

Workforce Competency Development in High-Tech Manufacturing

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Abstract

The United States is rapidly expanding domestic capacity for advanced battery manufacturing to support electric vehicles, stationary energy storage, and national security objectives. Industrial growth is outpacing the development of a workforce capable of delivering safe operations, high yields, and compliant, value-driven projects. The analysis identifies competency gaps among project managers and engineers in large battery programs and proposes a competency framework aligned with Project Management Institute (PMI) guidelines and standards, including the PMI Talent Triangle. Evidence synthesized from the U.S. Department of Energy's Battery Workforce Initiative, the United States Energy and Employment Report, Li-Bridge's supply-chain roadmap, National Renewable Energy Laboratory mapping, and evolving domestic-content guidance informs practical pathways for training, governance, and measurement. An implementation blueprint for regional partnerships across the emerging battery belt translates public policy and private investment into line-ready skills, measurable operating performance, and durable competitive advantage.

Keywords

Advanced Battery Manufacturing, Project Management Competencies, Talent Triangle, Workforce Development, Battery Workforce Initiative, Domestic Content

1. Introduction

The United States is accelerating the buildout of domestic capacity for advanced battery production to support transportation electrification, grid modernization, and strategic resilience across critical supply chains. Federal incentives have catalyzed private investment, and procurement and tax guidance has encouraged the use of domestically sourced materials and components. As a result, batteries have

moved from a specialized niche to a national priority that shapes industrial competitiveness, regional development, and workforce planning. Momentum is evident in announcements of new facilities, upgrades to existing plants, and parallel efforts to strengthen upstream materials processing and downstream reuse and recycling.

As projects advance from groundbreaking to commissioning and ramp-up, a limiting factor has become clear. The supply of workers with integrated competencies for safe operations, stable yields, and reliable compliance has not grown at the same pace as capital deployment. Employers report shortages of engineers, technicians, and project managers who can master battery manufacturing processes, contamination control in dry rooms, formation and testing requirements, and battery management systems. They also cite a need for stronger digital proficiency with automation and manufacturing information systems, combined with interpersonal skills that support cross functional coordination and effective stakeholder engagement. Without focused development, these gaps lengthen learning curves, elevate scrap, and delay the realization of financial and policy benefits.

Public agencies and industry have begun to respond through coordinated programs that connect training supply to operational demand. The Battery Workforce Initiative is developing industry recognized models and credentials, with pilot programs that link government, manufacturers, organized labor, and education providers (U.S. Department of Energy, National Energy Technology Laboratory, 2024). The aim is to replace fragmented approaches with a national architecture that supports portability, quality, and scale, while leaving room for regional customization and employer specific requirements. States are complementing these efforts by expanding technical pathways, pre-hire bootcamps, and hands-on labs that can be deployed before living operations, so teams arrive at start up with baseline safety knowledge, process discipline, and a shared vocabulary for quality and continuous improvement.

2. Methodology

This study uses a qualitative integrative analysis combining a structured literature review, synthesis of industry workforce datasets, and examination of policy guidance affecting battery manufacturing labor demand. The literature review covered articles, government reports, and industry analyses published between 2018 and 2025. Sources were identified through Google Scholar, Scopus, the U.S. Department of Energy technical library, and workforce research repositories. Materials were included when they addressed workforce competencies, advanced manufacturing, battery supply-chain development, or project delivery frameworks.

This approach reflects an integrative analysis that draws on multiple research streams to create a coherent understanding of sector-wide workforce challenges. Its value lies in the synthesis of diverse evidence, the development of a structured competency framework, and the alignment of policy guidance with practical strategies that support the growth and resilience of domestic battery manufacturing.

3. Context and Background

3.1. Industrial Trajectory and Policy Environment

Domestic battery manufacturing is expanding rapidly as electric vehicle adoption grows and grid storage projects scale. Analysts highlight the continued concentration of upstream materials processing and cell production in Asia, particularly China, which maintains significant dominance in the global battery supply chain. This concentration presents strategic risks for the United States as documented in federal assessments of domestic manufacturing policy and supply chain vulnerability (Congressional Research Service, 2025; U.S. Department of Energy, 2024). Recent legislation, including the Infrastructure Investment and Jobs Act and the Inflation Reduction Act, seeks to strengthen domestic capacity through incentives that support United States based production and processing operations (Congressional Research Service, 2025).

Federal agencies have issued guidance to clarify pathways for manufacturers and project developers to qualify for domestic content incentives (U.S. Department of the Treasury & Internal Revenue Service, 2025). Safe harbor methods from the United States Department of the Treasury and the Internal Revenue Service simplify cost percentage calculations for manufactured products, while supplemental materials from the United States Department of Energy provide interpretive resources for assessing eligibility and planning documentation activities (U.S. Department of Energy, 2024). These instruments translate policy objectives into operational requirements, which means teams must build competencies in procurement, cost analysis, and records management to avoid delays and secure available benefits.

National workforce data also indicates favorable labor conditions. The United States energy sector continues to add jobs, particularly in clean energy roles, and multiple studies predict sustained hiring demand driven by domestic manufacturing growth and supply chain investments (Steimer, Bui, & Xie, 2026). This growth trajectory suggests strong capacity to absorb new entrants and upskilled workers if training programs remain aligned with evolving employer requirements (OECD, 2024).

3.2. The Persistent Workforce Competency Gap

Despite these favorable policy and employment conditions, many firms report difficulty recruiting and retaining workers with the competencies required for high volume and high yield battery manufacturing. A comprehensive workforce assessment coordinated by Argonne National Laboratory documented widespread shortages across the North American battery supply chain. In this assessment, 82 percent of respondents reported shortages of skilled local applicants, and the most acute deficits appeared in upstream organizations, followed by downstream and complementary sectors (Krusemark, 2024). The Battery Industry Education and Training Needs Assessment (BIETNA) further quantified gaps across the talent pipeline, identifying critical shortages in electrochemistry, battery chemistry, ma-

materials science, mining, electrical and power electronics, software and battery management systems, system design, prototyping, battery testing, and safety, including electrical, fire, and hazardous materials competencies (Krusemark, 2024).

These findings align with data analyzed by the Center for Automotive Research (CAR). In a national survey of 158 stakeholders, CAR reported significant skills gaps across engineering, technician, and assembler roles, with more than 80 percent of respondents indicating shortages of skilled local candidates. The CAR study noted that engineering and general technical roles were in the shortest supply, followed by specialized roles in battery engineering, manufacturing engineering, and electrical engineering (Center for Automotive Research, 2024). Additional gaps emerged in battery management systems, product and system design, and in competencies required for scaling the workforce to meet projected sixfold growth in lithium battery demand by 2030. The report emphasized that recruitment challenges are compounded by limited education and training pathways, uneven regional capacity for workforce development, and the rapidly changing technical content that accompanies new chemistries and advanced manufacturing approaches.

Figure 1 below illustrates the Top Ten Jobs with the Highest Supply Shortage, as reported by HR personnel and recruiters across the battery sector. These roles represent positions for which demand consistently exceeds supply, often resulting in extended hiring cycles and elevated turnover risk.

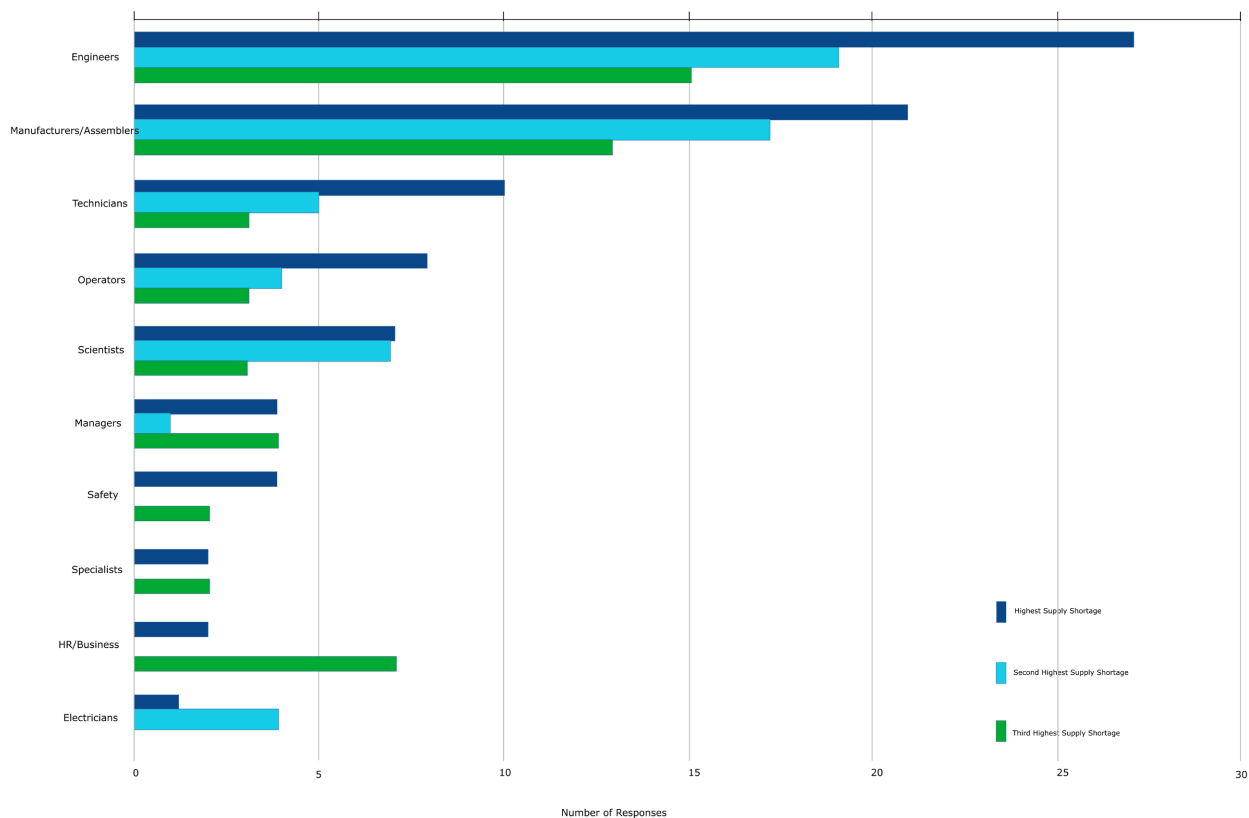


Figure 1. Top ten jobs with the highest supply shortage. Source: Center for automotive research (CAR).

Taken together, these data indicate that the battery industry faces a structural and persistent workforce competency gap, rather than a temporary labor imbalance linked to cyclical economic factors. Without targeted actions to expand training capacity, modernize curricula, strengthen regional workforce ecosystems, and integrate digital and interdisciplinary competencies, capital investments in new manufacturing facilities may not translate into stable operations, predictable yields, or competitive cost structures. These findings reinforce the urgency of coordinated workforce planning, deeper partnerships with educational institutions, and continuous upskilling strategies across the battery supply chain to ensure that human capital evolves at the same pace as technological advancement.

3.3. The Role of Project Management Skills in Battery Projects

Battery facilities combine large scale capital investments with complex operational learning curves, which makes project management competencies essential across development and operations. Construction and equipment installation typically rely on predictive planning methods that support schedule integration, contractor coordination, and interface control among civil, mechanical, and electrical work. As facilities transition into commissioning and process stabilization, project teams often employ adaptive or hybrid approaches that facilitate iterative improvement, rapid issue resolution, and alignment among engineering, operations, and quality functions. Digital system integration, including manufacturing execution and data platforms, requires repeated cycles of testing, adjustment, and verification.

Across these phases, project management skills such as risk analysis, schedule and change control, stakeholder communication, and cross functional coordination enable teams to manage technical uncertainty, regulatory requirements, and supply chain dependencies. These capabilities help ensure effective execution during permitting activities, documentation for domestic content compliance, supplier qualification, and early production ramp up.

A range of competency frameworks are used in industry to organize these capabilities. Among them, the PMI Talent Triangle is one example of a structured model that categorizes project management skills into Ways of Working, Power Skills, and Business Acumen. This framework provides a practical structure for conceptualizing capability development and role expectations, although it represents only one approach within the broader landscape of project management methodologies (Project Management Institute, 2025a). Importantly, referencing such frameworks does not imply endorsement of any model, but rather illustrates the types of multidimensional skill sets increasingly recognized as necessary for complex industrial programs.

Evidence also suggests that project management roles are part of a broader skills gap in the United States. The Global Project Management Talent Gap Report indicates that up to 30 million additional project professionals will be needed worldwide by 2035, with mature economies such as North America experiencing stalled

supply due to aging demographics and limited inflow of new entrants (Project Management Institute, 2025b). This aligns with national labor data showing sustained demand for project management specialists. The U.S. Bureau of Labor Statistics projects a 6 percent growth rate for project management specialists from 2024 to 2034, with 78,200 job openings per year, and notes that employers continue to struggle to find qualified candidates to meet this demand (U.S. Bureau of Labor Statistics, 2025). These trends, combined with evidence of shortages across technical and interdisciplinary roles in the battery sector, suggest that project management competencies form part of the broader workforce gaps affecting advanced manufacturing.

3.4. Supply-Chain Transparency and Its Impact on Skills

Supply chain transparency has become a critical factor in the development of a resilient North American battery ecosystem, and recent federal and industry analyses provide detailed insight into where workforce competencies will be most urgently needed. The National Renewable Energy Laboratory, working with NAAT-Batt International, maintains a comprehensive database that maps companies involved in mining, materials processing, electrode production, cell and pack manufacturing, equipment supply, end of life management, and recycling across North America (Putsche et al., 2023). This database, updated through 2025, highlights the concentration of activity in certain segments such as pack assembly and recycling, while revealing significant gaps in upstream materials processing and component manufacturing capacity (Putsche et al., 2023; NAATBatt, 2025). Identifying these gaps is essential for workforce planning because upstream segments depend heavily on specialized competencies in materials science, chemical processing, quality assurance, and equipment engineering.

These findings align with additional analyses conducted by the U.S. Department of Energy in its 2024 Four Year Review of the Advanced Battery Sector. The DOE reported that despite more than 100,000 jobs created through approximately 50 billion dollars of federal and private investment in the domestic battery supply chain, buildout remains constrained by structural challenges including production cost disadvantages, dependence on imported materials, and limited domestic capacity in critical processing steps (U.S. Department of Energy, 2024). The review further noted that manufacturing capacity is expected to exceed 1,100 gigawatt hours per year, but this expansion is threatened by bottlenecks in precursor materials, cathode and anode component production, and specialized workforce availability (U.S. Department of Energy, 2024). These constraints indicate that workforce shortages in technical, regulatory, and compliance roles may impede national targets for supply chain localization.

Moreover, industry surveys emphasize that transparency tools are not merely informational but operationally necessary. For example, NAATBatt's complementary analyses show that upstream deficits are most acute in chemical engineering, battery materials processing, and advanced equipment development, while down-

stream gaps center on recycling operations and end of life logistics (NAATBatt, 2025). These patterns reinforce the view that supply chain transparency identifies where targeted skill development is required, particularly in roles such as engineers, compliance specialists, industrial automation technicians, and recycling systems operators.

4. Competency Framework for Battery Manufacturing Projects

Developing large scale battery manufacturing facilities requires a competency architecture that integrates project management, engineering and operations, and cross cutting organizational capabilities. Rather than relying on a single professional standard, such architectures benefit from insights across the academic literature on project management and engineering competence. Studies consistently highlight that effective performance in complex industrial settings demands a blend of technical, behavioral, and contextual competencies (Rezende & Blackwell, 2019). This layered approach supports clearer role expectations, aligns training with lifecycle milestones, and links competency development to operational outcomes such as safety, equipment readiness, process stability, yield, and regulatory compliance.

4.1. Project Management Competencies

Academic research shows that project management in technologically intensive environments requires multidimensional competencies that extend well beyond procedural methods. Systematic reviews find that interpersonal and cognitive skills such as leadership, communication, emotional intelligence, adaptability, and systems thinking consistently predict project outcomes across sectors, particularly in complex industrial settings where uncertainty and rapid change are common (Ochoa Pacheco et al., 2023). These findings mirror the growing industry demand for project managers who can mediate technical, organizational, and social dynamics within large scale manufacturing programs.

In battery manufacturing projects, effective lifecycle planning is essential. Construction and equipment installation typically benefit from predictive scheduling methods, while commissioning, process optimization, and digital system deployment require adaptive or hybrid approaches to manage evolving risks. Evidence from engineering project literature shows that tailoring lifecycle strategies to the maturity and volatility of each phase improves responsiveness and reduces disruptions during line trials and early production (Rastovski et al., 2025). As a result, organizations increasingly seek project professionals who can navigate multiple methodological approaches rather than adhere to a single fixed model.

Responsible project management in this sector also requires the ability to integrate environmental, social, and community considerations into project objectives and risk frameworks. Peer reviewed studies highlight the importance of systems thinking and stewardship in projects with significant societal and ecological

footprints, noting that sustainability related competencies contribute to stakeholder trust, compliance readiness, and long-term project viability (Salimimoghadam et al., 2025). In battery manufacturing, this translates into competencies for incorporating metrics related to energy intensity, waste, recycling pathways, and labor engagement into planning and decision making.

Regulatory and supply chain driven competencies have also become central. Domestic content rules, documentation requirements, and audit pathways introduce compliance related constraints that directly affect project incentives, schedule risk, and supplier qualification activities. Academic research on project competency frameworks emphasizes the need for contextual and governance related capabilities, noting that project managers must understand how regulatory conditions shape strategy, sequencing, and resource allocation (Rezende & Blackwell, 2019). Fluency with digital project information systems also supports integrated reporting on cost, schedule, quality, readiness, and training, main reason for these capabilities to be increasingly required in highly automated battery facilities.

Interpersonal and relational skills remain critical. Systematic reviews find that leadership, communication, and stakeholder coordination strongly influence project success in environments with diverse partners and high interdependence (Salimimoghadam et al., 2025). Battery projects routinely involve owners, joint venture partners, equipment manufacturers, labor organizations, community groups, and regulators, making collaborative leadership and negotiation skills essential for decision alignment and issue resolution.

Taken together, academic literature and industry demand trends show that project managers in battery manufacturing require a combination of technical, regulatory, strategic, and interpersonal competencies. While various frameworks exist, the PMI Talent Triangle is one example that organizes many of these widely recognized requirements into a structured competency model. It reflects, rather than dictates, the multidimensional skill sets that research and industry analyses identify as essential for effective project delivery in advanced manufacturing contexts (Project Management Institute, n.d.).

4.2. Engineering and Operations Competencies

Engineering and operations roles in battery manufacturing require a blend of specialized technical knowledge and broader professional competencies. Peer reviewed analyses of engineering competency frameworks emphasize that effective performance depends on both domain expertise and non-technical skills such as information literacy, cross-disciplinary communication, and the ability to work within complex socio-technical systems (Richter, 2025). Within battery facilities, these demands translate into deep understanding of cathode and anode chemistry, moisture and contamination sensitivity, the dynamics of slurry mixing and coating, equipment calibration methodologies, and the formation and aging processes that ultimately determine cell performance.

Industry assessments consistently report shortages in capabilities related to bat-

tery management systems, end-of-line diagnostics, and safety protocols for thermal propagation and hazardous materials handling. These gaps align with findings from systematic reviews that identify insufficient technical competency as a contributor to ramp-up delays, process variability, and increased operational risk (Ochoa Pacheco et al., 2023). Plants lacking these skills tend to experience extended periods of yield volatility and higher defect-related costs during scale-up.

Digital literacy has become equally critical. Engineering education literature highlights the rising importance of robotics, automation, and cyber-physical systems in advanced manufacturing environments (Richter & Kjellgren, 2025). For battery production, engineers must work effectively with manufacturing execution systems and supervisory control and data acquisition platforms, interpret real-time quality and process data, and apply cybersecurity principles that protect automated lines from integrity breaches. These capabilities support system interoperability and enhance the reliability of high-throughput production lines, which are essential in gigafactory-scale facilities.

4.3. Cross-Cutting Competencies

Cross cutting competencies integrate project management, engineering, compliance, and organizational culture, enabling battery facilities to meet regulatory, operational, and community expectations. Peer reviewed research on project management competence underscores the importance of ethical awareness, contextual intelligence, and organizational learning in environments where technical and regulatory factors interact (Rezende & Blackwell, 2019). In battery manufacturing, these capabilities support the development of robust environment, health, and safety systems; the implementation of quality frameworks aligned to recognized standards; and the coordination of compliance activities across suppliers, contractors, and internal teams.

Supply chain transparency requirements (including domestic content rules and Foreign Entity of Concern classifications) make regulatory competence central to operational success. Organizations must be able to conduct material traceability, verify supplier classifications, and maintain audit-ready documentation. Academic literature on engineering and project governance highlights that such contextual competencies are essential in domains where policy incentives, technical risk, and supply chain dependencies intersect (Ochoa Pacheco et al., 2023). The ability to document, defend, and continuously update compliance determinations is critical, as incentive eligibility and market positioning increasingly depend on rigorous evidence of sourcing and production practices.

Cross cutting competencies also include cultural and organizational skills that support collaboration and workforce development. Studies on engineering and project leadership show that supportive cultures, effective communication practices, and systems enabling rapid learning to contribute to improved performance in complex industrial environments (Salimimoghadam et al., 2025). In battery manufacturing, these competencies help organizations manage rapid scale up, in-

tegrate new technologies, and build trust with employees, communities, and regulatory bodies.

The competency framework outlined above establishes the foundational capabilities required for effective performance in advanced battery manufacturing environments. These competencies span project management, engineering, operations, compliance, and cross-functional collaboration, reflecting the multifaceted demands placed on modern battery facilities. To translate this framework into actionable workforce strategies, it is necessary to organize these capabilities into a structured skills taxonomy that differentiates role-specific learning requirements while enabling coordinated development across job families. This taxonomy provides the bridge between conceptual competency expectations and the practical design of training pathways, which is the focus of the next section.

5. Evidence of the Competency Gap and Its Consequences

Multiple data sources converge on the same message: without targeted training and competency validation, battery projects face extended start-up curves, elevated scrap rates, and reduced ability to capture policy incentives.

One of the most consistent findings across manufacturing scale-up studies is the relationship between workforce capability and plant stabilization. Competency gaps in technical, digital, and supervisory roles correlate with longer start-up curves, reduced equipment utilization, and recurrent process interruptions during early production cycles. Facilities lacking adequately trained engineering and operations personnel frequently report extended periods of yield volatility, unplanned downtime linked to improper calibration or contamination events, and higher-than-anticipated scrap rates. These outcomes align with research showing that insufficient technical proficiency is a leading contributor to ramp-up delays and quality deviations in advanced manufacturing environments (Salimi-moghadam et al., 2025).

The consequences extend beyond production metrics. Regulatory and incentive structures place a premium on documentation accuracy, supplier verification, and traceability, meaning that competency gaps in compliance and governance functions can directly affect financial performance. Domestic-content incentives and related guidance introduce complex requirements for cost attribution, supplier data validation, and audit sequencing. Organizations without personnel trained in interpreting safe harbor provisions, conducting bill-of-materials analyses, or maintaining audit-ready documentation may face delays in incentive qualification or risk disallowances that reduce project returns at critical stages of capital expenditure recovery.

Competency gaps also influence supply chain resilience and risk exposure (Allianz Risk Barometer, 2024). As transparency tools identify vulnerabilities in upstream materials processing, component manufacturing, and recycling infrastructure, firms must coordinate technical assessments, supplier development activi-

ties, and multi-tier compliance reviews. Teams lacking the necessary analytical and regulatory skills often report bottlenecks in supplier onboarding, slower responses to quality issues, and increased dependence on a limited set of vendors. These challenges compound project-level risks by constraining options for cost optimization, domestic sourcing, and long-term resilience (Deloitte, 2024; Allianz Risk Barometer, 2024).

At the organizational level, insufficient competencies impede learning processes that are essential in rapidly evolving industrial environments. Studies in engineering and project management consistently show that effective knowledge transfer, structured problem-solving routines, and cross-functional collaboration contribute to faster stabilization and reduced defect recurrence. Where these competencies are underdeveloped, organizations tend to rely on reactive troubleshooting rather than proactive improvement cycles, reinforcing variability and delaying the attainment of steady-state operations.

Taken together, the evidence demonstrates that competency gaps in battery manufacturing are not merely a labor market concern but a central factor shaping project economics, operational reliability, and the ability to capitalize on federal incentives. Targeted training, competency assessment, and workforce development strategies therefore function not as ancillary activities but as critical path elements that determine the success and competitiveness of battery manufacturing investments.

6. Programs and Policy Instruments That Shape Workforce Development

The Battery Workforce Initiative, coordinated by the U.S. Department of Energy with the U.S. Department of Labor and national labor organizations, is charting a sectoral strategy to grow a highly skilled workforce. Its work includes developing National Guideline Standards for key occupations, launching pilot training programs, and promoting industry-recognized credentials that employers can trust. By convening manufacturers, unions, colleges, and training experts, the Initiative aims to standardize the core competencies required for safe, efficient battery operations while preserving room for company-specific tailoring.

State programs can amplify these efforts. Georgia's Quick Start program, one of the nation's longest-running and most highly ranked workforce-training initiatives, provides customized training at no cost to qualified employers through the Technical College System of Georgia. It has delivered tailored pre-hire assessments, simulations, and job-specific instruction for advanced manufacturing firms, including major clean-technology and battery employers such as SK Battery America and Hanwha Qcells, demonstrating how state-level infrastructure can reduce time-to-competency and accelerate operational readiness.

Quick Start's capabilities extend beyond curriculum design. The program operates purpose-built training facilities such as the Georgia Advanced Manufacturing Training Center in Savannah which enable employers to train workers on

state-of-the-art equipment before tools arrive onsite (SEDA, 2025). These centers allow companies to simulate production environments, benchmark operator performance, and refine work instructions ahead of commissioning, significantly compressing the learning curve for new hires.

Quick Start also partners with local technical colleges to extend training beyond startup through contract training and continuous upskilling. By coordinating pre-hire bootcamps, onboarding modules, and ongoing advanced manufacturing coursework, the program provides a talent pipeline that can evolve as firms scale, implement new chemistries, or adopt new process technologies (TCSG, 2025). This integration of state assets, employer needs, and regional education systems illustrates how public-industry partnerships can strengthen long-term workforce resilience in battery manufacturing.

Finally, the United States Energy & Employment Report provides a macro-level context in which to plan regional training capacity and workforce pipelines. Growth in clean-energy employment underscores the need to expand and align pathways from secondary school to apprenticeships and advanced certificates, so that regional labor markets can keep pace with project announcements (U.S. Department of Energy, 2024b).

It's important to highlight that while PMI's Talent Triangle provides a framework for project-oriented competencies, engineering and technician roles require a distinct technical pathway. These include electrochemistry fundamentals, slurry mixing and coating, dry room contamination control, formation and aging processes, automation troubleshooting, and battery management system diagnostics. These technical skills operate in parallel with PMI competencies. Together, they form a dual track development structure necessary for high yield battery manufacturing.

7. Skills Taxonomy and Learning Pathway

A structured skills taxonomy provides a foundation for designing training programs, sequencing learning activities, and ensuring consistent validation of competency across the battery manufacturing lifecycle. To maintain clarity between professional project management competencies and shop-floor technical proficiency, the taxonomy below differentiates project management skills from engineering and technician pathways, recognizing that both are essential but fundamentally distinct domains.

Building on the competency framework described in Section 4, the following skills taxonomy organizes these broad capability areas into clearly defined learning pathways. This structure distinguishes between the professional competencies required for project management and coordination roles and the technical proficiencies needed for engineers and technicians working directly with battery production systems. By translating high-level competencies into role-aligned skill sets, the taxonomy supports curriculum development, training system design, and workforce planning across the manufacturing lifecycle. It also provides a founda-

tion for aligning training investments with operational priorities, ensuring that competency development proceeds in a deliberate and measurable manner.

7.1. Competencies for Project Management and Coordination Roles

7.1.1. Digital Project Information Systems

Project delivery in battery manufacturing increasingly depends on the ability to use digital platforms that link training milestones, competency assessments, and operational indicators such as first-pass yield, overall equipment effectiveness (OEE), scrap ratios, and documentation cycle time. These systems include Product Lifecycle Management platforms, Enterprise Resource Planning tools, Manufacturing Execution Systems, and Supervisory Control and Data Acquisition interfaces. Integrating these tools enables project professionals to understand how workforce readiness influences commissioning performance, operational stability, and the pace of ramp-up.

7.1.2. Ways of Working (Methodological Adaptability)

Project professionals must be able to tailor their delivery approaches across construction, commissioning, and early production. This includes proficiency in planning and scheduling, risk management, requirements traceability, and change control, as well as the ability to integrate cost, schedule, and quality data using digital project systems. These competencies support effective coordination under conditions of evolving technical risk and changing stakeholder requirements—conditions typical of gigafactory development and equipment activation.

7.1.3. Power Skills (Interpersonal Effectiveness)

Fast-moving industrial programs require project professionals who can lead cross-functional teams, facilitate decision-making, and manage conflict constructively. Skills in collaborative leadership, communication, negotiation, and stakeholder engagement are essential when coordinating among owners, joint-venture partners, suppliers, labor organizations, regulators, and community representatives. These interpersonal capabilities help maintain alignment and momentum when technical uncertainty and schedule pressures are high.

7.1.4. Business and Regulatory Literacy

Battery manufacturing projects are shaped by financial constraints, evolving regulatory frameworks, and market dynamics. Project professionals therefore benefit from understanding the economic drivers of energy storage markets, the implications of localization strategies, and the requirements of domestic-content rules and Foreign Entity of Concern regulations. This literacy supports decisions that balance short-term ramp needs with long-term value creation and incentive eligibility.

7.2. Competencies for Project Management and Coordination Roles

Training should include electrochemistry fundamentals; cathode and anode ma-

materials behavior; contamination control and dry-room protocols; and process controls for slurry mixing, coating, drying, calendaring, assembly, and formation. These topics underpin the yield and performance characteristics of lithium-ion cells and are consistently identified in industry surveys as high-priority skill needs during commissioning and ramp.

7.2.1. Materials and Process Foundations

Training should include electrochemistry fundamentals; cathode and anode materials behavior; contamination control and dry-room protocols; and process controls for slurry mixing, coating, drying, calendaring, assembly, and formation. These topics underpin the yield and performance characteristics of lithium-ion cells and are consistently identified in industry surveys as high-priority skill needs during commissioning and ramp.

7.2.2. Automation, Robotics, and Digital Operations

Given the high degree of automation in modern battery plants, engineers and technicians must develop fluency with robotics, automated handling systems, manufacturing execution systems, supervisory control platforms, and data-driven diagnostics. Digital literacy also includes understanding cybersecurity, data integrity constraints, and the integration of information technology with operational technology systems.

7.2.3. Battery Management Systems and Testing

Competency in battery management systems, end-of-line test methods, diagnostic tools, and failure analysis is essential for ensuring product functionality and traceability. These capabilities support rapid root-cause identification and correction during early production.

7.2.4. Environment, Health, and Safety (EHS)

EHS frameworks tailored to high-energy devices and hazardous materials—especially thermal runaway prevention, hazardous waste handling, and emergency response—form a core element of technician and engineering preparation. EHS compliance is foundational to plant stability and workforce protection.

7.3. Structuring Learning Pathways

A comprehensive learning pathway spans pre-hire preparation through advanced on-the-job development:

- Pre-hire bootcamps can include simulations, hands-on job previews, and foundational training to reduce early attrition.
- Apprenticeships and registered programs aligned with National Guideline Standards can stack micro-credentials into technician or associate degrees, enabling accumulation of recognized qualifications while building plant-relevant skills.
- On-the-job modules can address equipment-specific tasks, advanced diagnostics, and integrated problem-solving routines, culminating in cross-functional

capstones that deliver measurable improvements in yield, throughput, documentation cycle time, or audit readiness.

The Battery Workforce Initiative's work on standardized credentials supports portability of these skills across employers while allowing individual sites to tailor learning sequences to their equipment, processes, and maturity stage.

8. Methods and Tools to Accelerate Competence Development

With the skills taxonomy established, the next step is to consider how organizations can accelerate the development of these competencies in practice. Advanced battery manufacturing environments introduce steep learning curves and tight production timelines, making traditional training approaches insufficient on their own. Methods such as simulation, digital project information systems, and integrated data platforms enable faster, more reliable progression along the learning pathways defined in Section 7. These tools link workforce readiness directly to operational performance, allowing development activities to influence commissioning outcomes, yield stabilization, and long-term manufacturing reliability.

Simulation is a well-established method for accelerating competence development in complex industrial environments. Research in project and program management education shows that simulations allow learners to test decision rules, explore risk scenarios, and compress learning cycles before high stakes operations. In battery manufacturing facilities, simulation tools can replicate commissioning sequences, model bottlenecks in formation and aging, and test operator responses to atypical events such as thermal excursions or equipment misalignment. These capabilities strengthen readiness while avoiding the risks and costs associated with experimenting on live production equipment.

Digital project information systems further accelerate learning by creating structured feedback loops between training progress and operational performance. In battery production environments, these systems typically include several categories of software used across the lifecycle of design, planning, production, and monitoring. These systems include:

- Product Lifecycle Management platforms, which manage design data, engineering changes, and specification control
- Enterprise Resource Planning systems, such as SAP S/4HANA, which track labor hours, training completion, procurement activities, and cost performance
- Manufacturing Execution Systems, such as Dassault Apriso or Rockwell FT MES, which record real time production data including first pass yield, overall equipment effectiveness, scrap rates, and equipment downtime
- Supervisory Control and Data Acquisition systems that monitor sensor data, alarms, and process stability across automated lines

When integrated, these tools allow training records, qualification results, and competency assessments to be directly linked to operational indicators. For exam-

ple, MES data can show whether teams that completed process control training achieve more stable throughput or lower scrap during ramp up. ERP and PLM data can reveal whether workforce readiness aligns with scheduled commissioning milestones or whether gaps in documentation competencies slow down audit readiness activities. SCADA logs can be correlated with technician training histories to identify whether equipment faults or process instability occur more frequently among recently onboarded operators, guiding targeted reinforcement.

Predictive resource allocation models and integrated dashboards combine these data streams to help program leaders anticipate the impact of workforce readiness on commissioning duration, early yield performance, and nonconformance rates. During ramp up, such tools help teams make informed decisions, for example whether to allocate additional training time to reduce maintenance related downtime, or whether to adjust staffing to stabilize overall equipment effectiveness. By linking learning metrics with operational outcomes, these systems transform training from a static requirement into an operational lever that directly affects manufacturing performance.

9. Implementation Blueprint: Governance, Financing, and Measurement

A durable solution requires regional governance that brings together manufacturers, labor organizations, education providers, and public entities. The Battery Workforce Initiative offers a national template; regions can build on this by creating councils that forecast demand, manage shared training facilities, and coordinate curricula with employer needs. State programs like Quick Start show how public infrastructure can deliver customized, hands-on training at the scale required by gigafactories.

Financing strategies should blend federal incentives, state support, and employer investment. Because eligibility for domestic-content bonuses depends on accurate cost accounting and supply-chain documentation, organizations should include compliance training in their workforce budgets and treat documentation cycle time as a project metric. Treasury and Internal Revenue Service safe harbors reduce friction, but they do not eliminate the need for internal capabilities to classify components and validate supplier claims.

Measurement closes the loop. Recommended indicators include time-to-proficiency for critical roles, training hours per worker, first-pass yield and scrap rates by process step, overall equipment effectiveness, leading safety indicators, documentation cycle time for domestic-content claims, and retention at six, twelve, and twenty-four months. These metrics translate training activity into operational and financial outcomes and can be incorporated into project dashboards for transparent governance. The U.S. Department of Energy's employment reports provide a macro backdrop for assessing whether regional capacity is keeping pace with national trends.

By implementing tools, the joint-venture facilities such as Ultium Cells (Ohio,

Tennessee, Michigan) and BlueOval SK (Kentucky, Tennessee) have scaled hiring while negotiating labor agreements that increased wages and clarified safety expectations. These agreements contributed to workforce stability during ramp-up.

In the Southeast, SK Battery America and AESC partnered with Georgia Quick Start and Tennessee Colleges of Applied Technology to deliver pre-hire assessments, simulated production lines, and role-specific technical training. These examples illustrate how regional partnerships can reduce time-to-proficiency and improve early-stage yield performance.

10. Case Illustrations from the Battery Belt

Across the Battery Belt, several high-profile joint venture facilities illustrate how workforce strategies, labor agreements, and state supported training infrastructure influence early-stage operational performance.

In the Midwest, Ultium Cells, the General Motors and LG Energy Solution joint venture with facilities in Ohio, Tennessee, and Michigan, has scaled hiring while negotiating and ratifying labor agreements that raise wages and strengthen workplace protections. These agreements, widely reported at the time of ratification, have contributed to workforce stability during commissioning and ramp up, an essential condition for maintaining safety, consistency in line balance, and early yield performance. Similarly, in the Southeast, BlueOval SK, the Ford and SK On joint venture operating in Kentucky and Tennessee, implemented new hiring models and clarified safety expectations through revised labor processes. These arrangements reduced turnover and helped aligning production teams during initial equipment activation and qualification runs.

Community-facing programs have complemented these labor efforts. Employers in these regions, including Ultium Cells and BlueOval SK, have hosted technical demonstration events, career fairs, and facility tours to introduce local residents to battery technology and related occupations. These activities reinforce regional talent pipelines by increasing awareness of manufacturing roles, technical credentials, and pathways into engineering, maintenance, and operations occupations.

In Georgia, SK Battery America in Commerce and AESC in Savannah partnered with the state's Quick Start program and nearby technical colleges to implement a structured, multistage workforce development model. This approach includes pre-hire assessments, job simulations based on actual production station layouts, and job specific training for production and maintenance roles. Training occurs both onsite and at purpose-built state facilities such as the Georgia Advanced Manufacturing Training Center, enabling workers to practice on equipment and digital systems that mirror gigafactory environments. Following startup, these partnerships continue through local technical college programs and customized courses that support ongoing upskilling in automation, robotics, safety, and quality systems (Georgia Quick Start & Lanier Technical College, n.d.).

Together, these cases illustrate how named joint venture facilities and employer

state education partnerships operationalize workforce development at scale. They demonstrate that targeted labor agreements, structured pre-hire preparation, and sustained collaboration with regional institutions can materially reduce time to proficiency, support early production stability, and strengthen the long-term talent pipeline required for the growth of the domestic battery industry.

11. Integrating Standards, Compliance, and Sustainability in Practice

While PMI's standards and the Talent Triangle offer a widely recognized structure for organizing professional competencies, they represent only one approach within a broader landscape of project-management frameworks. Alternative models such as the International Project Management Association's ICB4 competency baseline, the Association for Project Management's Body of Knowledge, and the process-oriented structure of PRINCE2 emphasize different dimensions of project performance, including behavioral competency assessment, governance maturity, and prescriptive lifecycle control. Together, these frameworks highlight that successful project delivery in technical manufacturing environments depends on contextual adaptability rather than adherence to a single methodology. PMI's guidance is valuable for integrating leadership, strategic thinking, and cross-functional coordination, yet it offers limited specificity for highly automated, equipment-intensive operations such as advanced battery manufacturing, where engineering controls, process stabilization, and commissioning-phase risk management are central. For this reason, PMI's standards are most effective when applied as a complementary reference, aligned with technical, regulatory, and industry-specific frameworks rather than treated as a complete solution.

Even within this more balanced perspective, PMI's principles remain useful for integrating multiple dimensions of project value. In battery manufacturing, project success requires aligning environment, health, and safety expectations with community relationships, economic objectives, and operational targets. PMI's performance domains provide a scaffold for organizing these elements, and the Talent Triangle highlights the professional capabilities needed to maintain consistency across complex teams. When applied in this broader context, these frameworks help translate policy objectives such as domestic-content requirements and supply-chain diversification into actionable work packages, schedules, risk controls, and measurable benefits.

A related area where project-management frameworks must evolve concerns compliance. Domestic-content rules and Foreign Entity of Concern restrictions increasingly shape procurement, supplier selection, and documentation strategy. Although safe-harbor methods and federal guidance have reduced uncertainty, the underlying requirements remain complex and highly dynamic. Project managers who can navigate these constraints, coordinate cross-functional input, and maintain audit-ready documentation reduce rework, accelerate incentive qualification, and reinforce stakeholder confidence.

Sustainability considerations add a further layer of complexity. As environmental and social performance expectations become central to manufacturing strategy, sustainability must be integrated into scope definition, risk baselines, and decision-making processes rather than treated as an external add-on. PMI's recent emphasis on sustainability supports this shift by linking project delivery to outcomes such as energy intensity, waste minimization, and recycling readiness. In advanced battery manufacturing, incorporating these dimensions strengthens long-term competitiveness and ensures that operational decisions remain aligned with both community expectations and the broader transition to clean-energy systems.

12. Recommendations

- Adopt a Project Management competency model. Anchor project roles and development plans with the help of industry standards like PMBOK® Guide principles and performance domains, the PMI Talent Triangle and the Prince2® methodology, to shape learning paths in Ways of Working, Power Skills, and Business Acumen. This ensures common language and rigor while preserving tailoring for battery-specific contexts.
- Institutionalize cross-functional compliance literacy. Provide targeted training for project managers, engineers, procurement, and finance on domestic-content safe harbors, supplier classifications, and audit-ready documentation, and measure documentation cycle time as a project key performance indicator.
- Build regional partnerships that scale hands-on learning. Use Battery Workforce Initiative guidance to align curricula and credentials and invest in state-level training centers that can deliver simulations and equipment-specific practice before live operations. The Quick Start model offers a proven reference.
- Connect training to ramp performance through digital dashboards. Integrate training throughput, proficiency milestones, and qualification results with yield, scrap, and overall equipment effectiveness in project information systems to make human-capital decisions visible and testable.
- Plan for lifecycle skills. This includes competencies in recycling, second use, and environmental compliance so that teams can respond to evolving market and regulatory expectations and capture value across the full battery lifecycle. Supply-chain mapping and the Department of Energy's sector review can inform these plans.

13. Limitations & Future Research

While this study integrates diverse data sources and synthesizes evidence across policy, workforce, and project-delivery domains, several limitations should be acknowledged. First, the analysis relies on secondary data from government reports, industry assessments, and peer-reviewed literature rather than primary empirical research. Although these sources provide a robust foundation for identify-

ing workforce gaps and competency needs, future research incorporating quantitative data collection (such as structured workforce assessments, time-to-proficiency measurements, or longitudinal yield data) would strengthen the empirical basis of these findings.

Second, the competency framework synthesized here reflects conditions and policy guidance available at the time of writing. Workforce demands in advanced battery manufacturing evolve rapidly due to changing chemistries, process technologies, and regulatory requirements. As federal domestic-content rules, Foreign Entity of Concern classifications, and state-level training programs continue to mature, updated analyses will be necessary to track their impact on role definitions, required competencies, and regional labor-market dynamics.

Third, while case illustrations of facilities such as Ultium Cells, BlueOval SK, SK Battery America, and AESC demonstrate current approaches to workforce development, these examples may not represent the full diversity of organizational strategies across the industry. Comparative case studies involving a broader sample of gigafactories (particularly those at varying stages of maturity or operating under different joint-venture structures) would help validate the generalizability of the proposed taxonomy and implementation blueprint.

Finally, opportunities exist to deepen understanding of how digital project information systems, simulation tools, and integrated training-operations dashboards influence ramp-up performance. Future research should explore the extent to which these tools can predict production stability, reduce commissioning duration, or improve long-term workforce resilience. Multisite studies using standardized indicators such as first-pass yield, time-to-proficiency, and documentation cycle time would support stronger evidence-based best practices.

Together, these limitations highlight the need for ongoing empirical research, cross-industry benchmarking, and periodic reassessment of competency models as the U.S. battery manufacturing sector continues to scale.

14. Conclusion

The United States has entered a decisive phase in the industrialization of advanced batteries. Factories are rising, supply chains are reconfiguring, and public policy provides clear incentives to localize production. The pivotal question is whether workforce capability can keep pace with capital investment. By aligning development efforts with the Project Management Institute's standards, building regional training partnerships that emphasize hands-on practice and credential portability, and integrating compliance and sustainability into the definition of value, organizations can convert policy momentum into durable competitive advantage. The immediate opportunity is to treat workforce development as a governing project function with measurable outcomes. Doing so will shorten learning curves, stabilize yields, and ensure that the next chapter of American industrialization is led by teams with the skills to deliver it.

Meeting this challenge will also require aggressive investment in STEM foun-

dations and skilled trades. Battery facilities depend on electricians, instrument and controls technicians, industrial maintenance mechanics, and mechatronics technologists who can install, program, and maintain highly automated systems. Expanding K-12 career and technical education, community college programs, and registered apprenticeships can build these capabilities quickly. Stackable credentials in safety, robotics, power distribution, and process controls, paired with paid on-the-job learning, will widen participation and shorten time to proficiency. Prioritizing veterans, displaced workers, and women in trades will expand the talent pool and anchor growth across battery belts and supplier ecosystems.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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