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Quantification of Commercially Planned Battery Component Supply in North America through 2035

Energy Systems and Infrastructure Analysis Division

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LIST OF ACRONYMS

AAM	anode active material
ATVM	Advanced Technology Vehicles Manufacturing
BIL	Bipartisan Infrastructure Law
BNEF	Bloomberg New Energy Finance
CAM	cathode active material
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
ESS	energy storage systems
FAST	Fixing America's Surface Transportation Act
FCAB	Federal Consortium for Advanced Batteries
FTA	free trade agreement
GM	General Motors
HDV	heavy-duty vehicle
HUD	U.S. Department of Housing and Urban Development
ICEV	internal combustion engine vehicle
IIJA	Infrastructure Investment and Jobs Act
IRA	Inflation Reduction Act of 2022
IRC	Internal Revenue Code
IRS	Internal Revenue Service
LDV	light-duty vehicle
LFP	lithium iron phosphate ($LiFePO_4$)
LMO	lithium manganese oxide
LPO	DOE Loan Programs Office
MDV	medium-duty vehicle
MESC	Office of Manufacturing and Energy Supply Chains
MSP	Mineral Security Partnership
NCA	nickel cobalt aluminum
NMC	nickel manganese cobalt
NMC	nickel manganese cobalt aluminum
NREL	National Renewable Energy Laboratory

OEM	original equipment manufacturer
PEV	plug-in electric vehicle
SLI	starter, lighting, and ignition
ZEV	zero-emission vehicle

QUANTIFICATION OF COMMERCIALLY PLANNED BATTERY COMPONENT SUPPLY IN NORTH AMERICA THROUGH 2035

ABSTRACT

There is the potential for rapid growth in battery manufacturing in North America in the coming years, as indicated by investment plans which companies have announced. Argonne National Laboratory is tracking these investment announcements to understand the availability of domestically produced battery cells and battery components over the next decade. We find that companies have made announcements for over 1,300 GWh/year of lithium-ion battery cell production by 2030, enough to conservatively supply ten million electric vehicles and expected growth in stationary grid storage. From 2021 to 2032, battery cell production is modeled to grow 28-fold. For each of the core battery components of lithium-ion batteries (cathodes, anodes, separators, electrolytes, and foils), we describe the current announced capacities for materials with respect to cell production and end-use demand, finding similar rapid growth for each.

1 INTRODUCTION

Deep decarbonization requires a transition from combustion of fossil fuels to use of low-carbon energy sources (White House 2016; Steinberg 2017). One pathway for decarbonization involves batteries as mobile or stationary energy storage. For the electric grid, installation of batteries allows for intermittent low-carbon power sources such as wind and solar power to be dispatched as needed. Electrification of transportation allows use of low-carbon energy rather than energy derived from fossil fuels (DOE, DOT, EPA, and HUD 2023). For transportation, plug-in electric vehicles (PEVs, or more simply EVs) fueled in part or in full by electricity from the grid can have significantly lower emissions than internal combustion engine vehicles (ICEVs) using petroleum fuels (ANL 2023a).

Rechargeable batteries are used in electronics, vehicles, and energy storage systems (ESS), also referred to as stationary energy storage. Rechargeable batteries are also known as secondary batteries. Historically, the most common secondary battery chemistry has been lead-acid. Through 2015, over 80% of total worldwide battery capacity was lead-acid (Pillot 2021). However, lithium-ion batteries have rapidly grown in prominence. Lithium-ion batteries use lithium ions as charge carriers between the anode and the cathode. These charge carriers cross a separator, mediated by an electrolyte. By 2020, lithium-ion comprised approximately 1/3 of the global market, and by 2025, lithium-ion batteries are forecast to be the most common chemistry (Pillot 2021). Lithium-ion batteries are comparatively lightweight and energy dense, making them a suitable type of battery for electronics and transportation use. Lithium-ion battery prices have dropped more than 90% since 2010 (DOE 2023; Catsaros 2023; Henze 2021). This has led to lithium-ion batteries becoming more cost competitive for stationary applications as well.

Historically, there has been little manufacturing of lithium-ion batteries in the United States at a commercial scale. Laws such as the Infrastructure Investment and Jobs Act (IIJA, also commonly known as the Bipartisan Infrastructure Law, or BIL) and the Inflation Reduction Act of 2022 (IRA) have encouraged investment due to the availability of incentives for the production and use of battery technologies (U.S. Congress 2021; 2022).

In this analysis, we synthesize investments which companies have made for development of battery supply chains in North America. These investments include raw minerals extraction, processing of these minerals into battery grade materials, fabrication of battery components, and manufacturing of battery cells and packs. This report focuses on those portions of the battery supply chain considered "midstream," from materials processing to cell fabrication. Figure 1 shows a graphic from the Federal Consortium for Advanced Batteries (FCAB), which delineates upstream, midstream, and downstream battery production.

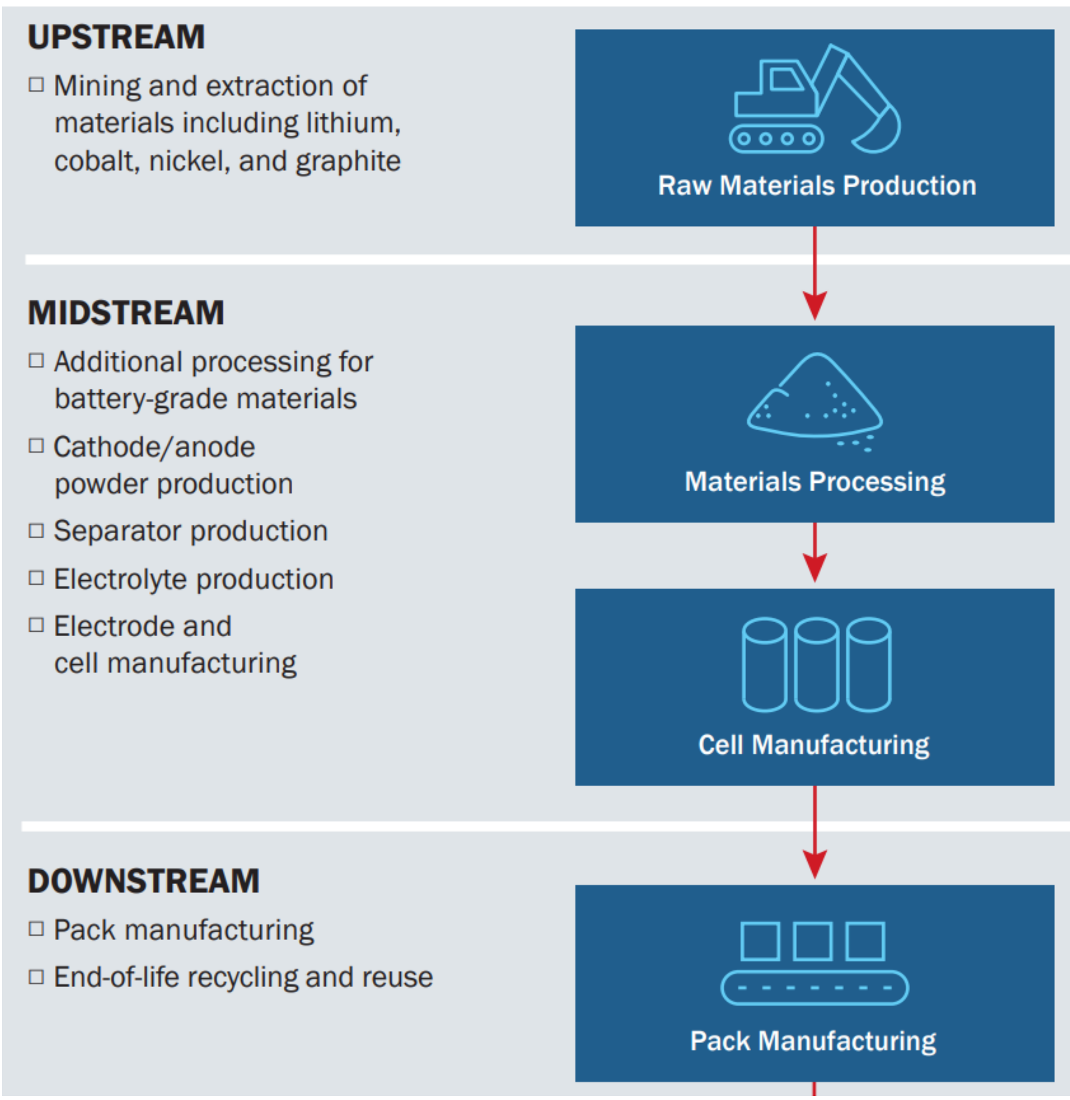

FIGURE 1 Battery supply chain (adapted from FCAB, 2021)

Section 2 of this report describes the landscape of existing manufacturing and recent investment announcements, along with forecasts of the overall demand for batteries. Section 3 shows the investments that have been announced for battery cells. Section 4 shows the investments that have been announced for manufacturing of battery components and processing of battery grade materials. Section 5 presents discussion and conclusions. Appendix A describes the methodology used to collect and analyze the data to estimate future manufacturing. Appendix B considers detailed sensitivity analysis on several assumptions to better understand and test the robustness of the results. Appendix C displays supply connections between battery cell companies and end-use from 2024 to 2029. Appendix D models international battery cell announcements within the Materials Security Partnership.

2 INVESTMENT AND DEMAND LANDSCAPE

2.1 INVESTMENTS IN BATTERY AND VEHICLE SUPPLY CHAINS

Argonne National Laboratory is tracking investments in battery and electric vehicle manufacturing to estimate growth of battery production in North America, based on press releases, financial disclosures, and news articles. This dataset is available online from Argonne (ANL 2024), and similar databases exist from other sources (Atlas Public Policy 2024; BGA 2023; Bockey 2023; Conness 2023; Turner 2022, White House 2023a). For the purposes of this analysis, battery production includes extraction of the raw minerals necessary to make batteries, processing of these ores into battery-grade materials, manufacturing of midstream battery precursors, and production of battery cells and packs for end use. Public announcements of investments often contain information about the expected capital expenditure and number of jobs that will be supported by the investment, along with an estimate of materials output capacity. By aggregating these announcements for the entire industry, we can make a qualitative assessment of the status of the domestic battery market.[1]

Since 2000, companies have announced over $150 billion in planned investments for battery production in the United States. This investment has accelerated in recent years, with over $100 billion dollars of investment announced in the last two years, as shown in Figure 2. In addition to economic investment, the number of announced jobs (when shared by the company) is also being tracked. Since 2021, companies have proposed manufacturing expansions entailing over 80,000 jobs in the battery supply chain in the United States and 100,000 jobs across North America. Figure 2 also shows the dates of enactment of the IIJA and IRA. Each of these laws was followed by an acceleration in new investment announcements.

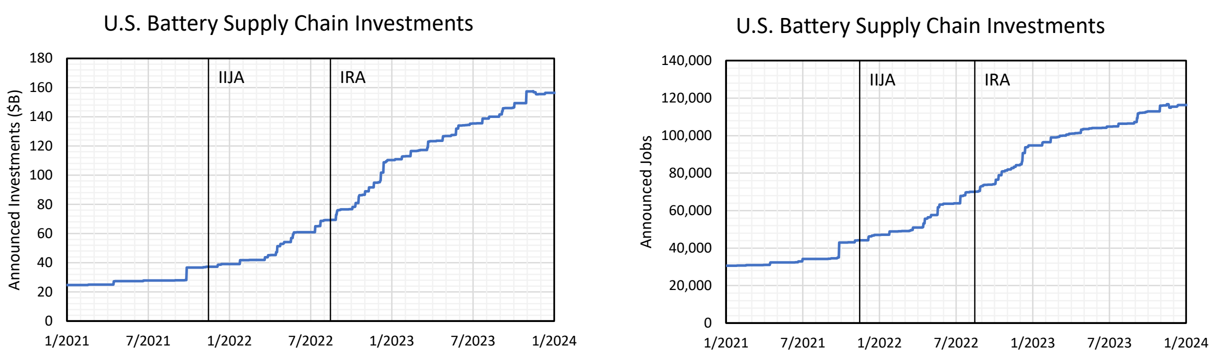

FIGURE 2 Evolution of battery supply chain investments and jobs in the U.S. since 2021

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[1] This value is based upon public statements of investment. Not all manufacturing facility expansions are announced publicly. Others which are announced may not include explicit statements about the scale of the investment, though the largest investments typically have this information. Additionally, this value is based on Argonne tracking of investments. While diligent effort has been paid to include existing facilities and older press releases, these historical announcements are more difficult to find, and so this data may be biased against older investments. Finally, the investment values are the nominal reported amounts, so older investments would need to be adjusted for inflation for a more direct comparison.

Much of the announced battery manufacturing is concentrated in the eastern half of North America, similar to existing automobile manufacturing. This is believed to be in part due to the high costs of transporting lithium-ion batteries (Klier and Rubenstein 2022; Plante and Rindels 2022). Figure 3 shows a map of the nominal full capacity for announced lithium-ion battery cell manufacturing plants, aggregated at the state/province level.[2] This map also overlays existing light-duty vehicle assembly plants (Automotive News 2021), which are also centralized in the eastern part of North America, particularly from Ontario to Alabama. The states and provinces with the largest announced capacity are Michigan, Nevada, Ontario, Georgia, Kentucky, and Tennessee, each of which have had at least 100 GWh/year of battery capacity announced.

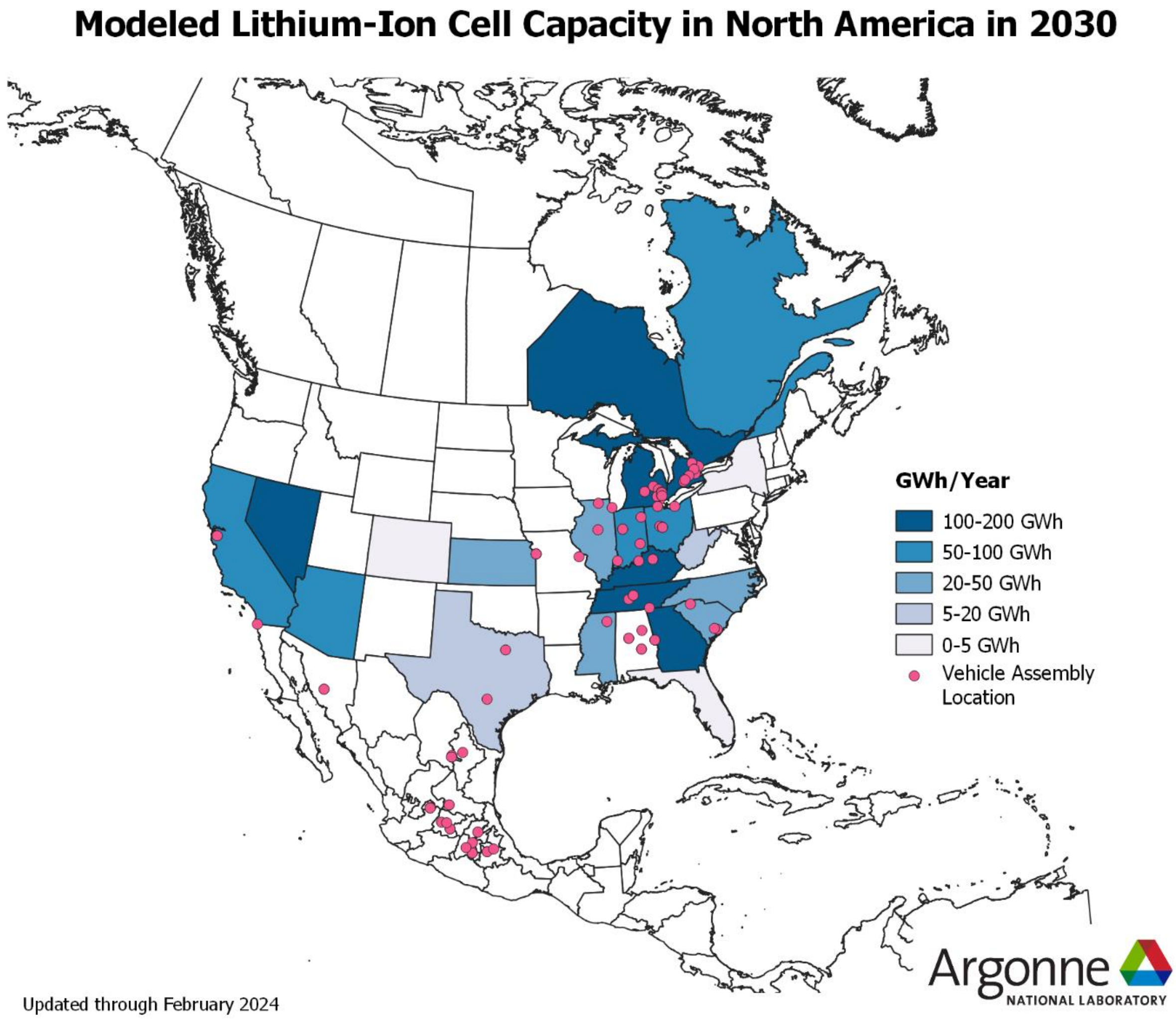

FIGURE 3 Planned battery plant capacity by state in 2030 (GWh/year)

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2 There is also existing or announced manufacturing of non-lithium-ion battery chemistries in other states not shown on this map. According to Battery Council International, there is existing production of lead-acid batteries in Florida, Iowa, Mississippi, Missouri, Oregon, Pennsylvania, and Washington (DOE 2020). There have also been announcements for Pennsylvania, South Dakota, Oregon, and Massachusetts for alternative battery chemistries.

Figure 4 explores the manufacturing announcements with more granularity. This map shows investments since 2000 in battery and electric vehicle supply chains. Locations in yellow represent minerals extraction investments, orange represents material processing and battery component production, red represents battery cell production, and purple represents battery pack production. Within the EV supply chains, blue represents investment in assembling electric vehicles, cyan represents facilities for vehicle components, and gray represents manufacturing of EV chargers. The size of each point represents its relative investment. As some plants have been announced in multiple stages, these appear as multiple overlaid circles.

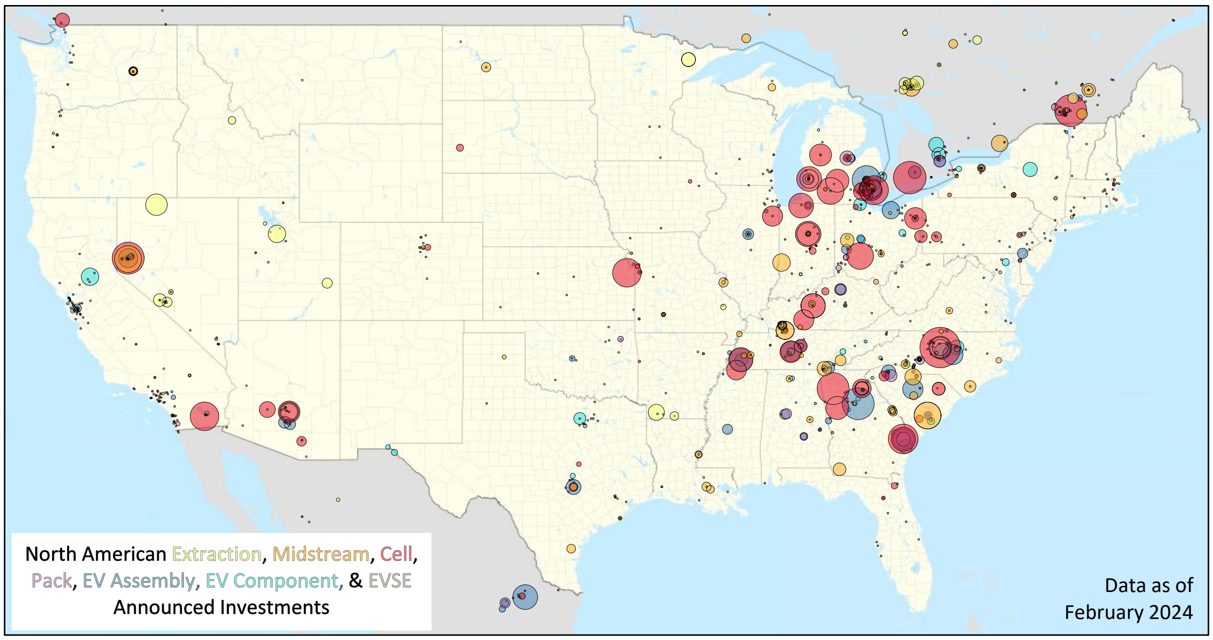

FIGURE 4 Announced investments in North American battery and electric vehicle supply chains

As seen in the map, most of the largest investments have been for battery cells and packs. Figure 5 shows the total battery and electric vehicle supply chain investments by product category as of a given date.[3] This figure matches the color scheme of Figure 4, except that some midstream battery components have been distinguished (specifically cathode active material (CAM), anode active material (AAM), electrolytes, and separators). Battery cells alone have had more than $120 billion in announced investments since 2000, with over $95 billion in announcements since during the 24-month span from January 2022 through December 2023. Over the same period, there has been over $30 billion in investment by automakers and suppliers for production of electric

[3] It is possible that a site will manufacture multiple products relevant to the battery and EV supply chain. If a minerals processing site is co-located with the extraction site, this is categorized as minerals extraction. Factories which build battery cells are categorized as such; if there is known precursor production at the site, we document the total quantity of each product, but attribute the investment to battery cells unless there is other information. Sites which have both cell and pack production are classified only under battery cells in this analysis. Announcements for both vehicle production and battery pack manufacturing are split across both categories, using an equal 50:50 split unless there is sufficient detail to change this ratio. Sites which host both vehicle assembly and component are characterized solely as vehicle assembly, as this is typically the larger portion of the investment.

vehicles. Figure 5 shows that most investments for battery components have been since the enactment of the Instructure Investment and Jobs Act and the Inflation Reduction Act, on November 15, 2021 and August 16, 2022, respectively. There was only $2 billion in investment announced for battery components prior to November 2021, growing to $11 billion by August 2022, and over $28 billion by December 2023.

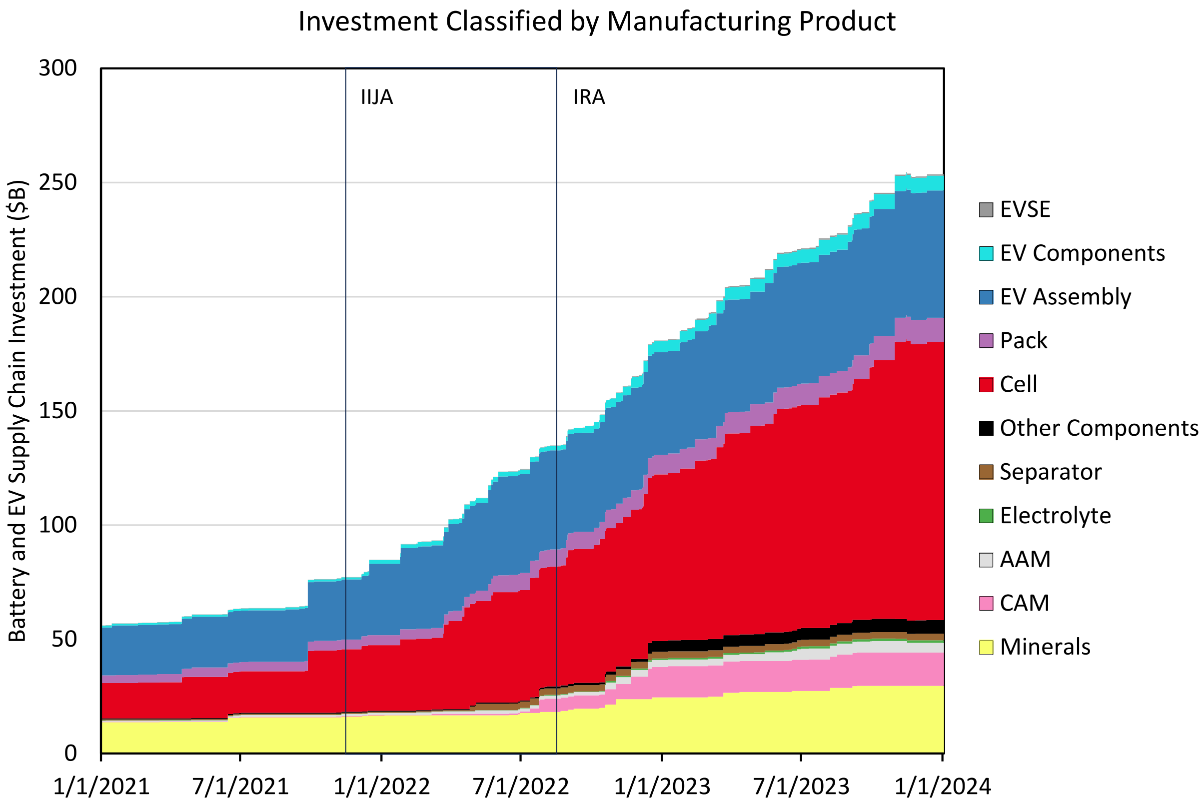

FIGURE 5 North American battery and electric vehicle investments classified by manufacturing product

This manufacturing boom in the private sector has been encouraged by the public sector (Boushey 2023). The advanced manufacturing production credit under Section 45X of the Internal Revenue Code (IRC) provides credits of up to $35/kWh for battery cell production, up to $10/kWh for battery pack production, and up to 10% of incurred costs for battery component production through 2032 (IRS 2023b). The Internal Revenue Service (IRS) has also released guidance on tax credits available for qualified investments in eligible qualifying advanced energy projects under Section 48C(e). Some examples of more direct federal support for battery manufacturing include financing from the DOE Loan Programs Office (LPO) utilizing previously earmarked funding from the Advanced Technology Vehicles Manufacturing (ATVM) Loan Program (DOE 2023a), direct funding for building of manufacturing facilities from the Department of Energy (DOE 2022; DOE 2023b), investments by the U.S. Department of Defense (DOD) to scale emerging technologies through the Defense Production Act (DOD 2023), and accelerated permitting through the Fixing America's Surface Transportation (FAST) Act (DOT 2023).

These enabling incentives, loans, and grants have already provided billions in capital to minerals processing, battery components manufacturing and recycling, and battery cell and pack production. Already awarded projects include CAM, AAM, separator, precursor material, and cell production facilities across the U.S. There is still a substantial portion of funding available from IIJA and IRA that has not yet been awarded, and LPO has considerable loan authority available for ATVM projects, which can include battery and battery components manufacturing. This analysis does not consider the impacts of to-be announced projects or as-yet unannounced grant, loan, and incentive recipients and thus should be a considered a conservative estimate of capacity. Table 1 summarizes funding allocated by or available for allocation by DOE and IRS to battery production, including components and precursor materials.

TABLE 1 Summary of Select DOE Funding for Battery and Electric Vehicle Supply Chain

Program	Funding Allocated*	Total Available**	Period of Availability	Project Examples
Battery Materials Processing Grants & Battery Manufacturing and Recycling Grants (MESC)	~$1.9B	~$4.1B	2022-2026; Until expended***	CAM and AAM production, separator production, precursor materials production, battery cell production.
Domestic Manufacturing Conversion Grants (MESC)	$0	$2B	To remain available through 9/30/2031	Eligible projects include facilities to produce components for electric vehicles.
ATVM (LPO)	~$15.9B	~$49.8B	No restriction	Battery cell production, lithium carbonate production, AAM production, foil production, CAM production.
Title 17 (LPO)	$398.6M	~$60B	No restriction	Zinc bromine battery energy storage systems.
48C Qualifying Advanced Energy Tax Credit (IRS, MESC)	$0	$10B	Until expended	Eligible projects include production and recycling of clean energy technologies, critical minerals processing and recycling.
45X Advanced Manufacturing Production Tax Credit (IRS)	--	No limitation	For critical minerals: permanent; For other items: full credit available between 2023-29 with phase down from 2030-32	Eligible projects include battery components, critical minerals, inverters, components for solar and wind energy technology.

*Funding announced since 2021, as of February 2024, for projects related to the scope of this study (cells, packs, CAM, AAM, electrolyte, foil, separator, precursor materials). Includes conditional commitments (LPO only)
**For grants, the total available is the total allocated subtracted from the allocation, and indicates how much grant funding is left. For LPO, this number represents approximate loan authority available as of January 2024, reported by LPO.
***For the purposes of this table, the Battery Materials Processing Grants & Battery Manufacturing and Recycling Grants are combined. These two programs are authorized separately in the IIJA. Their periods of availability are listed respectively.

2.2 DOMESTIC DEMAND FOR BATTERIES

A robust market for batteries requires a market for these batteries to be sold in. In general, forecasts show growth in battery usage for transportation and stationary storage over the next decade. In this analysis, this demand for batteries is used as a point of comparison to estimate if there will be sufficient production of cells or battery components.

Demand for vehicle batteries in the United States is generated using the TechScape model (ANL 2023b), which applies third-party sales forecasts to vehicle characteristics modeled using Autonomie (Islam et al. 2023). Sales forecasts come from the Bloomberg New Energy Finance (BNEF) EV Outlook 2023 for light-duty vehicles (LDV) and from a National Renewable Energy Laboratory (NREL) study for medium- and heavy-duty vehicles (MHDV) through 2035 (BNEF 2023; Ledna et al. 2022). The exact assumptions for vehicle mix and vehicle characteristics are described in greater detail in Barlock et al. (2024). Through 2032, this demand aligns closely with the modeled battery capacity by the U.S. Environmental Protection Agency (EPA) in its proposed rules for emissions standards for on-road vehicles (EPA 2023a; EPA 2023b), as shown in Figure 6. EPA standards are only proposed through model-year 2032, and so the modeling plateaus, while the expected battery demand for vehicles in the TechScape model continues to climb.

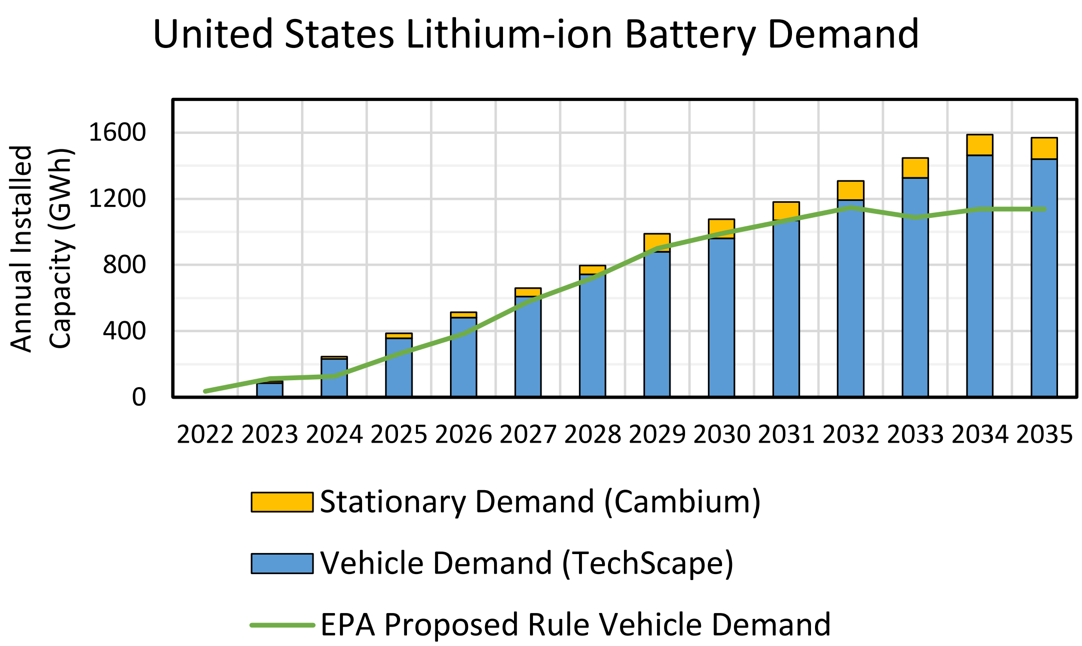

FIGURE 6 Modeled battery demand for stationary and transportation through 2035

The demand for stationary storage uses data modeled by NREL and available through the Cambium data sets (Gagnon 2023). NREL annually models the U.S. electricity sector through 2050, considering different scenarios for technology costs, fuel prices, demand growth, and policy drivers. The Cambium 2022 Mid Case is a central estimate for these inputs and uses electric sector policies as they existed in September 2022 and technology assumptions from the 2022 NREL Annual Technology Baseline (Gagnon 2023). However, due to the availability of tax credits in the

Inflation Reduction Act, costs for renewables and batteries are likely to be lower than the 2022 modeling, and so we use the Cambium 2022 Low Renewable Energy and Battery Cost Case in this analysis. The Cambium modeling includes grid-scale energy storage from batteries and shows the total amount of battery capacity installed. This total capacity is converted to an annual demand for new installations, assuming that battery installations have a maximal lifespan of 15 years (Cole and Karmarkar 2023), and we further assume that 5% of all installations will need to be replaced annually due to premature failure. For the stationary storage, 75% of the total is assumed to be lithium-ion batteries. Total battery demand for stationary storage is also shown in Figure 6 along with vehicle demand.

The baseline for battery demand considers transportation and stationary storage. Through 2014, 30 GWh out of the 50 GWh of lithium-ion batteries manufactured worldwide were used for electronic devices (Pillot 2021). However, the markets for transportation and stationary storage are forecast to grow much more than for electronics, where the overall global market for electronic devices using lithium-ion batteries is only forecast to reach 50 GWh by 2030 (Pillot 2021). Coupled with the fact that there is very little commercial-scale manufacturing of rechargeable batteries for electronics in the United States, we do not directly consider lithium-ion batteries used for electronics in our demand analysis.

For primary (non-rechargeable) batteries, the current market is estimated to be approximately 60 batteries per household per year with low growth over the long term (Energizer 2023), or 6.4 billion batteries per year. This is more than three times as many dry cell batteries as estimated by the EPA Office of Solid Waste and Emergency Response in 1992 (EPA 1992). At an average battery capacity of 3.7 watt-hours per battery, there is approximately 24 GWh of total demand for primary batteries within the United States.

Total demand for rechargeable batteries in the United States is modeled to grow steadily from 100 GWh in 2023 to 1,080 GWh in 2030 to 1,590 GWh in 2034. This growth is largely due to increasing market shares of electric vehicles. As shown in Figure 6, the demand for lithium-ion batteries for vehicles is much higher than the demand for batteries for stationary storage. In general, about 92% of the total battery demand is for transportation.

Calculations for battery demand do not directly consider exports and imports of finished goods. The analysis for total demand is largely qualitative, so we make no adjustments to the total demand based on these factors, but do note them here. Historically, approximately two-thirds of plug-in electric vehicles have been manufactured in the United States (Zhou et al. 2021; Gohlke et al. 2022). There were over one million vehicles exported from the United States in 2022 (USITC 2023). Nearly half of these exports were to Canada, which recently finalized its new Electric Vehicle Availability Standard which requires 100% zero-emission vehicle (ZEV) sales by 2035 (Government of Canada 2023; Ljunggren 2023). Since the U.S. and Canadian automotive markets are closely linked, this would increase the overall demand for batteries in North America. In the other direction, preliminary modeling for Corporate Average Fuel Economy (CAFE) standards by the U.S. Department of Transportation (DOT) forecasts approximately 50% of cars to be domestically assembled, and 50% to be imported, through 2032 (NHTSA 2023). Considering the mix of vehicle size classes (including light trucks), a reasonable assumption would be that about

25–30% of total LDV-required battery capacity in North America is imported (from Europe and Asia), which would reduce the overall demand for battery manufacturing in the North America.

3 CELL MANUFACTURING

Given the details for existing facilities and new investments, we can forecast the manufacturing capacity for batteries and battery components. In total, companies have announced over 1,200 GWh/year in additional battery production in North America over the next decade. The majority of this capacity is for lithium-ion batteries, most of which is dedicated for use in electric vehicles. This section describes these findings in greater detail, considering type and connections to end use, and more details about the modeling methodology can be found in Appendix A.

3.1 OVERALL BATTERY CAPACITY

Figure 7 shows the total year-by-year production capacity for battery cells in North America through 2035. In this and similar graphics, the blue bars represent the manufacturing in the United States, the red bars represent manufacturing in Canada, and the green bars represent manufacturing in Mexico. The vertical axis represents the net estimated manufacturing capacity based on formal manufacturing announcements. The total announced battery capacity in North America reaches nearly 1,600 GWh/year by 2030, starting from a value of around 300 GWh/year in 2023. After 2030, there is almost no further market growth modeled. Most cell production has a two-to-four-year timeframe between initial announcement and planned opening, and no cell manufacturing plant has been announced with an opening date after 2029.

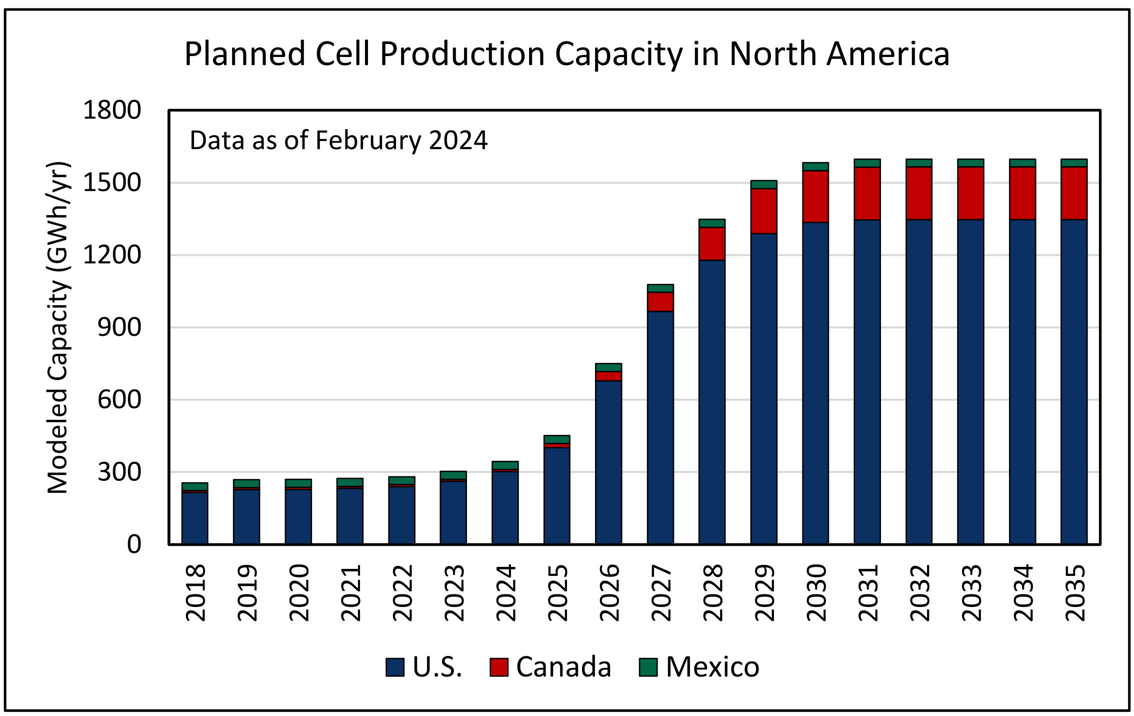

FIGURE 7 Modeled cell production capacity in North America from 2018 to 2035 by country

TABLE 2 Modeled Battery Cell Manufacturing by Location, Chemistry, and Year

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Lithium-ion, U.S. (GWh)	48	54	74	114	210	482	765	976	1,087	1,133	1,144	1,145
Lithium-ion, Canada (GWh)	0	0	0	0	9	30	70	128	178	207	210	210
Lithium-ion, Mexico (GWh)	0	0	0	0	0	0	0	0	0	0	0	0
Lead-acid, U.S. (GWh)	166	166	167	167	168	169	169	169	169	169	169	169
Lead-acid, Canada (GWh)	8	8	8	8	8	8	8	8	8	8	8	8
Lead-acid, Mexico (GWh)	33	33	33	33	33	33	33	33	33	33	33	33
Other chemistry, U.S. (GWh)	18	19	20	21	23	28	33	33	33	33	33	33
Other chemistry, Canada (GWh)	0	0	0	0	0	0	0	0	0	0	0	0
Other chemistry, Mexico (GWh)	0	0	0	0	0	0	0	0	0	0	0	0
Total capacity, U.S. (GWh)	232	240	261	302	401	679	966	1,178	1,289	1,335	1,346	1,347
Total capacity, Canada (GWh)	9	9	9	9	17	38	79	137	186	215	219	219
Total capacity, Mexico (GWh)	33	33	33	33	33	33	33	33	33	33	33	33
Total capacity (GWh)	274	281	303	344	451	750	1,078	1,348	1,508	1,582	1,597	1,598

Table 2 and Figure 8 distinguish the cell production by battery chemistry and manufacturing location. The majority of the battery capacity is in the United States. For existing battery cell manufacturing, Mexico is in second place, while Canadian manufacturing is forecast to surpass Mexican manufacturing by the middle of the decade. The historical volume is largely for manufacturing of lead-acid batteries. According to Battery Council International, there was 206 GWh of lead-acid battery manufacturing in North America in 2022 (BCI 2023a), which represents 75% of the total rechargeable battery manufacturing capacity in the United States in 2022 (BCI 2023b). Based on the lack of announced capacity growth, this is modeled to only increase to 210 GWh by the end of the decade. Existing capacity of lithium-ion batteries is modeled to be approximately 74 GWh in 2023. The largest of these plants are Panasonic in Nevada (39 GWh), Ultium in Ohio (11 GWh), SK Innovation in Georgia (7 GWh), Tesla in California (7 GWh), LG Energy in Michigan (5 GWh), and Envision in Tennessee (3 GWh). All of these capacity values are modeled based on company announcements of manufacturing start dates and do not take into account specific temporary closures, and as such, do not necessarily match exact production volumes in 2023.

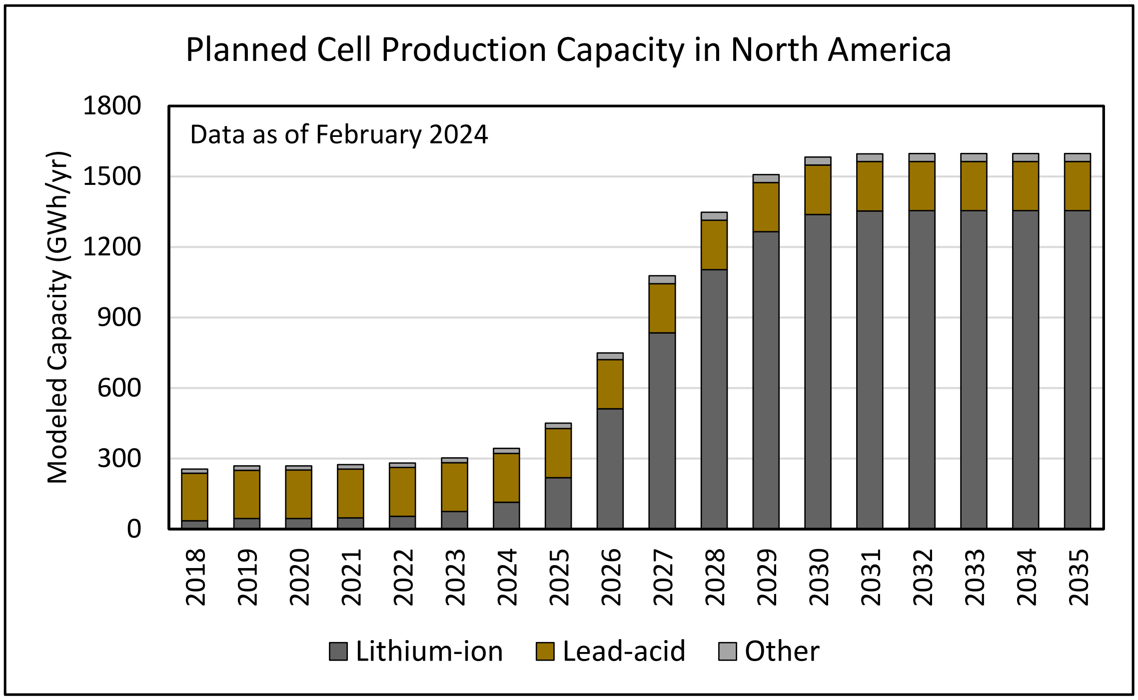

FIGURE 8 Modeled cell production capacity in North America from 2018 to 2035 by chemistry

Nearly all of the newly announced capacity through 2030 is for lithium-ion batteries. In 2024, we model 114 GWh of lithium-ion battery production capacity in North America, and in 2030, we model a total of 1,339 GWh of lithium-ion battery production capacity. As described in greater detail in the next section, these are largely for automotive use, but there is also a substantial amount of manufacturing dedicated to batteries used for stationary storage.

Other chemistries include a broad range of chemistries that are generally less energy-dense than lithium-ion batteries. For rechargeable batteries, this includes technologies such as iron-air batteries, nickel-zinc batteries, sodium-ion batteries, and vanadium flow batteries. These are often planned for use in stationary storage, though some automakers are considering sodium-ion batteries in vehicles (Huaihai 2023). This category also includes a small number of formally-announced manufacturing plants for solid-state lithium-ion batteries, totaling less than 2 GWh. We estimate primary (or non-rechargeable) batteries to have approximately 18 GWh of production capacity in the United States today, but with no additional capacity announced in North America over the next decade.

Figure 9 shows production by suspected end-use. This is imputed by announced supply agreements and by statements that the battery producers have made in press releases. Most batteries are clearly earmarked toward use in vehicles, either as motive power, which is the most common use of lithium-ion batteries, or for starter/lighting/ignition (SLI), which is typically the use case for lead-acid batteries. Over 100 GWh/year is nominally dedicated for stationary storage, which includes large-scale batteries for electric utilities and distributed batteries for personal use. Of the announced cell production capacity for stationary storage, over half has been for lithium-ion batteries. A small number of batteries are designed for other uses, such as electronics, forklifts, medical devices, and wearable sensors. The remainder of the batteries are produced by companies which do not have a clear offtake agreement. Often these companies have noted a broad range of possible uses in their press releases, and so these are labeled as being suitable for vehicle and stationary (Veh/Stat) in Figure 9. Table 3 summarizes this production for lithium-ion batteries and for other battery chemistries in North America, while Table 4 shows the same information for the United States.[4]

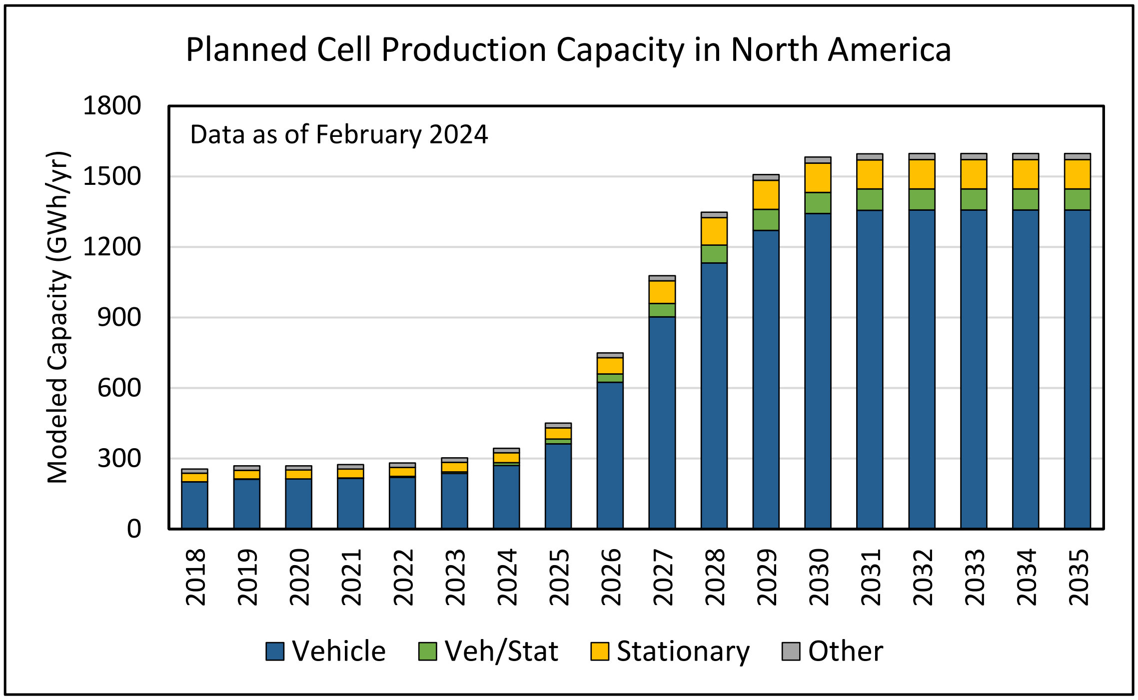

FIGURE 9 Modeled cell production capacity in North America from 2018 to 2035 by end-use

4 We assume that 82% of lead-acid batteries are used for automotive uses and 18% are used for stationary storage, following the Energy Grand Storage Market Report (DOE 2020).

TABLE 3 Modeled Battery Cell Manufacturing in North America by Use, Chemistry, and Year

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Lithium-ion, vehicle (GWh)	47	50	67	101	193	454	732	961	1,099	1,171	1,186	1,186
Lithium-ion, stationary (GWh)	0	0	0	0	5	22	45	64	71	72	72	72
Lithium-ion, other or unknown (GWh)	1	4	8	12	21	36	59	79	94	96	96	96
Other chemistry, vehicle (GWh)	169	169	169	170	171	171	171	171	171	171	171	171
Other chemistry, stationary (GWh)	38	39	40	41	42	48	52	52	52	52	52	52
Other chemistry, other or unknown (GWh)	18	19	19	19	20	20	20	20	20	20	20	20
Total capacity (GWh)	274	281	303	344	451	750	1,078	1,348	1,508	1,582	1,597	1,598

TABLE 4 Modeled Battery Cell Manufacturing in United States by Use, Chemistry, and Year

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Lithium-ion, vehicle (GWh)	47	50	67	101	184	427	667	841	932	975	986	987
Lithium-ion, stationary (GWh)	0	0	0	0	5	20	40	58	64	65	65	65
Lithium-ion, other or unknown (GWh)	1	4	8	12	21	36	58	77	91	92	93	93
Other chemistry, vehicle (GWh)	135	135	135	136	137	137	137	137	137	137	137	137
Other chemistry, stationary (GWh)	31	32	33	33	35	40	45	45	45	45	45	45
Other chemistry, other or unknown (GWh)	18	19	19	19	20	20	20	20	20	20	20	20
Total capacity (GWh)	232	240	261	302	401	679	966	1,178	1,289	1,335	1,346	1,347

3.2 LITHIUM-ION BATTERY CAPACITY

Given the lack of new announcements for lead-acid batteries and the low share of other battery chemistries, the remainder of the analysis in this section will focus solely on lithium-ion batteries. Figure 10 shows the modeled lithium-ion cell production capacity in North America for the United States and Canada. This graphic is similar to Figure 7 but is only for lithium-ion cell chemistry. In 2018, there was approximately 35 GWh of production in the United States, growing to 48 GWh in 2021. By 2032, the total modeled annual production capacity in North America is over 1,350 GWh, with 1,140 GWh in the United States and 210 GWh in Canada. This is a 28-fold increase in total lithium-ion cell production.

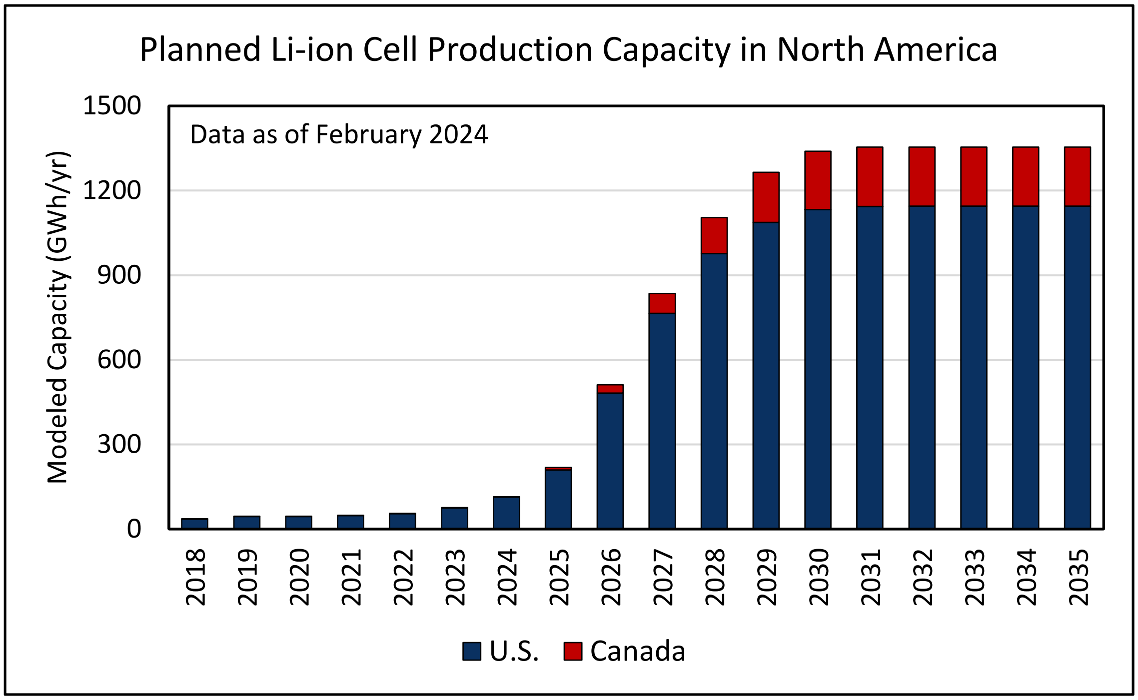

FIGURE 10 Modeled lithium-ion cell production capacity in North America from 2018 to 2035 by country

Figure 11 shows how new announced investments since 2021 have changed the overall projections for battery capacity. The vertical axis represents the estimated lithium-ion battery capacity in North America in 2030, and the horizontal axis represents the date of company announcements. As of December 2021, only 300 GWh/year had been announced, and by December 2022, there was only 800 GWh/year of expected capacity. This figure shows that cumulative announced capacity can decrease due to changes of company plans, as seen in November 2023 due to a downscaling of a plant by Ford and site cancellation by Nanotech Energy.[5]

[5] Note that this does include announcements where the battery maker formally shared information on a change in plans, but does not include rumored plants that never came to fruition, such as the rumored 60 GWh BritishVolt plant in Canada or the rumored 40 GWh Panasonic plant in Oklahoma.

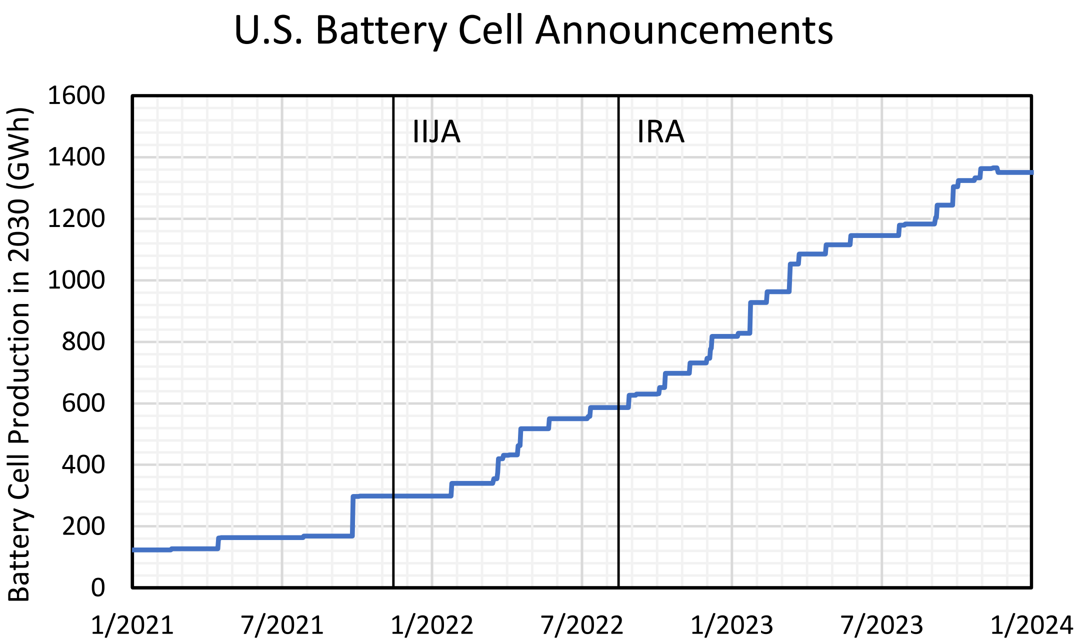

FIGURE 11 Evolution in battery cell production announcements in North America

Figure 12 shows where these announced lithium-ion battery cell plants are located. In this figure, the size of each point represents the nominal annual capacity of the announcement. As some plants have been announced in multiple stages, these appear as multiple overlaid circles. Table 5 shows the expected production per state/province. The majority of the manufacturing is in the eastern half of North America. Currently, the state with the largest production is Nevada, which houses the Panasonic / Tesla Gigafactory. By 2028, Michigan is forecast to surpass Nevada's battery production capacity. By the end of the decade, Michigan, Nevada, Ontario, Georgia, Kentucky, and Tennessee are all forecast to have over 100 GWh/year of lithium-ion cell production, followed by Indiana, Ohio, California, Quebec, and Arizona with over 60 GWh/year each.

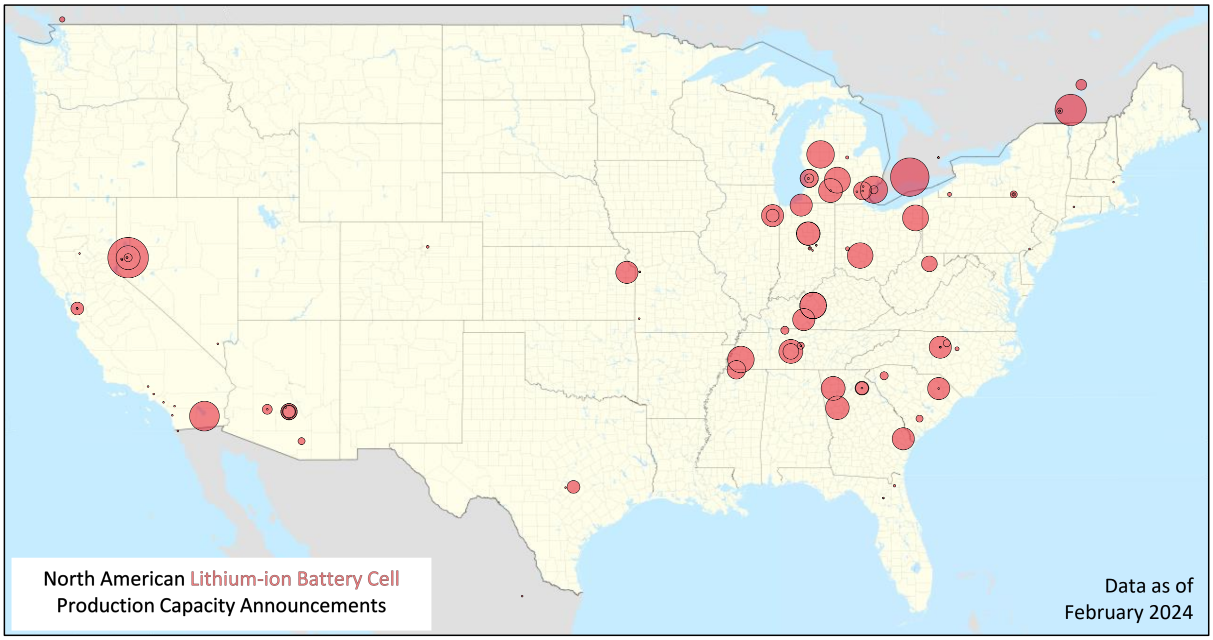

FIGURE 12 North American lithium-ion cell production map

TABLE 5 Projected Lithium-ion Battery Capacity by State (GWh/year)

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Michigan	5.9	6.0	6.0	7.4	27	68	112	142	157	166	172	173
Nevada	38	39	39	39	39	106	139	139	139	139	139	139
Ontario	0.2	0.2	0.2	0.2	8.4	25	45	79	109	136	139	139
Georgia	0.0	1.6	6.9	14	21	47	80	112	121	121	121	121
Kentucky	0.0	0.0	0.0	0.0	3.7	29	59	86	102	114	116	116
Tennessee	3.0	3.0	3.0	10	30	61	86	98	100	100	100	100
Indiana	0.0	0.0	0.2	0.5	5.3	18	41	68	88	97	98	98
Ohio	0.0	0.8	11	25	38	49	63	76	82	82	82	82
California	0.5	3.5	6.7	9.7	10	16	34	52	64	64	64	64
Québec	0.0	0.0	0.0	0.0	0.3	4.9	25	48	67	69	69	69
Arizona	0.0	0.0	0.0	0.0	1.5	14	33	52	60	61	61	61
Illinois	0.0	0.0	0.0	1.7	13	27	38	40	40	40	40	40
South Carolina	0.0	0.0	0.0	0.1	1.0	3.3	13	24	34	37	37	37
North Carolina	0.0	0.0	0.0	0.2	2.3	8.9	15	22	28	33	34	34
Kansas	0.0	0.0	0.0	0.0	2.8	13	23	30	30	30	30	30
Mississippi	0.0	0.0	0.0	0.0	0.0	0.0	0.9	7.0	14	20	21	21
West Virginia	0.0	0.0	0.0	0.6	5.0	10	14	15	15	15	15	15
Texas	0.0	0.0	0.4	3.3	6.7	9.6	10	10	10	10	10	10
New York	0.0	0.0	0.5	1.3	2.1	2.5	2.8	2.8	2.8	2.8	2.8	2.8
Colorado	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.5	0.5	0.5	0.5	0.5
Florida	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

From Figure 12, we see a broad range of different lithium-ion cell plant sizes. Figure 13 shows a histogram of the announced annual capacity for each lithium-ion cell manufacturing plant. Some of these plants are only pilot scale, and a total of 25 plants are under 2 GWh/year. The largest plants which have been announced are the Tesla Gigafactory in Nevada, which has a current capacity of 39 GWh/year and has made an announcement for an additional 100 GWh/year, and the PowerCo (Volkswagen) plant in Ontario, which has a planned capacity of 90 GWh. The majority of the production volume (860 GWh/year) comes from 22 plants with a nameplate capacity between 30–50 GWh/year.

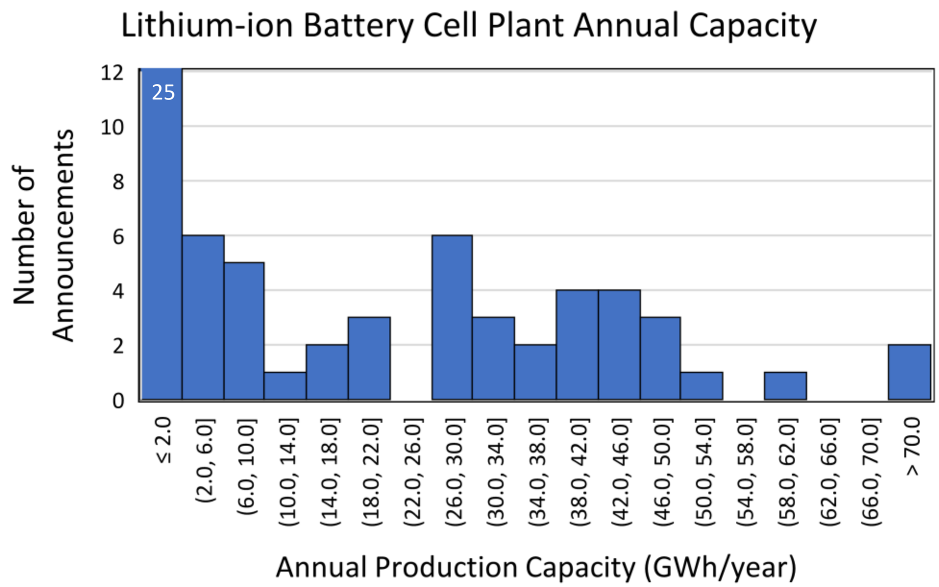

FIGURE 13 Histogram of lithium-ion cell plant sizes

Figure 14 considers what types of companies have made investments in lithium-ion battery cell production. The plurality of the total forecast capacity (approximately 580 GWh) comes from investments made by joint ventures of energy companies and traditional automotive companies. A similar amount of battery capacity (520 GWh) has been announced by battery companies without a formal joint venture with automakers. Finally, the remaining investments (260 GWh) have been made by traditional automotive original equipment manufacturers (OEMs). These OEMs include Ford, Tesla, and Volkswagen, each of which has decided to take full ownership of cell production for a portion of its electric vehicles.[6] It is worth noting that some of Tesla markets itself as an energy company and some of its manufacturing capacity is meant for stationary storage.

[6] It is worth noting that some of Tesla markets itself as a multivalent company with a mission to accelerate the world's transition to sustainable energy (Tesla 2023) and some of its manufacturing capacity is meant for stationary storage.

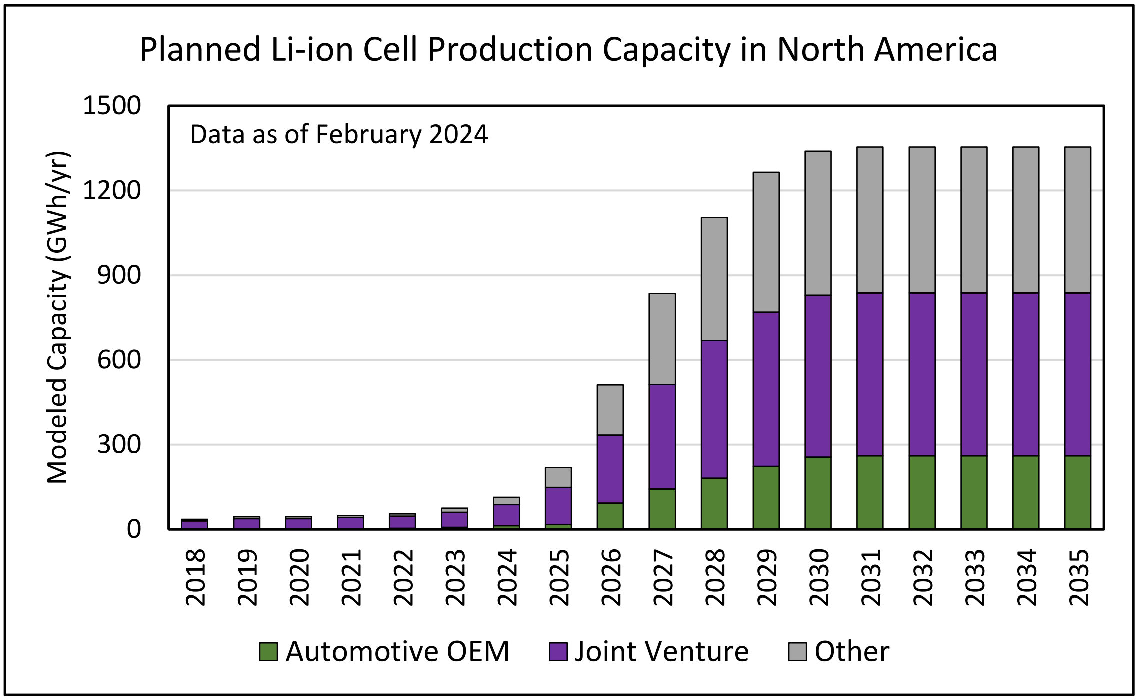

FIGURE 14 Modeled lithium-ion cell production capacity in North America from 2018 to 2035 by plant ownership

Table 6 lists the annual capacity by company for each of the largest lithium-ion cell producers. In Table 6, joint ventures between automotive and energy companies are listed under the company with historical experience in cell development. LG Energy Solution is the single largest cell producer, with over 300 GWh in capacity planned by 2028, including cell plants in their own name in Michigan and Arizona, and joint ventures with GM, Stellantis, Honda, and Hyundai. SK Innovation is the company with the second-largest announced capacity by the end of the decade (over 180 GWh) and has joint ventures with Ford and Hyundai along with a factory in Georgia. Panasonic currently has the largest capacity, operating cell production in the Tesla Gigafactory in Nevada, though it appears that future expansions at this site will be under the Tesla nameplate. The 100 GWh expansion of the Tesla Gigafactory is the largest contribution to Tesla's future production by the end of the decade, though the date of reaching full-scale production is unclear. Tesla's plant in Austin, Texas has been rumored to be of a similar capacity, but Tesla has not made a formal announcement as to the long-term plans of this site. Samsung, Volkswagen, and Gotion each have plans for nearly 100 GWh by the end of the decade.

TABLE 6 Projected Lithium-ion Battery Capacity by Company (GWh/year)

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
LG Energy Solution	5	6	16	37	87	171	264	328	347	348	348	348
SK Innovation	0	2	7	14	24	60	102	151	171	184	186	186
Tesla	0	3	7	13	17	86	120	120	120	120	120	120
Samsung SDI	0	0	0	0	5	17	40	67	87	97	97	97
Volkswagen	0	0	0	0	0	0	4	30	60	86	90	90
Gotion	0	0	0	2	14	34	54	63	71	79	85	86
Panasonic	38	39	39	39	42	52	62	69	69	69	69	69
Envision	4	5	5	5	7	21	43	55	64	65	65	65
Northvolt	0	0	0	0	0	3	20	40	58	60	60	60
Statevolt	0	0	0	0	0	6	24	42	54	54	54	54
Toyota	0	0	0	0	1	6	12	18	24	29	30	30
Freyr	0	0	0	0	1	11	23	33	34	34	34	34
EVE	0	0	0	0	0	0	1	7	14	20	21	21
Ford	0	0	0	0	0	1	7	13	19	20	20	20
Our Next Energy	0	0	0	1	8	16	20	20	20	20	20	20
Other	1	2	2	5	15	30	43	50	53	53	53	53

Figure 15 reproduces the end-use analysis of Figure 9, considering only lithium-ion batteries, showing data that is in Table 3. In this case, 88% of the total announced lithium-ion cell production is planned for vehicles, and only 5% is expected to be used specifically for stationary storage purposes. This ratio aligns well with the stationary-to-vehicle demand modeled in Figure 6.

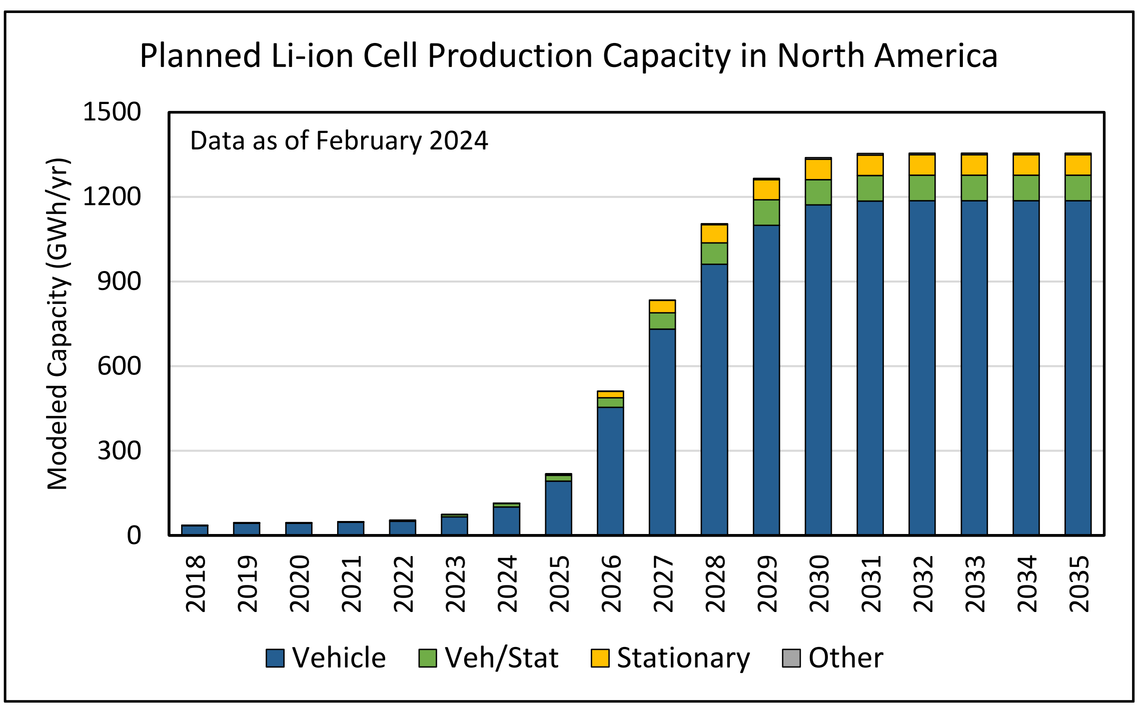

FIGURE 15 Modeled lithium-ion cell production capacity in North America from 2018 to 2035 by end-use

Figure 16 shows more clearly the distinction of the specific end-use for vehicles. In Figure 16, "Other" includes batteries for stationary storage as well as those labeled as "Veh/Stat" in Figure 15. These batteries may be used for motor vehicles, but these cell manufacturing facilities do not have a stated offtake agreement for end-use. Within the vehicle space, the vast majority (over 900 GWh) of the announced cell production is dedicated for light-duty vehicles (LDV). There is at least 45 GWh of announced cell production for heavy-duty vehicles (HDV).

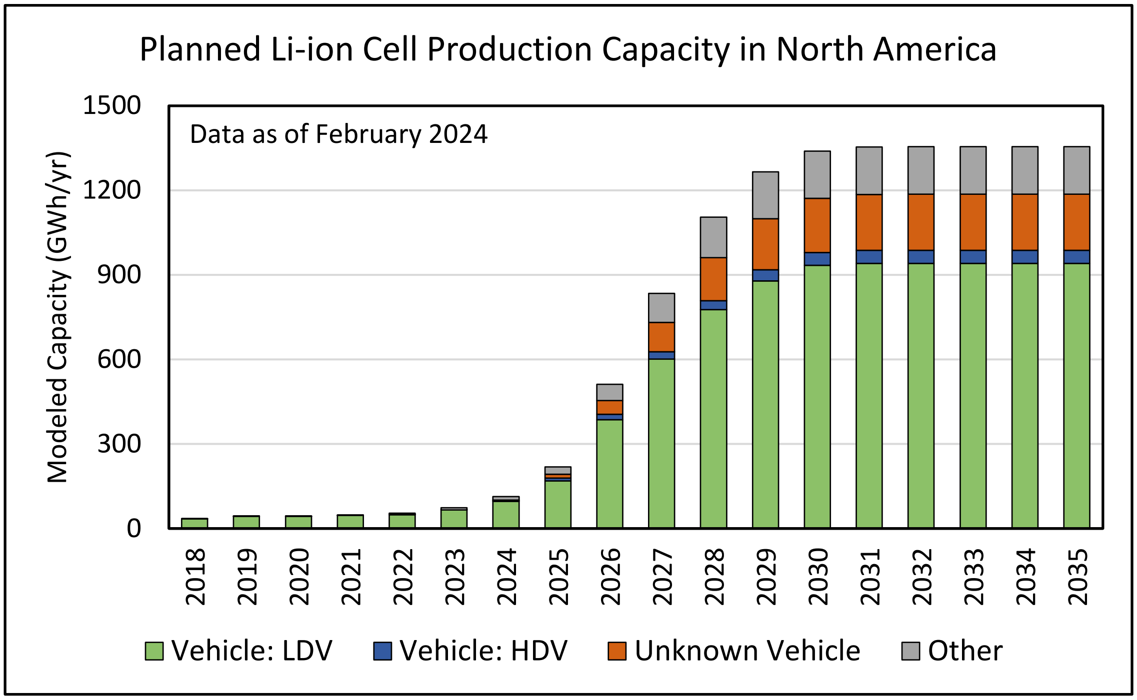

FIGURE 16 Modeled lithium-ion cell production capacity in North America from 2018 to 2035 by transportation sector

An alternative approach is to look at production by individual companies, as shown in the Sankey-type flow diagram in Figure 17. In this diagram, the left side of the diagram represents the companies making lithium-ion battery cells. The thickness of each curved line represents the total battery capacity, as modeled for the year 2030. These lines connect from cell manufacturers on the left to pack manufacturers in the center, and finally to the end use on the right side. On the right, battery production with unknown end use (283 GWh) is colored in dark gray. Below this are batteries dedicated to stationary storage in yellow. These batteries can be tracked back to their original cell producers. This diagram shows that much of battery cell manufacturing is in dedicated offtake agreements. The exact values in this diagram are informed by estimates of offtake agreements and announced vehicle production plans. GM, Ford, Tesla, Stellantis, and Volkswagen are all modeled to have over 100 GWh of battery consumption in 2030 (assuming no delays). On the other hand, approximately one-quarter of the battery cell market in 2030 has no clear buyer yet. This is an opportunity for continued end-use market growth, but also may indicate a greater risk of a cell manufacturing facility coming online. Production risk is described in greater detail in Appendix B. Sankey diagrams showing modeled production in years from 2024 to 2029 are shown in Appendix C.

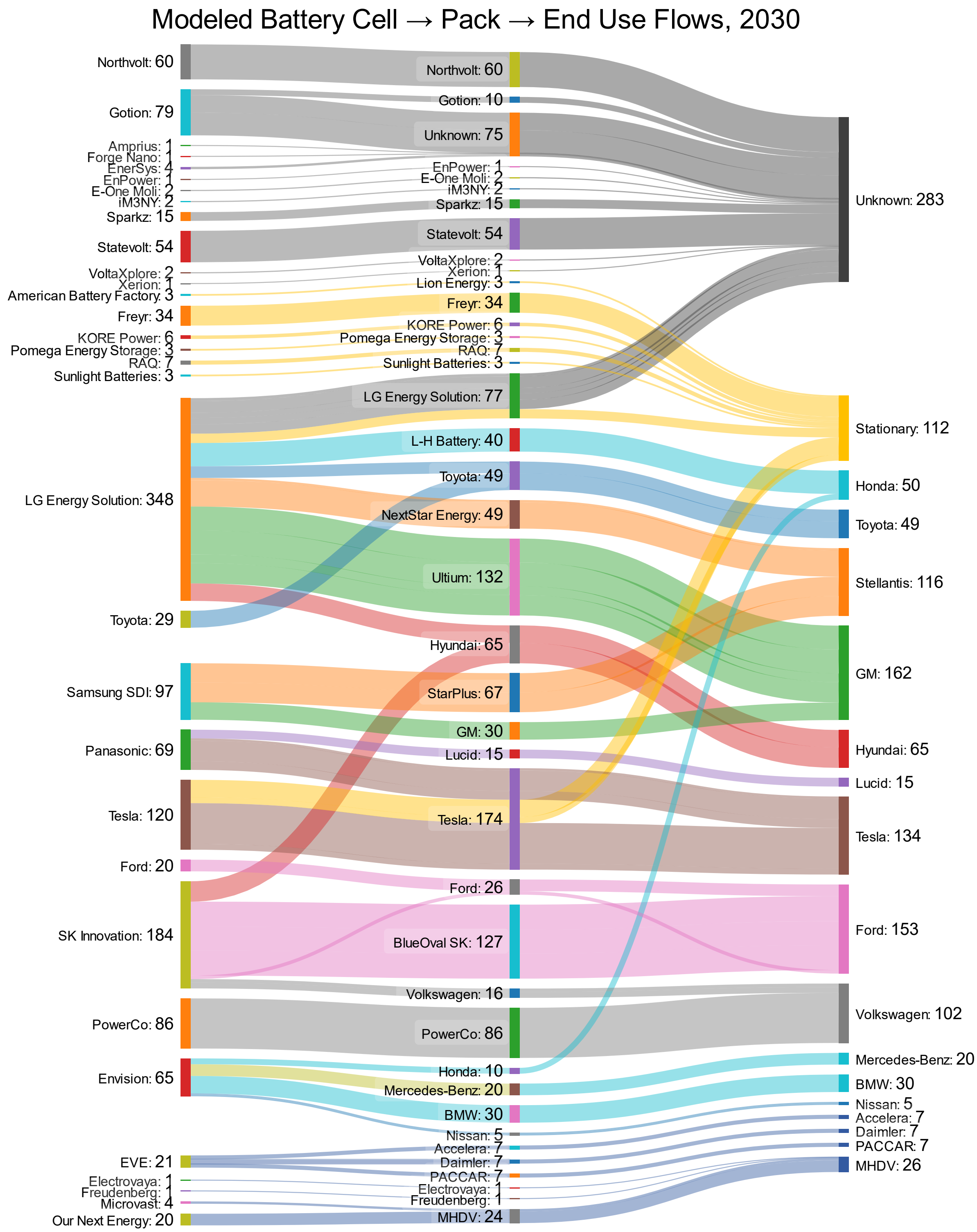

FIGURE 17 Flow diagram of North American cell and pack manufacturing, and vehicle assembly in 2030

Figure 18 shows the distribution of lithium-ion battery cell production by battery cathode chemistry. In this figure, cells with a cathode based on nickel, such as lithium nickel manganese cobalt (NMC) or lithium nickel cobalt aluminum (NCA), are shown in dark gray. Cells with a cathode based on iron, such as lithium iron phosphate (LFP), are shown in dark orange. Cells with nickel-based cathodes and iron-based cathodes have a similar announced production capacity (approximately 220 GWh/year each by 2030). LFP batteries are being used in a broad range of applications, including stationary storage, light-duty vehicles, and even heavy-duty vehicles. The majority of announced cell production facilities do not include information about the battery cathode chemistry. This may be because of the ability to easily transition between cathode chemistries based on available material.

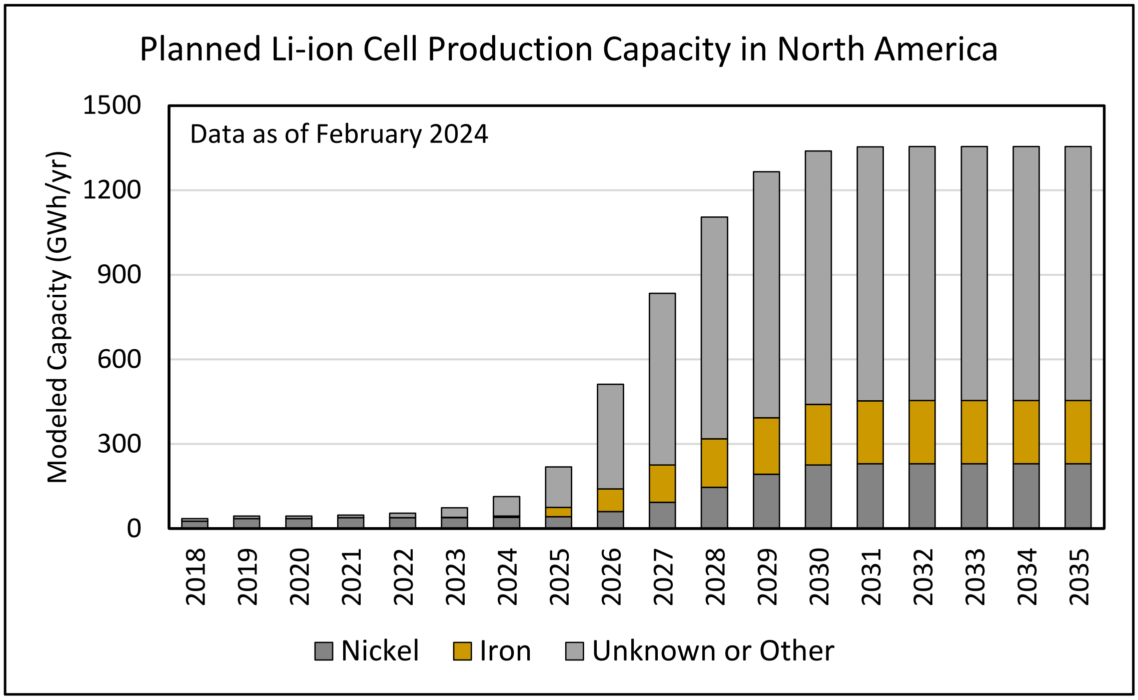

FIGURE 18 Modeled lithium-ion cell production capacity in North America from 2018 to 2035 by cathode chemistry

3.3 BATTERY CELLS AND PACKS

Figure 19 maps the locations for battery pack production. In this analysis, the terms pack and module are used interchangeably to mean some number of battery cells electrically linked together to deliver energy for a specific end-use. In this map, if a site manufactures both cells and packs, it will be shown in red, while sites manufacturing only battery packs are in purple. The size of the circle represents the total volume of pack production. Most announced high-volume pack production sites are also producing cells on site; the biggest exception is the Tesla Megapack facility in California. Some sites have made no announcements of the expected capacity, such as the BMW pack plant in South Carolina, and therefore their volume is not shown on the map.

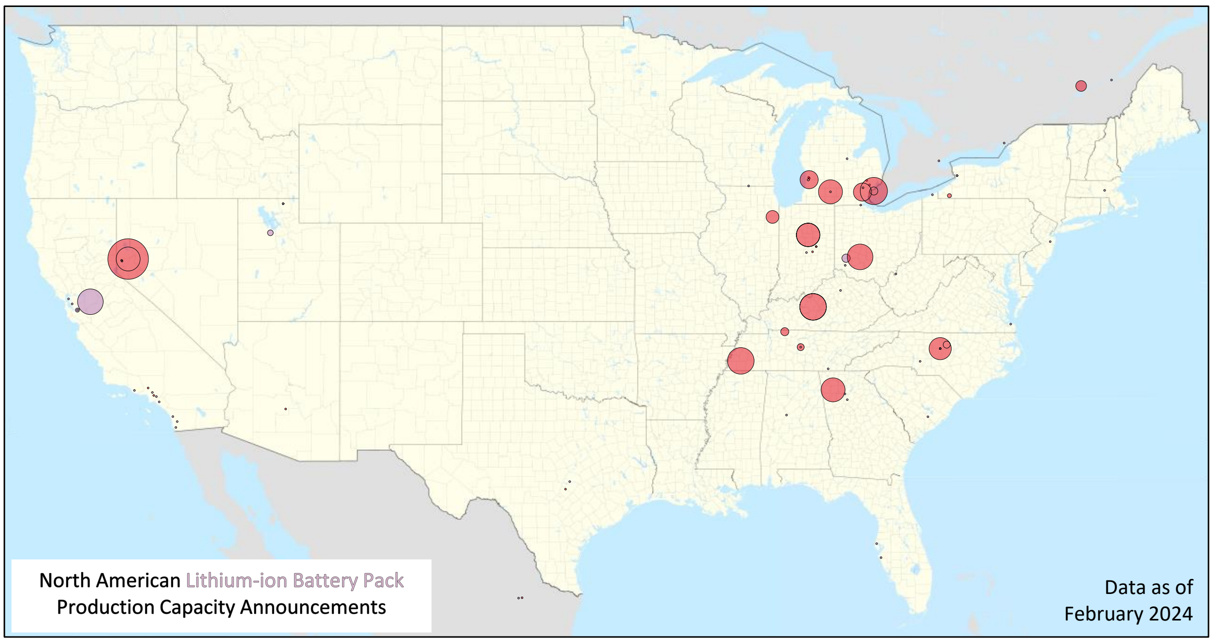

FIGURE 19 North American lithium-ion pack production map

The total announced volume of lithium-ion pack production is shown in Figure 20. This number is smaller than the production of lithium-ion cells in the United States, overlaid by the purple line (from Table 4). This apparent reduced capacity could be an artifact of limited information, such as lacking the capacity of announced downstream pack production plants (such as in the case of BMW in South Carolina). Additionally, as discussed in Appendix A, there is a wide variation in build-out plans for battery packs. As such, pack producers may be waiting for the availability of battery cells before formally announcing manufacturing plans. However, this could also be indicative of a lack of formal announcements for pack production. Ultium Cells, a joint venture of General Motors (GM) and LG Energy has made announcements for cell production at three sites. These cell announcements have noted that they will be used to supply cells to GM assembly plants, however, no explicit manufacturing announcement has been made for pack production, rather pack production is implied to be integrated with vehicle assembly. In other instances, the Alliance for Automotive Innovation notes that battery technologies may allow for a single large module or cells to be incorporated into a battery pack or a vehicle frame (Alliance for Automotive Innovation 2024) further suggesting the potential for integration of cells with vehicle assembly.

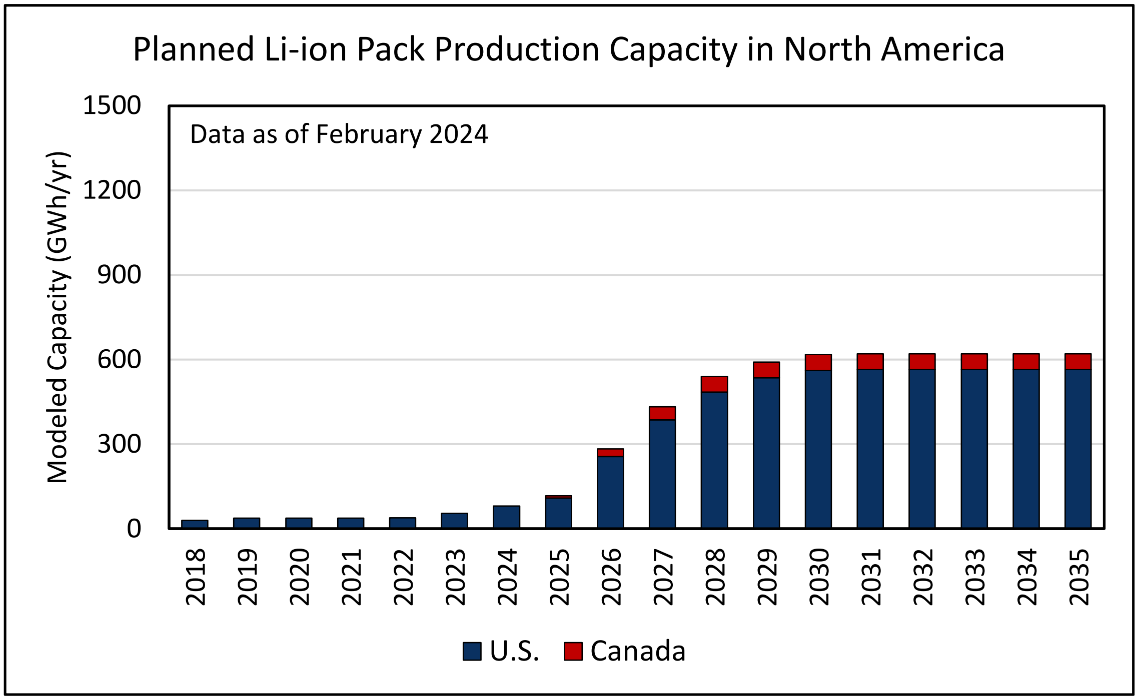

FIGURE 20 Modeled lithium-ion pack production capacity in North America from 2018 to 2035

3.4 COMPARISON OF CELL SUPPLY AND DEMAND

As noted in the previous section, there are difficulties with comparing announced cell and pack production. Given the lack of information for battery pack production, we compare the announced battery *cell* production to the end use demand described in Section 2. Figure 21 shows the total modeled lithium-ion cell production in North America based on company announcements relative to demand for lithium-ion batteries (Barlock et al. 2024), as shown in Figure 6.

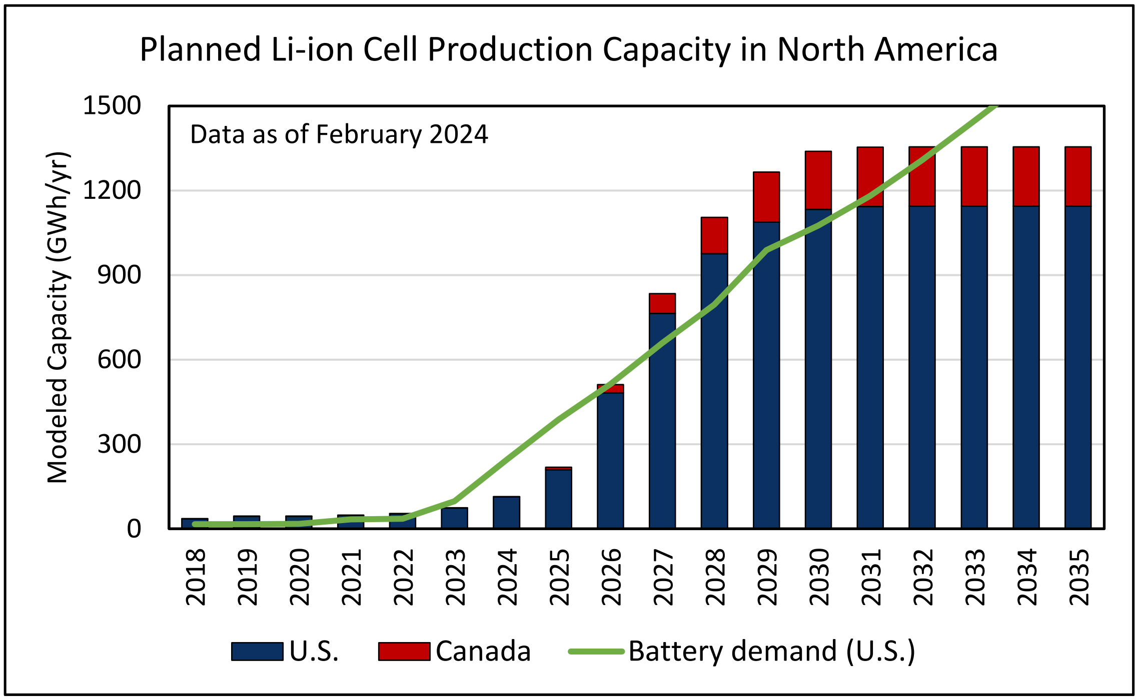

FIGURE 21 Modeled lithium-ion cell production capacity compared with forecast battery demand (Barlock et al. 2024)

Figure 21 shows that announced U.S. battery production appears to be sufficient to supply batteries for U.S. demand. The forecast demand exceeds modeled cell production in 2024 and 2025. This shortfall in battery cell supply could be satisfied by considering imports (particularly for imported vehicles which may be built outside of the United States). From 2026 to 2030 there is sufficient U.S. battery cell production to meet the full forecast demand. By 2030 the total cell production plateaus because of lack of new announcements, though the market demand is forecast to continue to grow. If the market continues to grow, there would need to be continual investments to have sufficient manufacturing capacity.

4 COMPONENT MANUFACTURING

This section considers production of key components necessary to build lithium-ion batteries, comparing the potential supply with required demand due to battery production and end use. There have been company announcements to increase production in North America of anode active material (AAM), cathode active material (CAM), electrolyte, foils, and separators. Table 7 summarizes total production for these components in North America through 2032. Each component is converted to GWh-equivalent. Most of the component manufacturing sites describe their total capacity in terms of annual tonnage; for these sites, we use values derived from the BatPaC model to convert mass into battery capacity (Knehr et al. 2022). For a point of comparison, this table also includes the modeled North American lithium-ion cell production from Section 3.2 and the end-use demand for vehicles and stationary storage discussed in Section 2.2. Comparing with domestic cell production is useful in understanding manufacturing supply constraints and estimating how much cell production will receive tax subsidies. Comparing with domestic battery demand is useful in estimating what share of vehicles may have lower cost batteries due to 45X tax credits.

In general, the total announced quantity of battery components is less than the total modeled lithium-ion cell production at this time. The manufacturing supply of each of these components is discussed in greater detail in Sections 4.1 through 4.5. Section 4.6 summarizes announced production for some precursor minerals, specifically lithium carbonate, lithium hydroxide, nickel sulfate, cobalt sulfate, and manganese sulfate.

TABLE 7 Modeled Lithium-Ion Battery Component Manufacturing in North America

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Anode material production (GWh)	2	5	7	18	72	191	362	507	558	573	584	585
Cathode material production (GWh)	4	4	12	79	215	301	416	503	543	558	568	569
Electrolyte production (GWh)	39	70	105	393	827	949	1,012	1,073	1,073	1,073	1,073	1,073
Foil (Al) production (GWh)	0	0	0	6	69	216	239	239	239	239	239	239
Foil (Cu) production (GWh)	0	0	12	86	173	207	337	380	384	384	384	384
Separator production (GWh)	41	56	59	59	86	255	318	328	339	339	339	339
Cell production (GWh)	48	54	75	114	218	512	835	1,104	1,265	1,339	1,354	1,355
End-use demand (GWh)	34	36	99	245	388	514	660	795	988	1,076	1,181	1,308

4.1 ANODE ACTIVE MATERIAL

The anode is the negative electrode of the battery. In a lithium-ion battery, the anode acts as the destination for the lithium ions coming from the cathode. The most common anode active material in use currently for lithium-ion batteries is graphite, though silicon is occasionally used as a dopant and has the potential to be more widely used in the future, and lithium titanate has also been used as the anode in some electric vehicles.

Figure 22 shows the modeled anode active material (AAM) production capacity in North America through 2035. As in Section 3, the blue bars represent the modeled manufacturing capacity for AAM in the United States and the red bars represent the modeled manufacturing capacity for AAM in Canada. The green line represents the lithium-ion battery end-use demand for vehicles and stationary storage in the United States (Section 2.2), and the purple line represents the modeled lithium-ion battery cell capacity. For AAM based on graphite, we convert from mass to battery capacity using the factor of 1,034 metric tons per GWh. This represents approximately the amount of graphite in a lithium-ion battery cell (Knehr et al. 2023). For AAM based on silicon, we convert using the factor of 115 metric tons per GWh, aligning the production claims of Sila Nanotechnologies of 20 GWh/year and 2,300 tons/year (Sila 2022; BFS 2023). This aligns with the known greater theoretical gravimetric capacity of silicon relative to graphite (Obrovac and Chevrier 2014).

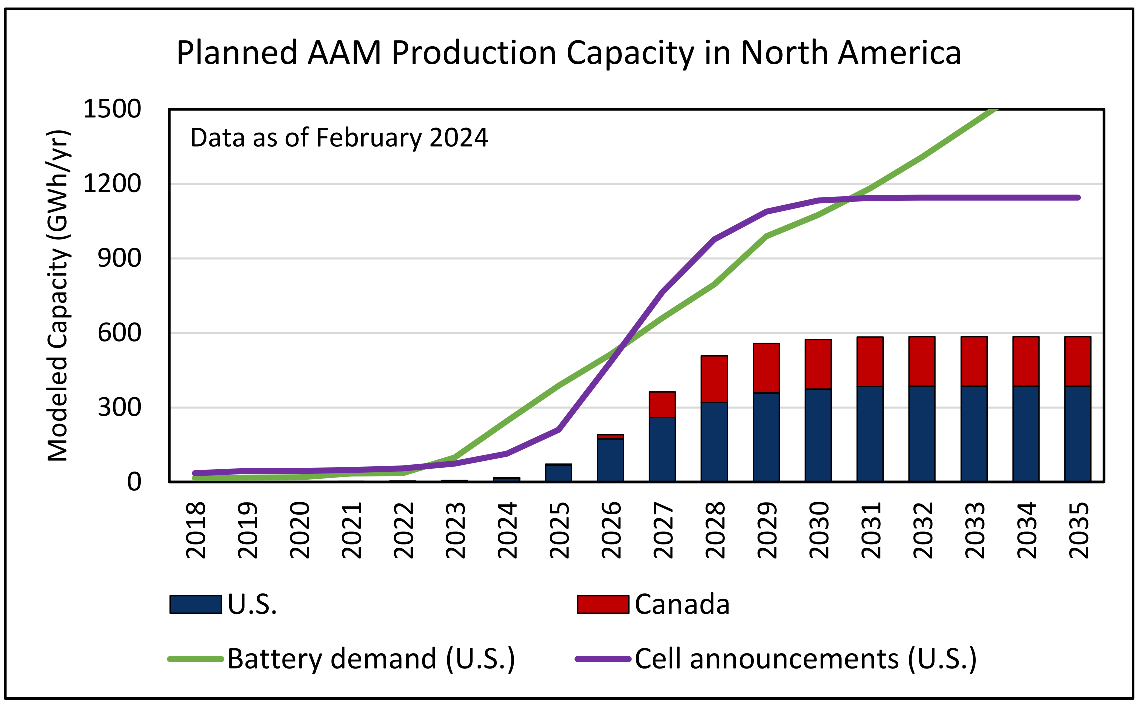

FIGURE 22 Modeled anode active material production capacity (GWh) compared with demand from cell production and end-use

AAM production is modeled to reach 585 GWh by 2032. Figure 22 shows that there is insufficient North American production of AAM planned to fully supply production of battery cells. Nearly two-thirds of the North American AAM production by the end of the decade is in the

United States, with the remainder located in Canada. In 2025, modeled capacity of approximately 72 GWh can satisfy about 33% of cell production, growing to 573 GWh and around 43% of cell production by 2030 and remaining steady afterwards.

There are multiple reasons why the AAM production announcements do not match the total demand; several are listed here:

- Companies need access to the raw material (particularly graphite and silicon) to be able to build a processing plant for AAM. There have been announcements for potential extraction and production of graphite and silicon in the United States and Canada. Much of this is in early stages of development (e.g., "prefeasibility study"), and not likely to be available for production until late in the 2020s at the earliest.
- Companies may be waiting for certainty in demand from cell production or for availability of financing before publicly committing to building a manufacturing plant. For example, this may be contingent upon the IRS finalizing the rulemaking on Section 45X, which includes anode electrode materials as an "electrode active material" that is eligible for a 10% production tax credit (IRS 2023b). Furthermore, MESC has solicited applications for the commercial scale domestic production of anodes, including anode materials, powders, and electrodes, due March 2024. MESC anticipates investing between $50 to $300 million per award in four to eight awards for both anode and cathode manufacturing, as similarly described below, with awards completed by January 2025 (DOE 2024). We have identified an additional 590 GWh/year in nominal AAM capacity by the end of the decade at facilities which are being planned or considered, but not yet formally announced by companies. This is explored in greater detail in Appendix B.
- AAM production could be underestimated if cell-production facilities are also creating electrode active material onsite without making a separate announcement.

Beyond these reasons, gaps in supply of AAM can potentially be satisfied by imports.

Table 8 shows the expected capacity for each company which has plans for over 10 GWh/year of AAM. Table 8 shows the anode material (graphite or silicon) as well as production in terms of tons and GWh. Approximately 86% of the total announced AAM capacity through 2030 is for graphite-based anodes. Three of these companies (Anovion, Epsilon Advanced Material, Novonix, and Solidion) intend to produce AAM using synthetic graphite. Figure 23 shows a map of the AAM manufacturing locations. Much of the anode active material production is in the southeastern United States, aligning with the location of potential graphite extraction. A major plant has been proposed for Quebec by Northern Graphite, and a potential plant in Washington is dependent upon a mine owned by Graphite One in Alaska.

TABLE 8 Companies Producing AAM in North America

Company	Anode material	AAM production (metric tons per year)	Equivalent battery capacity (GWh/year)
Northern Graphite	Graphite	200,000	193
Graphite One	Graphite	51,200	49
Epsilon Advanced Material	Graphite	50,000	48
Gotion	Graphite	50,000	48
Syrah Technologies	Graphite	45,000	44
Anovion	Graphite	42,500	41
Group14	Silicon	4,100	36
Superior Graphite	Graphite	24,000	23
Sila Nanotechnologies	Silicon	2,300	20
Novonix	Graphite	20,000	19
Ionic Mineral Technologies	Silicon	2,000	17
Graphex Technologies	Graphite	15,000	15
Solidion Technology	Graphite	10.000	10
Westwater Resources	Graphite	10,000	10
Other			11

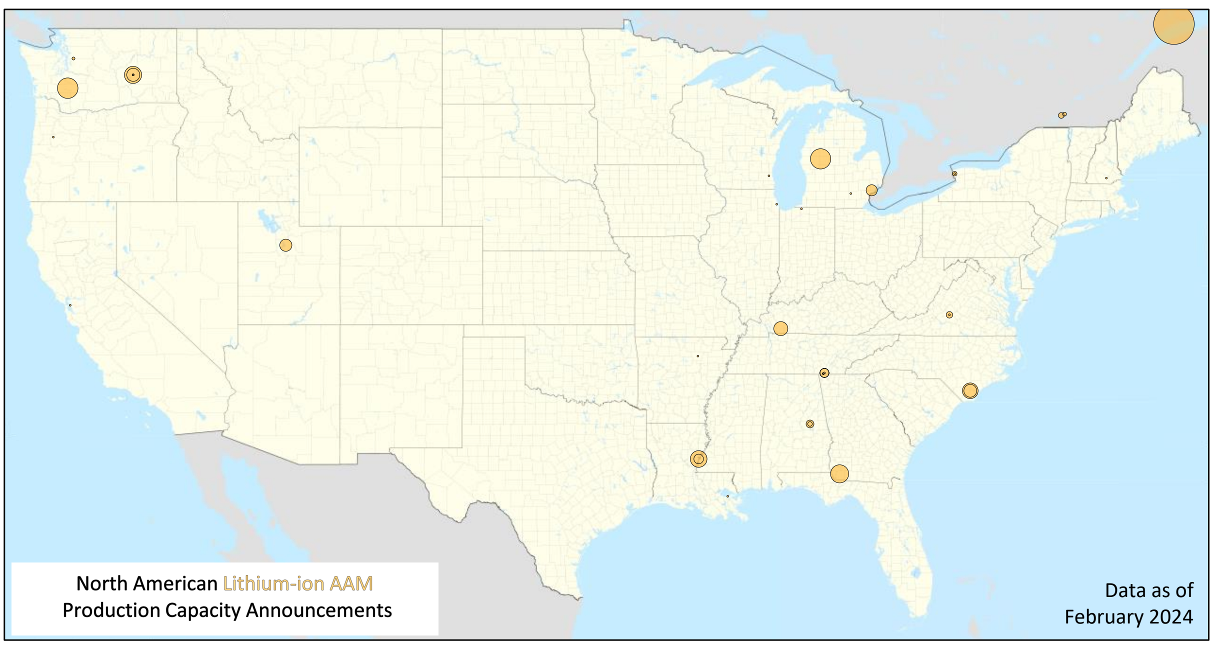

FIGURE 23 North American lithium-ion AAM production map

4.2 CATHODE ACTIVE MATERIAL

The cathode is the positive electrode of the battery. In a lithium-ion battery, the cathode acts as the source for the lithium ions migrating to the anode. There are numerous competing chemistries for the cathode active material. The most common cathode chemistries for lithium-ion batteries in the last ten years have been $Li[Ni_{1-x-y}Co_xAl_y]O_2$ (NCA), $Li[Ni_{1-x-y}Mn_xCo_y]O_2$ (NMC), $Li[Ni_{1-x-y-z}Mn_xCo_yAl_z]O_2$ (NMCA), $LiMn_2O_4$ (LMO), and $LiFePO_4$ (LFP). For a detailed description of the relative merits of each of these chemistries, see, e.g., Berman et al. (2018), Schmuch et al. (2018), and Shen et al. (2021).

Figure 24 shows the modeled cathode active material (CAM) production capacity in North America through 2035. As in earlier figures, the blue bars represent the modeled manufacturing capacity for CAM in the United States and the red bars represent the modeled manufacturing capacity for CAM in Canada. The green line represents the lithium-ion battery end-use demand for vehicles and stationary storage in the United States (Section 2.2), and the purple line represents the modeled lithium-ion battery cell capacity. For CAM based on nickel-based chemistries, we convert from mass to battery capacity using the factor of 1,450 metric tons per GWh. For CAM based on iron-based chemistries, we use the factor 2,202 metric tons per GWh. If the chemistry is unknown, we use the average value of 1,826 metric tons per GWh. These values represent the approximate amount of cathode active material in a lithium-ion battery cell (Knehr et al. 2023).

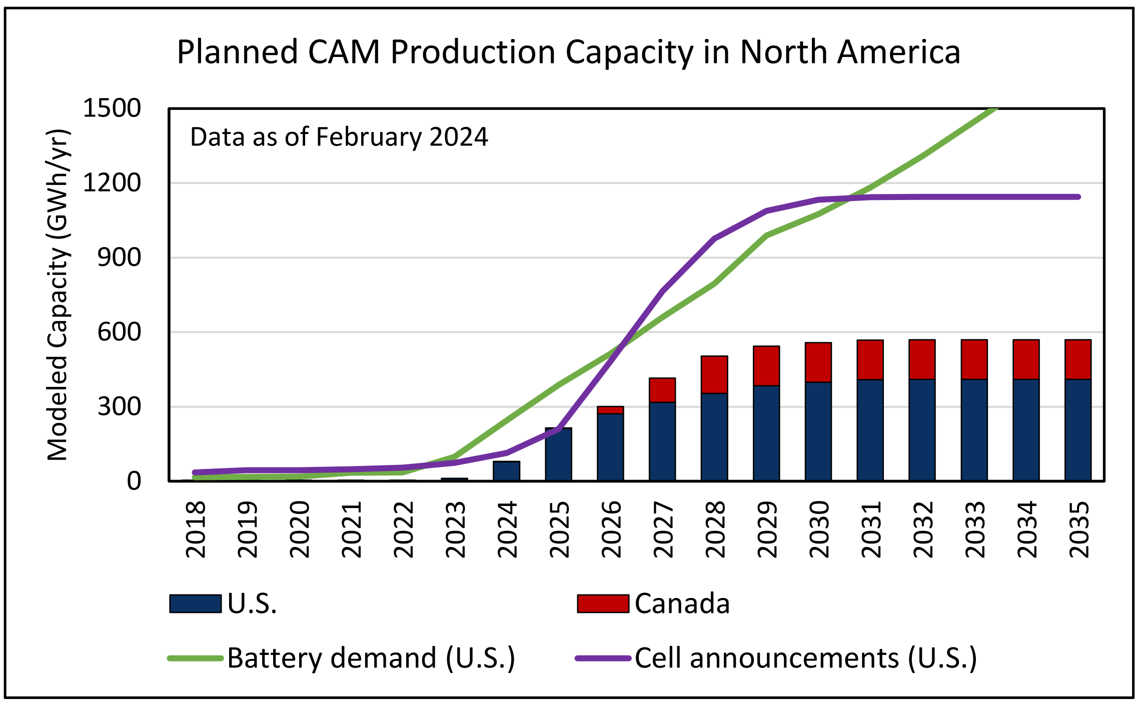

FIGURE 24 Modeled cathode active material production capacity (GWh) compared with demand from cell production and end-use

CAM production is modeled to reach 570 GWh by 2032. Incidentally, this is nearly identical to the production planned for AAM. Figure 24 shows that there is insufficient North American production of CAM planned to fully supply production of battery cells. Approximately

70% of the North American CAM production by the end of the decade is in the United States, with the remainder located in Canada. In 2025, modeled capacity of 215 GWh can satisfy nearly all North American cell production. However, the forecast ramp rate for CAM production in the mid-2020s is slower than cell production, and by 2028, 503 GWh can only supply less than half of North American cell production.

As with the AAM discussion in the previous section, there are multiple reasons why the CAM production announcements are less than total demand at this time. Several of these reasons are listed here:

- Companies need access to the raw material (particularly lithium, nickel, and cobalt) to be able to build a processing plant for CAM. As will be shown in Section 4.6, production of precursors in North America is less than production needs at this time. While modeled capacity for lithium salts grows throughout the decade, nickel and cobalt have a notable shortfall. Additional extraction is possible, but much of this is in early stages of development. To help mitigate this, companies are considering or increasing use of LFP rather than nickel-based cathode chemistries. Processing raw materials to serve the needs of precursor manufacturers is a key focus for MESC's second round of IIJA Section 40207 grants. MESC solicited two tranches of applications for the commercial scale separation of lithium from domestic sources and for the commercial scale domestic recovery of nickel, manganese, cobalt, aluminum and other minerals. Applications for both tranches are due in March 2024, and MESC anticipates investing between $50 to $300 million per award in three to seven awards for both tranches (lithium and other for non-lithium minerals), which could be completed by January 2025 (DOE 2024).
- Companies may be waiting for certainty in demand from cell production or for availability of financing before publicly committing to building a manufacturing plant. For example, this may be contingent upon the IRS finalizing the rulemaking on Section 45X, which includes cathode electrode materials as an "electrode active material" that is eligible for a 10% production tax credit (IRS 2023b). Furthermore, MESC has solicited applications for the commercial scale domestic production of cathodes, including cathode materials, powders, and electrodes, due March 2024. MESC anticipates investing between $50 to $300 million per award in four to eight awards for both anode and cathode manufacturing, as similarly described above, with awards completed by January 2025 (DOE 2024). An additional 100 GWh/year in nominal CAM capacity has been identified at facilities which are being planned or considered, but not yet formally announced by companies, further described in Appendix B Companies are aiming to maximize capacity utilization; Umicore noted "expansions will be closely matched to the customer volume ramp-up trajectories" (Umicore 2023).
- CAM production could be underestimated if cell-production facilities are also creating electrode active material onsite without making a separate announcement.

Beyond these reasons, gaps in supply of CAM can potentially be satisfied by imports.

Table 9 shows the expected capacity for each company which has plans for over 10 GWh/year of CAM. Table 9 shows the cathode material (nickel-based or iron-based) as well as estimated maximum production in terms of tons and GWh. For CAM announcements, there is a greater proportion of nickel-based chemistries than there is for cell production; this may be due to the protection of strategic information by cell production companies, as the majority of cells do not explicitly state their cathode chemistry. Figure 25 shows a map of the CAM manufacturing locations. Most cathode active material production has been announced for the eastern half of North America. Locations along the St. Lawrence River in Canada are readily accessible to mines in Canada. Redwood Materials has proposed sites in Nevada and South Carolina which can handle supply from recycled materials in addition to raw battery grade materials.

TABLE 9 Companies Producing CAM in North America

Company	Cathode material	CAM production (metric tons per year)	Equivalent battery capacity (GWh/year)
Redwood Material	Nickel	200,000	138
LG Chem	Nickel	120,000	83
Gotion	Iron	150,000	68
Northvolt	Nickel	87,000	60
Tesla	Iron	132,100	60
Umicore	Nickel	50,800	35
EcoPro BM	Nickel	45,000	31
Ultium CAM	Nickel	30,000	21
Ascend Elements	Unknown	36,500	20
6K Energy	Any	27,000	18
ICL-IP America	Iron	30,000	14
Nano One	Iron	27,500	13
Other			10

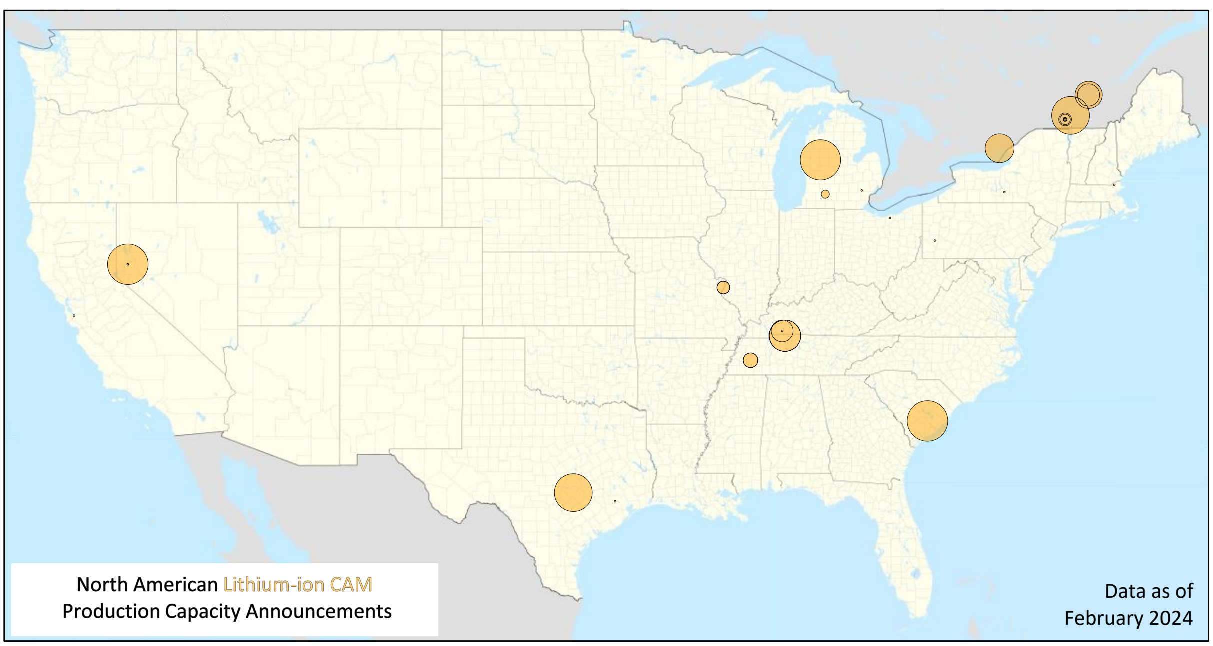

FIGURE 25 North American lithium-ion CAM production map

4.3 ELECTROLYTE

The electrolyte in a lithium-ion battery is the medium for ions to migrate from cathode to anode. The majority of commercially available lithium-ion batteries today use a liquid electrolyte consisting of a carbonate solvent and a lithium salt (Xing 2022). Solid-state batteries with a solid or semi-solid electrolyte are being considered for the next generation of batteries as well. Nearly all of the announcements that have been made to date for investments in commercial scale battery manufacturing have been for liquid electrolyte.

Figure 26 shows the modeled electrolyte production capacity in North America through 2035. As in previous graphics, the blue bars represent the modeled manufacturing capacity for CAM in the United States and the red bars represent the modeled manufacturing capacity for CAM in Canada. The green line represents the lithium-ion battery end-use demand for vehicles and stationary storage in the United States (Section 2.2), and the purple line represents the modeled lithium-ion battery cell capacity. For electrolyte, we convert from mass to battery capacity using the factor of 494 metric tons per GWh. This represents the average amount of cathode active material in lithium-ion battery cells based on LFP and NMC-811 chemistries (Knehr et al. 2023). BatPaC modeling shows a greater electrolyte demand (per kWh) for LFP cells than for NMC cells. As shown in Section 3.2, we do not always have information about the production of the battery cells, and so we use a simple average of NMC and LFP chemistries for determining electrolyte availability.

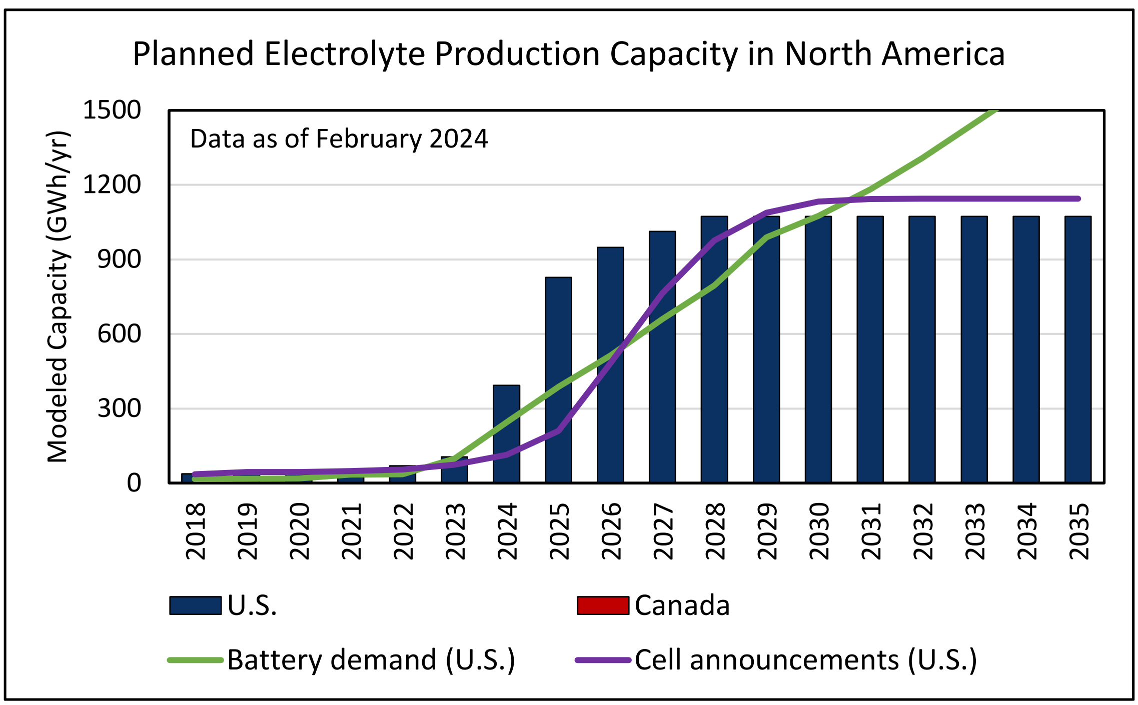

FIGURE 26 Modeled electrolyte production capacity (GWh) compared with demand from cell production and end-use

Electrolyte production is modeled to reach 1,070 GWh by 2028. Figure 26 shows that there is sufficient North American production of electrolyte planned to fully supply production of battery cells in North America through 2028, and 80% of North American cell production (or 94% of U.S. cell production) through 2035. All of the announced North American electrolyte production is in the United States. However, the coverage of electrolyte may be overestimated. The calculation is based on a mass-balance calculation of the amount of material within a battery cell using the BatPaC model (Knehr 2022). It may be that more electrolyte is needed during production than is accounted for.

Unlike AAM and CAM, there appears to be sufficient manufacturing capacity for lithium-ion electrolyte. However, there are potential upstream materials shortfalls. Lithium hexafluorophosphate ($LiPF_6$) is the most common salt used in electrolytes today. There is currently no manufacturing capacity for $LiPF_6$ or other electrolyte salts in North America at a commercial scale. The DOE Office of Manufacturing and Energy Supply Chains (MESC) has awarded a grant for production of up to 10,000 metric tons per year, which would be sufficient electrolyte salt to supply one million electric vehicles per year (DOE 2022), or approximately 80 GWh of complete battery cells. As this is less than the total projected electrolyte production, the remainder of the electrolyte salts would need to be imported or new yet-unannounced production will need to come online in North America. To illustrate the potential for additional domestic capacity that could come online, MESC has solicited applications for the commercial scale domestic production of electrolyte salts, solvents, and mixes due March 2024, and anticipates investing between $50 to $300 million per award in two to six awards that could be completed by January 2025 (DOE 2024).

As with electrode active material, companies may be waiting for certainty in demand from cell production or for availability of financing before publicly committing to building a manufacturing plant. We have identified 300,000 metric tons per year (or 600 GWh/year) in nominal electrolyte capacity at facilities which are being planned or considered, but not yet formally announced by companies. These companies (Guangzhou Tinci and Shenzen Capchem) are among the largest producers of electrolyte worldwide, though neither yet manufactures in the United States.

Table 10 shows the expected capacity for any each company which has plans for a commercially viable quantity of electrolyte. Table 10 shows the estimated maximum production in terms of tons and GWh. Figure 27 shows a map of the electrolyte manufacturing locations. Announced electrolyte production has been very aligned with historical automobile production in the eastern United States. Enchem is by far the largest producer in the United States based on its planned production, with an existing plant in Georgia and plans for expansion in Kentucky, Michigan, Ohio, and Tennessee. Enchem is largely supplying to LG Energy Solution and SK Innovation, which are currently the companies with the largest cell demand at the end of the decade.

TABLE 10 Companies Producing Electrolyte in North America

Company	Electrolyte production (metric tons per year)	Equivalent battery capacity (GWh/year)
Enchem	300,000	606
Dongwha Electrolyte USA	80,000	162
Duksan Electera America	60,000	121
Shenzen Capchem	44,000	89
Soulbrain	30,000	61
Mitsubishi Chemical Corporation	10,000	20
Advanced Electrolyte Technologies	5,000	10
Daikin America	2,000	4

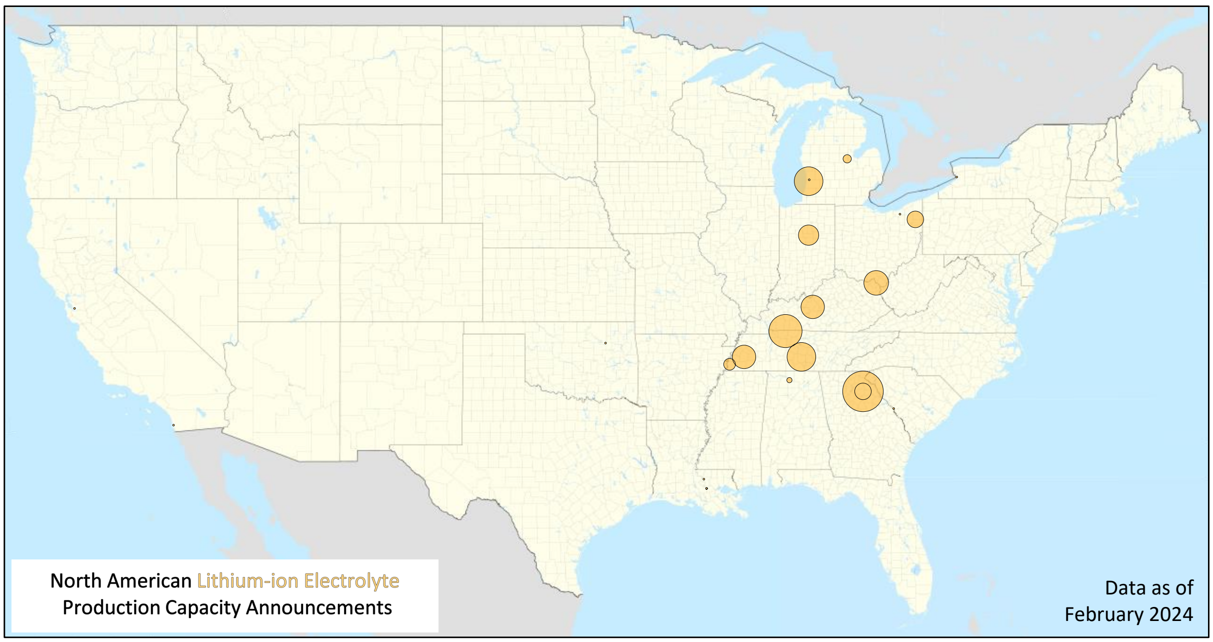

FIGURE 27 North American lithium-ion electrolyte production map

4.4 FOILS

Foils are used as the substrate for the anode and cathode active materials. Copper foil is most common for the current collector for anodes, and aluminum foil is used for cathodes. A typical thickness for these foils is around 10 to 20 microns (Zhu et al. 2021).

Figure 28 shows the modeled aluminum foil production capacity and Figure 29 shows the modeled copper foil production capacity in North America through 2035. As in previous graphics, the blue bars represent the modeled manufacturing capacity in the United States and the red bars represent the modeled manufacturing capacity in Canada. The green line represents the lithium-ion battery end-use demand for vehicles and stationary storage in the United States (Section 2.2), and the purple line represents the modeled lithium-ion battery cell capacity. For copper foil we convert from mass to battery capacity using the factor of 446 metric tons per GWh; for aluminum foil we use the factor 193 metric tons per GWh. These represent the average amount of foils in lithium-ion battery cells based on LFP and NMC-811 chemistries (Knehr et al. 2023).

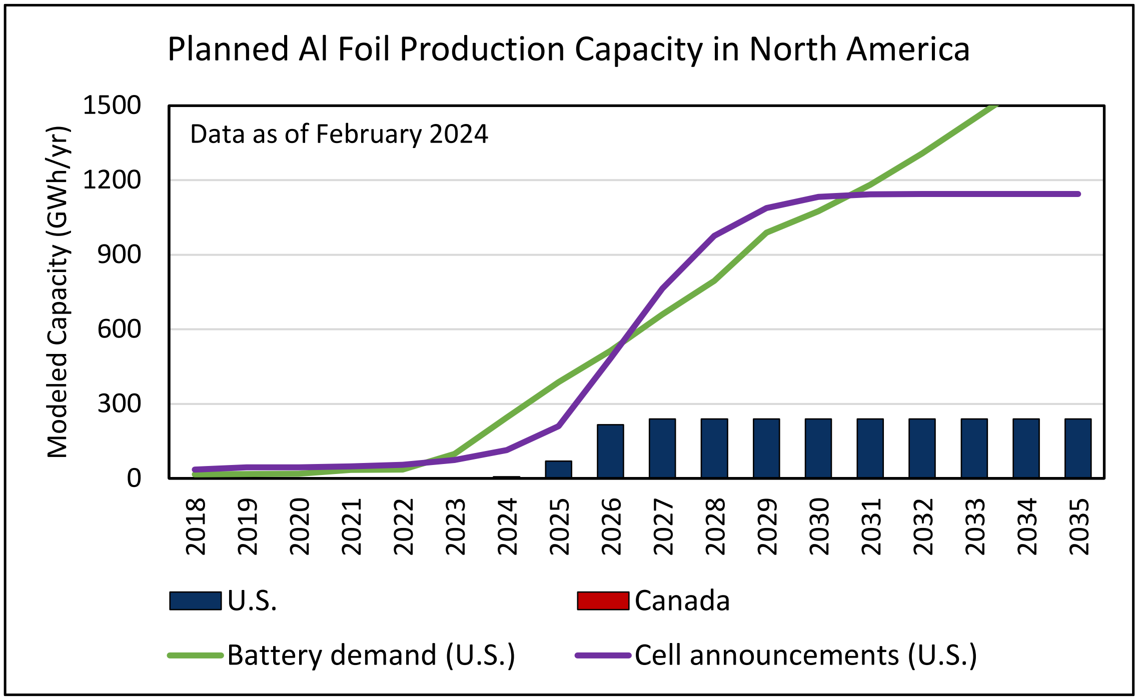

FIGURE 28 Modeled aluminum foil production capacity (GWh) compared with demand from cell production and end-use

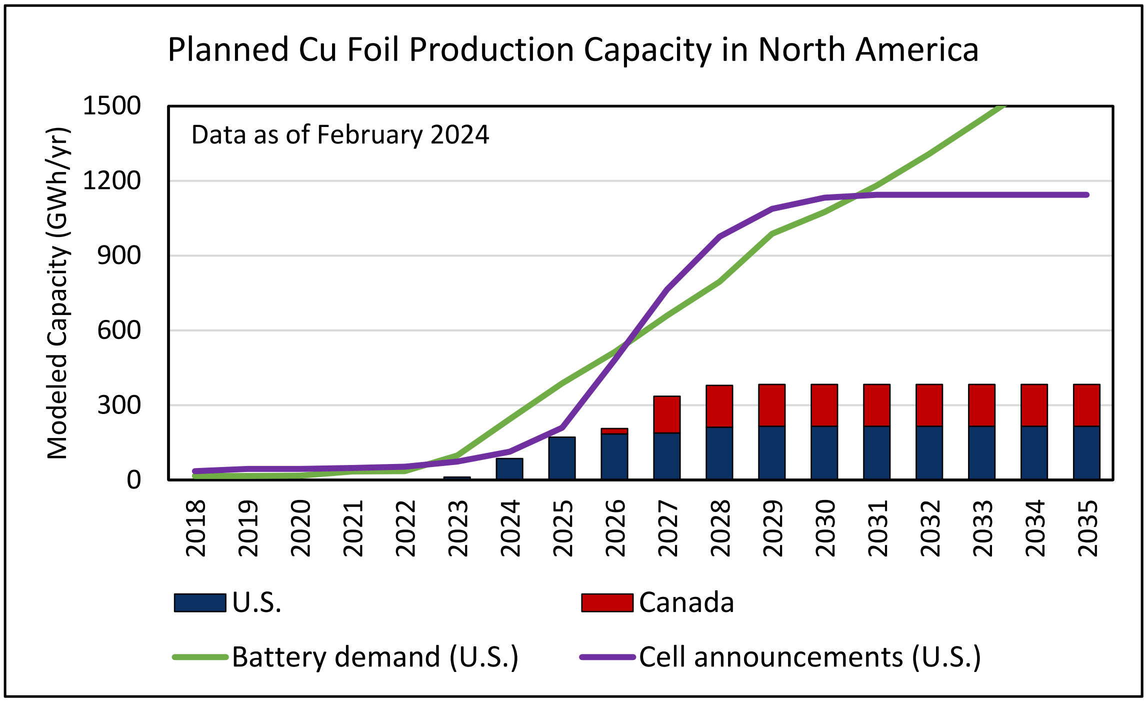

FIGURE 29 Modeled copper foil production capacity (GWh) compared with demand from cell production and end-use

Aluminum foil is modeled to reach 240 GWh by 2027 and copper foil is modeled to reach 380 GWh by 2028, with no formal announcements after that. Figures 28 and 29 show that this amount of foil is not sufficient to fully supply North American production of battery cells at this time. All of the aluminum foil production and about half of the copper foil production has been in the United States, with the remaining copper foil production in Canada.

Table 11 shows which companies are making foils. Lotte is the largest producer of aluminum foils, followed by Gränges. For copper foils, Redwood Materials has the largest announced production plans, followed by Volta Energy Solutions, Addionics, and Denkai America. These companies have also noted plans to expand beyond their original announcements, with another 160,000 metric tons (or 370 GWh) of copper foil combined. Investment decisions may be contingent upon the IRS finalizing the rulemaking on Section 45X, which include cathode foils and anode foils within the definition of electrode active materials as eligible for a 10% production tax credit (IRS 2023b). Figure 30 shows a map of the foil locations. These locations are distributed across North America, though there are currently only eight sites across six companies.

TABLE 11 Companies Producing Foils in North America

Company	Cathode material	Foil production (metric tons per year)	Equivalent battery capacity (GWh/year)
Lotte Aluminium Materials	Aluminum	36,000	187
Redwood Materials	Copper	72,000	162
Chang Chun Petrochemical	Copper	50,000	112
Volta Energy Solutions	Copper	25,000	56
Gränges	Aluminum	10,000	52
Addionics	Copper	13,400	30
Denkai America	Copper	10,700	24

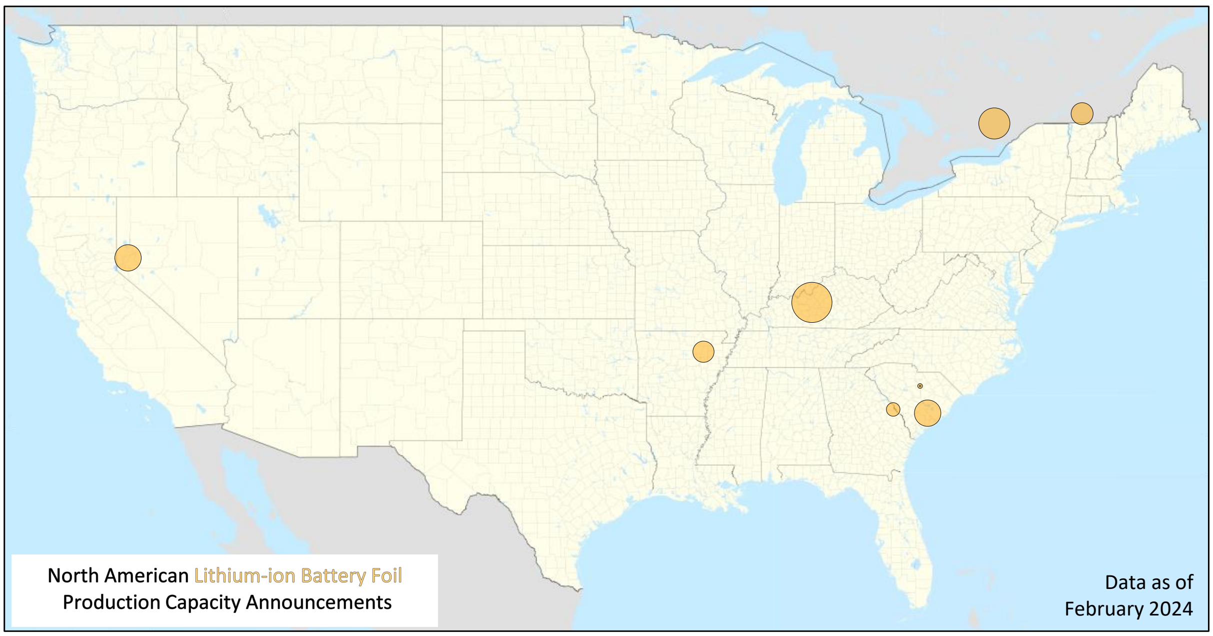

FIGURE 30 North American lithium-ion battery foil production map

4.5 SEPARATOR

The separator in a lithium-ion battery is a physical membrane between the anode and cathode which allows for the flow of ions while keeping the two components physically separated. The membrane is porous to allow for infiltration of the electrolyte enabling ionic transport (Xing 2022). In lithium-ion batteries, the most common separator materials are polypropylene and polyethylene.

Figure 30 shows the modeled separator production capacity in North America through 2035. As in earlier figures, the blue bars represent the modeled manufacturing capacity for lithium-ion separators in the United States and the red bars represent the modeled manufacturing capacity for separators in Canada. The green line represents the lithium-ion battery end-use demand for vehicles and stationary storage in the United States (Section 2.2), and the purple line represents the modeled lithium-ion battery cell capacity. For separator, we convert from mass to battery capacity using the factor of 9.67 million square meters per GWh. This represents the average amount of separator material in lithium-ion battery cells based on LFP and NMC-811 chemistries (Knehr et al. 2023). BatPaC modeling shows a greater separator demand (per kWh) for LFP cells than for NMC cells. As shown in Section 3.2, we do not always have information about the production of the battery cells, and so we use a simple average of NMC and LFP chemistries for determining separator availability.

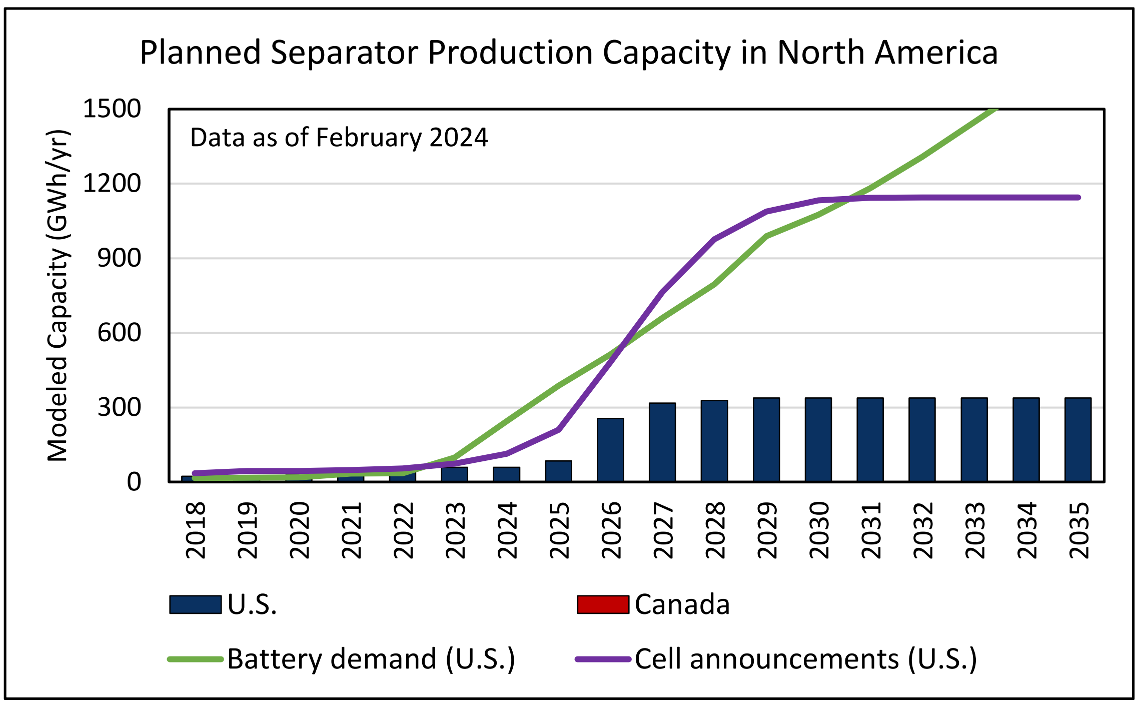

FIGURE 31 Modeled separator active material production capacity (GWh) compared with demand from cell production and end-use

Separator production is modeled to reach 340 GWh by 2029. Figure 31 shows that there is not enough North American production of separators planned to fully supply production of battery cells in North America, satisfying approximately half of the market in 2026, but only one-quarter of the market in 2030. All of the announced North American lithium-ion separator production is in the United States. There is also production of separators for lead-acid batteries in the United States, but it is unlikely that any company would repurpose these lines for lithium-ion batteries, as the three largest companies (Asahi Kasei, Entek, and Microporous) already have made announcements for lithium-ion-focused separator facilities.

Table 12 shows the expected capacity for each company making lithium-ion battery separators in North America. Table 12 shows the estimated maximum production in terms of square meters of separator membrane and in GWh. Figure 32 shows a map of the separator manufacturing locations. Historical production has been in North Carolina (Celgard) with a small amount in Oregon (Entek), while future announcements have been made for Indiana, Ohio, and Virginia. The largest planned capacity is by Entek, followed by Semcorp, Celgard, and Microporous. Beyond the values listed in Table 12, Entek and Microporous have noted aims of increasing production by another 2,800 million square meters (290 GWh), and SK Innovation has been linked to a potential facility in Canada.

TABLE 12 Companies Producing Separator for Lithium-ion Batteries in North America

Company	Separator production (million square meters per year)	Equivalent battery capacity (GWh/year)
Entek	1,420	147
Semcorp Advanced Materials	1,100	114
Celgard (Asahi Kasei)	550	57
Microporous	200	21

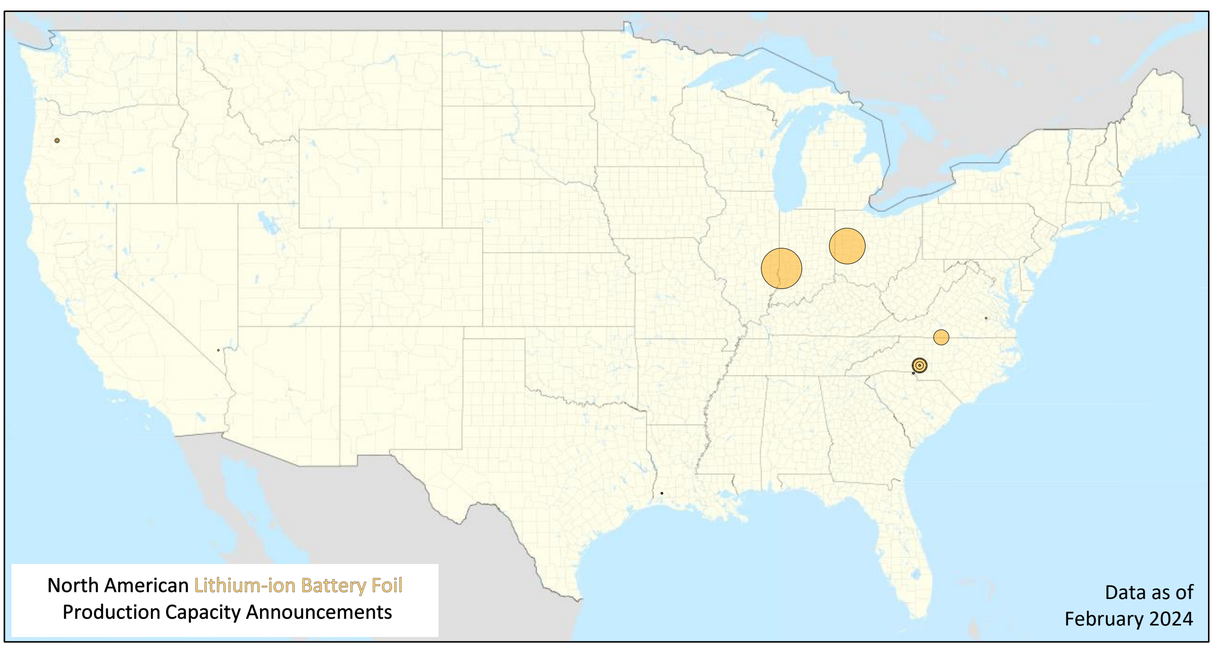

FIGURE 32 North American lithium-ion separator production map

4.6 BATTERY-GRADE PRECURSOR MATERIALS

In addition to manufacturing of battery components, we also consider the production of battery-grade precursor materials. These include lithium carbonate, lithium hydroxide, nickel sulfate, cobalt sulfate, and manganese sulfate.

Lithium carbonate and hydroxide

Lithium carbonate and hydroxide are combined because lithium can be processed into either for use in batteries. Each of these are utilized in production of CAM, and lithium carbonate is a precursor to the electrolyte salt $LiPF_6$. Figure 33 maps production for lithium salts. If a company producing the lithium salt is extracting the mineral on-site it is colored light yellow, if a lithium compound is delivered for processing it is colored orange. For extraction sites which produce lithium salts on-site, plants are only included if the company has released at least a preliminary feasibility study.[7]

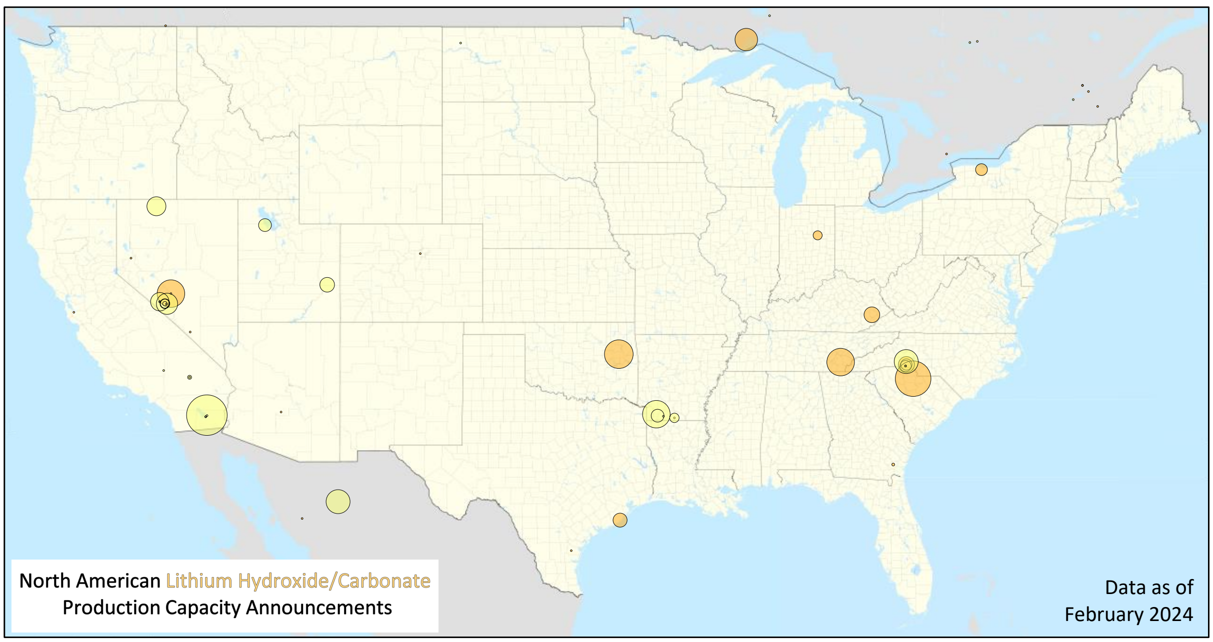

FIGURE 33 North American lithium carbonate and lithium hydroxide production map

Figure 34 shows the combined production capacity for battery-grade lithium salts. The majority of the formally announced production capacity is in the United States (91%). For lithium carbonate, we convert from mass to battery capacity using the factor of 592 metric tons per GWh; for lithium hydroxide we use the factor 384 metric tons per GWh, based upon analysis of LFP and NMC cathode batteries in BatPaC (Knehr 2022). The total capacity reaches 1,160 GWh-equivalent by 2032. There have been announcements for additional future growth, as 460 GWh of additional potential lithium salt capacity has been stated in preliminary economic analyses published by the

[7] In other words, a preliminary economic analysis, which happens prior to the publication of a prefeasibility analysis, is insufficient to include as a formal announcement.

mining companies. The exact ramp-up should be treated with caution. While we assume a relatively conservative 24-month ramp of each site from initial production to full production, it is likely that many of the initial start dates announced by the companies are overly optimistic, either in the time to acquire funding or the time for permitting. Additionally, mining companies make operational decisions based on their estimated profit. A glut of materials in the market may cause prices to drop and delay the company's operation of the plant. Lithium prices dropped in 2023 after spiking in 2022 (Liu and Patton 2023), but S&P Global still predicts long-term growth of lithium demand (Lazzarro 2023).

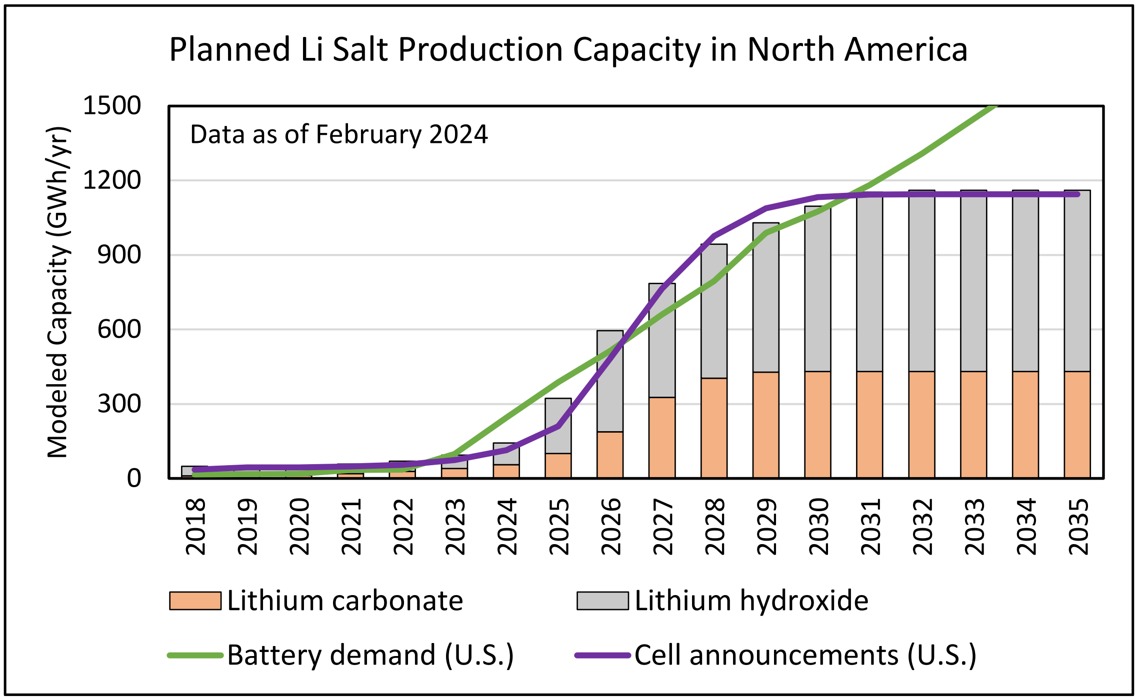

FIGURE 34 Modeled lithium carbonate and lithium hydroxide production capacity (GWh) compared with demand from cell production and end-use

Figure 35 shows the extraction source of the lithium used to process the lithium salt. Nearly 40% of the planned capacity is coming from brine extraction, 30% is coming from rock mining, and over 20% is coming from extraction from clay. Based on existing geologic formations, clay extraction mainly occurs in the west, rock extraction mainly occurs in the east, and brine extraction occurs across North America. Five percent of the lithium salts are coming from secondary sources, either from waste extraction at mining sites or from recycling of end-of-life batteries.

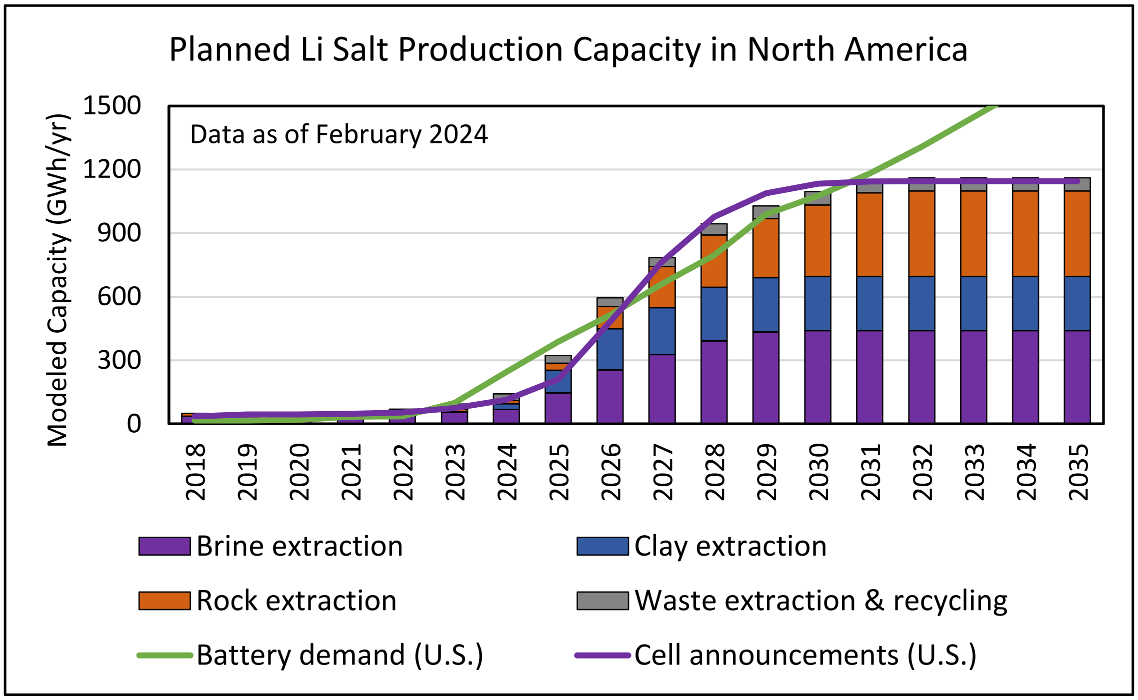

FIGURE 35 Modeled lithium salt production capacity by extraction method

Cathode metal sulfates

Nickel sulfate ($NiSO_4$), cobalt sulfate ($CoSO_4$), and manganese sulfate ($MnSO_4$) are the primary precursor salts for forming NMC cathode active material. There is currently very little processing of these sulfates in North America, with no known standalone facility dedicated to its production. To address this gap, MESC has solicited applications for the commercial scale domestic processing of battery-grade precursors that are fed directly as an input to CAM powders due March 2024. Within this area of interest MESC anticipates investing between $50 to $200 million per award in two to four awards that could be completed by January 2025 (DOE 2024).

Companies have made announcements to have a combined 200,000 tons per year of nickel sulfate, 75,000 tons/year of cobalt sulfate, and 120,000 tons/year of manganese sulfate by the end of the decade.[8] These correspond to 98 GWh $NiSO_4$, 293 GWh $CoSO_4$, and 479 GWh $MnSO_4$. To convert from nickel sulfate to GWh, we use a value of 2,050 tons/GWh, for cobalt sulfate we use a value of 257 tons/GWh, and for manganese sulfate we use a value of 250 tons/GWh. These correspond to a relatively high nickel concentration known as NMC-811 within the BatPaC model (Knehr 2022); battery makers can shift the production to optimize for battery characteristics while minimizing manufacturing costs.

Table 13 shows the announced nominal production capacity of battery-grade metal sulfates. Exact ramp-up for each site depends on the availability of materials. Three proposed

[8] Some companies present their tonnage in terms of the elemental metal contained in the sulfate, while other companies present in terms of tons of metal sulfate. All values shown here are in terms of the metal sulfate or alternatively in terms of GWh-equivalent.

facilities (Aleon, Li-Cycle, and Stelco) are directly linked with end-of-life recycling, and therefore need to have sufficient feedstock before producing at full volume. The other sites are dependent on mining, and so start date is uncertain for these as well. Figure 36 shows the locations of announced metal sulfate processing facilities in North America. Production of Co sulfate is shown in cyan, production of Co sulfate is shown in yellow, and production of Mn sulfate is shown in pink. Being recycling processing facilities, Aleon, Li-Cycle, and Stelco produce multiple products and are shown in black.[9]

TABLE 13 Companies Producing Metal Sulfates in North America

Company	Metal sulfate	Sulfate production (metric tons per year)	Equivalent battery capacity (GWh/year)
Vale	Ni sulfate	65,900	32
Li-Cycle	Ni sulfate	48,000	23
FPX Nickel	Ni sulfate	40,000	20
Aleon Renewable Metals	Ni sulfate	36,000	18
Stelco / Primobius	Ni sulfate	11,000	5
Evelution Energy	Co sulfate	33,000	128
Electra Battery Materials	Co sulfate	25,000	97
Li-Cycle	Co sulfate	7,500	29
Aleon Renewable Metals	Co sulfate	6,000	23
Stelco / Primobius	Co sulfate	3,700	14
Element 25	Mn sulfate	65,000	260
Vibrantz	Mn sulfate	45,000	180
Aleon Renewable Metals	Mn sulfate	6,000	24
Stelco / Primobius	Mn sulfate	3,700	15

9 Li-Cycle plans to process the manganese content into manganese carbonate rather than manganese sulfate.

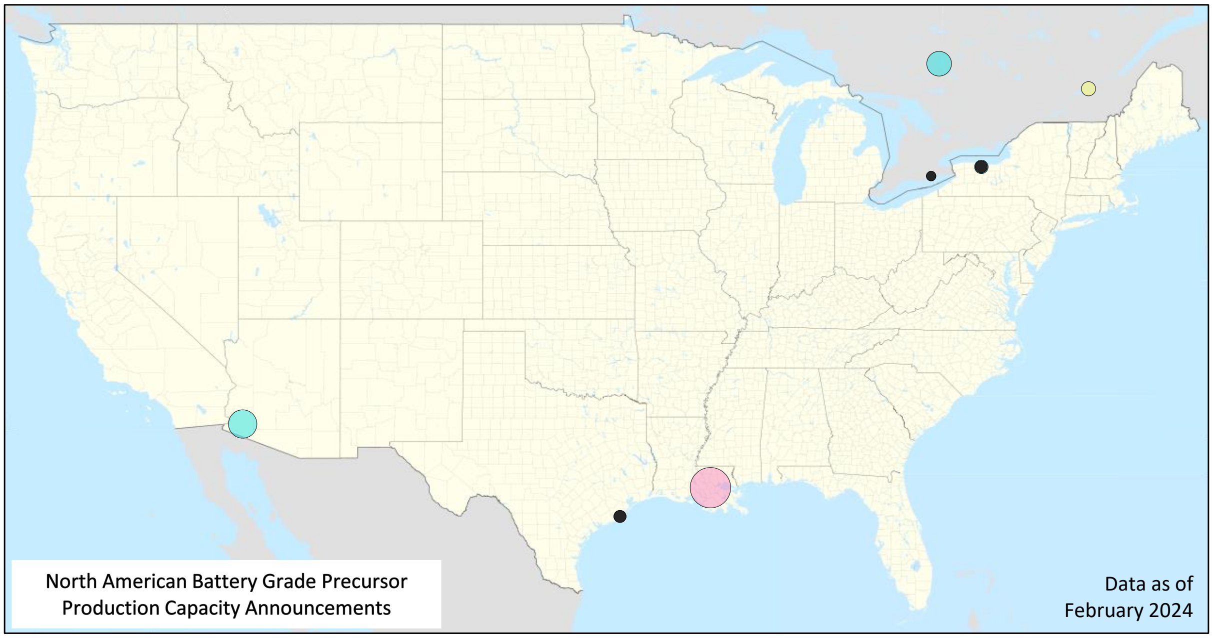

FIGURE 36 North American battery-grade precursor production map

5 DISCUSSION AND CONCLUSIONS

In the coming years, there is great demand for batteries for many purposes, including electric vehicles, stationary storage, and electronics. This leads to the need for major growth in manufacturing in the battery sector. Argonne National Laboratory has been tracking announcements made by companies on their updated manufacturing plans. By considering these manufacturing plans in the aggregate, we can begin to understand the evolution of manufacturing for batteries and estimate the availability of these batteries for different purposes. North American manufacturing will minimize risks of supply chain shocks and improve manufacturing resilience. Federal investment has been used to encourage private investment within North America. Financial incentives such as the Section 45X Advanced Manufacturing Production Credit encourage companies to build manufacturing facilities in the United States. In complement to this supply-side incentive, the Section 30D Clean Vehicle Credit provides a demand-side tax credit for electric vehicles with batteries that meet an annually-increasing value requirement for their critical minerals to be recycled and battery components manufactured in North America up to 2032 (IRS 2023c).

This analysis has shown that companies have made aggressive plans for deployment of battery cells, particularly for lithium-ion batteries in North America. From 2021 to 2032, we model a 28-fold increase in battery cell production. This production of battery cells is nominally sufficient to meet the demand for a rapidly electrifying economy. However, looking at the production of the components which go into these batteries, we do observe a shortfall for most of the constituent battery components. Taken on its own, this would lead to the need to import certain components to be included in North American-built batteries.

The most important components in a battery are the anode and cathode active materials, electrolyte, separator, and foils. We find that based on given announcements to date, that approximately half of the demand for lithium-ion battery production for electrode active material can be met by North American sources by the end of the decade, based on announcements that have already been made. There have been more announcements for electrolyte, reaching approximately 100% of the North American market, and fewer announcements for separators and foils, which currently only satisfy about one quarter of the domestic market. These manufacturing values are growing by large factors relative to existing production. For electrode active materials, there is over a 100-fold increase in manufacturing capacity from 2021 to 2032. Over the same timespan, a 27-fold increase in electrolyte manufacturing capacity and an 8-fold increase in lithium-ion separator manufacturing capacity has been announced. As of 2021, there was no commercial-scale manufacturing of thin electrode foils in North America.

Several other key governmental activities beyond North America will affect the development of the battery supply chain in the United States. For example, the Government of the Republic of Korea has acknowledged that "battery manufacturers are actively diversifying their supply chains through joint ventures and other arrangements in order to meet the criteria for tax credits under the IRA." (Government of the Republic of Korea 2024) The Australian Government stated that it is "committed to growing our downstream processing capability," and specifically that it is forecast to contribute 20 percent of global lithium processing by 2027 and that "investment from the United States will continue to be critical to these efforts." (Australian Government 2024) These examples illustrate the global and evolving nature of the battery production. However, it should be emphasized that the 30D tax credit most directly incentivizes critical minerals to be recycled and battery components to be manufactured or assembled in North America for vehicles that are in general sold less than $80,000 to taxpayers earning under certain income limits (IRS, 2023c). Specifically, this analysis does not assess whether or the extent to which the Clean Vehicle Credit may indirectly encourage the siting of manufacturing facilities in North America that could (beyond 30D eligibility) still serve demand for vehicles ineligible for the credit due to price or its buyer's income.

Uncertainty and Risk

Any forecast entails a high degree of uncertainty. This analysis takes a conservative view of future manufacturing announcements, only including sites which have been explicitly formally announced. In some cases, conditional expansions, undisclosed vertical integration, and rumored plants can double the total component manufacturing capacity, if all sites come to fruition. On the other hand, corporate investments may not occur, and so we must consider the relative risk.

Appendix B includes an assessment of risk for each cell plant, finding that the midstream is largely low risk. The risks analyzed are lack of offtake agreements, lack of previous experience, lack of public follow-on to initial announcements, and financial difficulties. Another potential risk, not analyzed in this report, is the availability of skilled labor. Nationwide, the investments from 2021 to 2023 in the battery supply chain included over $130 billion to support over 80,000 jobs. Investments have been announced across the country, but have been disproportionately concentrated near each other, particularly near existing auto manufacturing. Recent research examining workforce implications of electrification indicate that when including battery cell production and pack assembly, the total number of workers needed for electric vehicle manufacturing is likely to be overall comparable to ICEV production if U.S. firms succeed in onshoring battery production and assembly (Combemale 2023).

In Appendix B, we also consider the effect of variations in the underlying modeling assumptions in the analysis. The baseline analysis excludes rumored or conditional plant expansions or development. Rumored and conditional plants add a modest 110 GWh to the total modeled battery cell production capacity in 2033; however, rumored and conditional plants for AAM would add 850 GWh/year by 2033, which would allow AAM production to meet cell production. Appendix B also emphasizes that the 3-year ramp rate (described in Appendix A) from initial production to full-scale production embedded in the analysis is modestly conservative, and plants could reach nominal capacity more or less quickly.

Lack of announced production capacity today is not necessarily indicative of an import-heavy supply chain in the future. It is likely that manufacturing announcements for battery components will lag those announcements for battery cells. Without a robust battery cell market, indeed, there is no reason for battery component manufacturers to increase manufacturing capacity in North America. Likewise, some of the important battery grade precursor materials do not yet have announcements to meet the full demand for batteries in North America. Given the growing demand for production of battery components, however, there may be an increase in manufacturing announcements for these as well. Finally, it is instructive to look retrospectively to qualify the potential for the market to rapidly adapt in response to industrial policies. For example, Table 3 presents the planned cell production capacity for vehicle-related applications in *North America* by 2030 to be nearly 1,200 GWh, which is roughly equal to the forecast of *global* on-road vehicle battery demand under the policies in place as of 2020, according to modeling by Leiden University and Argonne National Laboratory (see Figure 6-1 of Zhou et. al. 2021).

Therefore it is reasonable to say that the battery supply chain in the U.S. and North America is in flux following the passage of the IRA. BNEF creates an annual ranking of 30 countries based on "potential to build a secure, reliable, and sustainable lithium-ion battery supply chain" (Gomes-Callus 2024). The 2024 report ranked Canada, the U.S., and Mexico in first, third, and nineteenth, respectively, with Mexico exhibiting the most growth of any country featured in the ranking. BNEF credits "clear policy commitment and implementation" for North America's success in expanding the battery supply chain, and notes that the IRA's "friendshoring" ambitions have contributed to Canada's thriving battery supply chain (Gomes-Callus 2024). Beyond North America, "friendshoring" (expanding battery components manufacturing in trusted allies or other partner countries) is not quantified in this analysis. However, allies and partners outside of North America are likely to be integral in meeting U.S. battery component demand. Allies Japan and the Republic of Korea, for example, are the world's second and third largest producers of CAM and AAM (IEA 2022). Appendix D contains estimated investments in cell manufacturing internationally, focusing on countries within the Minerals Security Partnership (MSP), as these are potential sources for imported batteries or vehicles to the United States (U.S. Department of State 2022; White House 2023b). The Minerals Security Partnership was launched in 2022 as a multilateral effort to responsibly secure critical mineral supply chains. The MSP is representative of strong ties with allies and partners that are driving the demand for stable sources of battery materials, in part through efforts to localize battery cell manufacturing.

There is still a substantial portion of supporting industrial policy for the battery supply chain that has not yet been finalized. This includes final rulemaking for the 45X tax credit (Advanced Manufacturing Production Tax Credit), the submission, selection, and award of the second round of funding from the Battery Materials Processing and Manufacturing Grants program by January 2025 (IIJA section 40207) and the 48C tax credit (Qualifying Advanced Energy Project Credit), and, respectively, final interpretive guidance and rulemaking from the Department of Energy and the Department of the Treasury on Foreign Entities of Concern (FEOC) and Excluded Entities for the 30D tax credit (Clean Vehicle Credit). This analysis only considers confirmed projects as of the report's writing (February 2024). Further study at periodic intervals in the next few years may be useful to assess how developments in implementation of the IIJA and IRA continue to impact project announcements within the battery supply chain.

APPENDIX A DATA AND METHODOLOGY

Investment tracking

Argonne National Laboratory is tracking announcements of existing, new, and expanded manufacturing plants in the battery and electric vehicle supply chains (ANL 2024). The battery chain data includes minerals extraction and processing, battery component manufacturing, battery cell manufacturing, and battery pack manufacturing. For minerals extraction, mines are included if they are operational, or if there has been a release of a prefeasibility study or a definitive feasibility study. Minerals processing considers sites to convert raw minerals to battery-grade materials. These are often, but not always, co-located with the extraction sites. For midstream processing, manufacturing facilities produce cathodes, anodes, electrolytes, separators, and other battery precursors. Battery cell and pack manufacturing includes commercial- and pilot-scale manufacturing to produce electrochemical energy storage.

The data for electric vehicle supply chains includes manufacturing of electric vehicle assembly, electric vehicle components, and electric vehicle chargers. Announcements are tied to manufacturing of equipment and vehicles, not deployment. The following vehicle types are included: light-, medium- and heavy-duty vehicles; non-road vehicles / mobile machinery; motorcycles; low-speed EV; and aircraft. Most announcements are in the on-road vehicle space. Only battery electric vehicles and plug-in hybrid electric vehicles are included. Investments in component manufacturing were only included if it is relevant for the electric vehicle drivetrain; body/interior/HVAC are not included. EV chargers include manufacturing of any vehicle chargers, including Level 2 alternating current (AC) chargers, Direct Current Fast Chargers (DCFC), and wireless charging.

The majority of the investment announcements being tracked are from company or governmental press releases. Announcement data is tracked through searching individual company press releases and social media posts and state announcements of new manufacturing investments. These announcements are often repeated through media outlets with additional information. All announcements are based on publicly available data. Where possible, we supplement these public this information with corporate investor presentations, permit filings, job postings, social media posts, and announcements in conferences/interviews. Rumored plants are excluded, as are those which are being planned or considered, but not yet formally announced by companies.[10] The full-scale volume of most large facilities is generally announced by the company either in press releases, investor presentations, or media interviews. For the few sites without any publicly released information, we make an educated guess for total volume based on the size of the investment. Some data for existing plants was supplemented using the NAATBatt Lithium-Ion Battery Supply Chain Database (NREL 2024), which was then tracked back to an original announcement where possible.

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[10] Occasionally a company will announce a project occurring in multiple stages of investment. These expansions are often contingent upon successful inauguration of the first stage and subject to funding constraints. In general, these conditional announcements are excluded from our analysis of total capacity, pending more concrete commitments by the companies.

Capacity modeling

When making investment announcements, companies often state the full nameplate capacity of the facility, along with an initial date of production. The ramp up of each site to its full nominal capacity is subject to uncertainty. If a company only states the year, rather than the month or quarter of initial production, we assume that initial manufacturing begins on July 1, as plants that open earlier or later will be uniformly distributed about this and our aggregate annual total will be reasonably accurate even if any individual plant is mischaracterized.

We assume that the production rate grows linearly from the initial date of production to full-scale production. If an announcement includes dates for both, then we use these values, unless there is subsequent information that the facility would be delayed or accelerated. However, most investment announcements do not include information about both initial production and full-scale production. For these sites, we assign a default value for the length of time to ramp up to full capacity. For battery cells and packs, we assume a ramp time of 36 months, as most plants intend to reach full production between 2 and 3 years after opening. Battery components tend to reach full production capacity faster than cells. For cathode and anode active materials and battery-grade precursors, we assume a ramp time of 24 months. For electrolytes, separators, and foils, we assume a ramp time of 12 months.

Due to lack of information about manufacturing volume for each plant, lead-acid batteries are included in the aggregate. Battery Council International claims that there is a total of 206 GWh of lead-acid battery manufacturing across North America (BCI 2023). We apply the historical worldwide growth in lead-acid battery manufacturing since 1990 (Pillot 2021) to the North American market to estimate annual battery capacity prior to 2022. Of this capacity, we assume that 82% is for automotive uses and 18% is for stationary storage, following the Energy Grand Storage Market Report (DOE 2020). Avicenne assumes a 1.77% annual growth rate in lead-based batteries through 2030 worldwide, but we have found no formal announcements for future growth in lead-acid capacity in North America after 2024, and so we assume a nearly constant capacity into the future. To distinguish between countries within North America, we note that 165 GWh of lead-acid battery manufacturing capacity is from the United States (BCI 2023a). Of the remaining 41 GWh, we estimate that 80% of the total is manufactured in Mexico and 20% is manufactured in Canada. This estimate is informed by U.S. trade data of lead-acid batteries (trade codes 850710 and 850720), Canadian lead-acid battery demand, relative vehicle registrations in Canada and Mexico, and a technical report on recycling of spent lead acid batteries (USITC 2023; CBA 2022; CEIC 2018; CEC 2013).

Similarly, non-rechargeable primary batteries are also included in the aggregate. In North America, the market for these is for personal electronics, and is dominated by Energizer and Duracell. After Energizer acquired the Rayovac brand, these companies combined for 75% of the consumer battery market (Energizer 2019). These companies have manufacturing facilities for alkaline batteries and lithium cell batteries in the United States. The total annual operating capacity of each of these facilities is not publicly shared. In an investor presentation, Energizer noted a total of 6.4 billion batteries sold to consumers in North America by all manufacturers (Energizer 2023). Considering plants which produce alkaline batteries and button cell batteries, we estimate an average of 3.7 watt-hours of capacity per battery, which equates to a total market size of 24 GWh.

Of this, we allocate 18 GWh to existing North American manufacturing facilities to match the overall market share and presume the rest of the demand to be met by imports. Unlike the secondary battery market, the primary battery market is exhibiting slow growth in the United States (Energizer 2019; 2023), with several plant consolidations and closings announced in recent years. As there have been no formal announcements for future growth in primary battery capacity after 2024, we assume a constant capacity into the future. This is allocated fully to the United States, and solely for electronics usage.

The majority of battery cell manufacturing plant and component manufacturing plant announcements have been since 2021. Figure 37 shows the relative delay from the initial announcement until the announced plan for starting production, which represents the time for permitting and construction. Most cell production and separator plants have a two-to-four year timeframe between initial announcement and opening. Most electrode active material (AAM and CAM) plants have a one-to-three year timeframe between initial announcement and opening, as do foil production plants (not shown). Most electrolyte plants have a zero-to-two year timeframe between initial announcement and opening. Because of their shorter construction and permitting time, most battery components can be responsive to the demand arising from battery cell plants. Battery pack plants are less consistent. The largest battery pack plants have a tendency to start production approximately three years after the initial announcement. However, there is a wide variation in this time, with smaller plants often planning production within one year of the announcement, and some pack production announcements planned for up to six years after the date of announcement.

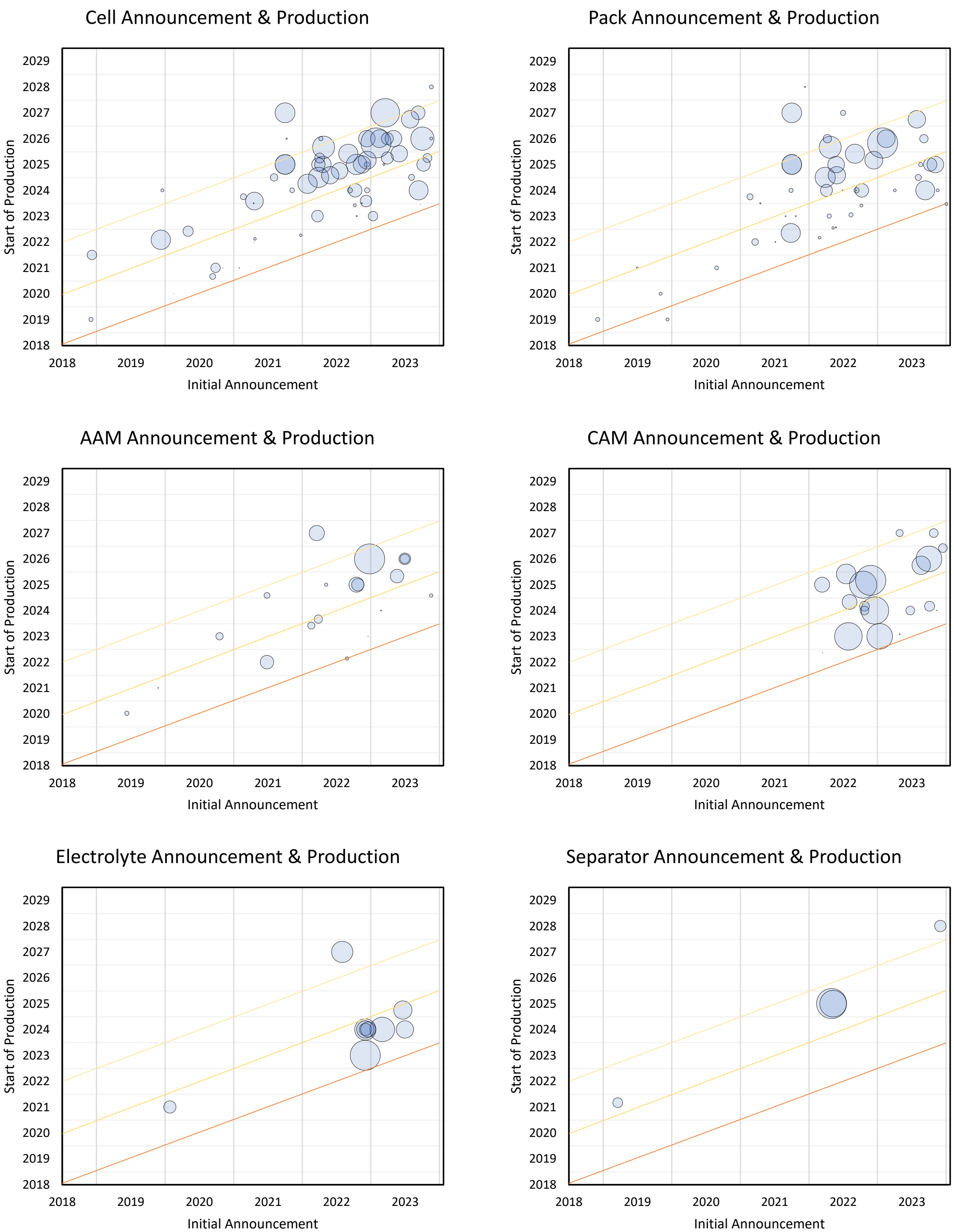

FIGURE 37 Delay from public announcement to planned start of production with lines indicating zero, two, and four-years

APPENDIX B ALTERNATIVE ASSUMPTIONS AND SENSITIVITY ANALYSES

This section explores variations in the input data and assumptions to examine the robustness of the results.

Comparison with previous estimates

As part of an annual assessment on the market status and characteristics of plug-in electric vehicles in the United States (Gohlke et al. 2022), Argonne estimated the total amount of lithium-ion battery capacity for vehicles in North America. This report was referenced by the EPA as part of its modeling for the proposed rule for emissions regulations for light-duty vehicles (EPA 2023b). The present report improves on the methodology of the previous report, by distinguishing between battery cells and other components, introducing a delay from initial production to full-scale production, and expanding the database. Previous analysis (Gohlke et al. 2022) effectively used a zero-year ramp rate, using a modeling simplification that all plants reached nominal capacity upon opening. Figure 38 overlays the estimate from the previous report with the baseline analysis for lithium-ion batteries in this report. The previous report forecast more production from 2023 to 2027 than the current baseline analysis, but ultimately reaches a lower total magnitude.

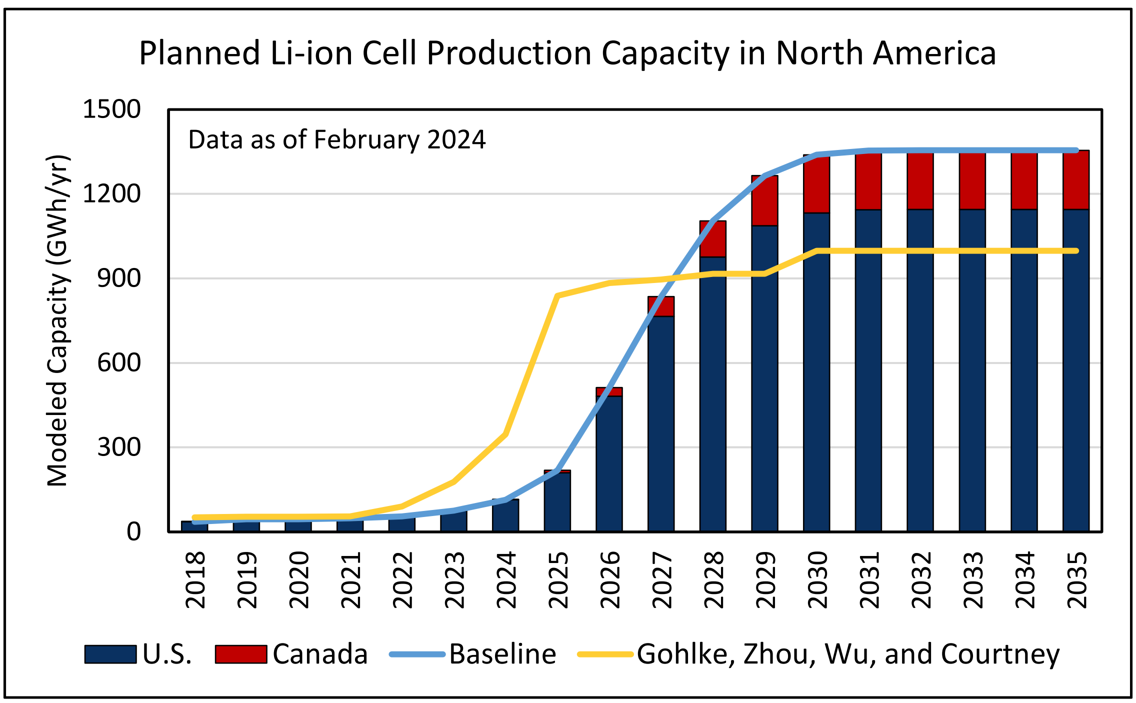

FIGURE 38 Comparison of baseline model with Gohlke et al. (2022)

Ramp rate to full-scale production

As described in Appendix A, the default ramp rate from initial production to full-scale production is 3 years for battery cells in this modeling. This is a modestly conservative estimate, but plants could reach nominal capacity more quickly or more slowly. Figure 39 shows the overall change in battery capacity if a 1-year ramp (shown in green) or 6-year-ramp (shown in yellow) is considered for each plant. A 1-year ramp would lead to production estimates approximately 30-50% higher through most of the 2020s, while a 6-year ramp would lead to a reduction in modeled capacity of about one-third relative to the baseline modeling.

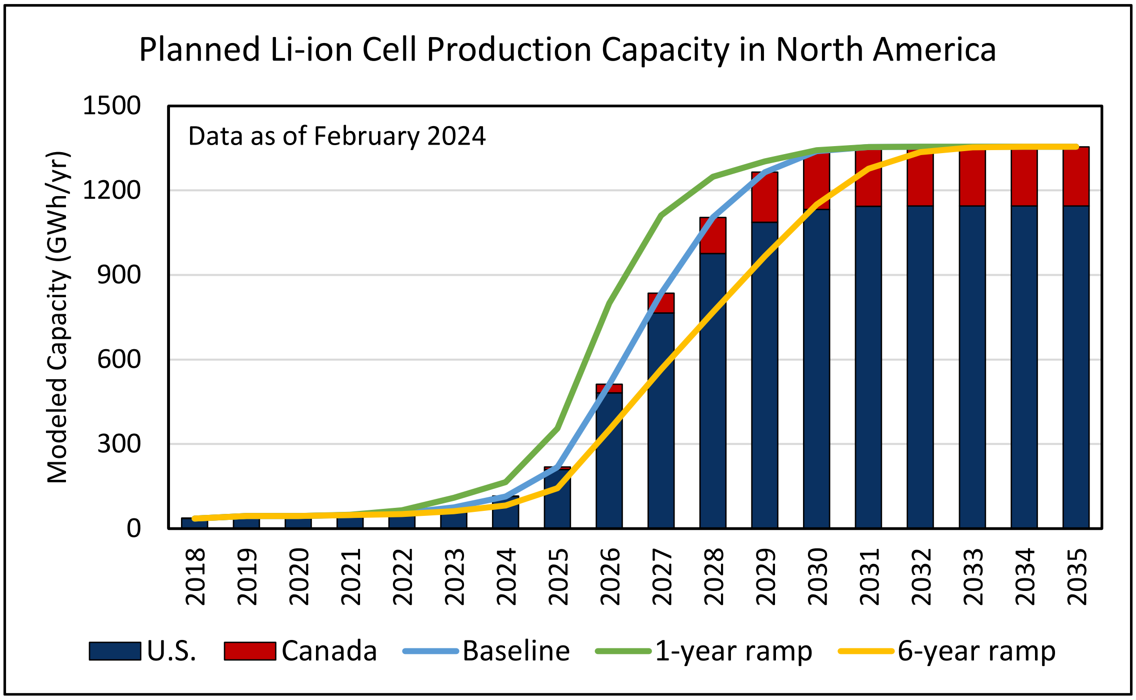

FIGURE 39 Line chart comparing baseline modeled cell manufacturing with longer or shorter scaling of production

Acceleration to full-scale production

In the baseline analysis, we assume a linear ramp up of three years from initial production to full nominal capacity. This can represent a gradual increase in the number of production lines, development of the necessary supply chains to supply the full production capacity, internal learning representing increased efficiency of manufacturing, and improved tooling. The shape of this ramp is in general unknown. For some plants it may be that production reaches close to its nominal capacity very shortly after the original opening, with relatively minor improvements to capacity afterwards. Conversely, other plants may have constraints early in their manufacturing time, either in supply chains or off-take agreements, and so may start slowly before rapidly building up to their nominal capacity.

Given the wide range of potential behavior, we use a simple linear ramp in manufacturing capacity as a function of time as the baseline. We can adjust this ramp rate to consider faster or slower ramps to full production. For analytical simplicity, we consider curves which have functional forms of x^2 and $x^{0.5}$, as shown in Figure 40 labeled here as “concave” and “convex” ramps. A representative example is shown on the left for a plant reaching full production two years after initial production.

The orange and gray lines overlaying the stacked bar chart on the right show how the total modeled production capacity would change with different assumptions for ramp-up. The greatest uncertainty comes around 2026 to 2027, where the two alternatives differ by 300 GWh/year.

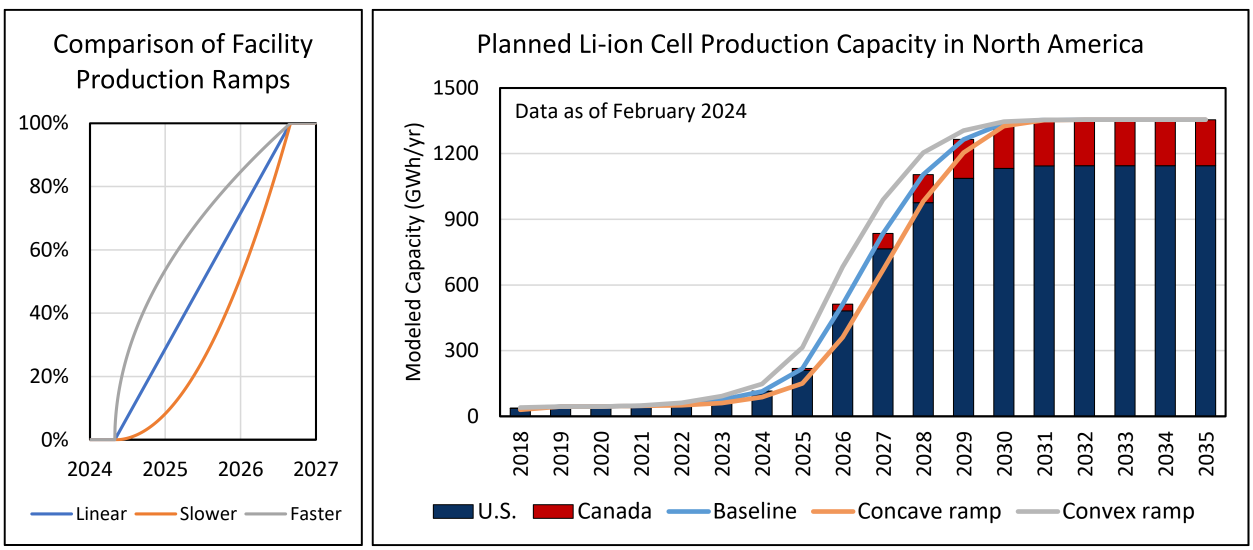

FIGURE 40 Line chart comparing baseline modeled cell manufacturing with faster or slower scaling of production

Delay in initial production

We consider a case in which initial production is delayed. This represents a scenario in which companies making announcements are too optimistic about the time for financing, permitting, and construction before the initial production from the plant. Figure 41 shows the change in total capacity if all plants have an average of 3-month delay or 12-month delay from their initial date of production. The baseline in blue is equivalent to the baseline in the previous figures, but the stacked bar chart is not shown in order to make the offset shift more apparent.

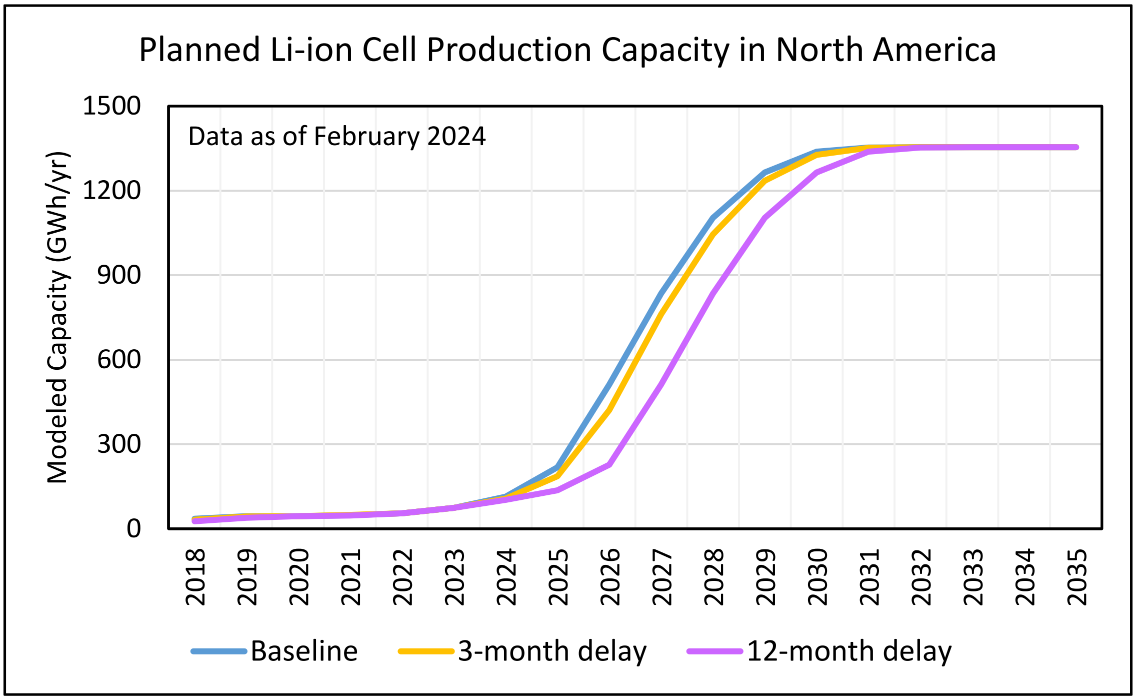

FIGURE 41 Line chart comparing baseline modeled cell manufacturing with delayed manufacturing

Less-committed and rumored plants

It is difficult to calculate the risk in these private sector investments based solely on publicly available information. In most cases, information about financing is not directly available. As a semi-quantitative approach, we consider a few factors which are public knowledge.

- First, we posit that companies with a known offtake agreement are more likely to reach full scale production, as they have a known market. As such, we flag any cell manufacturer that does not have a known buyer.
- A company which has previously succeeded in a similar investment will have knowledge of what is required to succeed in creating factory as well as market intricacies. Therefore, we flag cell manufacturers that do not have previous experience setting up a factory.
- While an active media presence is not necessarily correlated with the likelihood that a company is successful, a company with little follow-on after an announcement probably is less likely to ultimately finalize their initial intentions. We flag any company which has gone more than one year without a public follow-on related to manufacturing.
- A company with known financial difficulties may be in greater danger of not successfully completing its investment. We flag any company with publicly-reported financial concerns.

Figure 42 shows lithium-ion cell manufacturing in North America, partitioned by the number of risk factors identified above. Most of the announced cell manufacturing is by companies which exhibit zero of these risk factors. The most common risk factor (in terms of GWh/year) is having no dedicated offtake agreement.

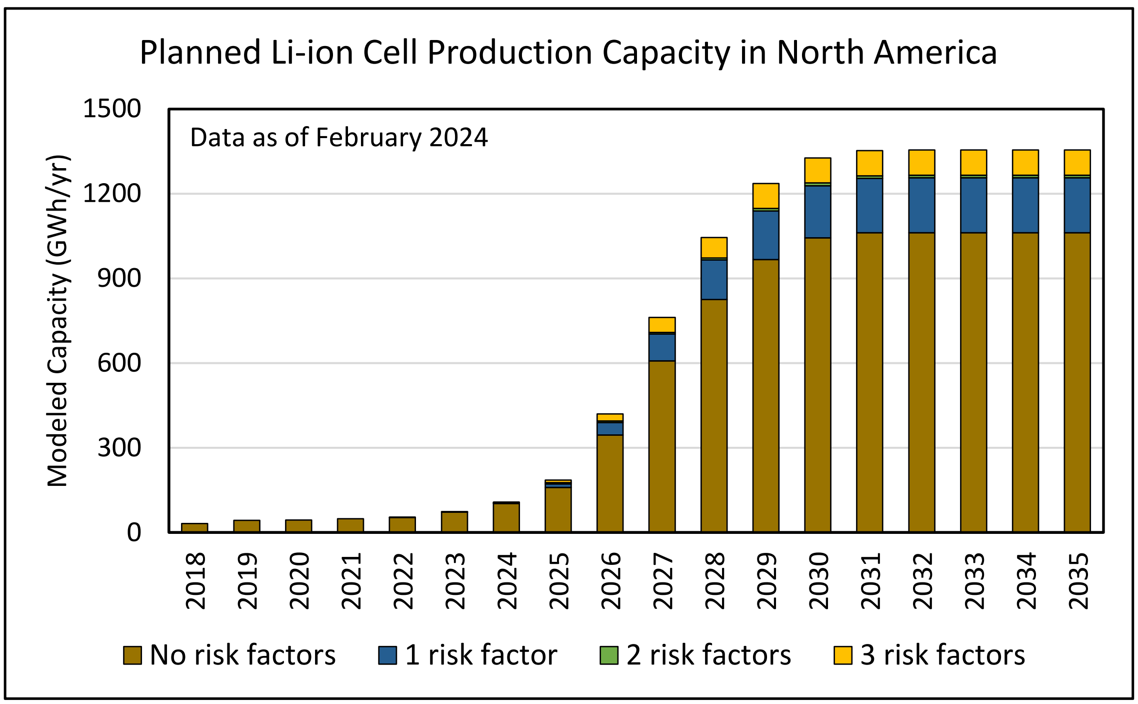

FIGURE 42 Modeled lithium-ion battery cell production considering investment risk

For the most part, adjustments based on perceived risk have a muted impact on total cell manufacturing. The largest cell producers are already those which have experience, and many of them have joint ventures which act as a dedicated offtake agreement. Over 1,000 GWh/year of lithium-ion cell capacity is made by these established battery manufacturers. Following this approach shows that the midstream is largely low-risk, as the components are generally made by large companies with manufacturing experience (in other countries).

On the other hand, manufacturing may be underestimated by a conservative selection of which plants to include. In this analysis, we exclude factories that are rumored or plant expansions which are aspirational or conditional upon future investment. Figures 43–48 show the total manufacturing capacity when considering these rumored or unannounced plants. In these graphics, dark blue and dark red represent formally announced production plants in the United States and Canada, respectively, and light blue and light red represent plants which companies have mentioned, but not formally committed to building. As these plants have not been announced by companies, the timeframe for startup of these conditional plants is estimated.

Figure 43 shows lithium-ion cell manufacturing when considering these rumored or unannounced plants. Including these plants adds a relatively modest 110 GWh to the total modeled manufacturing capacity in 2033. Most of these increases come from smaller start-ups rather than the established companies that comprise the majority of announced battery capacity. This analysis still mostly plateaus after 2030 due to the lack of very-long-term announcements.

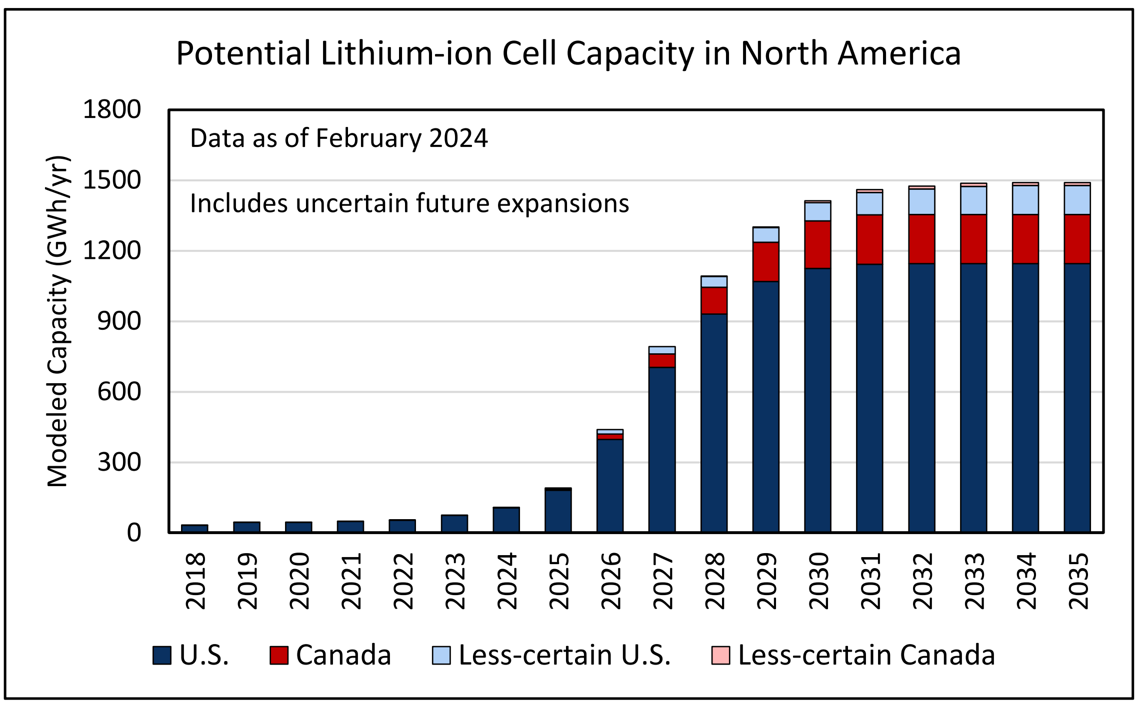

FIGURE 43 Modeled lithium-ion battery cell production including rumored and conditional plants

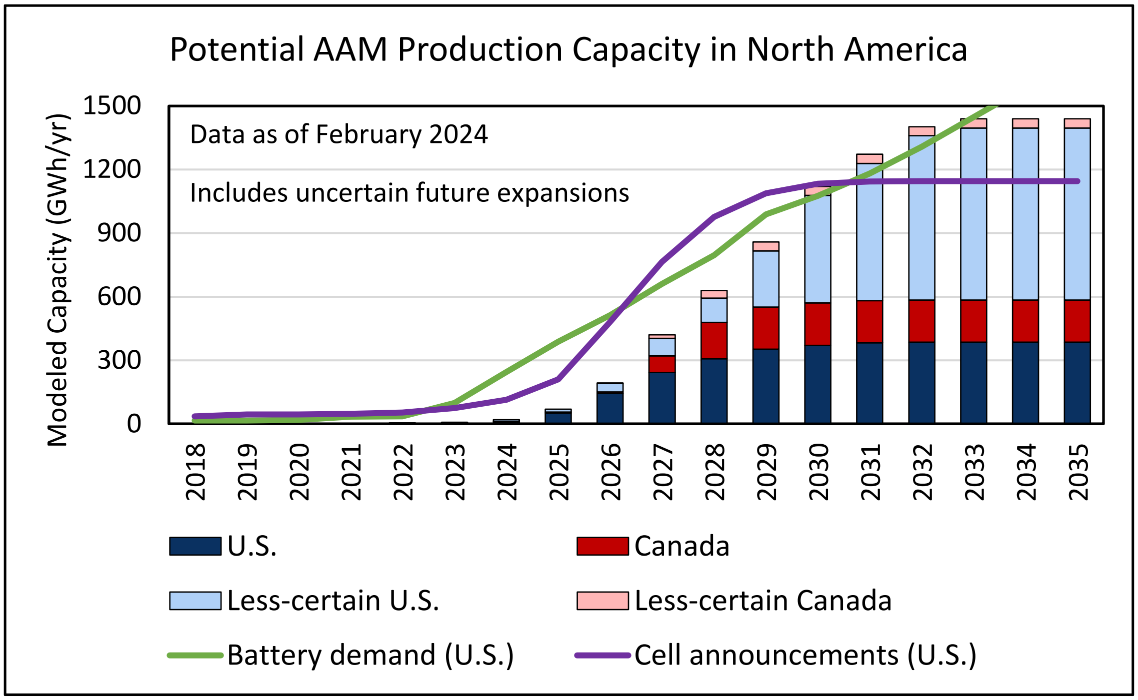

FIGURE 44 Modeled anode active material production capacity including rumored and conditional plants

Figure 44 shows not-yet-announced plants for AAM production in North America. Several companies have stated plans to expand manufacturing capacity later in the decade, but without any formal commitment to an investment. In total, these tentative announcements exceed 850 GWh/year by 2033. When including these with the 585 GWh/year of formal announcements, total AAM capacity is comparable to the overall demand for lithium-ion batteries. In this case, total production for AAM lags cell production announcements by approximately one year through 2030, at which point continued growth of AAM facilities exceeds announced cell production needs. However, as noted above, the start year for these facilities is very uncertain, so companies may proceed with production plans at an accelerated timeline relative to this graphic. Notably, the companies with the greatest volume of not-committed expansions for AAM are those which are producing synthetic graphite or using silicon in their anodes. These companies may be less constrained by materials availability than those which are relying on minerals extraction.

Figure 45 shows not-yet-announced plants for CAM production in North America. There is a comparatively small additional volume for CAM, approximately 100 GWh, nearly all of which is in Canada. Differences between AAM and CAM are potentially due to differences in materials constraints, as discussed in Section 4.1 and Section 4.2.

Figure 46 shows not-yet-announced plants for electrolyte production in North America. All of the announced production capacity has been in the United States. The amount of announced electrolyte plants is nearly sufficient to cover the full capacity of announced U.S. cell production; inclusion of rumored and conditional plants (600 GWh/year) adds a large buffer of production capacity.

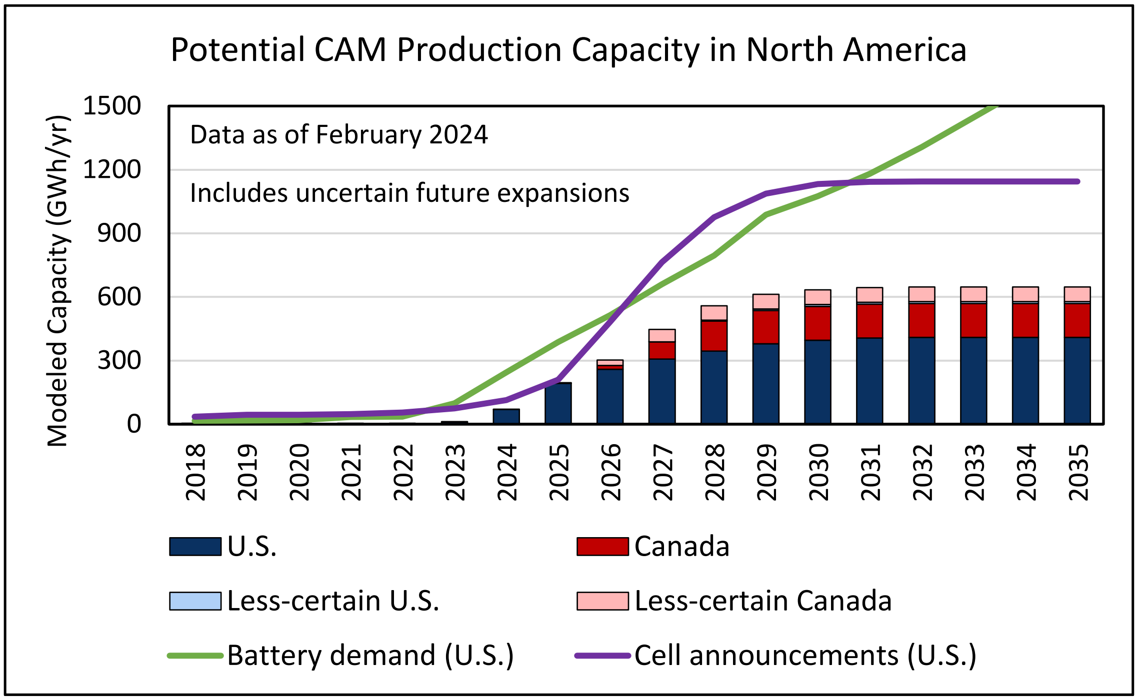

FIGURE 45 Modeled cathode active material production capacity including rumored and conditional plants

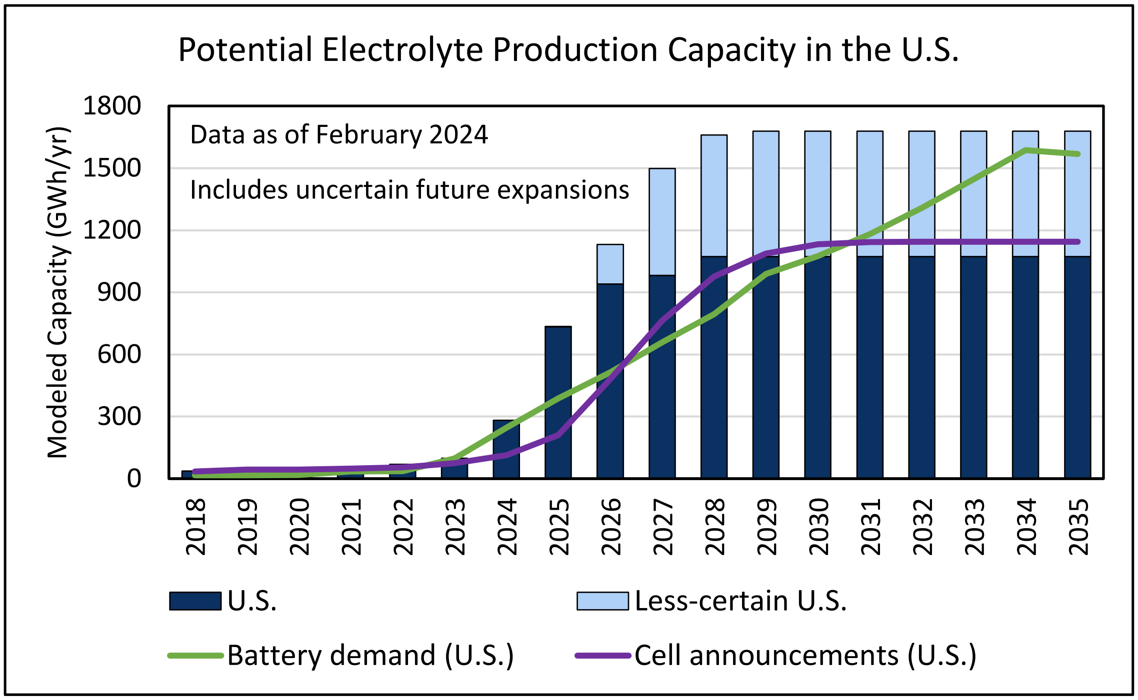

FIGURE 46 Modeled electrolyte production capacity including rumored and conditional plants

Figure 47 shows not-yet-announced plants for aluminum (top) and copper (bottom) electrode foil production in North America. No companies have been associated with uncertain plans for aluminum foil production. Announced copper foil production is approximately 380 GWh/year by the end of the decade; uncommitted facilities add another 370 GWh/year to this total.

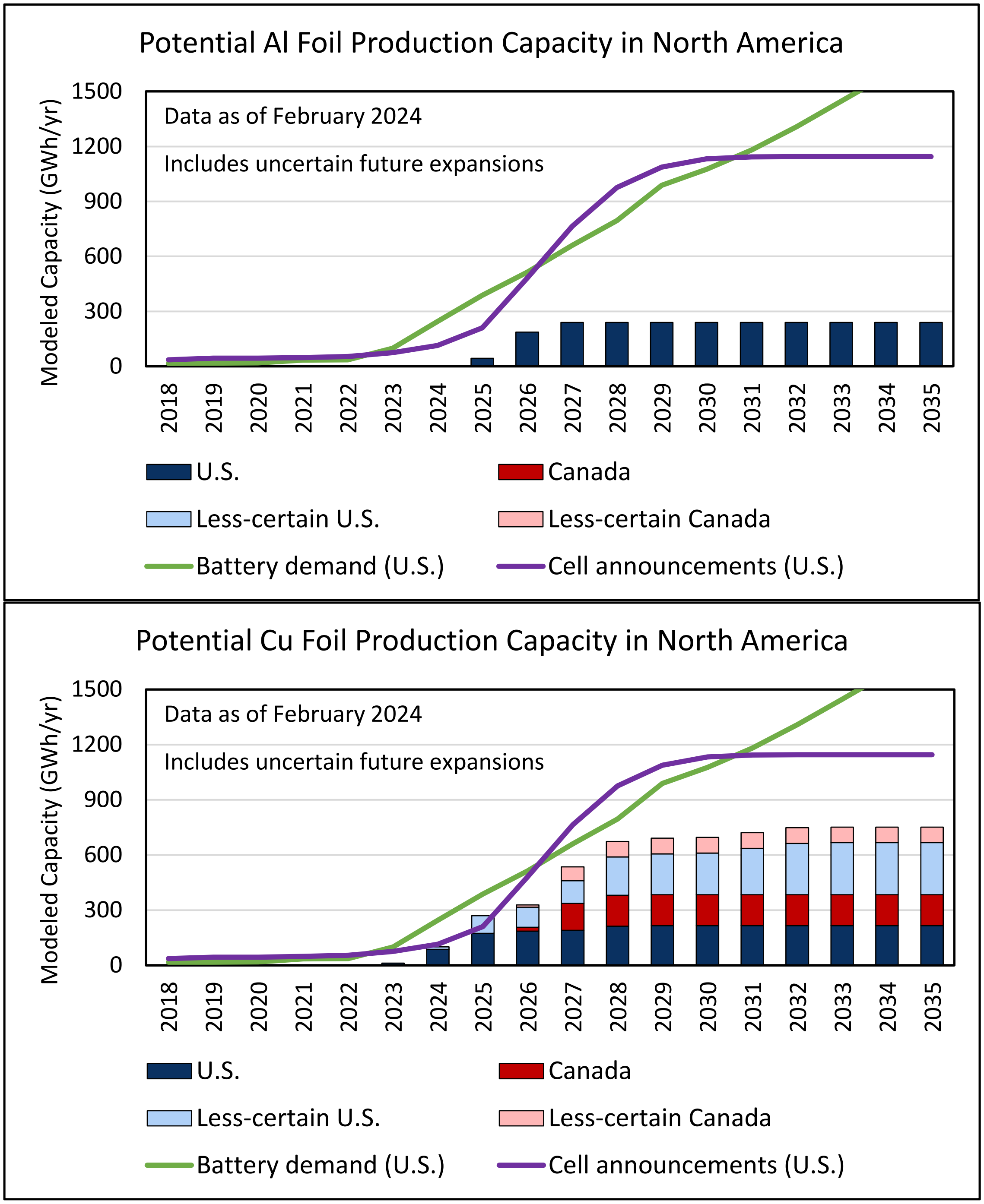

FIGURE 47 Modeled foil production capacity including rumored and conditional plants

Figure 48 shows not-yet-announced plants for separator production in North America. In total, adding uncommitted plants and expansions would double separator production in North America. The volume of the rumored plant in Canada by SK Innovation is estimated based upon existing plants the company has opened in Europe. Even including these not-committed plants, there is insufficient capacity to serve the full U.S. cell production market based on announcements made to date.

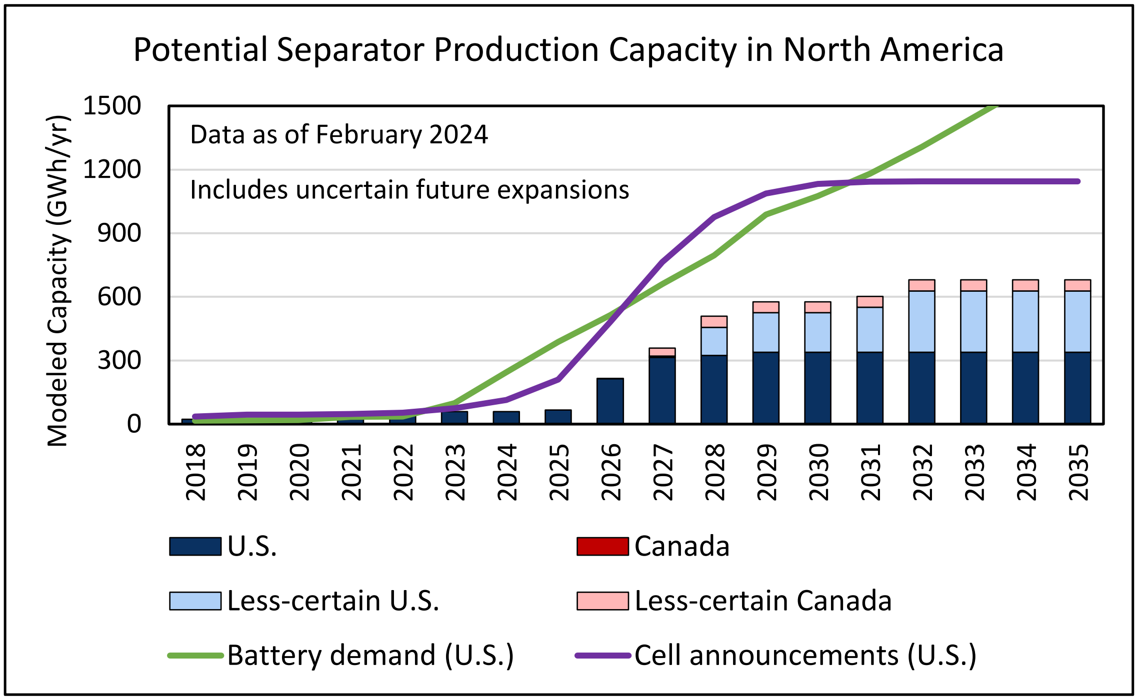

FIGURE 48 Modeled separator production capacity including rumored and conditional plants

APPENDIX C ANNUAL ANALYSIS OF SUPPLY CONNECTIONS

Cell production to end-use

Figures 49 through 54 show the same information as the Sankey-type flow diagram of Figure 17, for years 2024 through 2029. The total volume is based on the modeled cell manufacturing capacity. Exact off-take agreements are rarely published, so the share going to different pack manufacturers or automakers is estimated.

In these diagrams, the left side represents the companies making lithium-ion battery cells. The thickness of each curved line represents the total battery capacity in a given year. These lines connect from cell manufacturers on the left to pack manufacturers in the center, and finally to the end use on the right side. Below this are batteries dedicated to stationary storage in yellow. The colors of the curved lines represent the expected end-use, either unknown end use in gray, stationary storage in yellow, or a specific automaker.

This analysis only considers North American production of batteries, largely presumed to be for assembly of vehicles domestically. Historically, over one-quarter of plug-in vehicles have been imported to the United States from outside North America, nearly all of which with batteries also built outside of North America (Gohlke et al. 2022). Almost all U.S. imports of electric vehicles have come from countries in the Minerals Security Partnership, which is discussed in greater detail in Appendix D.

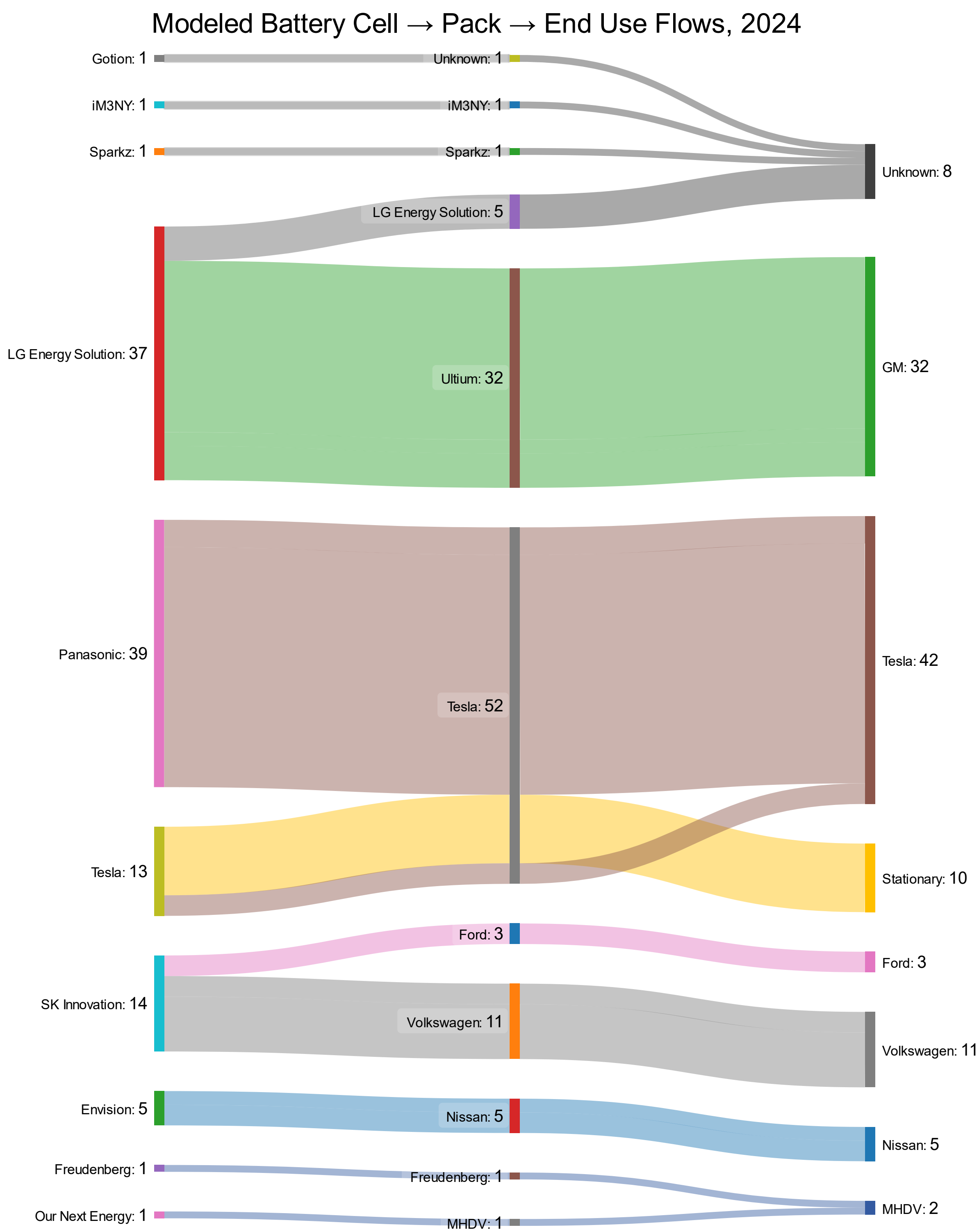

FIGURE 49 Flow diagram of North American cell and pack manufacturing, and vehicle assembly in 2024

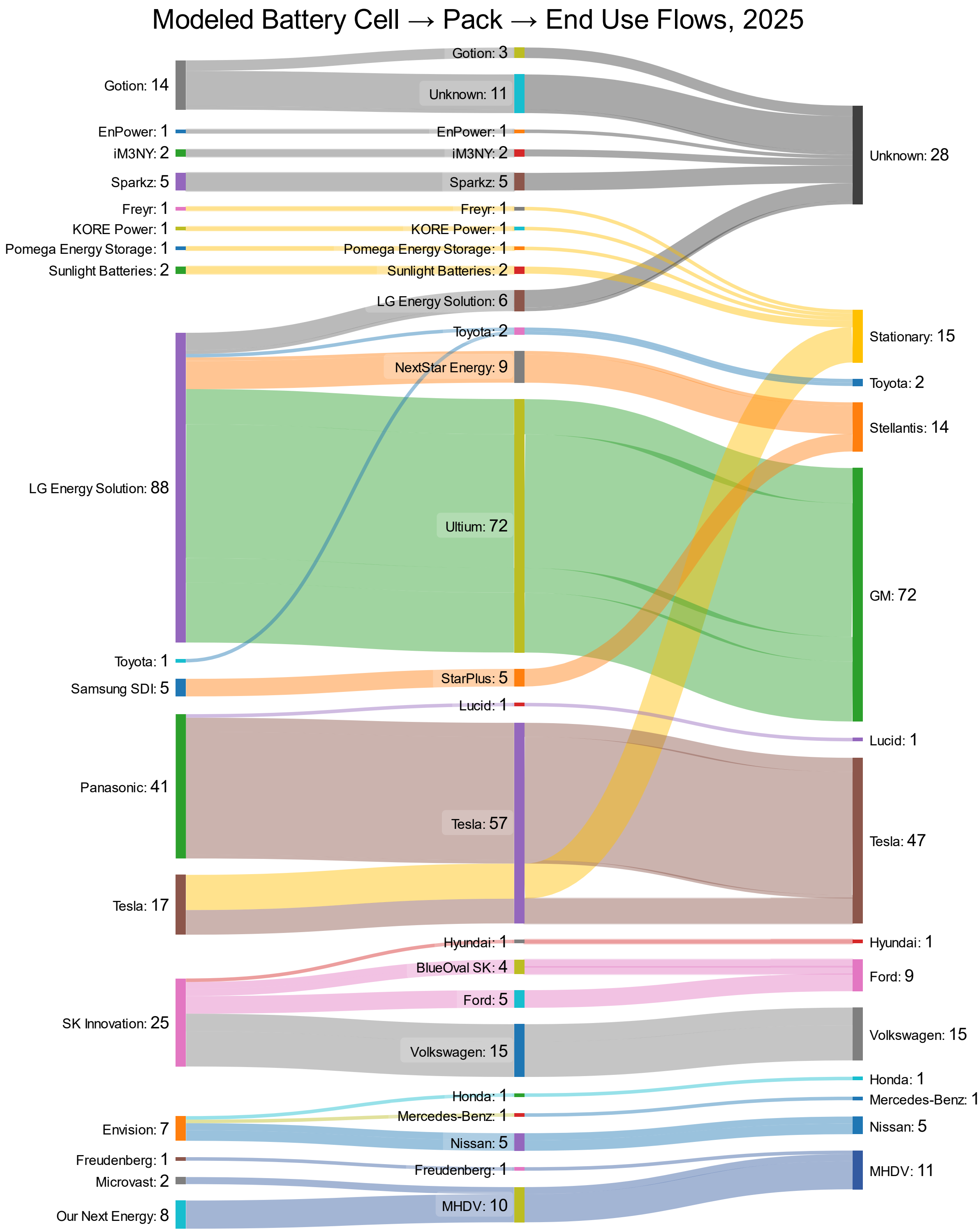

FIGURE 50 Flow diagram of North American cell and pack manufacturing, and vehicle assembly in 2025

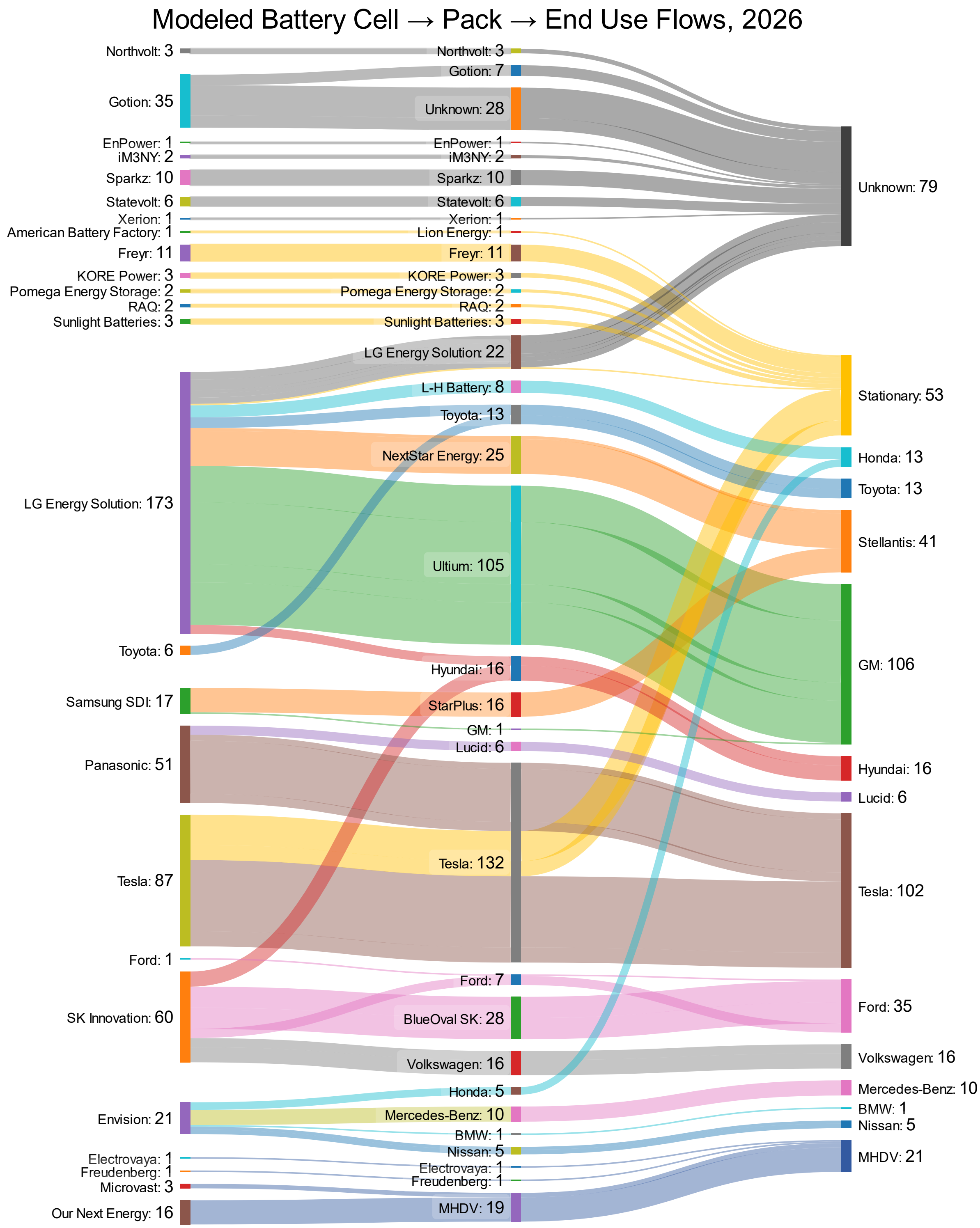

FIGURE 51 Flow diagram of North American cell and pack manufacturing, and vehicle assembly in 2026

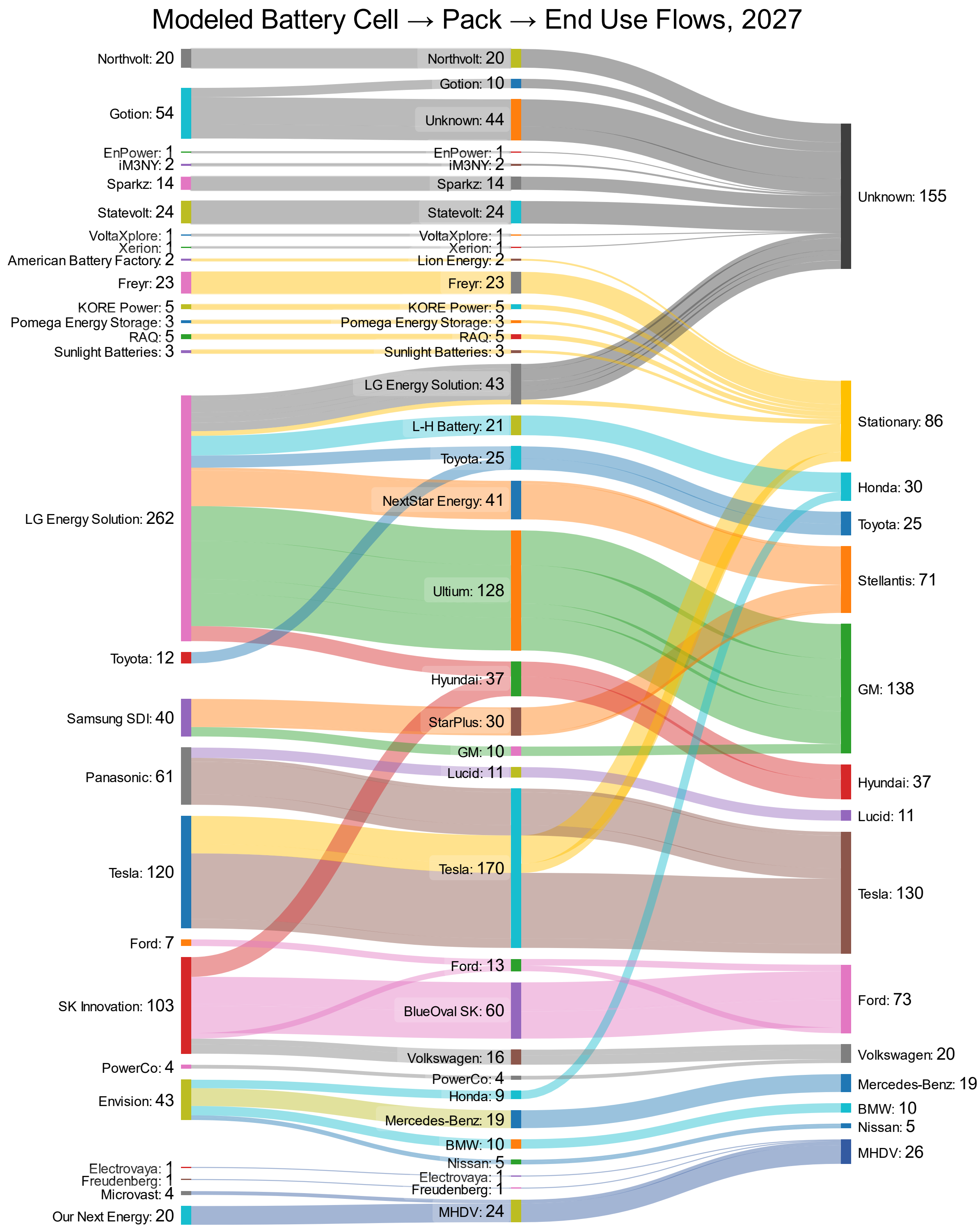

FIGURE 52 Flow diagram of North American cell and pack manufacturing, and vehicle assembly in 2027

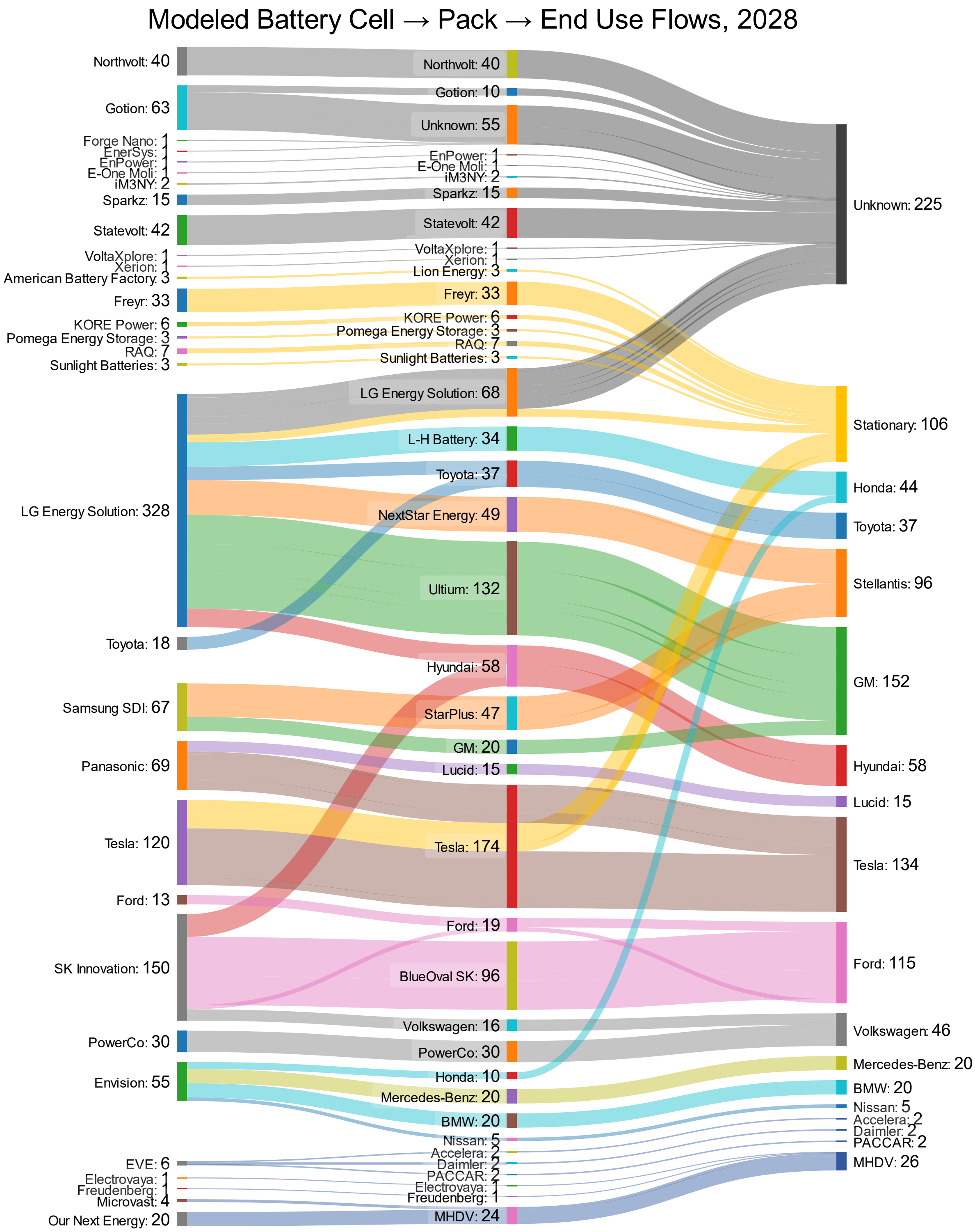

FIGURE 53 Flow diagram of North American cell and pack manufacturing, and vehicle assembly in 2028

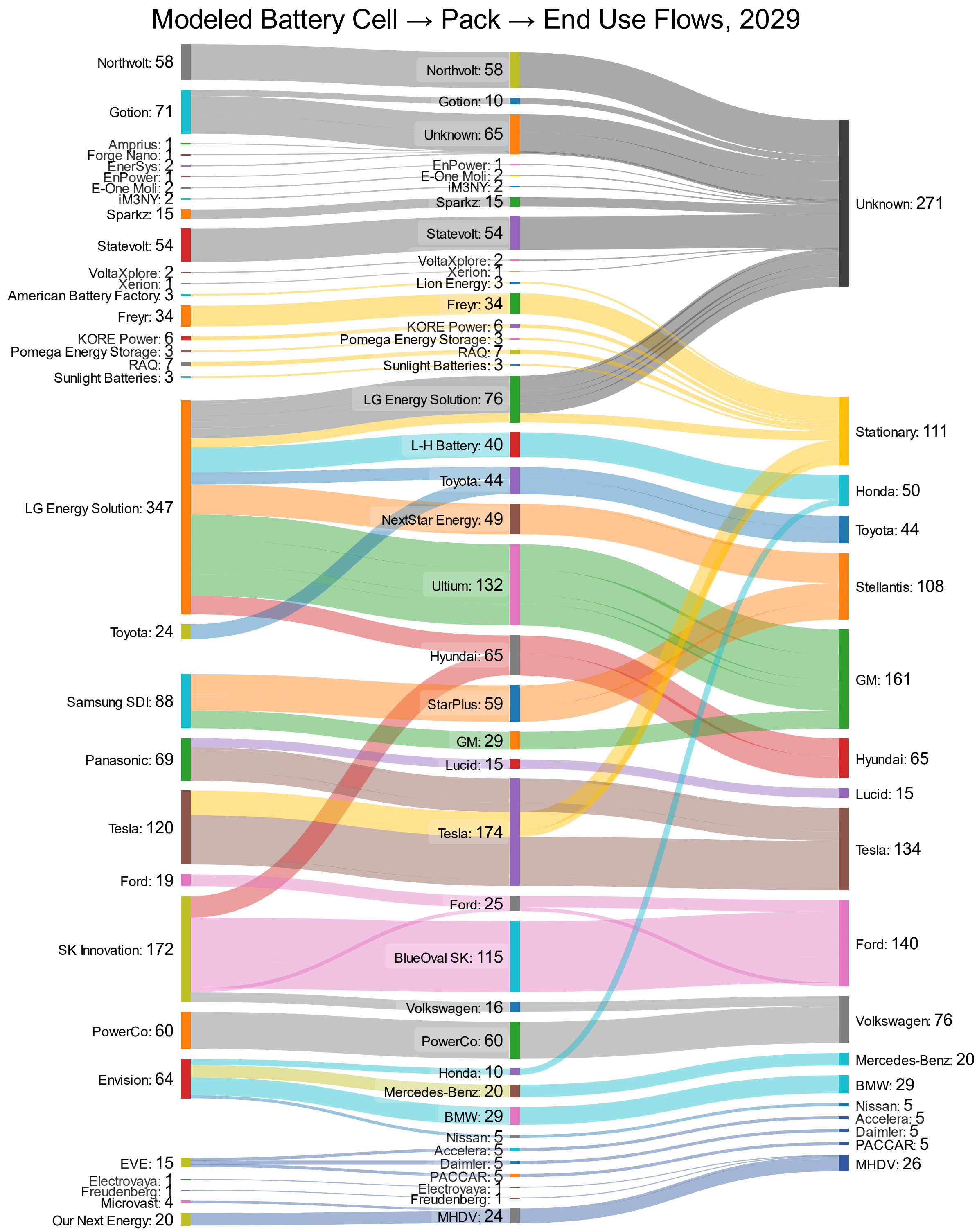

FIGURE 54 Flow diagram of North American cell and pack manufacturing, and vehicle assembly in 2029

APPENDIX D INTERNATIONAL BATTERY CELL ANNOUNCEMENTS

We model North American production of lithium-ion batteries to exceed 1,300 GWh/year by 2030, a marked increase over the 48 GWh of production modeled in 2021. There is also the expectation of growth in cell production internationally. The country with the largest production of battery cells currently is China (Wood Mackenzie 2022; Yu and Marjolin 2022). Over the next decade, Chinese production of lithium-ion battery cells has been forecast at over 3,000 GWh/year (BMI 2023; Griffith 2023; Ren 2023; Wood Mackenzie 2022; Yu and Marjolin 2022).

Other locations with large announcements in increased battery production include Europe and the rest of Asia which potentially will impact the North American market for batteries. The United States has free trade agreements (FTA) with the Republic of Korea, Japan, and Australia. Additionally, the Materials Security Partnership (MSP) includes Australia, Canada, Finland, France, Germany, India, Italy, Japan, Norway, the Republic of Korea, Sweden, the United Kingdom, the United States, and the European Union (U.S. Department of State 2023). Figure 55 shows the announced manufacturing for lithium-ion battery cell plants in MSP countries outside North America, similar to Figure 10. North American production is overlaid as a dashed black line. Through the end of the decade, the sum of announced battery cell production capacity in non-American MSP countries exceeds the sum in North America, with both reaching 1,300 GWh/year by 2030. The countries with the largest manufacturing planned are Germany, Hungary, Poland, Norway, and Sweden, each of which with over 100 GWh/year by 2030.

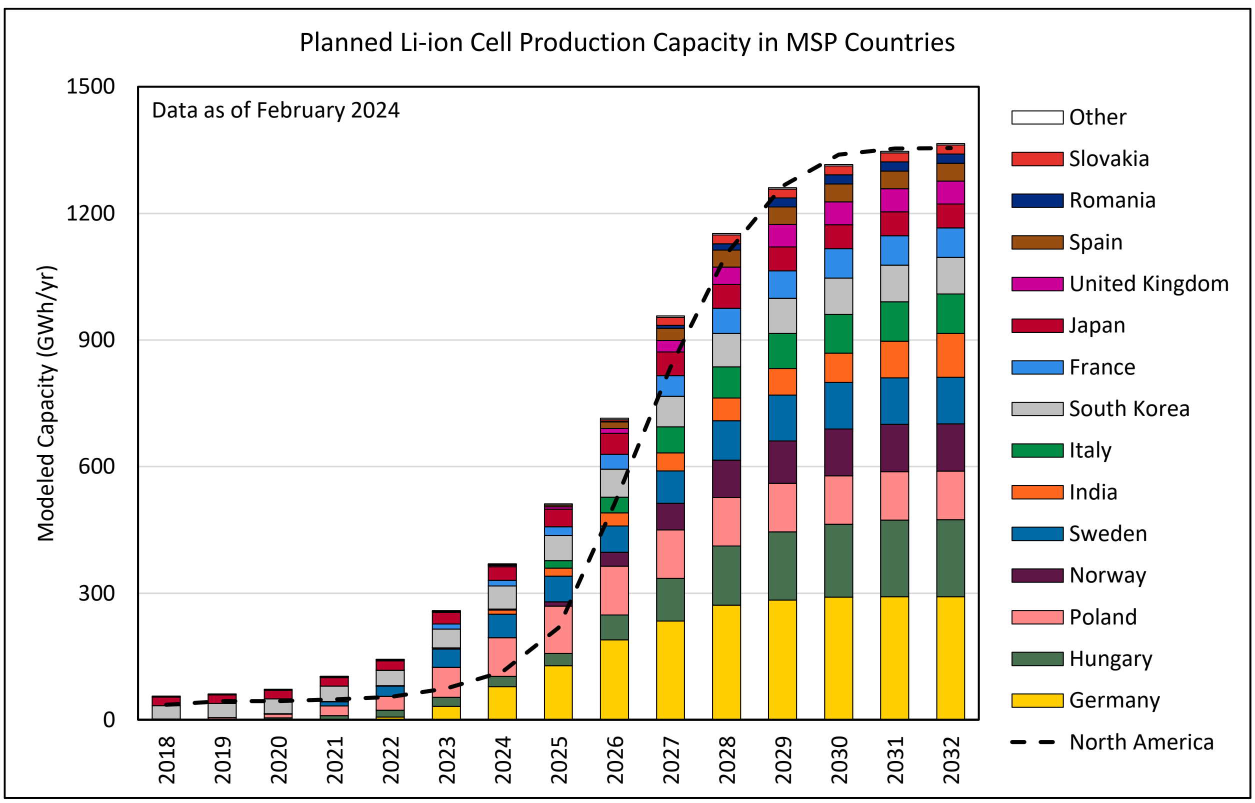

FIGURE 55 Modeled MSP lithium-ion battery cell production capacity through 2035

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