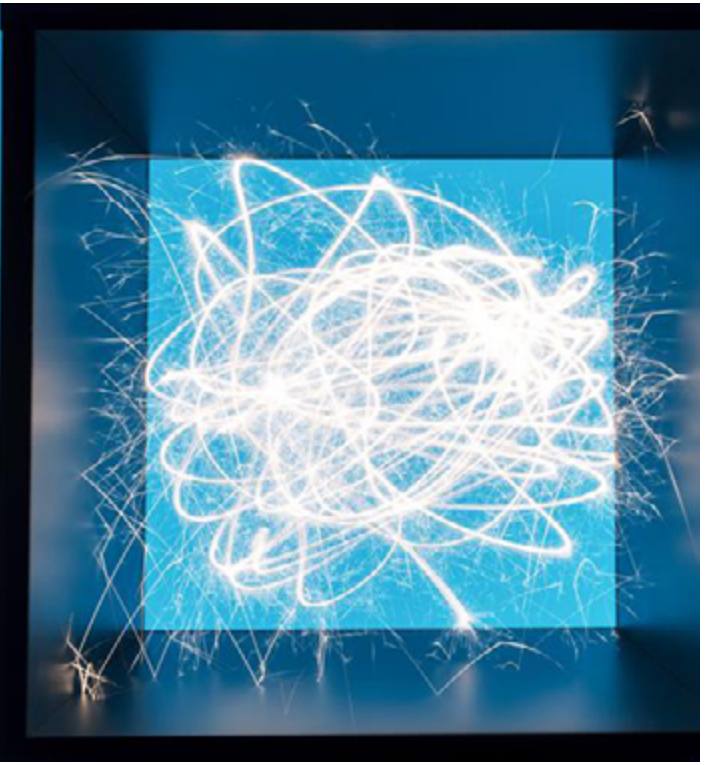


* Percentages show the proportion of executives who consider their organization's current data practices highly effective in the mentioned areas.
** Note: Data utilization refers to the effective use of collected data to gain insights and improve performance, quality, safety, and sustainability. Data sharing involves seamless exchange of information among stakeholders to streamline operations and make continuous improvement. Data collection involves gathering information throughout the battery lifecycle.`
Source: Capgemini Research Institute, Future of batteries survey, September–October 2024, N = 338 battery executives.

– Creating digital twins for battery systems to simulate and predict performance, lifecycle, and potential faults
– Utilizing AI and ML for predictive maintenance, quality control, and optimization of manufacturing processes

Process simulation
Understanding the production process is the key to continuous improvement of quality and increased output – and to profitability. Process simulation models can accelerate the process. In Capgemini's recent study with the Fraunhofer Institute at RWTH Aachen University in Germany, we demonstrated that the use of simulation in electrode drying processes significantly reduces reliance on trial-and-error, cutting development time by up to 50%, especially during new materials testing.

Improving product design
Standardizing data collection across the industry and ensuring it is communicated efficiently to all stakeholders will improve battery performance monitoring. A vehicle engineering head at a Swedish automotive organization explains: *"Predicting thermal events remains challenging, as these typically stem from manufacturing defects. With new legislation like the Zero Emission Vehicle initiative in the US, we need to share comprehensive data about battery performance, journey metrics, and environmental conditions with regulatory bodies. This is an opportunity to standardize our data practices across regions. By gathering this data – ideally with user consent*



– we can identify trends and develop predictive software that mitigates failures before they occur."

Digital battery passport
Mohammed Jerouane, Senior Director, Vehicle Chief Engineer, Powertrain and Battery Integration Testing at VinFast, notes: *"The battery passport concept will enable suppliers and OEM manufacturers to become increasingly competitive by seeking more sustainable battery properties. It will also empower customers to make informed decisions by considering the complete lifecycle of battery manufacturing and calculating carbon footprint."*

Fig. 14 shows that the proportion of executives implementing specific measures to improve traceability averages around 59%, indicating widespread recognition but insufficient prioritization.

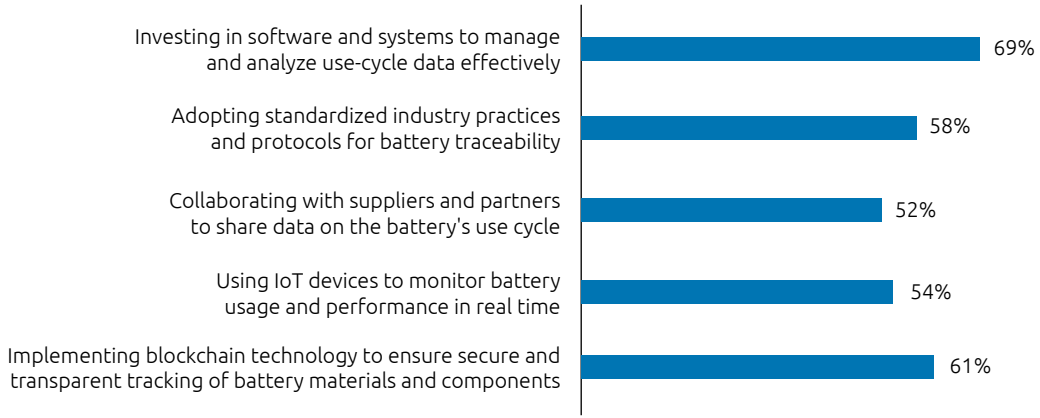
Insights and sustainability in supply chain

Enable supply chain visibility
Digital technologies provide visibility of the entire supply chain to inform business decisions. Gilles Moreau at Verkor says: *"Today, we're using AI more to validate the integrity of our supply chain data – spotting inconsistencies or gaps where certain details might be unreliable. Traceability is a serious issue, especially with concerns around labor practices and environmental impact. With blockchain and AI, I see the potential to make information not only more reliable but coherent, consistent, clear, and trustworthy."*

Driving sustainability
Organizations are investing in digitalization to ensure sustainability through traceability (**Fig. 14**). A senior executive leading global sustainability at a US-based energy storage solutions provider explains: *"Sustainability isn't a one-size-fits-all approach. In the Atacama Desert in Chile, we're using non-potable brines and solar power to drive the mining process – an impressively low-carbon method. In other geographies, it's a much more energy-intensive process, relying heavily on diesel-powered machinery. This approach can produce double or even triple the carbon emissions per unit of lithium produced by methods used in drier climates."*

Figure 14.
Organizations are incorporating traceability via digitization

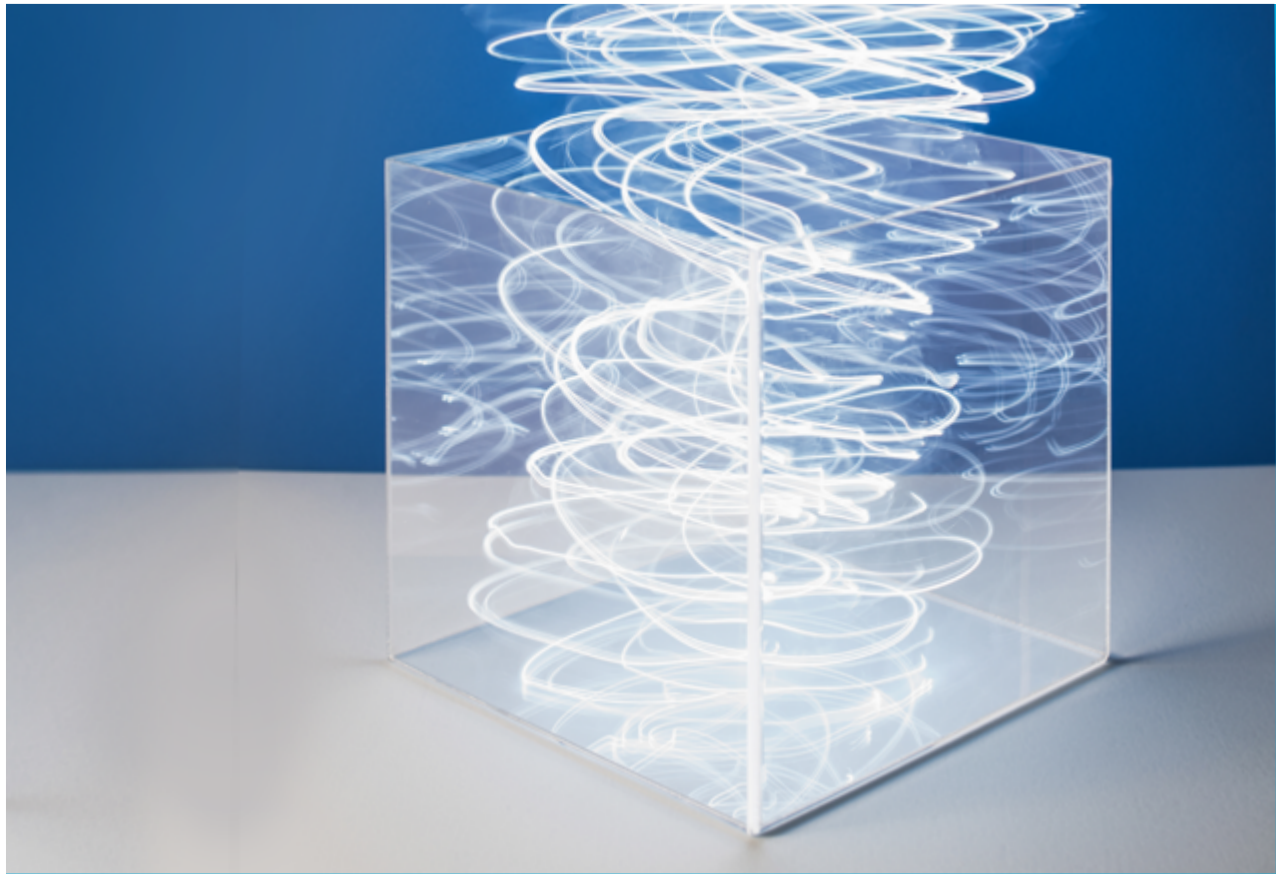
Steps taken to improve traceability of battery value chain



* Percentages represent the share of executives who currently implement or plan to implement the specified measures to improve traceability.
Source: Capgemini Research Institute, Future of batteries survey, September–October 2024, N = 751 executives from battery, automotive, energy and utilities.

"Batteries play a crucial role in electrifying transportation and enhancing renewable energy systems by storing excess energy during peak production, stabilizing the grid during demand fluctuations, enabling greater integration of renewables, providing backup power during outages, promoting decentralized energy management, and delivering economic benefits by reducing reliance on fossil fuels. Innovations in battery technology are paving the way for a cleaner, more efficient, and sustainable future."

Florent Andrillon
Executive Vice President, Global Head Climate Tech, Capgemini



Areas of focus:

- Establish industry standards for data collection and sharing across different stages of the battery lifecycle
- Utilize big data analytics to gather insights from production data, customer feedback, and market trends
- Provide training and development programs to enhance the digital skills of employees and foster a data-driven culture
- Establish data governance policies to ensure data quality, accuracy, and integrity.

Accelerate scaling-up of gigafactories

Gigafactories are key to escaping what ACC's Yvan Vincent calls the "valley of death" (see p. 32) caused by high OpEx costs in launching battery operations.

Build an efficient project organization
Some topics are key to effective project management, regardless of the selected project scheme (including EPC, design/build/bid, and integrated project).

Gigafactory projects are inherently complex due to the integration of numerous interconnected systems, including extensive building structures; specialized dry rooms with controlled humidity and temperature; essential utilities such as electricity and heating, ventilation and air-conditioning (HVAC); and advanced process equipment. Successfully coordinating these different packages requires meticulous planning.

Importance of building information modeling

Building information modeling (BIM) is a critical tool for managing complex gigafactory projects. BIM supports the creation of detailed 3D models of all systems and components of the gigafactory, allowing visualization of the entire project for stakeholders. This helps identify potential conflict and other issues early in the design phase, promoting coordination and collaboration between stakeholders.

Improving product and process maturity

Given the criticality and complexities of the battery manufacturing processes, close collaboration should be a core aspect of initial specifications.

Good practice would be to seek guidance from battery R&D experts. Specifications should include documents and information to be delivered with the equipment, including utility matrix, installation manual, energy balance, design failure mode and effect analysis (DFMEA) and control plan, 3D models, detailed bill of materials (BOM) and spare part list, operating manual, work instructions, maintenance manuals, and training manuals.

As equipment suppliers will be present during installation, commissioning, and potentially ramp-up, it is critical to define their roles across those phases.

Ensure suppliers commit to project success

Allotting responsibility for project activities through work packages and managed services is a strong fail-safe to reduce overall project risk in the following areas:

Quality: Agreeing up front on a list of precise deliverables and performance KPIs with the service provider mitigates quality risks.

Delays: Committing to a precise deadline for deliverables in the work package limits risk of overshooting.

Cost: Most recent gigafactory projects we examined experienced delays of at least three months, sometimes extending to over a year. If the work package covers a significant portion of the project resources, it will limit the financial impact of even extended delays (the extra cost being borne by the service provider, who can adapt its own workforce to limit exposure).

It is also vital to define and enforce high quality standards – whether on technical (welding, concrete works, etc.) or program management (document control, procedures, standard forms, etc.) aspects. This requires a dedicated quality assurance and quality control (QAQC) cell.

Digitalize to support faster construction and commissioning

To remain competitive by enabling rapid scaling, battery players must create fully digital and automated gigafactories. Digital twin can enable this, with a dynamic model that offers substantial time savings and significantly reduces costs by facilitating early detection of design flaws and optimizing plant layout.

Virtual commissioning of the gigafactory identifies potential errors through comprehensive testing. SES, a US-based technology organization, uses digital twin for manufacturing lithium-metal batteries with a high energy density. SES Avatar, a digital twin of physical lithium-metal cells, uses manufacturing and real-world battery data to enable predictive performance and longevity analysis. [83] The software has already been installed in SES's Shanghai and Chungju (South Korea) facilities.[84]

"Training talent across roles ensures that staff can offer excellent customer experience and troubleshooting, while ensuring safety and operational efficiency."

Kasturi Gomatham
Global Head of Battery Swapping and EV Partnerships
Shell

Optimize manufacturing and operations from day one

By integrating scalable data and digital levers from the outset – including an IS/IT masterplan, digital enablers, PLM, AI, and real-time capabilities – businesses can fully harness the benefits of digital.

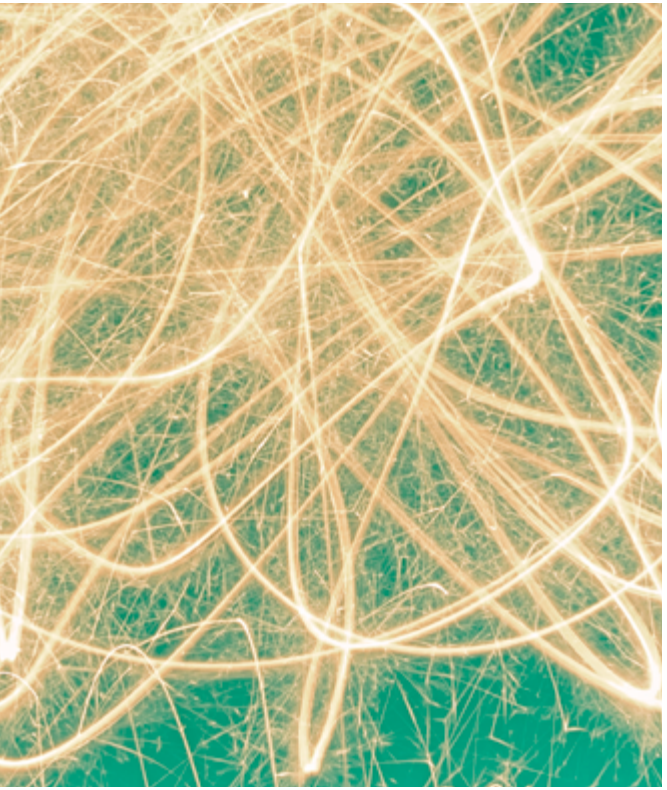
Bridge the talent gap

Collaboration between industry, academia, and R&D can bridge the talent gap

Each new technology brings with it a talent imperative. For batteries, this is uniquely challenging, demanding a bouquet of skillsets from chemical, thermal, electronic, and digital. A vehicle engineering head at a Swedish automotive organization explains: *"More than technical know-how, talent is about bridging disciplines and nurturing cross-functional expertise. We need a new generation of engineers who can meld chemistry with mechanical design, understand the nuances of high-voltage systems, and anticipate the rigors of real-world applications."*

Collaboration with universities is one way to bridge the talent gap. Kasturi Gomatham, Global Head of Battery Swapping and EV Partnerships at Shell, explains: *"Training talent across roles ensures that staff can offer excellent customer experience and troubleshooting, while ensuring safety and operational efficiency. Academia and industry relationships will be an important factor in building fit-for-purpose courses and training."*

For the next three years, Volkswagen's PowerCo will help fund the International Research School for Battery Chemistry, Characterization, Analysis, Recycling and Application



(BACCARA) at the University of Münster. Additionally, students will benefit from expert lectures and participation in on-site projects.[85] The UK's University of Warwick offers "Battery School" and "Electric Drivetrain School" and provides courses in battery systems and manufacturing. France has also launched battery-focused university programs.[86] As in China, government support is vital to these industry-academia joint ventures.

The industry needs a multifaceted solution: robust R&D initiatives, hands-on training, and a collaborative effort between government, industry leaders, and educational institutions. `

Verkor, in collaboration with 15 partners, launched the École de la Batterie (EDLB) initiative to address the growing need for skilled workers in French battery manufacturing. It offers a wide range of training programs, from vocational courses to advanced degrees, to prepare individuals for careers in battery production, engineering, and related fields.[87]

Those 15 partners include industry partners, innovation clusters, R&D institutions, academic institutions, and vocational and professional training actors. The network can tackle short-term stakes (how to provide 'hands-on' training for the thousands of operators and engineers required to run the current gigafactories projects) and long-term ambition (which new technologies should we focus on, and how can we build the battery industry of the future?).[88]

The school is part of France's broader strategy to reindustrialize the automotive industry and support the transition to EVs, with a goal of producing 2 million electric and hybrid vehicles by 2030.[89]

Incubate efficient market platforms for growth

Battery-friendly energy markets

Over the past five years, the overall capacity of European solar farms has surged from 127 GW to 301 GW, and wind capacity has grown from 188 GW to 279 GW.[90] However, energy storage solutions have not progressed at the required rate.

Steps toward market reform are necessary across geographies to enhance battery deployment. Regulatory stability is essential to optimize market conditions, encourage investment, and help generate revenue. However, in many markets, limited locational price signals, underdeveloped ancillary services markets, and structural metering challenges impede potential.

This is an opportunity for leading energy companies to collaborate to improve market design. Long-term stability of market structures is required to attract investment, which relies on predictable returns over extended periods. The cost of energy storage should be included in the cost of renewables to calculate the levelized cost of energy.

Battery marketplace

Over half (54%) of executives favor a battery marketplace to ensure competition and choice of battery packs, and 58% are hopeful that there will soon be common standards for battery cells and charging. This will also provide visibility of consumer needs, market segments, and appetite for price, and lead battery manufacturers to work with automobile organizations to understand customer needs.

K.V. Ramakrishnan explains how this is implemented in China: *"In China, users can effortlessly exchange batteries at gas stations or dealers. A novel concept for four-wheelers is now under trial: a 'battery superstore,' akin to a grocery store, where customers can select from various batteries based on their needs, much like choosing food items. Users would access this facility 24/7, just like an ATM, selecting their required battery through an app, making the process as simple as a vending machine. This approach promotes standardization and collaboration among manufacturers and enhances consumer accessibility through these kiosks."*

> ***"The battery passport concept will enable suppliers and OEM manufacturers to become increasingly competitive by seeking more sustainable battery properties. It will also empower customers to make informed decisions…"***
>
> **Mohammed Jerouane**
> Senior director, Vehicle Chief Engineer, Powertrain and Battery Integration Testing
> Vinfast

A vehicle engineering head at a Swedish automotive organization adds that the marketplace will also lower EV costs by decoupling battery price from vehicle sales, which will emerge as a new revenue stream for automotive dealers: *"Manufacturers may embrace BaaS, allowing users to easily exchange their batteries while ensuring performance and longevity through centralized reconditioning processes."*

He adds: *"Leasing models for EV batteries can transform the marketplace. By decoupling battery cost from vehicle price, manufacturers can offer lower purchase prices while charging customers based on usage. This approach not only keeps customers engaged with the manufacturer but also generates ongoing revenue for dealerships, ensuring profitability in an era where traditional maintenance revenue streams are declining."*

Government regulation and industry support will drive growth

Organizations welcome regulations that help scale battery production, innovation, and collaboration. Over half (55%) of executives agree that government policies and regulation help shape the future of the battery industry, particularly on sustainability and transparency. While nearly two-thirds (63%) of executives from APAC hold this view, a more moderate 50% of executives from Europe and 37% from North America share it. Standardized battery packs, for example, would support battery swapping, create common charging protocols, and lower production, maintenance, and recycling costs. The US IRA has been instrumental in boosting battery investment. A sustainability executive from a multinational automotive organization summarizes the US regulatory landscape: *"The IRA incentivizes automotive OEMs to source battery materials outside China, given geopolitical sensitivities. This has spurred investment in manufacturing capacity in non-sensitive [geographies] such as Morocco and Australia."*

The EU's Batteries Regulation, which came into effect in August 2023, is designed to ensure the sustainability of batteries throughout their lifecycle, ensuring low carbon footprint, minimal harmful substances, fewer raw materials from non-EU countries, and high recyclability within Europe, driving a competitive clean-energy transition to a circular economy and improving raw materials and energy security.[91]

A further 65% of executives state regulations such as the EU Ecodesign for Sustainable Products Regulation (ESPR) will encourage sustainable battery manufacturing and recycling practices. A senior executive leading lithium-ion battery EV and ICE powertrain costing at a French multinational automotive organization says: *"Regulations like the EU digital battery passport are going to force transparency in the supply chain. Manufacturers will be required to declare the carbon footprint of their battery cells using a standardized lifecycle assessment [LCA] process. While this may start as a reporting requirement, it will evolve into a system of taxation or penalties for those with large CO_2 footprints."*

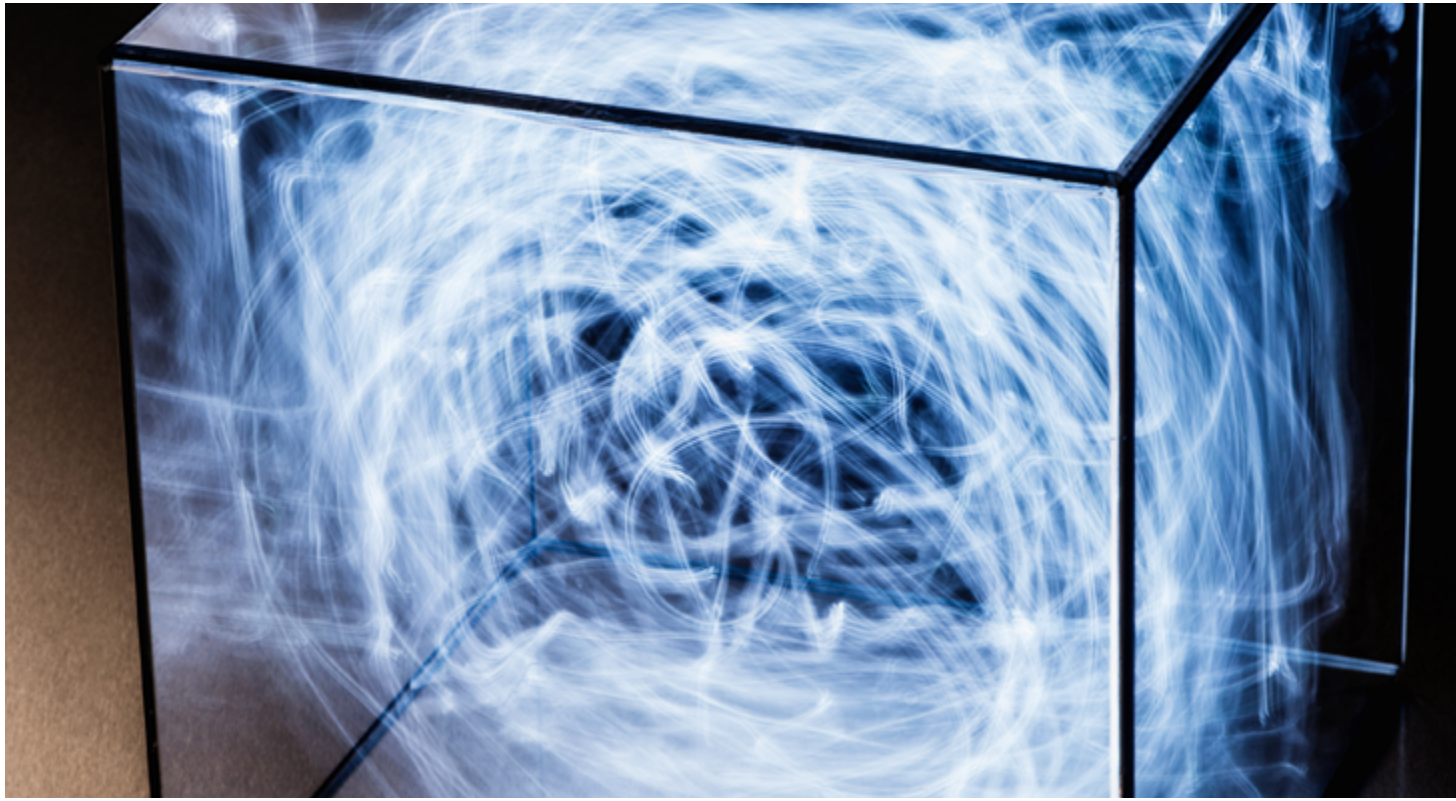
There is potential for increased collaboration and standardization within the EV industry, like the universal use of USB Type-C chargers in mobile devices. While Tesla and Rivian's move to open their charging stations to other automakers is a step in this direction, [92,93] it's still too early to call it a significant trend. The lack of regulatory pressure contributes to this slow pace.

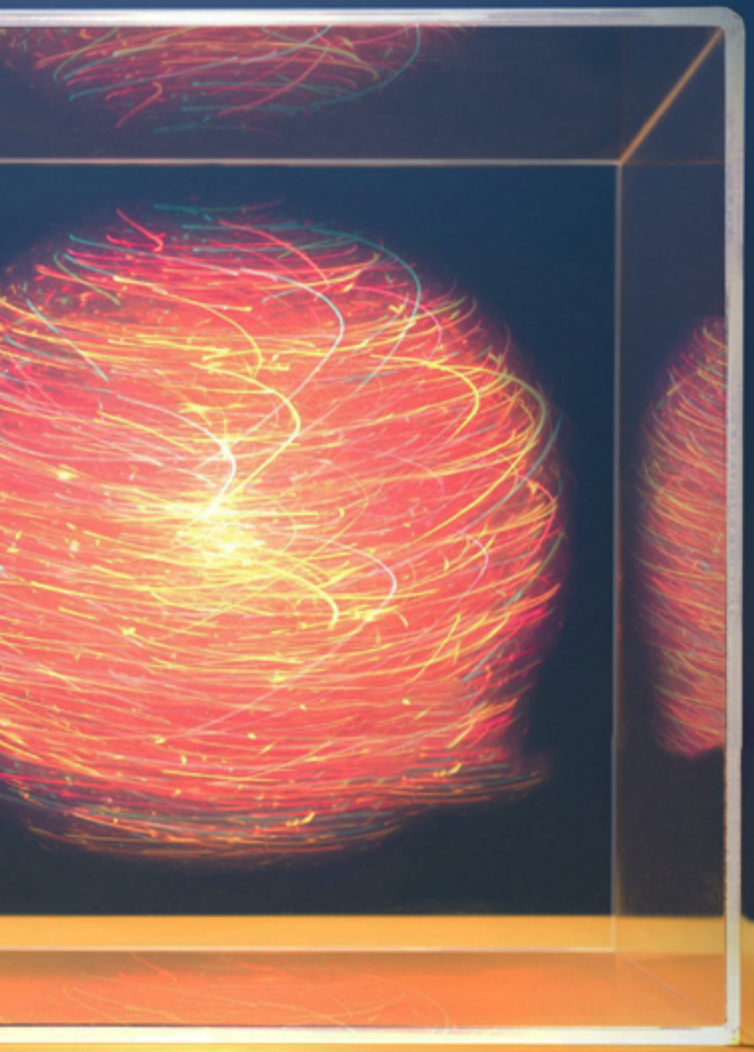
China has established three key national safety standards for EVs:

1. Alarm signals for thermal events and enhanced waterproofing and insulation to minimize risks during normal operation

2. Addressing the unique safety challenges posed by buses in terms of high passenger capacity and large battery size, specifically collision safety and mandating that high-voltage components be fire-resistant
3. The thermal, mechanical, electrical, and functional safety of battery systems[94]

The Chinese government has long played a significant role in supporting both supply and demand of EVs. Through generous subsidies, tax breaks, procurement contracts, and other policy incentives, China has maintained its dominance in the global battery market, generating a slew of homegrown EV brands. Recently, China's Ministry of Commerce proposed export restrictions on technologies used to produce battery components and process-critical minerals such as lithium and gallium. This announcement, preceding the inauguration of Donald Trump as US president (with his promise of punitive tariffs on China, in particular), reflects China's strategic intent to maintain its pre-eminence in the global battery supply chain. These measures aim to secure domestic supply chains and strengthen the country's competitive edge in battery manufacturing, where it already controls 70% of global lithium processing capacity.[95]





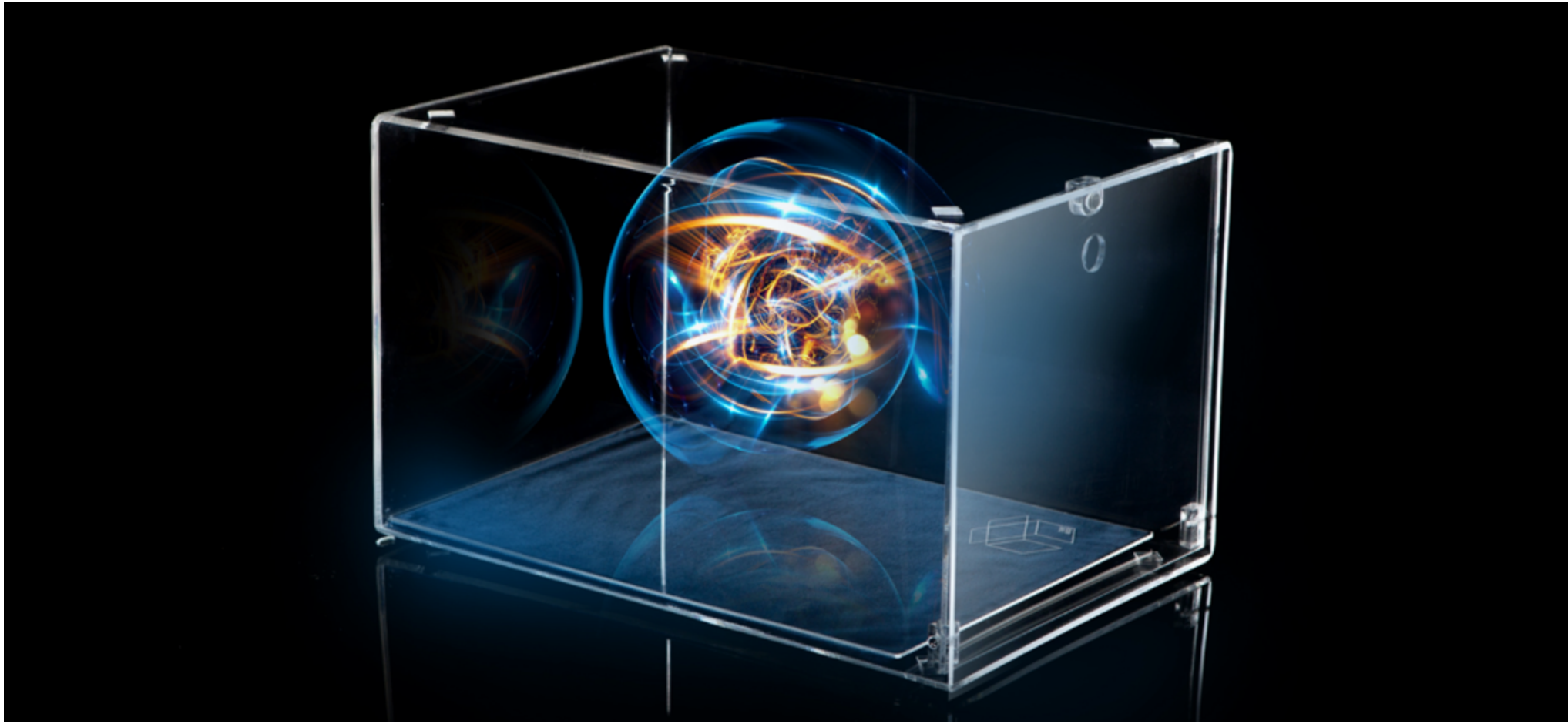
Conclusion

Amid a rise in battery adoption across various sectors, organizations must focus on meeting current production demands while working on new battery chemistries. For the growth and seamless adoption of battery technologies, collaboration and cooperation between four key stakeholder groups – regulators, battery manufacturers, automotive manufacturers, and energy/utilities firms – is essential. Regulators need to establish clear standards and incentives that foster innovation while ensuring safety and sustainability, whether this involves new production processes and facilities, strategic expansion, or other innovative approaches.

To adapt to changing consumption patterns and ensure widespread adoption, organizations are exploring innovative business models. BaaS, battery swapping, leasing, and renting are gaining traction, especially in regions with high EV penetration. These models are designed to reduce up-front costs, enhance convenience, and promote recycling, thereby maximizing ROI and addressing critical resource issues. Amid rapid industrial growth, the scarcity of experienced talent is a significant challenge. Organizations are establishing battery academies to attract and retain skilled workers. They are also looking into collaborative efforts with academic institutions and the use of digital tools to accelerate the learning curve and transfer of skills within the industry.

Creating a comprehensive IT masterplan is essential for the effective integration and expansion of data and digital technologies in gigafactories. Establishing the appropriate IT and digital architecture will be a significant performance enabler for battery production.

Battery manufacturers must focus on advancing technologies that meet the diverse needs of the automotive industry and energy sector. Automotive and energy and utilities organizations, meanwhile, must invest in infrastructure that supports the adoption of new battery technologies and business models, facilitating broader market acceptance. New competitors will emerge in this space, and organizations that fail to innovate may not survive. Long-term planning, adherence to regulations, investment in digitalization, ecosystem collaboration, and data utilization will all be crucial to those aspiring to be players in the battery industry of the future.

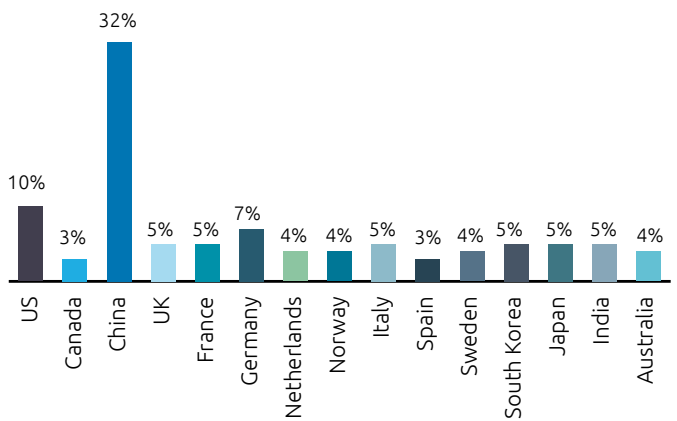


Research methodology

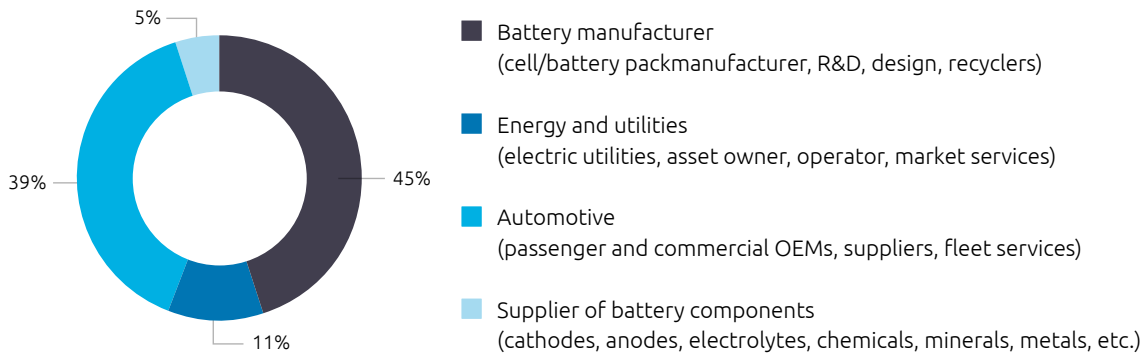
We surveyed 750 senior executives from large battery, automotive, and energy and utilities organizations across 15 countries. The global survey took place in September–October 2024. The survey findings are complemented by in-depth discussions with 22 experts from battery, automotive, and energy and utilities sectors.

The distribution of executives and their organizations is shown in the following figures.

Organizations, by country of headquarters

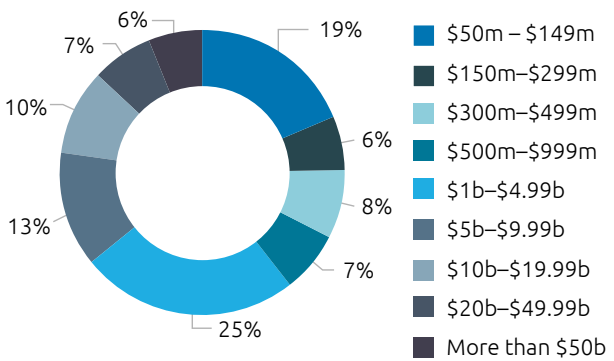


Organizations, by sector

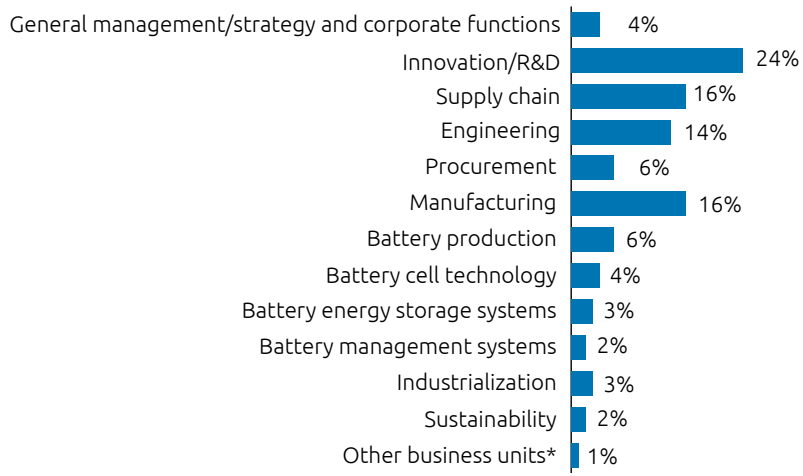


*Includes executives involved in energy transition, renewable energy, accelerator programs, public affairs, regulatory affairs, and policy business units.

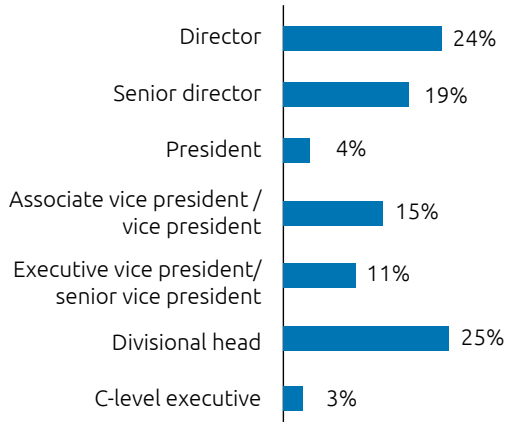
Organizations, by annual revenue



Executives, by job function



Executives, by job title



*Includes executives involved in energy transition, renewable energy, accelerator programs, public affairs, regulatory affairs, and policy business units.

Source: Capgemini Research Institute, Future of batteries survey, September–October 2024, N = 751 executives from battery, automotive, energy and utilities.

References

1. A flexible model that allows users to access battery power without purchase. Leasing and renting provide convenient, cost-effective battery use based on requirements, reducing up-front financial burden.
2. COP28 UAE, COP28: Global renewables and energy efficiency pledge, accessed January 2025.
3. IRENA, World Energy Transitions Outlook 2023, June 2023.
4. IEA, "Batteries and secure energy transitions," April 2024.
5. Ibid.
6. IEA, Global EV Outlook 2024, April 2024.
7. The Economic Times, "How China's BYD beat Tesla at its own game," January 2024.
8. World Economic Forum, "Industry leaders on the future of EV supply chains amid US-China tensions," January 2025.
9. GlobeNewswire, "Solid state battery market size and forecast 2020-2030: Market poised for strong growth with projected CAGR of over 30% from 2023 to 2030," December 2024.
10. Carnegie Endowment for International Peace, "Winning the battery race: How the United States can leapfrog China to dominate next-generation battery technologies," October 2024.
11. Asia Financial, "After chips, China to pour millions into solid-state batteries," May 2024.
12. Bloomberg NEF, "China to spend $828 million on high-tech EV batteries, China Daily says," May 2024.
13. AutomotiveDive, "Volkswagen subsidiary PowerCo lands battery tech licensing deal," July 2024.
14. Volkswagen, "PowerCo and QuantumScape announce landmark agreement to industrialize solid-state batteries," November 2024.
15. Stellantis, "Stellantis and Factorial take next step to accelerate the future of electric vehicles with solid-state battery technology," October 2024.
16. Electrek, "BYD exec predicts solid-state EV batteries will hit the market sooner than expected," September 2024
17. Industry Week, "Natron Energy to invest $1.4 billion in new sodium-ion battery gigafactory," August 2024.
18. CarNewsChina, "Volkswagen-backed JAC Yiwei EV powered by sodium-ion battery starts mass production in China," December 2023.
19. ETN, "BYD begins construction of 30GWh sodium-ion battery plant in China," January 2024.
20. IEA, Batteries and Secure Energy Transitions.
21. Stellantis, "Stellantis and CATL to invest up to €4.1 billion in joint venture to build large-scale LFP battery plant in Spain," December 2024.
22. S&P Global, "Commodity Insights," May 2024.
23. EVBoosters, "The gigafactory boom: How the UK risks falling behind in Europe's EV revolution," January 2025.
24. Extended Producer Responsibility is a policy approach that makes producers responsible for their products throughout the entire lifecycle, including at post-consumer stage.
25. TechCrunch, "Tracking the EV battery factory construction boom across North America," July 2024.

26. NREL, "Online NAATBatt Lithium-Ion Battery Supply Chain Database," February 2025.
27. TechCrunch, "Tracking the EV battery factory construction boom across North America," July 2024.
28. Tesla, "Continuing our investment in Nevada," January 2023.
29. Sustainable Bus, "Hungary – the future paradise for EV battery manufacturers?" June 2024.
30. LG Energy Solutions website, accessed January 2025.
31. Bne Intellinews, "Africa's critical role in the global battery mineral value chain," October 2024.
32. CSIS, "Morocco, an unexpected winner of China's strategy to circumvent the U.S. Inflation Reduction Act," January 2024.
33. Investment Monitor, "Deal of the week: Gotion High Tech's $6.4bn battery plant in Morocco," June 2023.
34. LG press release, "LG Chem Teams Up with Huayou Group to Build LFP cathode plant in Morocco," September 2023.
35. ECA, "With ECA support, Morocco, the DRC and Zambia outline joint E-mobility roadmap," December 2024.
36. Harvard Business Review, "How one Chinese EV company made battery swapping work," May 2024.
37. MIT Technology Review, "How 5-minute battery swaps could get more EVs on the road," May 2023.
38. CnEV Post, "Nio says over 70% of its car buyers have opted for BaaS battery rental since Mar," August 2024.
39. IEA, Global EV Outlook 2024, April 2024.
40. Fortune, Germany's EV sales crash as buyers abandon electric cars in droves," January 2025.
41. IEA, Global EV Outlook 2024.
42. Business Standard, "Vidyut, JSW MG Motor India launch battery-as-a-service for passenger EVs," September 2024.
43. S&P Global, "The risks of leaving long-duration energy storage short of money," June 2024.
44. Ibid.
45. Energy-Storage.News, Startup Form Energy's '100-hour' iron-air battery.[DATE?]
46. Energy Mix, "New investment speeds development of 100-hour battery for local energy storage," October 2024.
47. S&P Global, "Commodities Insights," May 2024.
48. Enel X, "Vicinity Centres and Enel X partner on battery storage projects," January 2023.
49. Ford Newsroom, "BMW, Ford and Honda agree to create ChargeScape, a new company focused on optimizing electric vehicle grid services," September 2023.
50. ETN, "Octopus Energy kick-starts vehicle-to-grid tariff for EVs in UK," February 2024.
51. Octopus Energy website, accessed October 2024.
52. Capgemini, World Energy Markets Observatory 2024 – 26th Edition, 2024.
53. Toyota website, "Joby Aviation and Toyota accelerate efforts to realize air mobility," November 2024.
54. Capgemini, "Capgemini and Ascendance extend their partnership to accelerate industrialization of decarbonized air transport," January 2025.

55. Rapid transition alliance, “Making waves: Electric ships are sailing ahead,” July 2022.
56. Sustainable Ships, “Inside the world's first electric cargo ship - Yara Birkeland,” accessed May 2024.
57. Reuters, “Germany launches electric truck charging network,” July 2024.
58. Automotive Cells Company, official LinkedIn page, accessed January 2025.
59. Advanced battery chemistries that enhance performance, energy density, charging speed, safety, and lifespan beyond the capacity of batteries currently on the marker (e.g., solid-state, sodium-ion).
60. S&P Global, “Europe's battery supply chain faces hurdles on path to self-sufficiency,” November 2024.
61. Ibid.
62. Reuters, ”Exclusive: Trump's transition team aims to kill Biden EV tax credit,” November 2024.
63. S&P Global, Europe's battery supply chain.
64. BloombergNEF, “Lithium-ion battery pack prices hit record low of $139/kWh,” November 2023.
65. The Wall Street Journal, “These Tesla wannabes are running out of road,” December 2023.
66. IEA, EU Sustainable Batteries Regulation, September 2024.
67. Reuters, “European battery maker ACC partners with Circulor to map supply chain, carbon emissions,” January 2024.
68. Rockwell Automation Website, “Rockwell automation teams up with Circulor to enhance supply chain traceability for auto, tire, and battery industries,” October 2024.
69. Earth.org, “The environmental impacts of cobalt mining in Congo,” March 2023.
70. Batteries International, “Battery supply chain breaks labour laws,” September 2024.
71. Atomic Energy and Alternative Energies Commission, “Modernization of European Battery Regulations,” July 2020.
72. European Commission, “Batteries,” accessed February 2025.
73. Compliance Gate, “Battery producer responsibility in the EU: A practical guide,” September 2024.
74. Ibid.
75. European Commission, “Questions and answers on sustainable batteries regulation,” December 2020.
76. Electrive, “Battery reuse & recycling expand to scale in China,” January 2024.
77. Forbes, “Electric car batteries lasting longer than predicted delays recycling programs,” August 2022.
78. Ecobat, “Recycling,” accessed February 2025.
79. Eurostat, “Waste statistics - recycling of batteries and accumulators,” November 2024.
80. TechCrunch, “How generative AI is creeping into EV battery development,” October 2023.
81. Autoweek, “Battery plant scrap rates can hit 90% at ramp up, but the situation is improving,” February 2024.
82. Bosch Solutions, “Software and services: Battery in the cloud,” November 2024.
83. Technology Networks, “Digital twin technology drives major improvements in battery efficiency and cost,” September 2024.

84. SES website, Software, Avatar, November 2024.
85. Volkswagen, "PowerCo SE and the University of Münster sign cooperation agreement," press release, May 2024.
86. StoreDot, "Why upskilling future talent is vital for a seamless transition to sustainable mobility," February 2023.
87. EDLB, "Drum School," accessed February 2025.
88. Verkor, "Verkor and 11 partners launch the 'École de la Batterie'," August 2022.
89. Grenoble INP - Phelma, UGA, "Drum School," accessed February 2025.
90. IEA, Electricity Mid-Year Update, July 2024.
91. European Commission, "Circular economy: New law on more sustainable, circular and safe batteries enters into force," August 2023.
92. Tesla, "Supercharging Other EVs," accessed February 2025.
93. Automotive Dive, "Rivian to open its charging network to all EV drivers," December 2024.
94. F&L Asia, "China issues three national standards for electric vehicles and their batteries," May 2020.
95. Reuters, "China proposes further export curbs on battery, critical minerals tech," January 2025.

Authors

Meet the experts

Pierre Bagnon
Executive Vice-President, Global Head of Intelligent Industry Accelerator, Capgemini
pierre.bagnon@capgemini.com

Pierre is Executive Vice President at Capgemini, heading Intelligent Industry for the group. He focuses on digital and sustainable transformation, entailing intelligent operations, intelligent product and services and digital continuity, with a particular focus in the Manufacturing and Automotive sectors. With more than 10 years of experience in advanced manufacturing, Pierre is a global subject matter expert for Smart factory and Industrial ramp-up.

James Forrest
Executive Vice President, Global Energy Transition & Utilities Industry Leader, Capgemini
james.forrest@capgemini.com

James has spent over 28 years consulting to the utility industries. James has a range of experience in the electricity and gas sectors and he specializes in climate change and energy transition; business transformation under the reform of water, gas and electricity markets; wholesale market structure, design and implementation in competitive electricity and gas sectors, including energy trading processes and systems; and major software and infrastructure transformations for utilities. James is also a Board Member of the Institute of Water.

Laurence Noël
Executive Vice President, Head of Global Automotive Industry, Capgemini
laurence.noel@capgemini.com

Laurence Noël is a distinguished professional with a robust background in the automotive industry. She has more than 25 years of experience and leadership and was previously Senior Vice President of the Circular Economy Business Unit at Stellantis. Leveraging a diverse background across management of business units, strategic planning and engineering, Laurence empowers clients to shape profitable and successful strategies, achieve transformation, and meet automotive sustainability goals.

Vincent Charpiot
Executive Vice President, Head of Group Sustainability Business Accelerator, Capgemini
vincent.charpiot@capgemini.com

Based in New York, Vincent has over 25 years of experience supporting global organizations across industries on their digital transformations and more recently, on their sustainability journeys as Capgemini Group Sustainability Business Accelerator head since 2023. His passion is to help companies leverage innovative digital and engineering solutions to deliver sustainable and business outcomes.

Authors

Meet the experts

Florent Andrillon
Executive Vice President, Global Head Climate Tech, Capgemini
florent.andrillon@capgemini.com

Florent Andrillon is the Climate Tech Global Leader at Capgemini, where he drives strategy and business development across sustainability and intelligent industry teams. With over two decades of experience in the energy and utilities sector, he helps businesses navigate their sustainability journeys and transition to a low-carbon economy.

Richard Biagioni
Vice President, Climate Tech, Capgemini
richard.biagioni@capgemini.com

Richard is part of the Global Climate Tech team at Capgemini, where he focuses on gigafactories and battery industry. With 12+ years of experience in the battery industry he accompanies the cells manufacturers and the battery industry in their strategies, business models, fundraising, start of production and ramp-up. Before joining Capgemini Richard was CEO France and member of the Executive Board of InnoEnergy, working with multiple battery players and was part of the creation of the European Battery Alliance.

Lv Zhongqi
Client Partner of BMW and CATL, China, Capgemini
zhongqi.lv@capgemini.com

With over 20 years of consulting and implementation experience in the automotive industry, Lv is well-versed in SAP, production planning, and logistics, with a focus on electrification and intelligentization in China's automotive sector.

Michael Müller
Senior Director, Head of Battery, Capgemini Engineering
michael.c.mueller@capgemini.com

As Head of Battery, Michael Müller is responsible for Capgemini's business and portfolio development in the areas of battery cell and system development, the production value chain and the optimization of battery systems in operation. Michael brings expertise in battery development, battery production and digital transformation from his more than 10 years of experience as an advisor in the industry.

Authors

Meet the experts

Pierre-Etienne Bougon
Director - Energy Transition & Utilities,
Capgemini Invent
peter.king@capgemini.com

Pierre-Etienne has over 15 years of experience in the energy sector, in transformation and business development roles. He plays a pivotal role within Capgemini Gigafactory practice, where he assists battery manufacturing companies in building and ramping up their assets in France.

Rajendra Negi
Senior Manager - Battery Center of Excellence,
Capgemini Engineering
rajendra.negi@capgemini.com

Rajendra Negi is Senior Manager at the CoE Battery of Capgemini Engineering. He has over 8 years of experience in the battery industry, with roles in research, engineering and business development fields. He supports companies across the battery value chain on a strategic and technical level, with a particular focus on battery production and battery materials.

Authors

Meet the Capgemini Research Institute

Jerome Buvat
Head of the Capgemini Research Institute
jerome.buvat@capgemini.com

Jerome is the head of the Capgemini Research Institute. He works closely with industry leaders and academics to help organizations understand the business impact of emerging technologies.

Subrahmanyam KVJ
Senior Director,
Capgemini Research Institute
subrahmanyam.kvj@capgemini.com

Subrahmanyam is a director at the Capgemini Research Institute. He loves exploring the impact of technology on business and consumer behavior across industries in a world being eaten by software.

Sumit Cherian
Program Manager,
Capgemini Research Institute
sumit.cherian@capgemini.com

Sumit is a Program Manager at the Capgemini Research Institute. He is an avid follower of how technology innovations disrupt the business landscape and works with industry leaders to help organizations understand the impact of technology innovations.

Vaishnavee Ananth
Senior Consultant,
Capgemini Research Institute
vaishnavee.a@capgemini.com

Vaishnavee is a senior consultant at the Capgemini Research Institute. She works closely with industry leaders and academics to inform clients about the impact of emerging technologies and evolving consumer behavior on their businesses and society.

Contributors

Praveen Cherian
Executive Vice President, Global Automotive Industry, Capgemini
praveen.cherian@capgemini.com

Praveen Cherian has over two decades of experience in the automotive and electrification industries. Previously, he held leadership roles including Global CTO of EV and Battery solutions - Cox Automotive, EVP of Operations at Canoo, and VP of Engineering at ELMS. He has also led significant growth and localization efforts in China as part of Changan Ford's senior leadership.

Jean-Marie LAPEYRE
Executive Vice-President, Chief Technology and Innovation Officer, Global Automotive Industry, Capgemini
jean-marie.lapeyre@capgemini.com

Jean-Marie initiated his career in the industry as CTO of the French Tax Authority. He held senior positions with GM and PSA. He is now an architect of Capgemini's Software-Defined Transformation in the Automotive Industry.

Emmanuelle Bischoffe-Cluzel
Vice President, Sustainability Lead, Global Automotive Industry, Capgemini
emmanuelle.bischoffe-cluzel@capgemini.com

Emmanuelle helps OEMs to define and realize sustainability ambitions. Emmanuelle spent 28 years with a global automaker and two with a tier 1 supplier of green steel and aluminum automotive products, as head of automotive business. She gained four patents for inventions to improve engine assembly, including the use of aluminum components.

Peter King
Vice President, Global Head of Energy Transition and Utilities, Capgemini Invent
peter.king@capgemini.com

Peter King heads the Global Energy and Utilities sector for Capgemini Invent, focusing on new business models, transformational programs and digital platforms across Europe, APAC, and North America. Peter has over 30 years of experience and has held significant roles at Ernst and Young, PwC Consulting, and Arthur Andersen. He also serves as the lead editor of the annual World Energy Markets Observatory Report.

Contributors

Sam Baker
Manufacturing and Operations practice lead, North America, Capgemini Engineering
sam.baker@capgemini.com

Sam leads all go to market engineering initiatives in battery technology in North America. He has hands-on design and manufacturing expertise in mobile handsets, telecom network equipment, and semiconductor fabrication plants including related software applications and operating systems. He has over 25 years of experience in leading professional consulting services, sales, and marketing engagements globally. Prior to Capgemini, he held multiple leadership positions as Partner and Managing Director at Accenture, IBM, and Samsung Electronics.

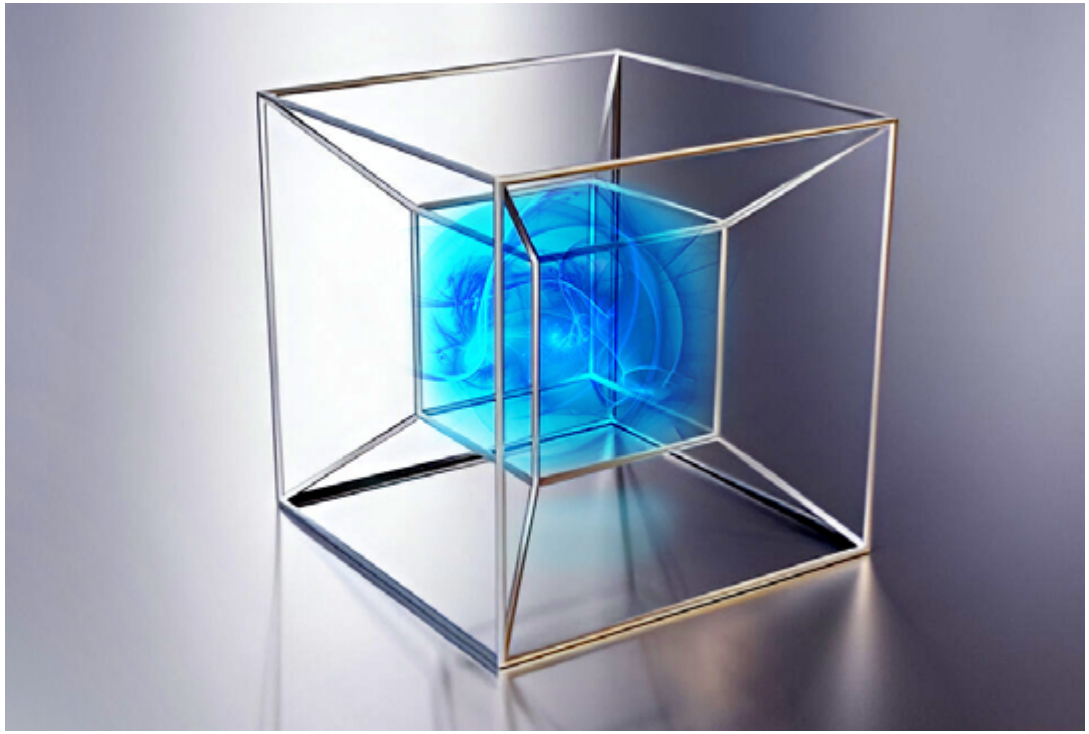
Carlos Naranjo Gonzalez
Manager, Battery Center of Excellence, Capgemini Engineering
carlos.naranjo-gonzalez@capgemini.com

Carlos Naranjo is Manager at the CoE Battery of Capgemini Engineering. He has over 5 years of experience in strategic and engineering projects in the battery industry. He focuses on supporting battery producers and recyclers to plan, build and ramp-up their plants.

Fei Wang
fei.c.wang@capgemini.com

Yao Zhang
yao.b.zhang@capgemini.com

Philippe Ravix
philippe.ravix@capgemini.com



The contributors would like to especially thank Meenakshi Malik from the Capgemini Research Institute for her contributions to the research.

The contributors would also like to thank Laurent Bromet, Patrick Sitek, Sergey Patsko, Arne Roßmann, Christian Völl, Shekhar Burande, Vamshi Rachakonda, Khalid Sebti, Elfije Lemaitre, Franco Amalfi, Julian van Velzen, Salomon Salinas, Victoria Pascal, Roshan Batheri, Nicolas Jeandat, Carl Haigney, Mike Lewis, Melanie Bertiaux, Siren Sundby, Scott Farr, Daniel Borenstein, Mercy Paul, Gustavo Rossi Vilela Dias, Ferdinand Siegert, Marc Schmid, Dominik Nostadt, Alexandra Werner, Hariharan Krishnamurthy, Alyzee Lepeltier, Denis Fortmann, Robert Morasche, Elizabeth Lugnier, Anthony DeMarco, Emmanuel Lochon, Lucy Colling, Ruth-Ann Peters, Punam Chavan, Manish Saha, Amitabha Dutta and Mithun Dutta for their contributions to the research.

About the Capgemini Research Institute

The Capgemini Research Institute is Capgemini's in-house think tank on all things digital. The Institute publishes research on the impact of digital technologies on large traditional businesses. The team draws on the worldwide network of Capgemini experts and works closely with academic and technology partners. The Institute has dedicated research centers in India, Singapore, the UK, and the US. It was recently ranked number one in the world by independent analysts for the quality of its research.

Visit us at www.capgemini.com/researchinstitute/

For more information, please contact:

Global
Pierre Bagnon
pierre.bagnon@capgemini.com

Florent Andrillon
florent.andrillon@capgemini.com

James Forrest
james.forrest@capgemini.com

Emmanuelle Bischoffe-Cluzel
emmanuelle.bischoffe-cluzel@capgemini.com

Laurence Noel
laurence.noel@capgemini.com

Richard Biagioni
richard.biagioni@capgemini.com

Laurent Bromet
laurent.bromet@capgemini.com

Anthony DeMarco
anthony.demarco@capgemini.com

Vincent Charpiot
vincent.charpiot@capgemini.com

Regional

Germany
Michael Müller
michael.c.mueller@capgemini.com

Carlos Naranjo-Gonzalez
carlos.naranjo-gonzalez@capgemini.com

Patrick Sitek
patrick.sitek@capgemini.com

France
Hubert Clément
hubert.clement@capgemini.com

Philippe Ravix
philippe.ravix@capgemini.com

Manuel Chareyre
manuel.a.chareyre@capgemini.com

Pierre-Etienne Bougon
pierre-etienne.bougon@capgemini.com

North America
Mark Landry
mark.landry@capgemini.com

Sam Baker
sam.baker@capgemini.com

Seth Vogel
seth.vogel@capgemini.com

Alison Thurber
alison.thurber@capgemini.com

Scott Farr
scott.farr@capgemini.com

Norway
Siren Sundby
siren.sundby@capgemini.com

Sweden
Fredrick Gunnarson
fredrik.gunnarsson@capgemini.com

China
Chu Yan
yan.chu@capgemini.com

Lv Zhongqi
zhongqi.lv@capgemini.com

Zhang Yao
yao.b.zhang@capgemini.com

Huu Hoi Tran
huu-hoi.tran@capgemini.com

WEI SONG
wei.a.song@capgemini.com

Accelerate your journey to the gigafactory of the future

The automotive industry is transitioning to electric vehicle battery production at scale, and innovating for efficiency, sustainability, and rapid growth is more crucial than ever.

Battery manufacturers are all racing to increase speed to production, speed to market, and speed to revenue. However, building a gigafactory with successful and profitable battery production requires advanced technologies and processes that can offset production costs, reduce total cost of ownership (TOC), and ultimately accelerate EV adoption.

Capgemini is helping organizations build gigafactories from pilot to production. In a race where time is of the essence, our accelerated solutions environment (ASE) workshops can fast-track your progress.

As a trusted advisor and pioneer in the battery industry, we can be your guide, providing expertise around our proven capabilities:

- Digital Core and Industrial Data Platform: Implementing end-to-end optimized business processes such as ERP, MES, and MOM, leading to a hyper-efficient gigafactory.
- Capgemini Battery Academy: A comprehensive approach for talent acquisition, onboarding, training, and certifying employees, to provide a timely production kick-off
- Sustainable supply chain and operations: From raw material procurement, traceability, and regulatory compliance to circular economy practices, we help prioritize sustainability at every step. We can help your organization engineer secure, sustainable, and resilient gigafactory supply chains, while emphasizing recycling and reducing the carbon footprint.

Capgemini is playing a key role in the battery industry

We cofounded the European battery alliance with InnoEnergy, bringing together more than 800 industrials and innovation actors. Together with key research institutions and industrial partners, we have developed a first-of-its-kind Technology Cluster Battery Cell to drive innovation in the domain. We deliver powerful impact to gigafactory players, from strategic design, R&D, and pilot line to gigafactory ramp-up.

For more information:

Visit: https://www.capgemini.com/solutions/accelerate-your-journey-to-the-gigafactory-of-the-future/

Ascendance and Capgemini talk battery strategy

Is the aviation industry ready for onboard batteries?

Capgemini - Electrification is seen by many industries as the root to carbon emission reduction, and aviation is no exception. Improved battery performance and decreasing costs make electrification a promising solution for achieving net-zero emissions.

Some of the challenges to battery adoption in aviation are similar to other sectors, such as: ensuring the battery industrial eco-system is itself sustainable, and cost-effective. However, aviation faces some unique challenges around design and safety, aircraft weight being a key driver for performance, and its confined environment allowing limited mitigation options compared to ground transport.

How do batteries fit into Ascendance's product strategy?

Ascendance - The battery is a major element in our technological positioning. The increase in performance over the last few decades means that batteries can be considered as a source of propulsive energy for aircraft, without being the only solution. Our conviction since the creation of Ascendance and our strategy are based on the hybridization of the propulsion system, an electric/thermal mix, which makes it possible to cover a regional range (400 km) while reducing the carbon impact by 80%. The battery represents a significant portion of the aircraft's operational cost as it is needs to be replaced regularly to ensure optimal and safe performance. Therefore, we are fully focused on the challenges of industrialization and certification, the highlights of which are the crashworthiness of batteries which is a major challenge and differentiating factor to existing propulsive battery technologies in other industries as well as cost effective weight mitigation technologies to ensure that the battery is as light as possible while keeping costs increase to a minimum.

How is Ascendance finding the right battery strategy?

Capgemini- To date, Ascendance is converging its battery strategy - and that's an area where Capgemini is working with them. Together we are comparing cell suppliers, analyzing the components and actors in the value chain, and developing scenarios for the verticalization of battery industrialization. Decisions on these factors will inform Ascendance's battery technology strategy and underpins their overall technology positioning.

More Capgemini Research Institute publications

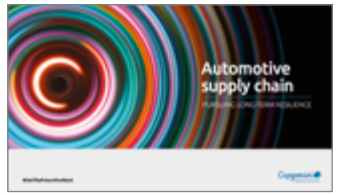
The resurgence of manufacturing: Reindustrialization strategies in Europe and the US

Data-powered enterprises: The path to data mastery

Harnessing the value of generative AI: Top use cases across sectors (Second edition)

Joining the race: Automotive's drive to catch up with customer experience

A world in balance 2024: Accelerating sustainability amidst geopolitical challenges



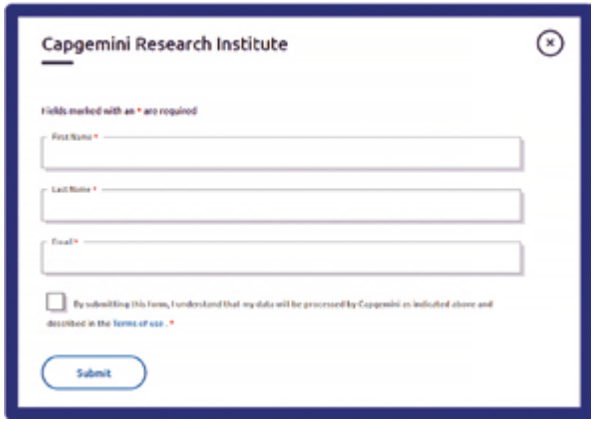
Automotive supply chain: Pursuing long-term resilience

Sustainability in automotive: from ambition to action

Low-carbon hydrogen: A path to a greener future

Subscribe to latest research from the Capgemini Research Institute

Receive copies of our reports by scanning the QR code or visiting https://www.capgemini.com/capgemini-research-institute-subscription/



Notes

Notes

About Capgemini

Capgemini is a global business and technology transformation partner, helping organizations to accelerate their dual transition to a digital and sustainable world, while creating tangible impact for enterprises and society. It is a responsible and diverse group of 340,000 team members in more than 50 countries. With its strong over 55-year heritage, Capgemini is trusted by its clients to unlock the value of technology to address the entire breadth of their business needs. It delivers end-to-end services and solutions leveraging strengths from strategy and design to engineering, all fueled by its market leading capabilities in AI, generative AI, cloud and data, combined with its deep industry expertise and partner ecosystem. The Group reported 2024 global revenues of €22.1 billion.

Get the Future You Want | **www.capgemini.com**

Copyright © 2025 Capgemini. All rights reserved.