5-6-2024

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W.E. UPJOHN INSTITUTE
FOR EMPLOYMENT RESEARCH
Researching the causes and consequences of unemployment

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May 2024

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EXECUTIVE SUMMARY

This report develops a model to project the future demand for workers within the manufacturing supply chain for lithium-ion batteries in the United States. As the dominant energy storage technology for electric vehicles, global demand for lithium-ion batteries is rapidly increasing. In recent years, the United States has held a relatively small share of the global supply chain, which is dominated by companies operating in China and East Asia. Recently, the United States has accelerated investment in domestic battery production with generous grants and subsidies to producers of electric vehicles.

Using publicly available data, we provide estimates of the workforce associated with the domestic production of lithium-ion batteries in 2023 across the entire supply chain, from mining and refining of critical raw materials through midstream cell and pack manufacturing, to distribution, service and repair, recycling, and end-of-life applications. The same data provide estimates of U.S. battery manufacturers' productive capacity in 2023, establishing a production relationship between gigawatt hours of battery capacity and supply chain employment. Using estimates of productive capacity in 2030, we project that the supply chain workforce will reach 310,000 in that year. Employment levels are provided by supply chain segment and by industry. We use data from the Bureau of Labor Statistics on occupational employment shares by industry, both in 2023 and projections for 2030, to project net occupational employment changes and annual job openings associated with lithium-ion battery production in the United States. We use data on the typical educational requirements to enter occupations as well as training received after hire to assess the workforce development and skill requirements needed for battery production. In addition, we also analyze these trends for the state of Michigan, where we project a battery production workforce of 30,000 individuals in 2030.

We find that employment growth in lithium-ion battery manufacturing and related industries is connected to a broad range of occupations with diverse skill requirements. We also find that the greatest share of employment growth will be in occupations with training requirements met by associate and technical degree programs offered by community colleges, as well as through apprenticeships and on-the-job training. These include the top three occupations that account for 32 percent of total employment growth: assemblers and fabricators, other production occupations, and metal and plastics workers. Additional occupations that generally require a bachelor's degree or higher, include three that account for 16 percent of total employment growth: engineers, business operations specialists, and operations specialty managers.
Overall, the transition from internal combustion engines to electric vehicles will require substantial training or retraining of workers to ensure that the United States has a chance to reach and sustain its share of the global automotive industry.

JEL Classification Codes: J23, L52, L62, L63

Key Words: electric vehicles, EVs, lithium batteries, GWh, workforce demand, downstream supply chain, occupations, industries, Michigan

Acknowledgments: Thank you to the authors of the North American Lithium-Ion Supply Chain Database: Vicky Putsche, Erik Witter, Shriram Santhanagopalan, Maggie Mann, and Ahmad A. Pesaran. This analysis builds on the directory of employers compiled in the fourth version of the database, published June 30, 2023, by the National Renewable Energy Laboratory and funded by NAATBatt International under technical service agreements TSA-21-17854 and TSA-21-21593. Thank you to Lisa Abbott, Travis Mann, and Karen Kalnins for responding to requests for literature and for facilitating access to establishment databases within the W.E. Upjohn Institute Information Center. Thank you to the member organizations and individuals within the Michigan Labor and Economic Opportunity Electric Vehicle Jobs Academy and Detroit Regional Chamber Statewide EV/Mobility Talent Initiatives Alignment Working Group for inviting our participation and sharing comments on this research during its development. Thanks to Aaron Sojourner, Allison Hewitt Colosky, Beth Truesdale, Brad Hershbein, Claire Black, Gabriel Ehrlich, and Michael Morrissey for review and draft copyedits.

INTRODUCTION

The market for electric vehicles (EVs) has experienced significant growth in recent years, part of a once-in-a-lifetime transition toward a green economy. Improvements in technology, including increased vehicle range and wider model availability, have spurred consumer demand. Government incentives, including tax credits to consumers and grants and loans to manufacturers, are lowering the cost of ownership of many new EVs to near parity with internal combustion engine (ICE) vehicles (Hummel et al. 2017; Woody et al. 2024). Hybrid and battery EVs accounted for 16 percent of new U.S. light-duty vehicle sales in 2023, with a record 1.2 million fully electric vehicles sold within the year—more than twice as many units as were sold in 2021 and 18 years ahead of official projections made just three years ago (Cox Automotive 2024; Michalek and Whitefoot 2023; U.S. Energy Information Administration 2023; White House 2023a). Forecasts from S&P Global Mobility predict that EV sales in the United States could reach 40 percent of total passenger car sales by 2030, while more optimistic sources see sales exceeding 50 percent of all sales by then (Brinley 2023; Wayland 2021). Electric vehicles are regarded as a key technology to decarbonize road transportation, which accounts for one-sixth of global carbon (CO2) emissions, placing cars on a path in line with achieving net zero emissions among advanced economies by 2050 (International Energy Agency, n.d.).

The historic transition from ICE to EVs has already begun to bring about changes in the labor market for automotive parts manufacturing in the United States; the sector represents more than one million jobs as of December 2023 (Bureau of Labor Statistics 2024a). Changes in the labor market are expected to accelerate through 2030 and beyond, as automakers increase the proportion of their operations dedicated to producing EVs.

Tempering this decidedly optimistic long-run view are the realities of short- to –medium-run market conditions affecting the demand for EVs that will impact the length of time until we achieve full EV penetration into the transportation sector. These conditions include the comfort consumers have with driving ranges for EVs as the technology improves over time, the speed of building out the infrastructure for fast charging stations in locations that appeal to consumer demand, and decisions by automakers on how long they plan to bridge the transition from ICE to EVs through the production of hybrid or plug-in hybrid EVs.

Even as domestic manufacturers in the United States are increasing production of EVs, Chinese manufacturers remain dominant in the battery technology that powers them. In 2022, more than 76 percent of global production capacity for lithium-ion batteries was in China, compared to 7 percent in the United States and 8 percent in Europe. The U.S. government has identified the development of a domestic supply chain for lithium batteries as a critical national security concern and crucial to maintaining leadership in the global automotive industry. Responding to Executive Order 14017 (White House 2021), the Departments of Energy, Defense, Commerce, and State created the Federal Consortium for Advanced Batteries (FCAB), a group of agencies charged with ensuring the domestic supply of lithium batteries and developing a robust lithium battery ecosystem in the United States. In June 2021, FCAB released the *National Blueprint for Lithium Batteries 2021–2030*, which establishes a vision for the lithium battery supply chain: "By 2030, the United States and its partners will establish a secure battery materials and technology supply chain that supports long-term U.S. economic competitiveness and equitable job creation, enables decarbonization, advances social justice, and meets national security requirements" (FCAB 2021). The blueprint outlines a specific goal to "support [the] development of a trained battery supply chain workforce that promotes career transition and equitable access through programs in trade schools, community colleges, and public universities" (FCAB 2021).

The CHIPS and Science Act, the Bipartisan Infrastructure Law, and the Inflation Reduction Act combined represent a federal investment of more than $135 billion toward vehicle electrification, with much of that directed toward critical mineral sourcing and lithium-ion battery manufacturing incentives (White House 2022). Industry leaders have responded in kind, announcing more than $100 billion dollars of private investment into battery manufacturing, a sum anticipated to create tens of thousands of jobs (Environmental Defense Fund 2023b; White House 2023b).

To be prepared with the skilled workforce those jobs will require, this report seeks to answer the following question: What are the occupational needs of the emerging lithium battery industry between now and 2030? To answer to this question for both the United States and for the state of Michigan, we use a comprehensive database for 2023 that provides estimates of gigawatt-hour (GWh) production capacities of lithium-ion battery manufacturers in North America and the labor required across the input, production, and downstream supply chain. We use the North American Industrial Classification System (NAICS) to derive industry employment from these labor supply chain estimates. We then identify the occupational staffing patterns associated with each of these industries in 2023. Finally, we develop a model that projects the employment of occupations related to the production of lithium-ion batteries in 2030, using estimates of GWh production capacity in 2030 as a critical input. We then analyze the training needs associated with these occupations.

This report is divided into six sections. The first describes the database we use to identify the scale of lithium-ion battery production in the United States in 2023. The second section details the methodology used to develop estimates of future labor demand for occupations related to lithium-ion battery production. The fourth section provides estimates of gigawatt production capacity in both 2023 and 2030 and the associated levels of employment by both supply chain segment and NAICS industries. The fourth section provides a perspective on the overall risk factors that may impact this industry, including geopolitical concerns, availability of critical raw materials, and challenges to scaling up productive capacity. The fifth section details the data used to identify the associated occupational staffing patterns by NAICS industry and uses our estimates of the relationship between GWh production capacity and industry and occupational employment to generate estimates of occupational requirements in 2030. This section reports our estimates of occupational demand between 2023 and 2030 in terms of net employment change, annual job openings, and the educational and training requirements needed for these occupations. The final section provides the results of the model as applied to Michigan and the implications of the findings for Michigan on the training needs for the EV battery workforce. The report then provides concluding remarks.

SCALE OF BATTERY MANUFACTURING

Commercial-scale production of lithium-ion batteries is measured in GWh, annualized as GWh/year. Throughout this report, we use “nameplate” production capacity of lithium-ion battery manufacturers to characterize the scale of the domestic manufacturing market. Nameplate production capacity refers to the full-line capacity, or maximum productive output of a facility operating continuously over a calendar year. When a new gigafactory is announced, or capacity is added to existing facilities, this measure of capacity is published in GWh/year.

We derive our estimates of battery plant nameplate capacity and the associated workforce in the United States from a database created jointly by the National Alliance for Advanced Transportation Batteries (NAATBatt) and the National Renewable Energy Laboratory (NREL). NAATBatt is a research and development consortium of companies working to promote the manufacturing of lithium-ion and other advanced batteries. Incorporated as a Section 501(c)(6) trade association in 2009, its members include over 320 energy storage industry corporations. In response to FCAB's national blueprint, NAATBatt and NREL created a publicly available directory of North American companies in the lithium-ion supply chain, releasing the first edition in September 2021 and updating it in June 2023. The second edition documents 791 firms engaged in the lithium-ion battery supply chain in North America, which includes "upstream" delivery of critical input materials, the "midstream" manufacture and wrapping of battery cells, and "downstream" activities including distribution and research and development (see Table 1). In the United States, 40 facilities are documented to operate in the midstream manufacturing of battery cells in June 2023. Summing the stated productive capacity of these facilities shows 200 GWh of annual nameplate capacity in the United States, and 32.2 GWh in Michigan in 2023.

The NAATBat/NREL database provides for each company their name, address, product type, nameplate productive capacity, workforce size, operating status (planned, under construction, pre-commercial, or commercial), and which part of the supply chain they operate in. The database differentiates the supply chain into 12 segments, shown in Table 1.

Table 1 Supply Chain Segments

Upstream supply chain segments	
Critical Mineral Mining	
Raw Material Manufacturing	
Battery Grade Component Manufacturing	
Other Battery Components and Materials Manufacturing	
Midstream supply chain segments	
Electrode and Cells Manufacturing	
Modules and Packs Manufacturing	
Downstream supply chain segments	
End of Life/Recycling	
Equipment Manufacturing	
R&D	
Service and Repair	
Modeling	
Distributors	

SOURCE: NAATBatt/NREL Lithium-Ion Supply Chain Database (June 2023).

METHODOLOGY

To estimate the demand for occupational employment associated with future levels of lithium-ion battery production, a number of analytical steps and assumptions are needed. The database for this study provides for each employer their supply side category, associated employment, and for midstream manufacturing of battery cells, their current (2023) nameplate production capacity. However, to use these data to infer occupational staffing patterns, it is necessary to identify the NAICS industry of each establishment, since we use occupational/industry staffing patterns, both current and projected, to develop occupational demand estimates. The procedures for identifying the three-digit NAICS codes of each establishment and associated imputation requirements (as needed) are provided in the next section. By identifying NAICS codes for each employer in the NAATBatt/NREL database, we obtain estimates of employment by industry across the supply chain.

Data from the 2022 Bureau of Labor Statistics' (BLS) Occupational Employment and Wage Survey are used to estimate the most recent occupational shares of employment for each NAICS industry at both the national level and for Michigan. For the time period under study, 2023–2030, it is necessary to estimate occupational industry shares in both 2023 and 2030. Data from U.S. and Michigan occupational employment projections programs provide such occupational industry shares that allow inference of the shares.[1]

We note that while estimates of nameplate production capacity, by definition, correspond to 100 percent capacity utilization, the associated supply chain workforce measured in the NAATBaat database reports the labor used in the actual production of GWh of U.S. manufacturers in 2023. In addition, the database reports wage and salary employment and does not include the use of self-employed contract labor or temporary help supply workers. In general, it is very difficult to measure either the use of contract labor or the industry to which temporary help supply employees are placed. To the extent that firms along the lithium-ion battery supply chain increasingly use contract or temporary help supply labor as their productive capacities expand, our estimates will not capture that shift.

We estimate the change in labor demand for wage and salary employment across all supply chain inputs based on applying the scalar change in the nameplate capacity of U.S. battery manufacturers from 2023 to 2030 to the labor used in actual production in 2023.

Implicitly, we assume that the capacity utilization of battery production in 2023—the ratio of actual production of GWh to nameplate productive capacity—remains constant from 2023 to 2030. Data on actual production and capacity utilization rates for battery manufacturing

[1] At the time of this study, the U.S. occupational projections provided occupational/industry shares for the 2021–2031 period. The Michigan occupational employment projections provided similar shares for the 2020–2030 period. We derive annual growth rates in occupational/industry shares for both series and infer the corresponding shares for 2023 and 2030 (as needed).

are not readily available; however, capacity utilization data for the related manufacturing industries are available at the NAICS three-digit level. These rates range from 69 percent to 82 percent across industries and, more importantly, are stable across long periods of time within industries.[2] As a result, we assume that capacity utilization rates will remain relatively stable while nameplate capacity increases from 2023 to 2030, and that this variation does not materially affect supply chain labor demand in the near term.

Another factor potentially affecting employment levels are changes in the productivity of workers by industry. Recent research, however, has demonstrated the difficulty in measuring labor productivity due to the lack of data on the use of contract labor (Abraham et al. 2023). In addition, the official measures of labor productivity for the NAICS industries most closely related to battery production, while subject to mismeasurement, vary considerably on an annual basis and are often negative. For example, in NAICS industry 3359, "Other Electrical Equipment and Component Manufacturing," which includes midstream manufacturers of lithium-ion batteries, labor productivity fell by more than 20 percent from 2015 to 2022 (Bureau of Labor Statistics 2024b). The uncertainty and variability of these official measures result in our making a conservative assumption of no productivity changes over the period of study.

U.S. LITHIUM-ION BATTERY PRODUCTION CAPACITY AND WORKFORCE

As noted above, the NAATBatt Database collects information on facilities in various stages of development. Facilities are recorded with a status of planned, under construction, pre-commercial, or commercial. Our analysis is based on 502 entries of commercial and pre-

[2] Authors' analysis of industry capacity utilization data from the Board of Governors of the Federal Reserve.

commercial facilities active in the United States as of June 2023. Facilities classified as planned and under construction are excluded from analysis.

The resulting selection of facility entries from the NAATBatt database includes missing data. Of the 502 facilities, there is missing information on workforce for 180 and on nameplate productive capacity for 20. For facilities with missing employment, we filled in the information through direct company outreach, Web-based research, and databases such as the National Establishment Time Series, Gale Business Insights, and Claritas. In the process of doing this research, we also validated the employment estimates contained in the NAATBatt database (or corrected them as appropriate).[3] For the missing GWh production capacity, we used a linear regression of GWh capacity on employment for the facilities with complete information to estimate the GWh capacity associated with that facility's employment level, imputing the expected value for any missing values.

Next, we estimate employment by both supply chain segment and industry classification codes.[4] Tables 2 and 3 reflect the supply chain workforce in the United States that is associated with 200 GWh of annual production capacity in the year 2023. It is important to note that the data reflect wage and salary employees of each facility and do not account for the contract and temporary labor that may be present in all supply chain segments.

The critical driving element to this study is the assumption of overall nameplate gigawatt production in 2030. Estimates from Argonne National Laboratory (2022), S&P Global Market Intelligence (2023), and the Environmental Defense Fund (2023a) all point to a consensus of

[3] In researching facilities with missing employment, there were 23 companies with employment that included both battery-related operations and other unrelated activities for which we could not determine the battery-related employment levels. We did not include these facilities, which tended to be larger, contributing to an undercount of the supply chain workforce in 2023.

[4] There are companies in the database that operate in multiple segments of the supply chain. In instances where those companies' aggregate employment levels rather than their employment by facility was available, we used national supply chain segment proportions to allocate the employment into the appropriate segments.

Table 2 U.S. Lithium-Ion Battery Supply Chain Employment by Segment, 2023

Supply chain segment	Description	NAATBatt U.S. employment in 2023 associated with 200 Gigawatt hours of battery production	Relative share of total employment in 2023 (%)
1	Raw Materials	1,825	2.9
2	Battery Grade Materials	4,701	7.4
3	Other Battery Component Materials	6,743	10.6
4	Electrodes and Cells	10,585	16.6
5	Modules and Packs	13,903	21.8
6	End of Life	2,963	4.7
7	Equipment	4,228	6.6
8	Service and Repair	9,809	15.4
9	Research and Development	6,160	9.7
10	Modeling	2,675	4.2
11	Distributors	75	0.1
	Total	**63,667**	

SOURCE: NAATBatt/NREL Lithium-Ion Supply Chain Database and authors' calculations.

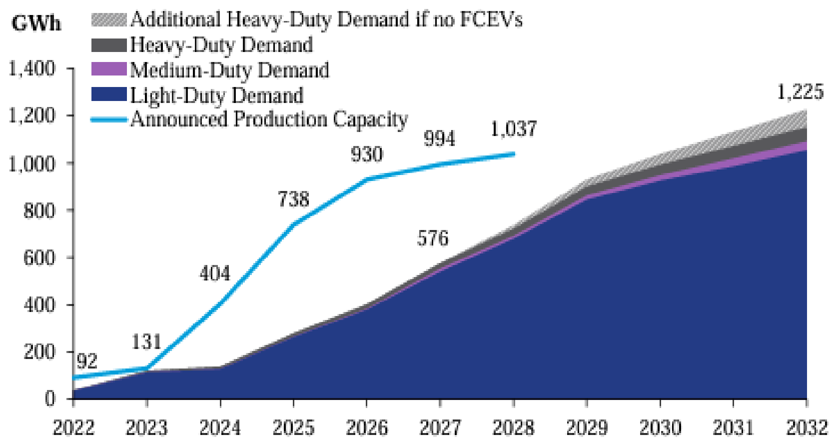
Table 3 U.S. Lithium-Ion Battery Supply Chain Employment by NAICS Industry, 2023

NAICS 3-Digit	Description	NAATBatt U.S. employment in 2023 associated with 200 GWh of battery production	Relative share of total employment in 2023 (%)
212	Mining (except Oil and Gas)	2,012	3.2
237	Heavy and Civil Engineering Construction	385	0.6
325	Chemical Manufacturing	15,299	24.0
326	Plastics and Rubber Products Manufacturing	1,455	2.3
327	Nonmetallic Mineral Product Manufacturing	1,452	2.3
331	Primary Metal Manufacturing	447	0.7
332	Fabricated Metal Product Manufacturing	335	0.5
333	Machinery Manufacturing	1,509	2.4
334	Computer and Electronic Product Mfg.	3,935	6.2
335	Electrical Equipment, Appliance, and Component Mfg.	22,347	35.1
336	Transportation Equipment Manufacturing	2,506	3.9
339	Miscellaneous Manufacturing	335	0.5
423	Merchant Wholesalers, Durable Goods	2,576	4.0
424	Merchant Wholesalers, Nondurable Goods	215	0.3
441	Motor Vehicle and Parts Dealers	165	0.3
488	Support Activities for Transportation	200	0.3
513	Publishing Industries (incl. Software)	739	1.2
541	Professional, Scientific, and Technical Services	7,008	11.0
561	Administrative and Support Services	99	0.2
562	Waste Management and Remediation Svcs	483	0.8
811	Repair and Maintenance	165	0.3
	Total	**63,667**	

SOURCE: NAATBatt/NREL Lithium-Ion Supply Chain Database and authors' calculations.

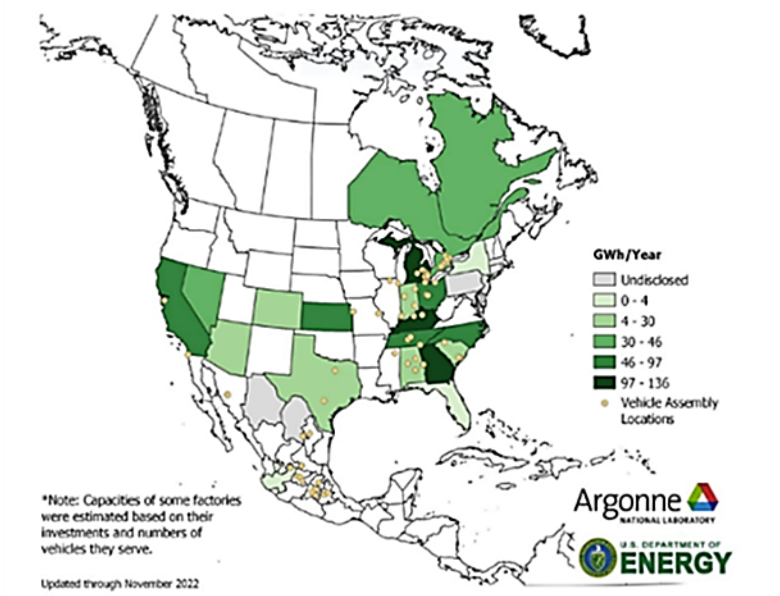
1000 GWh as the planned U.S. productive capacity by 2030 (see Figures 1 and 2). These analyses track the announced investment and intended production capacity of EV battery manufacturers in the United States and reflect the expectation of 45 battery manufacturing facilities operating with an average annual capacity of 23 GWh by 2030.

Figure 1 Projected U.S. EV Battery Demand and Announced Battery Production Capacity (2022–2032)



SOURCE: Environmental Defense Fund (2023a).

Figure 2 Planned Battery Plant Capacity in North America by 2030



SOURCE: Argonne National Laboratory (2022).

The consensus estimate of 1,000 GWh of planned battery manufacturing capacity in the United States by 2030 represents a fivefold factor of growth from the June 2023 value of 200 GWh. Assuming proportionality in the labor demand across supply chain inputs, the workforce required to support the domestic battery manufacturing industry at 1000 GWh of annual capacity would be approximately 310,000 individuals, as shown in Table 4.

Table 4 U.S. Lithium-Ion Battery Supply Chain Employment by NAICS Industry, Current and Projected

NAICS 3-Digit	Description	NAATBatt U.S. employment in 2023 associated with 200 GWh of battery production	Projected U.S. employment in 2030 associated with 1000 GWh of battery production
212	Mining (except Oil and Gas)	2,012	2,012[a]
237	Heavy and Civil Engineering Construction	385	1,925
325	Chemical Manufacturing	15,299	76,495
326	Plastics and Rubber Products Mfg.	1,455	7,275
327	Nonmetallic Mineral Product Mfg.	1,452	7,260
331	Primary Metal Manufacturing	447	2,235
332	Fabricated Metal Product Manufacturing	335	1,675
333	Machinery Manufacturing	1,509	7,545
334	Computer and Electronic Product Mfg.	3,935	19,675
335	Electrical Equipment, Appliance, and Component Mfg.	22,347	111,735
336	Transportation Equipment Manufacturing	2,506	12,530
339	Miscellaneous Manufacturing	335	1,675
423	Merchant Wholesalers, Durable Goods	2,576	12,880
424	Merchant Wholesalers, Nondurable Goods	215	1,075
441	Motor Vehicle and Parts Dealers	165	825
488	Support Activities for Transportation	200	1,000
513	Publishing Industries (incl. Software)	739	3,695
541	Professional, Scientific, and Technical Svcs.	7,008	35,040
561	Administrative and Support Services	99	495
562	Waste Management and Remediation Svcs.	483	2,415
811	Repair and Maintenance	165	825
	Total	**63,667**	**310,287**

[a] Employment in Raw Materials held constant over the projection period. We exclude Mining from our projections based on uncertainty over the supply of, permitting for, and the development of economically viable sites for extraction of critical mining inputs.
SOURCE: NAATBatt/NREL Lithium-Ion Supply Chain Database and authors' calculations.

Mining is one industry where employment growth is likely to lag other industries in the expansion of the domestic supply chain. Employment growth in this industry is contingent on the supply, permitting, and development of economically viable sites of extraction. Timelines from mineral discovery to commercial operation of new mining facilities are often beyond the seven-year scope of the projection period. In addition, metal ore mining employment (NAICS 2122), the mining industry most closely aligned with battery production, has remained at a steady 44,000 over the last 10 years. As a result, we hold the employment level in mining constant over our projection period.

Conversely, it appears possible that some supply chain segments will occupy increasing shares of the domestic supply chain in coming years. For example, literature suggests that the recycling industry could expand well beyond its current share of the supply chain (Yu et al. 2022). Presently, most of the EVs that have been made are still on the roads; as these vehicles wear out and technological advancements improve the use-cases of recycled feedstock, recycling may become a more prominent part of the lithium-ion battery supply chain (Yu et al. 2022). We regard these changes as likely to occur outside of the projection period, so we treat recycling to the same growth factor as its connected industries over the period 2023–2030.

Outside of these two industries, however, we do not have specific industry insight into anticipated changes in relative industry shares that will affect the battery supply chain. We adopt the conservative assumption that industry employment shares, except for mining, will remain constant through 2030. Fixing the employment level of mining at 2,012 and scaling the rest of the segments by a factor of 5 leads to an employment projection of 310,287 workers in 2030.

RISKS TO ACHIEVING FORECAST PRODUCTION CAPACITY TARGETS

Global demand for batteries continues to motivate original equipment manufacturers (OEMs) to pursue increases in production capacity for lithium-ion batteries. Federal policy is in place to encourage onshoring of this production in the United States. Still, OEMs and battery manufacturers face numerous risks in their efforts to expand production capacity and build new gigafactories. Failure to surmount these obstacles could result in the forecast production capacity targets and the associated domestic labor inputs being overstated.

Critical Raw Materials

China dominates the world market for critical raw materials (lithium, cobalt, natural graphite, and manganese) and in the chemical refining of components (manganese chemicals, lithium chemicals, cobalt sulphate, and nickel sulphate). China also currently dominates the world market in the production of the two critical manufactured components of batteries: anodes and cathodes. The consensus among industry experts is that while the United States will greatly expand our capacity to produce battery cells, we will still have a significant reliance on imported raw and chemically refined materials as well as anodes and cathodes (Mehdi and Moerenhout 2023).

The dominance of China and the current worsening of the relationship between the United States and China creates a nontrivial geopolitical risk for the EV market. For example, as recently as October 2023, China announced new restrictions on its graphite exports. Leadership in the United States and allied governments remains anxious about what China's control of the market may mean for their EV ambitions (Home 2023; Reuters 2023).

There are some potential moderating factors to these risks. China is dependent on (and has made significant investments in) Australian-sourced spodumene (source of high-grade lithium) and Chilean-sourced brine (used to provide lithium carbonate), suggesting there is a need for international cooperation (S&P Global Commodity Insights 2023). The dependency on inputs from China is also leading to heavy U.S. investments in R&D to provide alternative battery technologies not requiring reliance on these critical minerals (Center for Strategic and International Studies 2021).

Construction

Gigafactories are large and complex, requiring sophisticated design and specialized inputs in terms of electric utilities, heating, cooling, and air purification systems. Construction of these facilities takes time and involves large capital expenditures. Location of these facilities on large sites requires local cooperation, where resistance to development may take the form of ecological concern.

Specialized Manufacturing Equipment

A relatively small group of companies, located predominantly in China, Japan, and South Korea, supplies the specialized manufacturing equipment used for slurry mixing, electrode manufacturing, cell assembly, and cell finishing. These companies have been identified to operate at more than 95 percent capacity, prioritizing orders from established customers and leaving little room for orders from new entrants in the United States and Europe. Growing demand for this equipment may present an opportunity for American and European machinery manufacturers with similar competencies to pivot toward the evolving industry in battery manufacturing (McKinsey and Company 2022).

Technical Expertise

Establishing commercial-scale battery manufacturing facilities requires specialized skill sets and knowledge of best practices. The Li-Bridge consortium identified lack of domestic technical know-how, especially in midstream activities, as a critical challenge to meeting domestic production goals (Li-Bridge 2023). Companies headquartered in China, Japan, and

South Korea—such as CATL, BYD, LG Chem, Panasonic, and Samsung SDI—possess industry-leading technical knowledge. Recent years have seen an acceleration in OEM-supplier partnerships, as domestic manufacturers seek access to this knowledge.

These factors may influence an OEM's decision to continue sourcing batteries from foreign suppliers rather than invest in the expansion production capacity through the addition of domestic gigafactories.

Market Demand Conditions

The focus thus far in this report has been on the productive capacity of the lithium-ion supply chain. Of critical importance are the future trends in the demand for EVs that will drive the production of batteries. Except for the enthusiasm of a relatively small group of early adopters of EVs, consumers remain concerned with the maturity of EV charging infrastructure, driving range of available models, and cost and convenience of EV ownership compared to ICE vehicles (Fischer et al. 2024; Lee 2024). Recent auto sales data indicate that current consumer demand for EVs may be easing. In 2024 Q1, market leader Tesla reported its first decline in quarterly deliveries in four years, and GM's first-quarter sales fell 20.5 percent compared to the previous year (Gomes 2024). Demand for lithium-ion batteries may also be impacted by automakers' decisions to bridge the transition from ICE with hybrid and plug-in hybrid EV models for an extended period of time. In March, Ford CFO John Lawler said the automaker will rely on demand for its hybrid models "as an important part of that bridge over the next five years" (Gomes and White 2024).

Overall, we do not view these concerns as anything but temporary on the road to full adoption of EVs in the U.S. auto market. However, they will affect the time it takes to achieve this long-run scenario. These caveats notwithstanding, the next section uses the 310,000 employment estimate, which is consistent with the projected capacity growth in battery production to 1000 GWh by 2030, to identify the demand for occupational employment related to lithium-ion battery production in the United States. We view the employment estimate of 310,000 as an upper bound, depending critically on the confluence of risk factors that may serve to mitigate expansion of the domestic supply of batteries, despite the national security importance being placed on it. The final section applies the same methodology to forecast occupational employment related to battery production in Michigan.

CONNECTING SUPPLY CHAIN EMPLOYMENT TO SPECIFIC OCCUPATIONS

After identifying the NAICS industry of each facility in our database, we use the occupational staffing patterns associated with each three-digit NAICS industry using data from the BLS' 2022 Occupational Employment and Wage Survey for the United States. Assuming the composition of firms engaged in battery production mirrors those of their industry peers, this provides the occupational composition of the 63,667 people we estimate to be working in the domestic lithium-ion battery supply chain in June 2023.

The BLS also releases projections of how each industry's occupational shares will change over the next decade. For each NAICS industry in our database, we estimate their occupational employment in 2030 using the product of projected industry employment by the 2030 industry occupational shares. That is, we apply the estimated 2030 occupational shares to the employment associated with a production level of 1,000 GWh annually. From there, we sum across the three-digit NAICS categories to obtain estimates of the number of workers projected to be engaged in each occupation of the lithium-ion battery supply chain in 2030, resulting in the total estimate of 310,287.

Table 5 provides the results by minor occupation,[5] providing for each occupation the median annual wage in 2023, battery-related employment in 2023 and 2030, employment change, and our estimate of annual job openings.[6] We constructed rankings of each occupation by employment change and annual job openings and sorted the occupations in the table based on the sum of ranks. The table provides the top 36 minor occupations, which account for over 90 percent of the total estimated employment change between 2023 and 2030 the sum of ranks. The table provides the top 36 minor occupations, which account for over 72 percent of the total estimated employment change between 2023 and 2030.[7]

Consider the occupation of assemblers and fabricators. The third column in Table 5 shows our total estimate of 8,881 assemblers and fabricators engaged in battery production across the industries in the lithium-ion battery supply chain in June 2023. The fourth column inflates those values by the growth in GWh production (apart from 212 Mining, which is held constant), showing a 2030 employment estimate of 43,101. The next column shows the net

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[5] https://www.bls.gov/soc/. The Standard Occupational Classification system divides occupations into four levels of aggregation with the highest level of aggregation being major groups, then minor groups, broad occupations, and detailed occupations.

[6] Our methodology for estimating annual job openings is based on applying, for each occupation, the known ratio of annual job openings in the U.S. projections from 2022–2032 to employment in 2022 and assuming it equals the ratio of unknown job openings for battery-related employment from 2023–2030 to known occupational employment for battery-related employment in 2023.

[7] Every industry has a mix of a large number of occupations with relatively small sizes. In future research, we will report validation of a selection of the minor occupations that are most critical to lithium-ion battery production based on feedback from industry experts.

Table 5 Battery-Related Occupational Employment for the United States, 2023–2030

Occupation code	Occupational title	U.S. annual median salary 2022	Battery-related occupational employment 2023	2030	Employment change	Annual job openings
51-2000	Assemblers and Fabricators	$38,246	8,881	43,101	34,220	4,427
51-9000	Other Production Occupations	$42,529	7,934	38,344	30,410	4,154
51-4000	Metal Workers and Plastic Workers	$46,114	3,816	18,964	15,148	1,814
17-2000	Engineers	$90,884	3,723	19,434	15,711	1,166
53-7000	Material Moving Workers	$38,440	3,145	15,472	12,328	2,151
13-1000	Business Operations Specialists	$73,972	3,639	18,211	14,572	1,536
49-9000	Other Installation, Maintenance, and Repair Occupations	$53,252	2,203	11,361	9,159	1,024
11-3000	Operations Specialties Managers	$123,531	2,148	10,966	8,818	828
51-1000	Supervisors of Production Workers	$66,605	1,895	9,548	7,653	884
41-4000	Sales Representatives, Wholesale and Mfg.	$72,501	1,828	9,160	7,332	812
43-5000	Material Recording, Scheduling, Dispatching, and Distributing Workers	$43,654	1,684	8,019	6,334	761
11-1000	Top Executives	$118,413	1,736	8,485	6,749	675
43-4000	Information and Record Clerks	$42,681	1,302	5,991	4,689	757
17-3000	Drafters, Engineering Technicians, and Mapping Technicians	$59,539	1,343	6,702	5,359	622
53-3000	Motor Vehicle Operators	$43,381	1,043	4,585	3,542	517
11-9000	Other Management Occupations	$131,533	1,028	5,158	4,130	422
13-2000	Financial Specialists	$79,775	1,082	5,330	4,248	401
43-3000	Financial Clerks	$46,202	887	4,004	3,117	426
43-9000	Other Office and Admin. Support Workers	$39,851	809	3,610	2,801	407
11-2000	Advertising, Marketing, Promotions, Public Relations, and Sales Managers	$136,685	754	3,758	3,004	290
19-4000	Life, Physical, and Social Science Technicians	$52,309	614	3,069	2,455	370
47-2000	Construction Trades Workers	$53,366	910	3,500	2,590	295
43-6000	Secretaries and Administrative Assistants	$45,809	753	3,203	2,450	330
19-2000	Physical Scientists	$86,147	578	2,982	2,404	222
43-1000	Supervisors of Office and Administrative Support Workers	$65,384	460	2,119	1,659	196
49-3000	Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	$56,272	444	1,852	1,408	160
19-1000	Life Scientists	$105,403	393	2,001	1,608	138
51-8000	Plant and System Operators	$55,177	378	1,759	1,381	156
41-3000	Sales Representatives, Services	$69,641	338	1,657	1,319	149
41-2000	Retail Sales Workers	$39,024	219	1,094	875	177
27-1000	Art and Design Workers	$58,828	285	1,412	1,127	133
49-2000	Electrical and Electronic Equipment Mechanics, Installers, and Repairers	$59,025	284	1,371	1,088	131
49-1000	Supervisors of Installation, Maintenance, and Repair Workers	$78,907	310	1,436	1,126	120
37-2000	Building Cleaning and Pest Control Workers	$34,378	215	1,062	847	149
23-1000	Lawyers, Judges, and Related Workers	$176,904	351	1,780	1,429	78
53-1000	Supervisors of Transportation and Material Moving Workers	$61,288	248	1,208	961	123

NOTE: The Standard Occupational Classification system divides occupations into four levels of aggregation with the highest level of aggregation being major groups, then minor groups, broad occupations, and detailed occupations.
SOURCE: NAATBaat/NREL Lithium-Ion Supply Chain Database, Bureau of Labor Statistics Occupational Employment Projections Data, and authors' calculations.

employment of 34,220 and the final column provides our estimate of annual job openings of 4,427 from 2023 to 2030, reflecting both net employment growth and hiring to replace workers who retire or leave the profession.

Each of the minor occupation groups can be further stratified by the underlying detailed occupations that are most relevant to lithium-ion battery production. Table 6 lists the detailed occupations associated with the top-ranked minor group, assemblers and fabricators, including BLS data on the median annual earnings in 2022, the typical education level needed to enter the occupation, and the type of training—none, short-, medium-, or long-term—needed after hire to become competent in the occupation.[8] These classifications provide guidance in terms of the kinds of educational credentials and workforce development training that will be needed for these occupations.

ASSEMBLERS AND FABRICATORS

The largest share of jobs forecasted are for assemblers and fabricators, SOC 51-2000. These represent production occupations taking place at facilities up and down the value chain. Median earnings for this occupation range from $37,280 to $50,850 in 2022, with typical entry-level education being a high school diploma or equivalent. Assemblers and fabricators will be employed in facilities that manufacture cells and electrodes, finished modules and packs, and the plastic and metal component-inputs and specialized equipment used in manufacturing. In many cases, these jobs will take place in advanced manufacturing settings that make use of cutting-edge industrial automation technology. Stringent standards for material purity require some of

[8] The BLS definitions of internship/residency, apprenticeships, and long-, moderate-, and short-term on-the-job training are found here: https://www.bls.gov/emp/documentation/definitions.htm.

Table 6 Assemblers and Fabricators

SOC Code	Description	U.S. annual median wage 2022	Typical education needed for entry	Typical on-the-job training needed to attain competency
51-2021	Coil winders, tapers, and finishers	$43,160	High school diploma or equivalent	Moderate-term
51-2028	Electrical, electronic, and electromechanical assemblers, except coil winders, tapers, and finishers	$38,580	High school diploma or equivalent	Moderate-term
51-2031	Engine and other machine assemblers	$50,850	High school diploma or equivalent	Moderate-term
51-2041	Structural metal fabricators and fitters	$47,200	High school diploma or equivalent	Moderate-term
51-2051	Fiberglass laminators and fabricators	$38,110	High school diploma or equivalent	Moderate-term
51-2061	Timing device assemblers and adjusters	$42,290	High school diploma or equivalent	Moderate-term
51-2090	Miscellaneous assemblers and fabricators	$37,280	High school diploma or equivalent	Moderate-term

SOURCE: Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook.

these jobs to be performed in clean-room environments. Employers within the industry often offer training in specific technical processes. Skills beneficial to prospective workers in this industry include industrial mechatronics and PLC programming, electrical and chemical safe-handling, detail-orientation, and ability to follow complex processes.

All of the detailed occupations listed require moderate-term on-the-job training that generally lasts one month to a year and can include a mix of direct on-the-job experience and classroom instruction and may be part of an apprenticeship program.

Appendix A provides similar tables of detailed occupations for the next 9 top-ranked occupations. Combined, these 10 minor occupations account for over half of the change in lithium-ion battery related employment from 2023 to 2030. In future research, we plan to validate these choices of most relevant detailed occupations with industry experts. We also welcome input from interested readers of this report.

EDUCATION AND TRAINING REQUIREMENTS ACROSS ALL DETAILED OCCUPATIONS

Looking at *all* of the detailed occupations that make up the 2030 estimate of 310,000 employees, we examine the education needed to enter these occupations and the kinds of training generally received after hire. Overall, 32 percent of employees were in occupations requiring a bachelor's degree or higher, and 68 percent were in occupations generally requiring an associate degree, a postsecondary nondegree award, a high school diploma, or no formal education to enter.

In terms of the training generally received after hire, we focus on occupations that generally provide moderate (1 month to a year) or long-term (more than 12 months) training or have apprenticeships (often 1–5 years). We are specifically interested in occupations that generally require an associate degree, postsecondary nondegree award, high school or equivalent, or no formal training to enter. We find that 67 percent of the employees in occupations with these general educational requirements also receive moderate, long-term, or apprenticeship-type training after hire. In other words, the search for workers in occupations related to lithium-ion battery production will require a significant amount of employer-sponsored training.

MICHIGAN CASE STUDY

With a rich legacy in automotive manufacturing, Michigan is uniquely suited to participate in changes to the manufacturing landscape associated with the transition to EVs.

Many battery plants co-locate with automotive plants to optimize supply chain logistics. As of March 2023, the Environmental Defense Fund (2023b) estimated Michigan's share of the currently announced future U.S. lithium battery investment at 14 percent. The Environmental Defense Fund highlights Michigan as the top battery manufacturing state followed by Georgia, Tennessee, and Kentucky. Argonne National Labs estimates 97–136 GWh of announced capacity in Michigan by 2030, while the Environmental Defense Fund (2023b) estimates 140 GWh of capacity to be installed by 2028. We use the upper bound of 136 GWh from Argonne National Laboratory for our estimate of Michigan's nameplate capacity in 2030.

Data from the NAATBat/NREL database indicates a nameplate productive capacity of 32.2 GWh/year in Michigan in 2023. Table 7 shows employment levels across segments of the lithium-ion battery supply chain.

Table 7 Michigan Lithium-Ion Battery Supply Chain Employment by Segment, 2023

Supply chain segment	NAATBatt employment in Michigan associated with 32.2 GWh of battery production	Relative share of total employment (%)
1-Raw Materials	400	5.3
2-Battery Grade Materials	54	0.7
3-Other Battery Components Materials	63	0.8
4-Electrodes and Cells	1,406	18.7
5-Modpacks	3,534	46.9
6-End of Life (EOL)	114	1.5
7-Equipment	41	0.5
8-Service and Repair	446	5.9
9-Research and Development	1,315	17.5
10-Modeling	160	2.1
11-Distributors	0	0.0
Total	**7,533**	**100**

SOURCE: NAATBaat/NREL Lithium-Ion Supply Chain Database and authors' calculations.

Michigan is well represented in key segments of the supply chain, including Electrode and Cell manufacturing, Module and Pack manufacturing, Service and Repair, and Research and

Development. As such, the relative shares of employment by supply chain segment in Michigan are not dissimilar from the distribution of employment nationwide.

Table 8 shows how these supply chain employment levels correspond to NAICS employment levels.

Table 8 Michigan Lithium-Ion Battery Supply Chain Employment by NAICS Industry, Current and Projected

NAICS 3-Digit	Description	NAATBatt employment in Michigan in 2023 associated with 32.2 GWh of battery production	Projected employment in Michigan in 2030 associated with 136 GWh of battery production
212	Mining (except Oil and Gas)	400	400[a]
325	Chemical Manufacturing	107	452
326	Plastics and Rubber Products Manufacturing	995	4,202
333	Machinery Manufacturing	10	42
334	Computer and Electronic Product Mfg.	318	1,343
335	Electrical Equipment, Appliance, and Component Manufacturing	3,344	14,124
336	Transportation Equipment Manufacturing	795	3,358
423	Merchant Wholesalers, Durable Goods	77	325
441	Motor Vehicle and Parts Dealers	125	528
541	Professional, Scientific, and Technical Svcs.	1,191	5,030
561	Administrative and Support Services	105	443
562	Waste Management and Remediation Svcs.	40	169
811	Repair and Maintenance	26	110
	Total	**7,533**	**30,527**

[a] Employment in Raw Materials held constant over the projection period. We exclude Mining from our projections based on uncertainty over the supply of, permitting for, and the development of economically viable sites for extraction of critical mining inputs.
SOURCE: NAATBaat/NREL Lithium-Ion Supply Chain Database and authors' calculations.

Applying our methodology for calculating the changes in occupation/industry shares for the 2023–2030 projection period, Table 9 shows employment projections for occupations in Michigan with an employment change of at least 75.

In this analysis, a Michigan workforce of 7,533 individuals is associated with 32.2 GWh of production capacity in 2023. If installed capacity reaches the upper bound of the estimate provided by Argonne National Laboratory, a workforce of over 30,000 individuals may be required to support the production of 136 GWh in Michigan by 2030. Michigan's occupational demand mirrors nationwide trends, with assemblers and fabricators, engineers, metal and plastic

Table 9 Battery-Related Occupational Employment in Michigan, 2023–2030

Occupation code	Occupational title	Battery-related occupational employment 2023	Battery-related occupational employment 2030	Employment change	Annual job openings
51-2000	Assemblers and Fabricators	1,431	5,851	4,420	637
51-4000	Metal Workers and Plastic Workers	582	2,397	1,815	248
17-2000	Engineers	654	2,903	2,248	202
51-9000	Other Production Occupations	414	1,707	1,293	192
13-1000	Business Operations Specialists	424	1,806	1,383	167
53-7000	Material Moving Workers	324	1,366	1,042	183
15-2000	Computer Occupations	294	1,337	1,043	93
11-3000	Operations Specialties Managers	256	1,122	866	87
51-1000	Supervisors of Production Workers	194	838	644	86
49-9000	Other Installation, Maintenance, and Repair Occupations	158	739	581	73
17-3000	Drafters, Engineering Technicians, and Mapping Technicians	150	625	475	60
43-4000	Information and Record Clerks	145	565	421	70
43-5000	Material Recording, Scheduling, Dispatching, and Distributing Workers	144	599	455	59
43-9000	Other Office and Administrative Support Workers	134	529	394	60
11-1000	Top Executives	134	573	438	50
47-2000	Construction Trades Workers	123	517	394	56
41-4000	Sales Representatives, Wholesale and Manufacturing	129	547	418	55
13-2000	Financial Specialists	123	516	392	46
11-9000	Other Management Occupations	115	493	377	37
43-3000	Financial Clerks	83	324	241	35
11-2000	Advertising, Marketing, Promotions, Public Relations, and Sales Managers	75	318	243	28
41-2000	Retail Sales Workers	46	195	149	26
49-3000	Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	53	228	175	23
43-6000	Secretaries and Administrative Assistants	52	188	136	19
53-3000	Motor Vehicle Operators	35	148	113	18
43-1000	Supervisors of Office and Administrative Support Workers	41	161	121	16
41-3000	Sales Representatives, Services	31	131	100	15
19-2000	Physical Scientists	33	133	100	13
23-1000	Lawyers, Judges, and Related Workers	44	188	144	10
37-2000	Building Cleaning and Pest Control Workers	26	111	85	15
27-1000	Art and Design Workers	28	118	90	11
23-2000	Legal Support Workers	26	107	80	12
49-1000	Supervisors of Installation, Maintenance, and Repair Workers	23	99	75	9

SOURCE: NAATBaat/NREL Lithium-Ion Supply Chain Database, Michigan Department of Technology, Management, and Budget's Occupational Employment Projections, Bureau of Labor Statistics Occupational Employment Projections Data, and authors' calculations.

workers, business operations specialists, material moving workers, and other production occupations experiencing high employment change over the projection period and the greatest number of annual job openings.

Estimates of occupational demand are critical to the state's efforts to develop and scale training curriculums, including CTE courses, which will be needed for the transition from internal combustion to EVs. The results of this analysis are intended to provide guidance to the EV Jobs Academy, a state of Michigan joint consortium of community colleges, workforce developers, and employer partners.

CONCLUDING REMARKS

This report develops estimates of projected net employment changes and annual job openings for occupations related to battery production in the United States. Industry estimates of current and future GWh production capacity are used with official national and state projections of changing industry/occupational shares for this purpose. Industry employment related to battery production is assumed to increase proportionally to the projected increase in battery production.

Our analysis suggests that employment growth in battery manufacturing and related industries is connected to a broad range of occupations with a diversity of skills requirements. Based on our analysis of the growth in broadly defined occupations and the most relevant detailed occupations related to battery production, we find the greatest share of employment growth will be in production occupations whose training requirements may be met by associate and technical degree programs offered by community colleges, as well as through apprenticeships and on-the-job training (assemblers and fabricators, other production occupations, metal and plastics workers). Other occupations with significant projected growth, such as engineers, business operations specialists, and operations specialty managers generally require a bachelor's degree or higher.

Overall, the transition from ICE to EV will require substantial training or retraining of workers to ensure that the United States has a chance of sustaining its share of the global automotive industry.

Appendix A: Detailed Occupations in the Lithium-Ion Battery Supply Chain

Table A1 Other Production Occupations

SOC Code	Description	U.S. annual median wage 2022	Typical education needed for entry	Typical on-the-job training needed to attain competency
51-9011	Chemical equipment operators and tenders	$49,330	High school diploma or equivalent	Moderate-term
51-9012	Separating, filtering, clarifying, precipitating, and still machine setters, operators, and tenders	$46,250	High school diploma or equivalent	Moderate-term
51-9021	Crushing, grinding, and polishing machine setters, operators, and tenders	$43,290	High school diploma or equivalent	Moderate-term
51-9022	Grinding and polishing workers, hand	$36,960	No formal educational credential	Moderate-term
51-9023	Mixing and blending machine setters, operators, and tenders	$43,410	High school diploma or equivalent	Moderate-term
51-9031	Cutters and trimmers, hand	$36,130	No formal educational credential	Short-term
51-9032	Cutting and slicing machine setters, operators, and tenders	$39,880	High school diploma or equivalent	Moderate-term
51-9041	Extruding, forming, pressing, and compacting machine setters, operators, and tenders	$39,480	High school diploma or equivalent	Moderate-term
51-9051	Furnace, kiln, oven, drier, and kettle operators and tenders	$44,530	High school diploma or equivalent	Moderate-term
51-9061	Inspectors, testers, sorters, samplers, and weighers	$43,900	High school diploma or equivalent	Moderate-term
51-9111	Packaging and filling machine operators and tenders	$36,750	High school diploma or equivalent	Moderate-term
51-9123	Painting, coating, and decorating workers	$38,270	No formal educational credential	Moderate-term
51-9124	Coating, painting, and spraying machine setters, operators, and tenders	$43,960	High school diploma or equivalent	Moderate-term
51-9141	Semiconductor processing technicians	$44,690	High school diploma or equivalent	Moderate-term
51-9151	Photographic process workers and processing machine operators	$36,280	High school diploma or equivalent	Short-term
51-9161	Computer numerically controlled tool operators	$46,760	High school diploma or equivalent	Moderate-term
51-9162	Computer numerically controlled tool programmers	$60,800	Postsecondary nondegree award	Moderate-term
51-9191	Adhesive bonding machine operators and tenders	$38,780	High school diploma or equivalent	Moderate-term
51-9195	Molders, shapers, and casters, except metal and plastic	$39,590	High school diploma or equivalent	Long-term
51-9198	Helpers--production workers	$34,670	High school diploma or equivalent	Short-term
51-9199	Production workers, all other	$35,490	High school diploma or equivalent	Moderate-term

SOURCE: Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook.

Other production occupations typically require only a high school diploma or equivalent or no formal educational credential to enter (see Table A1). The annual salaries range from $34,670 to $49,330. One occupation, *Computer numerically controlled tool programmers*, requires a postsecondary nondegree award, such as industry certified or a community college credential, and had median annual earnings of over $60,000 in 2022.

The on-the-job training required for these occupations varies widely and includes short-term (less than 1 month), moderate-term (1 month to a year), and long-term (more than 12 months). Generally, moderate- and long-term training includes a mix of direct on-the-job and classroom instruction and may be facilitated through an apprenticeship program.

Metal and Plastic Workers, SOC 51-4000, set up and operate equipment that cuts, shapes, and forms metal and plastic materials or pieces. This occupation is forecast to see significant growth within input supply chain segments at facilities that manufacture components for battery cells and assemblies. Median pay for this occupation was $41,060 in 2022, with a typical education of an associate degree or high school diploma and moderate-term on-the-job training (see Table A2). As already noted, such training generally lasts up to a year, often with a mix of classroom and on-the-job technical training and may be part of an apprenticeship program. Familiarity with CAD, CAM, CNC and/or PLC industrial control applications is often required for this minor occupation. It is common for individuals to advance from machine operating positions to machine set-up and maintenance and supervisory positions.

Table A2 Metal and Plastic Workers

SOC Code	Description	U.S. annual median wage 2022	Typical education needed for entry	Typical on-the-job training needed to attain competency
51-4021	Extruding and drawing machine setters, operators, and tenders, metal and plastic	$39,970	High school diploma or equivalent	Moderate-term
51-4022	Forging machine setters, operators, and tenders, metal and plastic	$46,540	High school diploma or equivalent	Moderate-term
51-4023	Rolling machine setters, operators, and tenders, metal and plastic	$46,310	High school diploma or equivalent	Moderate-term
51-4031	Cutting, punching, and press machine setters, operators, and tenders, metal and plastic	$39,340	High school diploma or equivalent	Moderate-term
51-4032	Drilling and boring machine tool setters, operators, and tenders, metal and plastic	$42,450	High school diploma or equivalent	Moderate-term
51-4033	Grinding, lapping, polishing, and buffing machine tool setters, operators, and tenders, metal and plastic	$38,910	High school diploma or equivalent	Moderate-term
51-4034	Lathe and turning machine tool setters, operators, and tenders, metal and plastic	$47,020	High school diploma or equivalent	Moderate-term
51-4035	Milling and planing machine setters, operators, and tenders, metal and plastic	$46,870	High school diploma or equivalent	Moderate-term
51-4041	Machinists	$48,510	High school diploma or equivalent	Long-term
51-4051	Metal-refining furnace operators and tenders	$50,280	High school diploma or equivalent	Moderate-term
51-4052	Pourers and casters, metal	$45,070	High school diploma or equivalent	Moderate-term
51-4061	Model makers, metal and plastic	$57,620	High school diploma or equivalent	Moderate-term
51-4062	Patternmakers, metal and plastic	$54,970	High school diploma or equivalent	Moderate-term
51-4071	Foundry mold and coremakers	$40,120	High school diploma or equivalent	Moderate-term
51-4072	Molding, coremaking, and casting machine setters, operators, and tenders, metal and plastic	$37,050	High school diploma or equivalent	Moderate-term
51-4081	Multiple machine tool setters, operators, and tenders, metal and plastic	$39,210	High school diploma or equivalent	Moderate-term
51-4111	Tool and die makers	$59,800	Postsecondary nondegree award	Long-term
51-4121	Welders, cutters, solderers, and brazers	$47,540	High school diploma or equivalent	Moderate-term
51-4122	Welding, soldering, and brazing machine setters, operators, and tenders	$44,920	High school diploma or equivalent	Moderate-term
51-4191	Heat treating equipment setters, operators, and tenders, metal and plastic	$40,900	High school diploma or equivalent	Moderate-term
51-4192	Layout workers, metal and plastic	$58,260	High school diploma or equivalent	Moderate-term
51-4193	Plating machine setters, operators, and tenders, metal and plastic	$37,900	High school diploma or equivalent	Moderate-term
51-4194	Tool grinders, filers, and sharpeners	$41,940	High school diploma or equivalent	Moderate-term
51-4199	Metal workers and plastic workers, all other	$38,340	High school diploma or equivalent	Moderate-term

SOURCE: Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook.

Growth of the lithium-ion battery manufacturing industry in the United States is also expected to bring significant job demand for Engineering occupations, SOC 17-2000. This includes Chemical, Computer Hardware, Electrical, Industrial, and Mechanical engineers who will be required to design, develop, and test new products, systems, and processes in the manufacturing setting. These will be employed in all segments of the supply chain, from mining and materials processing, production, research and development, and recycling/end-of-life. Median U.S. wages in 2022 ranged from $92,459 to $112,978, with entry-level education of a bachelor's degree required for most engineering occupations (see Table A3). Successful job applicants are assumed to have the technical background and education to perform the work and generally do not require further formal classroom training. Attraction and retention of qualified candidates for these job roles is considered critical for sustained growth of the industry in the United States.

Table A3 Engineers

SOC code	Description	U.S. annual median wage 2022	Typical education needed for entry	Typical on-the-job training needed to attain competency
17-2041	Chemical engineers	$106,260	Bachelor's degree	None
17-2051	Civil engineers	$89,940	Bachelor's degree	None
17-2061	Computer hardware engineers	$132,360	Bachelor's degree	None
17-2071	Electrical engineers	$103,320	Bachelor's degree	None
17-2072	Electronics engineers, except computer	$108,170	Bachelor's degree	None
17-2081	Environmental engineers	$96,530	Bachelor's degree	None
17-2111	Health and safety engineers, except mining safety engineers and inspectors	$100,660	Bachelor's degree	None
17-2112	Industrial engineers	$96,350	Bachelor's degree	None
17-2131	Materials engineers	$100,140	Bachelor's degree	None
17-2141	Mechanical engineers	$96,310	Bachelor's degree	None
17-2151	Mining and geological engineers, including mining safety engineers	$97,490	Bachelor's degree	None
17-2199	Engineers, all other	$104,600	Bachelor's degree	None

SOURCE: Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook.

Lithium-ion batteries are regulated as a hazardous material by the U.S. Department of Transportation.[9] The energy density and flammable electrolyte composition of batteries can, under specific conditions, cause overheating and ignition such as through a short circuit, improper design or assembly, or external source of damage. Material moving workers are required to understand and implement the appropriate safety precautions when handling these batteries. The detailed occupations listed above generally require no formal credential for entry and only short-term on-the-job training of less than one month.[10] The median annual wages vary from $34,000 to $59,000 (see Table A4).

Table A4 Material Moving Workers

SOC Code	Description	U.S. annual median wage 2022	Typical education needed for entry	Typical on-the-job training needed to attain competency
53-7011	Conveyor operators and tenders	$36,890	No formal educational credential	Short-term
53-7021	Crane and tower operators	$61,340	High school diploma or equivalent	Moderate-term
53-7031	Dredge operators	$47,090	High school diploma or equivalent	Moderate-term
53-7041	Hoist and winch operators	$58,950	No formal educational credential	Short-term
53-7051	Industrial truck and tractor operators	$41,230	No formal educational credential	Short-term
53-7061	Cleaners of vehicles and equipment	$31,000	No formal educational credential	Short-term
53-7062	Laborers and freight, stock, and material movers, hand	$36,110	No formal educational credential	Short-term
53-7063	Machine feeders and offbearers	$38,040	No formal educational credential	Short-term
53-7064	Packers and packagers, hand	$32,920	No formal educational credential	Short-term
53-7065	Stockers and order fillers	$34,220	High school diploma or equivalent	Short-term

SOURCE: Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook.

[9] "Transporting Lithium Batteries: Lithium Battery Safety."

[10] A relevant question for the authors to explore is the need for specific material moving training as a result of DOT classification of lithium-ion batteries as a regulated and hazardous material.

Business operations specialists perform a variety of roles to evaluate and maintain productive workflows in facilities at all points of the supply chain. These occupations include buyers and purchasing manager*s* and logisticians responsible for managing the flow of materials throughout the manufacturing process, as well as human resource specialists, training and development and labor relations specialists responsible for human capital assets. All of the detailed occupations listed as relevant to lithium-ion battery production require a BA degree for entry and generally no on-the-job training except for a few detailed occupations (purchase agents, compliance officers, and cost estimators) that require moderate on-the-job training (1 to 12 months) in employer specific practices and applications. Median annual wages vary from $63,000 to $95,000 (see Table A5).

Table A5 Business Operations Specialists

SOC Code	Description	U.S. annual median wage 2022	Typical education needed for entry	Typical on-the-job training needed to attain competency
13-1020	Buyers and purchasing agents	$67,620	Bachelor's degree	Moderate-term
13-1041	Compliance officers	$71,690	Bachelor's degree	Moderate-term
13-1051	Cost estimators	$71,200	Bachelor's degree	Moderate-term
13-1071	Human resources specialists	$64,240	Bachelor's degree	None
13-1075	Labor relations specialists	$82,010	Bachelor's degree	None
13-1081	Logisticians	$77,520	Bachelor's degree	None
13-1111	Management analysts	$95,290	Bachelor's degree	None
13-1141	Compensation, benefits, and job analysis specialists	$67,780	Bachelor's degree	None
13-1151	Training and development specialists	$63,080	Bachelor's degree	None
13-1161	Market research analysts and marketing specialists	$68,230	Bachelor's degree	None
13-1199	Business operations specialists, all other	$75,990	Bachelor's degree	None

SOURCE: Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook.

The detailed entries in this 'Other' minor group of installation, maintenance, and repair occupations vary in terms of technical skill requirements. A common element they share, however, is the generally more extensive training requirements, many with either moderate-term or long-term on-the-job training, which, as mentioned previously, include a mix of technical classroom training and on-the-job experience, and can include apprenticeships (millwrights are listed specifically as requiring that form of training). The education requirement is generally a high school diploma or equivalent and the median annual wages for many of the occupations are in the $50,000 to $82,000 range, reflecting their specific skill requirements (see Table A6).

Table A6 Other Installation, Maintenance, and Repair Occupations

SOC Code	Description	U.S. annual median wage 2022	Typical education needed for entry	Typical on-the-job training needed to attain competency
49-9012	Control and valve installers and repairers, except mechanical door	$64,810	High school diploma or equivalent	Moderate-term
49-9021	Heating, air conditioning, and refrigeration mechanics and installers	$51,390	Postsecondary nondegree award	Long-term
49-9041	Industrial machinery mechanics	$59,830	High school diploma or equivalent	Long-term
49-9043	Maintenance workers, machinery	$53,310	High school diploma or equivalent	Long-term
49-9044	Millwrights	$60,930	High school diploma or equivalent	Apprenticeship
49-9051	Electrical power-line installers and repairers	$82,340	High school diploma or equivalent	Long-term
49-9052	Telecommunications line installers and repairers	$60,580	High school diploma or equivalent	Long-term
49-9069	Precision instrument and equipment repairers, all other	$61,690	High school diploma or equivalent	Long-term
49-9071	Maintenance and repair workers, general	$44,980	High school diploma or equivalent	Moderate-term
49-9098	Helpers—installation, maintenance, and repair workers	$35,100	High school diploma or equivalent	Short-term
49-9099	Installation, maintenance, and repair workers, all other	$44,500	High school diploma or equivalent	Moderate-term

SOURCE: Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook.

This minor group of occupations focuses on individuals who plan, direct, and coordinate operations and the functions of numerous business domains, including administration, facilities, IT related, industrial production, HR and training related, transportation and storage, among others. The general educational requirement is a BA without specific training requirements after the point of hire. The salaries are very high, ranging from $99,000 to $164,000 (see Table A7).

Table A7 Operations Specialties Managers

SOC Code	Description	U.S. annual median wage 2022	Typical education needed for entry	Typical on-the-job-training needed to attain competency
11-3012	Administrative services managers	$103,330	Bachelor's degree	None
11-3013	Facilities managers	$99,030	Bachelor's degree	None
11-3021	Computer and information systems managers	$164,070	Bachelor's degree	None
11-3031	Financial managers	$139,790	Bachelor's degree	None
11-3051	Industrial production managers	$107,560	Bachelor's degree	None
11-3061	Purchasing managers	$131,350	Bachelor's degree	None
11-3071	Transportation, storage, and distribution managers	$98,560	High school diploma or equivalent	None
11-3111	Compensation and benefits managers	$131,280	Bachelor's degree	None
11-3121	Human resources managers	$130,000	Bachelor's degree	None
11-3131	Training and development managers	$120,000	Bachelor's degree	None

SOURCE: Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook.

The detailed occupation of supervisors of production workers generally requires a high school degree and the wages are commensurate with the promotion of production and operating workers from within (see Table A8). Workers who are promoted to supervisory roles may benefit from training resources related to leadership and management skills in manufacturing settings.

Table A8 Supervisors of Production Workers

SOC Code	Description	U.S. annual median wage 2022	Typical education needed for entry	Typical on-the-job training needed to attain competency
51-1011	First-line supervisors of production and operating workers	$63,510	High school diploma or equivalent	None

SOURCE: Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook.

The detailed occupations of sales representatives in wholesale and manufacturing involve the sales of battery-related products that may include sufficient technical and scientific knowledge of critical minerals, chemical composition, battery cell electronic, and density performance requirements, among other requirements. The occupations both require moderate-term on-the-job training with the requisite mix of on-the-job and classroom training (see Table A9). The sales representatives that feature technical and scientific products have significantly higher median wages.

Table A9 Sales Representatives, Wholesale and Manufacturing

SOC Code	Description	U.S. annual median wage 2022	Typical education needed for entry	Typical on-the-job training needed to attain competency
41-4011	Sales representatives, wholesale and manufacturing, technical and scientific products	$97,710	Bachelor’s degree	Moderate-term
41-4012	Sales representatives, wholesale and manufacturing, except technical and scientific products	$63,230	High school diploma or equivalent	Moderate-term

SOURCE: Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook.

Appendix B: Data Disclaimer

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Version 4 June 30, 2023
NAATBatt International funded this project under two Technical Services Agreements (TSA-21-17854 and TSA-21-21593) with NREL.

Appendix C: Additional Sources

National Blueprint for Lithium Batteries 2021–2030. Federal Consortium for Advanced Batteries. June 2021.

NAATBatt Lithium-Ion Battery Supply Chain Database. NAATBatt. Last updated June 2023.

Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010–2021. David Gohlke, Yan Zhou, Xinyi Wu, and Calista Courtney. Energy Systems and Infrastructure Analysis Division, Argonne National Laboratory. November 2022.

Occupational Employment and Wage Survey, Bureau of Labor Statistics, May 2022, Michigan Occupational Employment Projections by Industry, Michigan, 2020–2030, Department of Technology, Management, and Budget, Michigan Department of Labor and Economic Opportunity.

Building a Robust and Resilient U.S. Lithium Battery Supply Chain. Li-Bridge. February 2023.

Capturing the Battery Value-Chain Opportunity. Nicolò Campagnol, Alexander Pfeiffer, and Christer Tryggestad. McKinsey&Company. January 7, 2023.

Charging Into the Future: The Transition to Electric Vehicles. Beyond the Numbers, Vol. 12, No. 4. BLS. February 2023.

Electric Vehicle-Battery Value Chain Talent Requirements. Invest Windsor Essex. December 2021.

The New York Jobs Project: A Guide to Creating Jobs in Energy Storage. American Jobs Project and New York Battery and Energy Storage Technology Consortium (NY-BEST). December 2018.

Vocational Skills Gap Assessment And Workforce Development Plan. South Metropolitan Tafe, Western Australia. Future Battery Industries Cooperative Research Centre. August 2021.

References

Abraham, Katherine G., Brad Hershbein, Susan Houseman, and Beth Truesdale. 2023. "The Independent Contractor Workforce: New Evidence on Its Size and Composition and Ways to Improve Its Measurement in Household Surveys." Upjohn Institute Working Paper No. 23-380. Kalamazoo, MI: W.E. Upjohn Institute for Employment Research.

Argonne National Laboratory. 2022. *Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010–2021*. DuPage County, Illinois: Argonne National Laboratory.

Brinley, Stephanie. 2023. "EV Chargers: How Many Do We Need?" January 9. New York: S&P Global Mobility.

Bureau of Labor Statistics. 2024a. "Current Employment Survey." Washington, DC: Bureau of Labor Statistics.

———. 2024b. "Industry Productivity and Costs." Washington, DC: Bureau of Labor Statistics.

Center for Strategic and International Studies. 2021. "The United States' Industrial Strategy for the Battery Supply Chain." Washington, DC: Center for Strategic and International Studies.

Cox Automotive. 2024 "A Record 1.2 Million EVs Were Sold in the U.S. in 2023, according to Estimates from Kelley Blue Book." January 9. Atlanta, GA: Cox Automotive.

Environmental Defense Fund. 2023a. "U.S. Electric Vehicle Battery Manufacturing on Track to Meet Demand." Washington, DC: Environmental Defense Fund.

———. 2023b. "U.S. Electric Vehicle Manufacturing Investments and Jobs: Characterizing the Impacts of the Inflation Reduction Act after 6 Months." Washington, DC: Environmental Defense Fund.

Federal Consortium for Advanced Batteries (FCAB). 2021. *National Blueprint for Lithium Batteries, 2021–2030.* Washington, DC: Federal Consortium for Advanced Batteries.

Fischer, Lauritz, Felix Rupalla, Shivika Sahdev, and Ali Tanweer. 2024. "Exploring Consumer Sentiment on Electric-Vehicle Charging." McKinsey and Company.

Gomes, Nathan. 2024. "GM's First-Quarter US Sales Dip on Lower Commercial Deliveries but Beats Toyota." April 2. Reuters.

Gomes, Nathan, and Joseph White. 2024. "GM, Ford Are Upbeat on 'Really Strong' US Demand." March 26. Reuters.

Home, Andy. 2023. "China Ups Critical Minerals Heat With Graphite Controls." London: Reuters.

Hummel, Patrick, et al. 2017. *UBS Evidence Lab Electric Car Teardown—Disruption Ahead?* Zurich: UBS Global Research.

International Energy Agency. N.d. "Electric Vehicles: Where Do We Need To Go?" Washington, DC: International Energy Agency.

———. 2023. "Lithium-Ion Battery Manufacturing Capacity, 2022–2030." Paris: IEA.

Lee, Medora. 2024. "What electric Vehicle Shoppers Want Isn't What's for Sale, and It's Hurting Sales: Poll." April 3. USA TODAY.

Li-Bridge. 2023. *Building a Robust and Resilient U.S. Lithium Battery Supply Chain.* DuPage County, Illinois: Li-Bridge and Argonne National Laboratory.

McKinsey and Company. 2022. "Unlocking the Growth Opportunity in Battery Manufacturing Equipment." McKinsey and Company.

Mehdi, Ahmed, and Tom Moerenhout. 2023. "The IRA and the US Battery Supply Chain: Background and Key Drivers." New York: Center on Global Policy at Colombia/School of International and Public Affairs.

Michalek, Jeremy, and Kate Whitefoot. 2023. "Tech Advances Will Drive the Transition to Electric Vehicles." Pittsburgh: Carnegie Mellon University.

Reuters. 2023. "China Gallium, Germanium Export Curbs Kick In; Wait For Permits Starts." Beijing: Reuters.

S&P Global Commodity Insights. 2023. "Australia Set To Boost Lithium Refining Capacity, To Surpass Spodumene Output." New York: S&P Global.

S&P Global Market Intelligence. 2023. "Lithium-Ion Battery Capacity to Grow Steadily to 2030." New York: S&P Global Market Intelligence.

U.S. Energy Information Administration. 2023. "Electric Vehicles and Hybrids Surpass 16% of Total 2023 U.S. Light-Duty Vehicle Sales." September 7. Washington, DC: U.S. Energy Information Administration.

Wayland, Michael. 2021. "Auto Executives Say More Than Half of U.S. Car Sales Will Be EVs by 2030, KPMG Survey Shows." November 30. Englewood Cliffs, NJ: CNBC.

White House. 2021. "Executive Order on America's Supply Chains." Washington, DC: White House.

———. 2022. "Fact Sheet: Biden-Harris Administration Driving U.S. Battery Manufacturing and Good-Paying Jobs." White House Press Release, October 19. Washington, DC: White House.

———. 2023a. "Building a Thriving Clean Energy Economic in 2023 and Beyond." *White House Briefing Room* (blog). December 19.

———. 2023b. "Fact Sheet: Biden-Harris Administration Announces New Private and Public Sector Investments for Affordable Electric Vehicles." White House Press Release, April 17. Washington, DC: White House.

Woody, Maxell, Shawen A. Adderly, Rushabh Bohra, and Gregory A. Keolian. 2024. "Electric and Gasoline Vehicle Total Cost of Ownership across US Cities." *Journal of Industrial Ecology*.

Yu, Xiaolu, Weikang Li, Varun Gupta, Hongpeng Gao, Duc, Tran, Shatila Sarwar, Zheng Chen. 2022. "Current Challenges in Efficient Lithium-Ion Batteries' Recycling: A Perspective." *Global Challenges* 6(2200099).