ANL/CSE-24/1

Cost Analysis and Projections for U.S.-Manufactured Automotive Lithium-ion Batteries

Final Report

Chemical Sciences and Engineering Division

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Abstract

This document reports on a study conducted to estimate the cost of U.S-produced automotive battery packs for model years (MY) 2023 to 2035, using Argonne National Laboratory's BatPaC tool. The costs were estimated by designing batteries for several classes of vehicles for four discrete model years (2023, 2026, 2030, and 2035), where a representative battery technology and material prices are selected based on information available today. Correlations were developed from the four discrete years to enable annual pack cost estimates as a function of pack size (kWh) and model year. A consolidated cost curve was then developed that includes battery size, technology by model year, and the anticipated sales volumes of each class of vehicles over the years. This cost curve estimates the volume-averaged, U.S.-manufactured battery pack cost of PHEVs and BEVs in the United States to be $140/kWh for the model year 2023, which will reduce to $86/kWh in MY2035. Applying tax credits from section 45X of the Inflation Reduction Act can further reduce the average pack cost to as low as $56/kWh in MY2029. The report also includes several sensitivity studies that investigate the effect of pack production volume, material prices, fast charge requirements, and labor rates.

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Introduction

Electric vehicles are expected to represent increasing percentages of the vehicles sold in the US in the next 10-15 years. The cost of these vehicles will depend largely on the cost of the energy storage component, the lithium-ion battery pack. With fierce competition for the large automotive market, domestic and international battery and automobile manufacturers have been preparing to produce a competitive product that balances performance and cost. With such new products on the horizon, scientists, engineers, and entrepreneurs are pushing novel chemistries and manufacturing technologies as they compete for the market. The U.S. Department of Energy (DOE) has funded the R&D of lithium-ion batteries for nearly 40 years, which has progressively supported the scientific community. Asia and Europe have aggressively developed the manufacturing and marketing of EVs in the past two decades. The US government has legislated various incentives to promote the domestic production and adoption of EVs.

Some electric vehicles today can compete with internal combustion engine vehicles (ICEV) based on total cost of ownership, principally due to the lower cost of electric energy per mile (Liu, et al., 2021). DOE has set a target of $80/kWh (Office of Energy Efficiency and Renewable Energy, 2023), which is also the price at which popular media expects EVs to achieve purchase price (without any government incentives) parity with internal combustion engine (ICE) vehicles (Voelcker, 2023). Various organizations offer values of the current battery prices and projections for the future. Organizations such as the Department of Transportation’s National Highway Traffic Safety Administration (NHTSA) and the U.S. Environmental Protection Agency (EPA) have their own estimates, often composites of multiple forecasts, that have been used for prior rule making. This analysis intends to develop a cost curve for automotive batteries that can support proposed fuel economy (National Highway Traffic Safety Administration, 2023) and greenhouse gas (United States Environmental Protection Agency, 2023) standards.

The study simulates the cost of EV batteries for HEV, PHEV, BEV, and MHD vehicles. The PHEV, BEV, and MHD results are used to calculate a volume-averaged, composite cost curve for EV packs in the U.S. Since HEV batteries are designed for regenerative braking and supplementing power, and require very small batteries, these were excluded from deriving the composite cost curve. This allowed the curve to estimate the cost of batteries for plug-in vehicles that require significant energy storage for sustained propulsion.

Objective and Approach

The objective of this record is to document the development of a cost curve for automotive batteries:

- For the period 2023-2035,
- Using Argonne National Laboratory’s Battery Performance and Cost (BatPaC) model (Chemical Sciences and Engineering, 2023) (Knehr K. W., Kubal, Nelson, & Ahmed, 2022),
- With assumptions and parameter values proposed by the model developers, under the guidance of DOE, NHTSA, and EPA staff.

All costs are reported in 2023 $\$/kWh_{rated}$.

Methodology

Vehicles – The electric vehicles considered included light duty vehicles, which comprised of hybrid electric vehicles (HEVs), plug-in hybrid vehicles (PHEVs), electric vehicles (EVs), and medium-heavy duty vehicles (MHDs). Two batteries were designed to represent the HEV batteries for this study: 48 kW – 1.2 kWh and 70 kW – 1.8 kWh, where the pack kWh is rated energy. Each of the PHEV and EV batteries were subsequently designed to represent four classes of vehicles: Compact, Midsize, Midsize SUV, and Pickup. Each PHEV and EV battery was then assigned a combination of power (kW) and energy (rated kWh) (National Highway Traffic Safety Administration, 2023).

Electrode Chemistries and Model Years – A combination of electrode chemistries and associated properties was selected to represent each of the Model Years (MY) where the BatPaC simulations were run (BloombergNEF, 2023; Benchmark Minerals Intelligence, 2023; Firth, Implications of Economy-Wide Decarbonization on the Battery Industry, 2021; Gokhale, 2023; Mell, 2021; Berry, 2023; Miller, 2023; Sekine, 2023; Moganty, 2023). The distinct changes in the dominant electrode chemistry were made for four MYs, namely 2023, 2026, 2030 and 2035. Separate specifications were selected for the two main cathode materials, the nickel-manganese containing layered oxides (Ni/Mn) and the lithium iron phosphates (LFP). The costs of the materials were estimated from market research reports (Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Intercalation, Ltd., 2023; Ballif, Haug, Boccard, Verlinden, & Hahn, 2022; Sanders, 2023).

With the representative electrode chemistries selected for each of the four model years, their associated properties, the cell and pack design parameters, and manufacturing plant parameters were selected. For example, the cell capacities (Ah), the cell plant capacity (GWh), and the number of packs produced were all increased in future years to lower the pack costs by leveraging economies of scale. Decisions on pack designs and plant capacities were based on observed trends in the market and manufacturing announcements (EV/Hybrid Analyses, 2023; EV Sales Forecast, 2023; Ricardo, 2023; National Highway Traffic Safety Administration, 2023; Irle, 2023; Fox-Penner, Gorman, & Hatch, 2018).

Simulation Inputs – Tables 1-12 show the specifications for the different vehicles for the four model years for which the BatPaC simulations were run. This was done separately for the Ni/Mn and the LFP vehicles.

Table 1. Production volumes assumed for vehicle types in BatPaC simulations (numbers in thousands of vehicles produced per year per plant).

Vehicle Type	2023	2026	2030	2035
Hybrid Electric Vehicle (HEV)	200	200	200	200
Plug-in Hybrid Electric Vehicle (PHEV)	20	60	100	100
Battery Electric Vehicle, Light Duty (BEV LD)	60	140	250	400
Battery Electric Vehicle, Medium/Heavy Duty (BEV MHD)	2	4	7	10

Table 2. Cells per pack and rated energy/power combinations for HEV and PHEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
1.2 / 48	HEV	60	60	60	48
1.8 / 70	HEV	60	60	60	48
12 / 100	PHEV Compact (Ni/Mn)	84	84	84	72
12 / 100	PHEV Compact (LFP)	90	90	90	90
18 / 150	PHEV Midsize (Ni/Mn)	84	84	84	72
18 / 150	PHEV Midsize (LFP)	90	90	90	90
24 / 200	PHEV Midsize SUV (Ni/Mn)	90	84	84	72
24 / 200	PHEV Midsize SUV (LFP)	90	90	90	90
40 / 250	PHEV Pickup (Ni/Mn)	156	120	102	84
40 / 250	PHEV Pickup (LFP)	156	90	90	90

Table 3. Modules per pack and rated energy/power ratings for HEV and PHEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
1.2 / 48	HEV	1	1	1	1
1.8 / 70	HEV	1	1	1	1
12 / 100	PHEV Compact (Ni/Mn)	6	6	6	6
12 / 100	PHEV Compact (LFP)	6	6	6	6
18 / 150	PHEV Midsize (Ni/Mn)	6	6	6	6
18 / 150	PHEV Midsize (LFP)	6	6	6	6
24 / 200	PHEV Midsize SUV (Ni/Mn)	6	6	6	6
24 / 200	PHEV Midsize SUV (LFP)	6	6	6	6
40 / 250	PHEV Pickup (Ni/Mn)	6	6	6	6
40 / 250	PHEV Pickup (LFP)	6	6	6	6

Table 4. Total cells per pack and rated energy/power rating for high performance (Ni/Mn cathode), BEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
65 / 125	BEV250 Compact	260	192	168	132
75 / 165	BEV250 Midsize	300	224	192	152
80 / 130	BEV300 Compact	320	240	192	160
90 / 200	BEV250 Midsize SUV, BEV300 Midsize	360	272	228	184
105 / 260	BEV250 Pickup	420	312	264	216
110 / 210	BEV300 Midsize SUV	440	330	264	220
130 / 270	BEV300 Pickup	520	390	312	260
190 / 380	BEV MHD	800	576	480	384
220 / 440	BEV MHD	880	672	576	440
250 / 500	BEV MHD	960	768	624	520

Table 5. Total modules per pack and rated energy/power rating for high performance (Ni/Mn cathode), BEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
65 / 125	BEV250 Compact	20	8	6	4
75 / 165	BEV250 Midsize	20	8	6	4
80 / 130	BEV300 Compact	20	10	8	5
90 / 200	BEV250 Midsize SUV, BEV300 Midsize	20	8	6	4
105 / 260	BEV250 Pickup	20	8	6	4
110 / 210	BEV300 Midsize SUV	20	10	8	5
130 / 270	BEV300 Pickup	20	10	8	5
190 / 380	BEV MHD	20	12	10	8
220 / 440	BEV MHD	20	14	12	10
250 / 500	BEV MHD	20	16	12	10

Table 6. Total cells per pack and rated energy/power rating for low cost (LFP cathode), BEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
65 / 125	BEV250 Compact	260	168	104	78
75 / 165	BEV250 Midsize	300	192	120	90
90 / 200	BEV250 Midsize SUV	360	224	144	108
105 / 260	BEV250 Pickup	420	264	168	126
190 / 380	BEV MHD	768	462	304	228
220 / 440	BEV MHD	896	528	360	264
250 / 500	BEV MHD	1024	594	408	300

Table 7. Total modules per pack and rated energy/power rating for low cost (LFP cathode), BEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
65 / 125	BEV250 Compact	20	8	4	1
75 / 165	BEV250 Midsize	20	8	4	1
90 / 200	BEV250 Midsize SUV	20	8	4	1
105 / 260	BEV250 Pickup	20	8	4	1
190 / 380	BEV MHD	24	14	8	1
220 / 440	BEV MHD	28	16	10	1
250 / 500	BEV MHD	32	18	12	1

Table 8. Material, cell design, and manufacturing inputs for HEV packs in BatPaC simulations.

Active Material Composition	**2023**	**2026**	**2030**	**2035**
Cathode Active Material (CAM)	NMC622	NMC811	NMC95	LMNO
Anode Graphite wt.%	100%	100%	100%	100%
Anode Silicon wt.%	0%	0%	0%	0%
CAM specific capacity, mAh/g	191	210	226	150
AAM combined capacity, mAh/g	350	350	350	350
Cell voltage (50% OCV)	3.705	3.713	3.734	4.550
Cell Design	**2023**	**2026**	**2030**	**2035**
Electrode Thickness, µm	75	85	95	120
Positive Active wt.%	94%	94%	94%	94%
Negative Active wt.%	96%	96%	96%	96%
Negative-to-Positive Capacity, N2P	1.10	1.05	1.05	1.05
Target Cell Capacity, Ah	5.0-7.5	5.0-7.5	5.0-7.5	5.0-7.5
Cell thickness, mm	12	12	12	12
Cell Length to Width (L/W) ratio	3	3	3	3
Cell Manufacturing	**2023**	**2026**	**2030**	**2035**
Cell Plant Capacity, GWh/yr	35	50	70	70
Cell Yield, %	89%	91%	93%	95%

Table 9. Material, cell design, and manufacturing inputs for high performance (Ni/Mn cathodes) PHEV and BEV vehicles.

Active Material Composition	**2023**	**2026**	**2030**	**2035**
Cathode Active Material (CAM)	NMC622	NMC811	NMC95	LMNO
Anode Graphite wt.%	100%	95%	85%	65%
Anode Silicon wt.%	0%	5%	15%	35%
CAM specific capacity, mAh/g	191	210	226	150
AAM combined capacity, mAh/g	350	458	673	1103
Cell voltage (50% OCV), V	3.705	3.704	3.631	4.400
Cell Design	**2023**	**2026**	**2030**	**2035**
Electrode Thickness, µm	75	85	95	120
Positive Active wt.%	96%	96%	96%	96%
Negative Active wt.%	98%	98%	98%	98%
Neg.-to-Pos. Capacity ratio	1.10	1.05	1.05	1.05
Cell Capacity (BEV), Ah	70	90	110	110
Cell Capacity (PHEV), Ah	40-70	40-90	40-110	40-110
Cell thickness (BEV), mm	20	20	20	12
Cell thickness (PHEV), mm	16	16	16	16
Cell L/W ratio (BEV)	3	5	5	8
Cell L/W ratio (PHEV)	3	3	3	3
Cell Manufacturing	**2023**	**2026**	**2030**	**2035**
Cell Plant Capacity, GWh/yr	35	50	70	70
Cell Yield, %	89%	91%	93%	95%

Table 10. Material, cell design, and manufacturing inputs for low cost (LFP cathodes) PHEV and BEV vehicles.

Active Material Composition	**2023**	**2026**	**2030**	**2035**
Cathode Active Material (CAM)	LFP	LFP	LFP	LFP
Anode Graphite wt.%	100%	95%	95%	95%
Anode Silicon wt.%	0%	5%	5%	5%
CAM specific capacity, mAh/g	157	157	157	157
AAM combined capacity, mAh/g	350	458	458	458
Cell voltage (50% OCV), V	3.325	3.316	3.316	3.316
Cell Design	**2023**	**2026**	**2030**	**2035**
Electrode Thickness, µm	75	90	110	130
Positive Active wt.%	96%	96%	96%	96%
Negative Active wt.%	98%	98%	98%	98%
Neg.-to-Pos. Capacity ratio	1.10	1.05	1.05	1.05
Cell Capacity (BEV), Ah	75	125	190	255
Cell Capacity (PHEV), Ah	40-80	40-135	40-135	40-135
Cell thickness (BEV), mm	20	20	20	20
Cell thickness (PHEV), mm	16	16	16	16
Cell L/W ratio (BEV)	3	5	5	8
Cell L/W ratio (PHEV)	3	3	3	3
Cell Manufacturing	**2023**	**2026**	**2030**	**2035**
Cell Plant Capacity, GWh/yr	35	50	70	70
Cell Yield, %	89%	92%	95%	95%

Table 11. Assumed price of active materials used in BatPaC.

Cathode	**2023**	**2026**	**2030**	**2035**
NMC622, $/kg	31.9	-	-	-
NMC811, $/kg	-	34	-	-
NMC95, $/kg	-	-	31.3	-
LMNO, $/kg	-	-	-	17.3
LFP, $/kg	13	11.5	10	9.5
Anode	**2023**	**2026**	**2030**	**2035**
Graphite, $/kg	10	9	8	8
Silicon, $/kg	30	30	30	30
95% G, 5% Si, $/kg	-	10.1	-	-
85% G, 15% Si, $/kg	-	-	11.3	-
65% G, 35% Si, $/kg	-	-	-	15.7

Table 12. Assumed price of other cell components in BatPaC simulations.

Other Components	2023	2026	2030	2035
Electrolyte, $/L	10	10	10	10
Separator, $/m²	0.5	0.5	0.5	0.5
Carbon additive, $/kg	7	7	7	7
Positive binder, $/kg	15	15	15	15
Positive solvent, $/kg	2.7	2.7	2.7	2.7
Positive current collector, $/m²	0.2	0.2	0.2	0.2
Negative binder, $/kg	10	10	10	10
Negative current collector, $/m²	1.2	1.2	1.2	1.2

Correlation Development – Cost results ($\$/kWh_{rated}$) were generated for each vehicle for each MY by conducting BatPaC simulations with the input values in Tables 1-12. These results were correlated with a simpler equation form, with two independent variables: pack energy (kWh_{rated}) and model year (MY). This correlation facilitated the calculation of the cost on a smoothed curve. Three sets of correlation coefficients were determined for *i)* HEV packs (Ni/Mn only), *ii)* Ni/Mn–PHEV+BEV+MHD packs, and *iii)* LFP–PHEV+BEV+MHD packs.

Composite Cost Curve – The cost correlations were used to generate an estimate of the volume-averaged cost of PHEV and BEV (LD+MHD) battery packs in the United States between MY2023 to MY2035. The curve was generated using data on the number of each type of new vehicle sold each year, an average pack energy for each vehicle type, and the split between LFP and Ni/Mn cathodes in the market, The Ni/Mn and LFP costs were included in the final cost curve by weighing them with the percentage of vehicles that are estimated to use Ni/Mn and LFP batteries in the U.S. Further details on the cost curve methodology can be found in Appendix A5.

An analysis was also conducted to understand how the cost curve is impacted by the Internal Revenue Code 45X advanced manufacturing production tax credits (45X credits) established through the Inflation Reduction Act (IRA) for the domestic production of qualified battery components and critical minerals. Pack costs were reduced by applying tax credits based on guidance from the Internal Revenue Service (IRS) (Internal Revenue Service, 2023) and expectations for pack eligibility (U.S. Department of Energy, 2023). Details on the methodology and input values for the 45X study can be found in Appendix A6.

Sensitivity Studies – Some parameters were investigated further to determine their cost sensitivity and make decisions on whether these should be included in the consolidated cost curve. These included the effects of:

1. NMC811 vs. NMC622 in MY2023 – NMC811 is slightly more expensive but NMC622 is the dominant cathode material used in MY2023.
2. Pack production volume – was specified for each MY and not for each type of vehicle.
3. Material prices, i.e., vary each year or remain the same as in MY23.
4. Charge time constraints – with lack of clarity on fast charge times and the number of such packs available in vehicles, the fast charge constraint was not imposed on the results for the cost curve.
5. Labor wage rates of $25 vs. $50/hr.

Results

Trends in Battery Pack Cost

Simulations of the different batteries for the different vehicles and their production volumes described in Tables 1-12 generated the pack costs as shown in the following graphs (see tables in Appendix A1 and A2 for values and breakdowns). All costs are reported in 2023 $/kWh$_{rated}$. The decreases in cost in the future model years are attributable to the following parameters:

1. Better active materials and improved cell design (*e.g.*, higher electrode loading)
2. Cheaper materials per Wh
3. Better economies of scale resulting from larger cells and production volumes

Figure 1 shows the results for the HEV battery packs modeled in this work. Figure 1a indicates the 1.2 kWh packs are expected to decrease in cost from $570/kWh in MY2023 to $450/kWh in MY2035. The 1.8 kWh pack cost is predicted to decrease from $430/kWh to $340/kWh. Both cases correspond to a ~20% decrease in cost from MY2023 to MY2035.

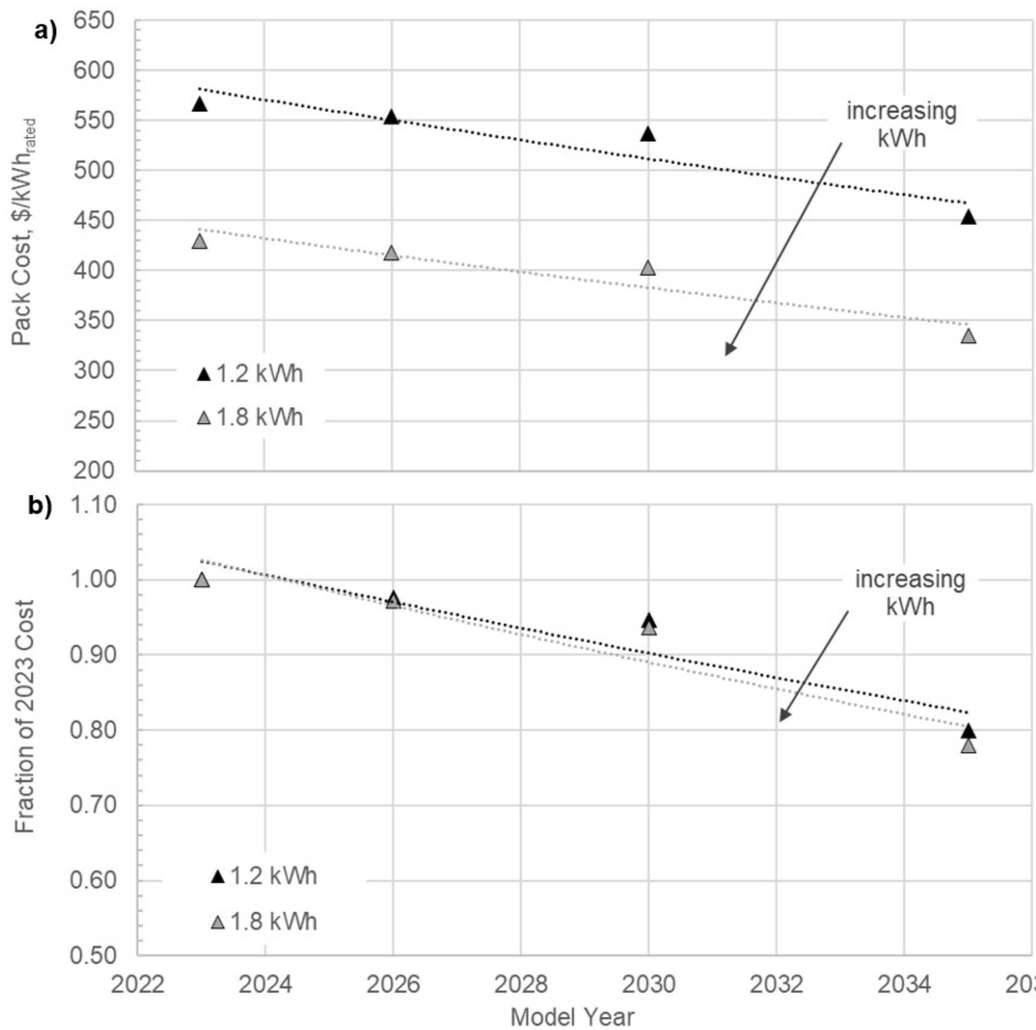

Figure 1. a) Estimated pack cost ($/kWh$_{rated,2023}$) and b) fraction of MY2023 pack cost for HEV packs.

Figure 2 provides the results for the PHEV packs. In the figure, circles and dotted trend lines correspond to high performance packs with Ni/Mn containing cathodes. Triangles and dashed trend lines correspond to low-cost packs with LFP containing cathodes. The reductions in cost from MY2023 to MY2035 are similar for a given chemistry type across all pack sizes – *i.e.*, \$30 to \$38/kWh for low-cost LFP and ~\$50/kWh for Ni/Mn packs. The relative decreases in pack cost vary between the different pack sizes due to changes in the absolute cost (denominator value) of the packs. LFP packs are estimated to have a 17-27% decrease in cost from MY2023 to MY2035, and Ni/Mn packs are estimated to have a 25-35% decrease in cost. The larger decrease in the Ni/Mn packs is caused by advancement of the cathode past current nickel-manganese-cobalt (NMC) materials.

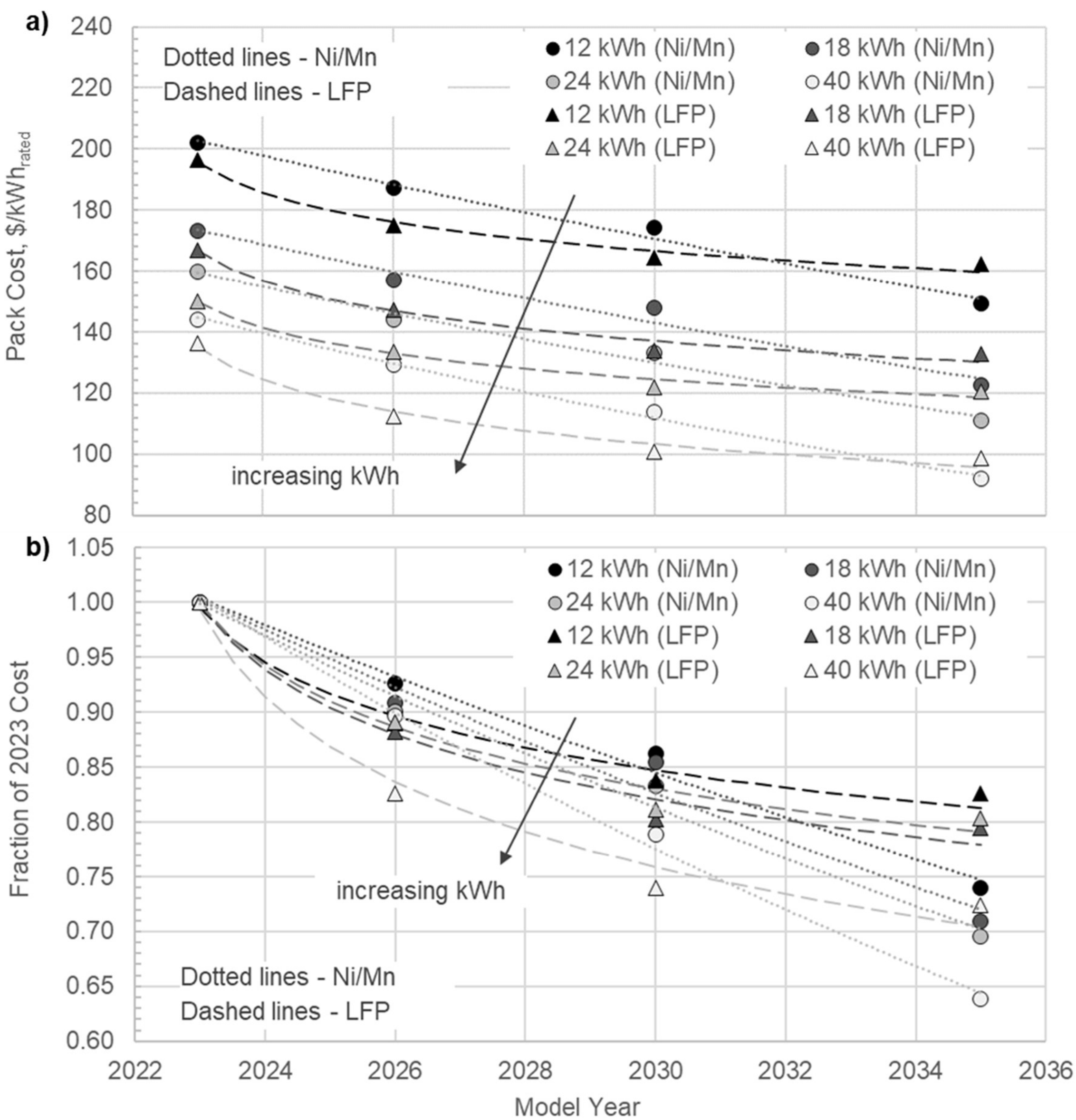

Figure 2. a) Estimated pack cost (\$/kWh$_{rated,2023}$) and b) fraction of MY2023 pack cost for PHEV packs.

Figure 3 shows the results for the light duty BEV packs. The reductions in cost from MY2023 to MY2035 are similar for a given chemistry type across all pack sizes – *i.e.*, ~$45/kWh (~40% reduction) for LFP and ~$55/kWh (~40% reduction) for Ni/Mn packs. Both packs are estimated to have similar costs by MY2035. Ni/Mn packs have a more linear trend because of the adoption of advanced cathode materials in the Ni/Mn case, e.g., LMNO for MY2035, compared to an exponential decaying trend of the LFP packs.

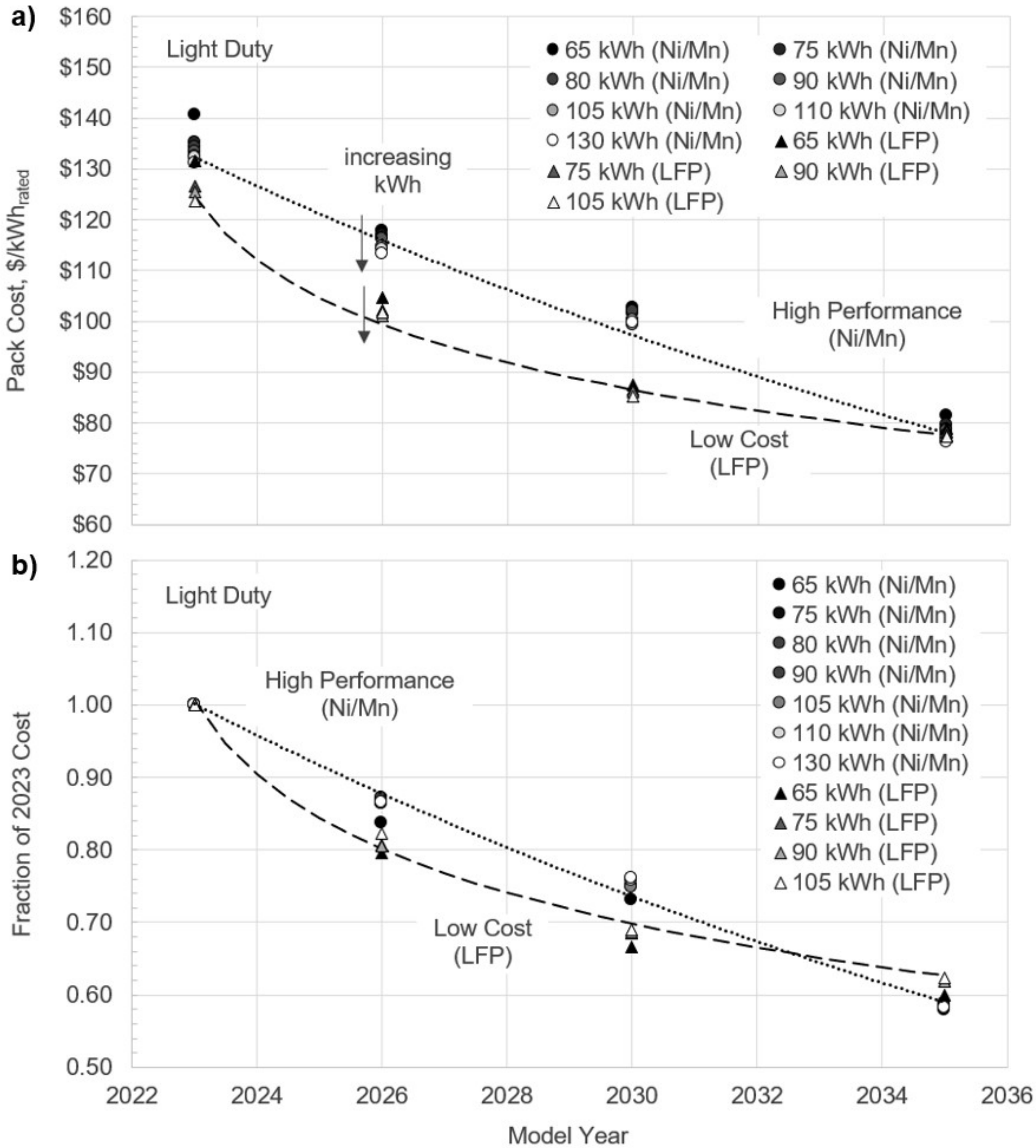

Figure 3. a) Estimated pack cost ($/kWh$_{rated,2023}$) and b) fraction of MY2023 pack cost for light duty BEVs.

Figure 4 provides the results for the medium/heavy (MHD) duty BEV packs. LFP packs are estimated to have a cost reduction of ~$40/kWh (40%) from MY2023 to MY2035, and Ni/Mn packs are estimated to have reductions of ~$50/kWh (40%). The MHD results are close to the LD results because the input parameters assumed MHD packs will benefit from the same technological advances and economies of scale on the cell level as the LD vehicles. The pack production levels were decreased to account for a lower market adoption (see Table 1); however, these changes had a minimal impact on the results (see sensitivity study in Figure 13). Larger packs were also not modeled because it was assumed vehicles with larger kWh requirements will incorporate multiple, smaller packs. These smaller packs will benefit from economies of scale since they will be used in several vehicle sizes.

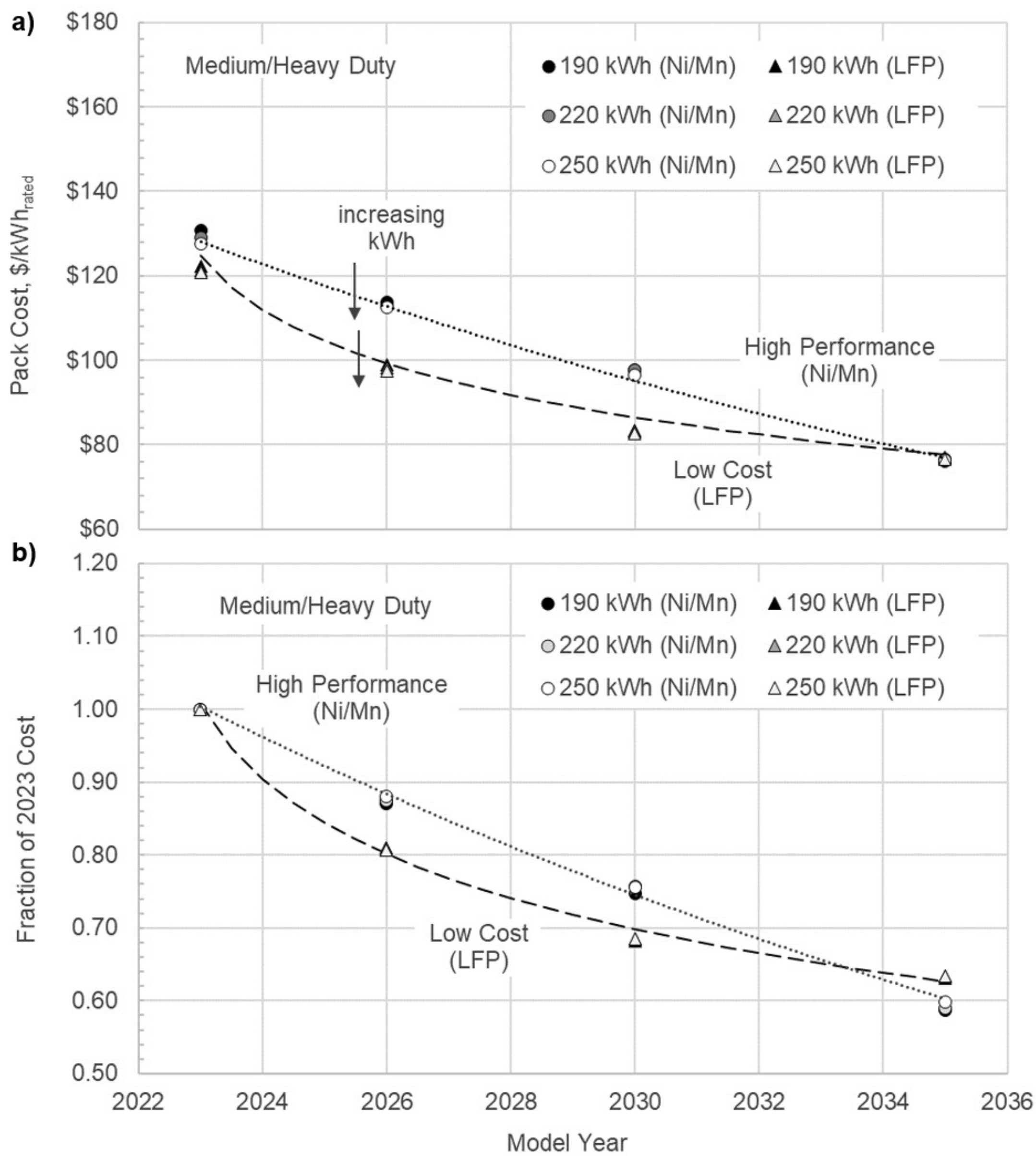

Figure 4. a) Estimated pack cost ($/kWh$_{rated,2023}$) and b) fraction of MY2023 pack cost for medium and heavy duty BEVs.

The results in the previous figures are summarized in Figure 5, which shows the pack costs for the Ni/Mn and LFP packs as a function of pack energy for each model year. The figure shows that the pack cost decreases rapidly as the pack energy increases above ~10 kWh, which is due to the decreased power-to-energy ratio requirements in the PHEV and BEV packs. The pack cost is also shown to level off as the energy increases past ~50 kWh, where power requirements are the same and the energy is increased by adding more, similar cells and modules.

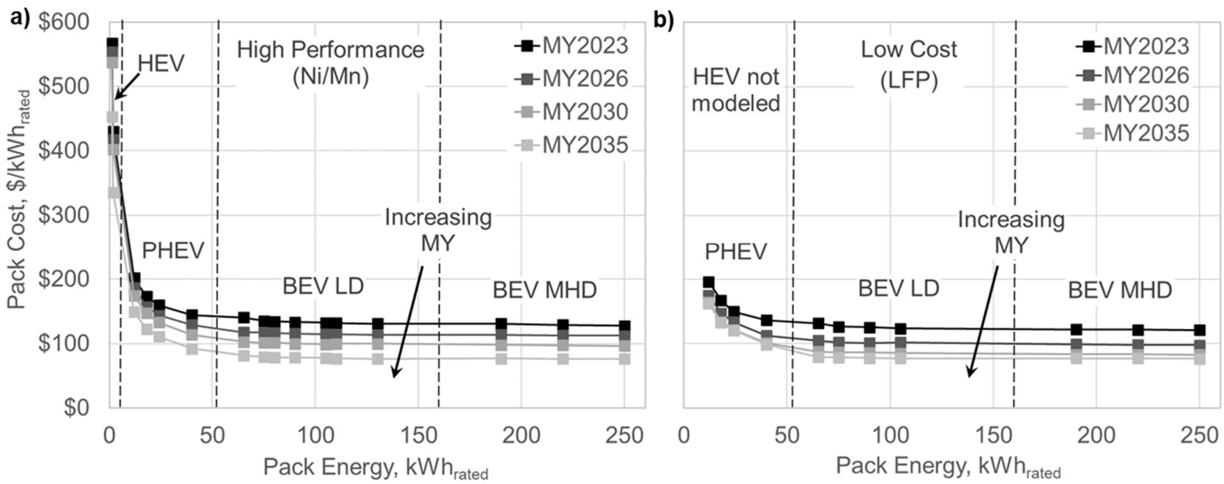

Figure 5. Estimated packs cost ($\$/kWh_{rated,2023}$) for all vehicle types and model years for a) Ni/Mn and b) LFP containing cathodes.

HEV, PHEV, and BEV Cost Correlations

Correlations were developed from the simulated data to calculate the pack cost as a function of model year and pack size (kWh). The correlations had the following functional form:

$$C_{pack} = A + \frac{B}{x^C} - D(y - 2023)e^{E(y-2023)} \quad (1)$$

where C_{pack} is the cost of the pack in $\$/kWh_{rated,2023}$, x is the pack energy in kWh, and y is the model year. A, B, C, D, and E are constants given in Table 13. Three sets of constants were generated from the fits: one set for HEV packs, one for high performance (Ni/Mn) PHEV and BEV packs, and one for low cost (LFP) PHEV and BEV packs. The agreement between the equation and the simulated data is shown in Figure 6. Similar correlations generated for the pack specific energy (Wh/kg) and energy density (Wh/L) can be found in sections A3 and A4 in the Appendix, respectively.

Table 13. Constants for pack cost ($\$/kWh_{rated,2023}$) correlations given in Equation 1.

Constant in Eq. 1	High Performance (Ni/Mn) (HEV, ≤5 kWh)	High Performance (Ni/Mn) (PHEV, EV)	Low Cost (LFP) (PHEV, EV)
A	119.3	124.5	115.7
B	492.4	1071	1141
C	0.7667	1.068	1.138
D	4.131	4.617	9.489
E	0.01352	-0.005038	-0.08312

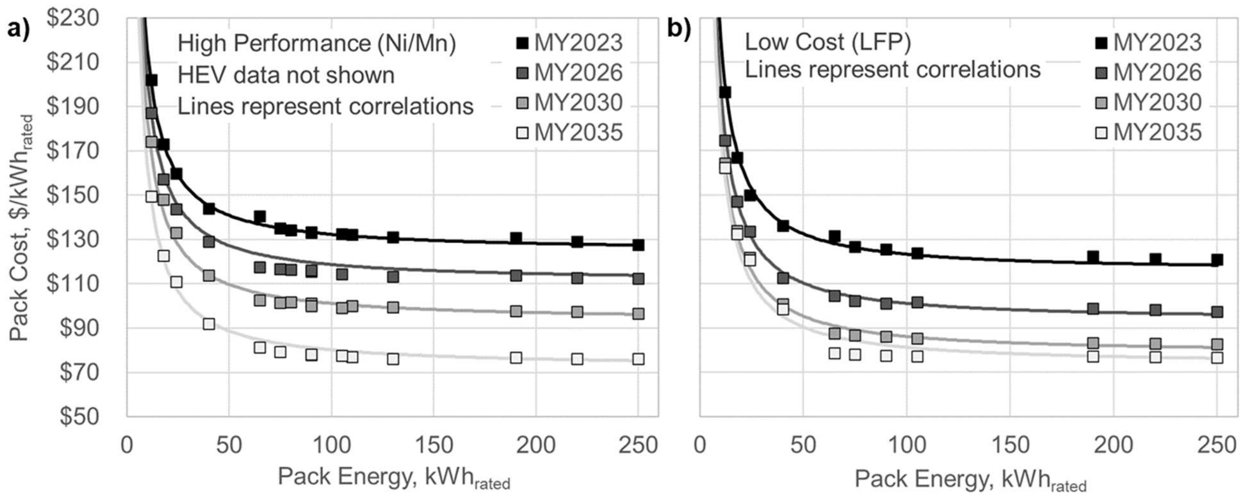

Figure 6. Comparison of pack cost ($/kWh$_{rated,2023}$) between full BatPaC simulations (symbols) and correlations in equation 1 (lines) for a) high performance (Ni/Mn) and b) low cost (LFP) packs.

Estimated Volume Averaged PHEV and BEV Costs

The correlation in Equation (1) was used to generate an estimate of the volume-averaged cost of PHEV and BEV battery packs in the United States between MY2023 to MY2035. Details of the calculations are provided in Appendix A5. In short, the costs were determined by first segmenting the entire vehicle fleet into twenty-four vehicles (v) based on vehicle type (BEV or PHEV), class (Compact, Midsize, Small SUV, Midsize SUV, Pickup, and MHD), and cathode chemistry (Ni/Mn or LFP). Ni/Mn was assumed to include NCA cathodes due to similarities in cost. The number of vehicles sold each year (N_v) was then estimated for each vehicle type based on available models and market research reports – *i.e.,* NREL TEMPO model, EPA OMEGA model, Rho Motion data, and Benchmark Minerals Intelligence data (United States Environmental Protection Agency, 2023; Benchmark Minerals Intelligence, 2023; Muratori, et al., Forthcoming; Rho Motion, 2023). The cost of each vehicle pack for each model year (C_v) was also estimated based on the projected pack energy, in kWh, for each class using the Argonne Autonomie model (Islam, et al., 2023) and the correlations shown in Equation (1). These two pieces of information (N_v and C_v) were used to estimate the volumed averaged pack cost at each model year using the following equation:

$$C_{fleet} = \frac{\sum_{v=1}^{v=24} C_v N_v}{\sum_{v=1}^{v=24} N_v} \qquad (2)$$

where C_{fleet} is the estimated cost in $/kWh$_{rated,2023}$ and the summations are evaluated from 1 to 24 to account for all twenty-four vehicle segments. The results of the calculation are shown in Figure 7. The volume averaged pack cost is estimated to decrease from ~$140/kWh in MY2023 to ~$85/kWh in MY2035. This is a 40% reduction in cost. Most of the reduction is attributed to advances in pack chemistry, manufacturing, and design captured in Tables 1-12.

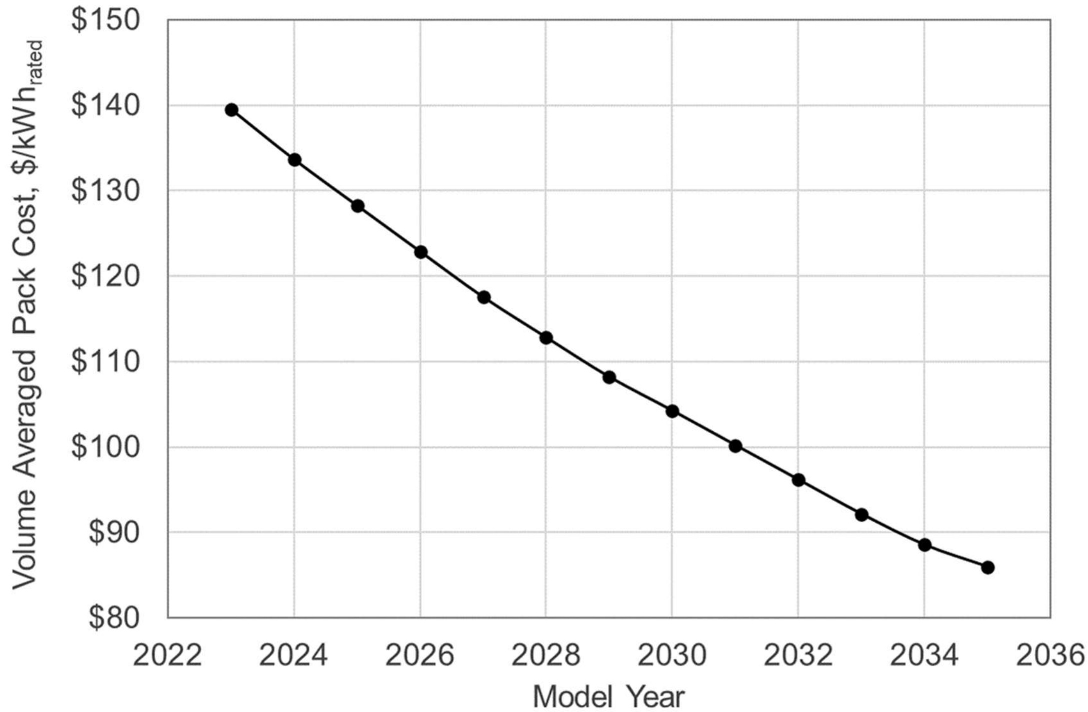

Figure 7. Estimated volume averaged pack cost ($/kWh$_{rated,2023}$) for PHEV and BEV packs in U.S. fleet.

Impact of 45X Tax Credit on Pack Costs

The Internal Revenue Code 45X advanced manufacturing production tax credits (45X credits) established through the Inflation Reduction Act (IRA) for the domestic production of qualified battery components and critical minerals have the potential to significantly reduce the projected costs of packs in this work. An analysis was conducted to quantify the effect of the 45X credits. Details on the methodology and input values can be found in Appendix A6. Figure 8 to Figure 10 provide the estimated tax credits for each of the three vehicle categories reflected in the correlation development in equation 1. Tabulated results are included in the Appendix. Figure 8 provides the credits for Ni/Mn HEV packs. Figure 9 provides the credits for Ni/Mn PHEV and BEV packs. Figure 10 provides the credits for LFP PHEV and BEV packs. The credits were determined using the component mass and cost breakdowns for a representative pack within each category.

The figures provide values for eight different tax credits. There are four datasets that reflect the four different 45X credits [*i.e.,* modules, cells, electrode active materials (EAM), and critical minerals (CM)]. Each of these sets have two credits in the figure that reflect two scenarios corresponding to different levels of eligibility based on the U.S. supply chain: “full” refers to full market response where 100% of packs are eligible for the credit eligible for domestic producers and “low-end” refers to low-end market response where the percentage of packs eligible for the credit is based on the availability of domestic production of eligible minerals and components, as projected by Argonne analysis of market announcements as of November 2023 (U.S. Department of Energy, 2023). The results reflect the ramp downs of the tax credits prescribed in the IRA for cells, modules, and EAM after MY2029.

According to Figure 8, HEVs have the potential to achieve a total 45X tax credit of ~$56/kWh through MY2029 based on the summation of the “full” results (see Table 40 in the Appendix for tabulated results). The maximum credit drops nearly linearly to ~$1.7/kWh by MY2033 due to the ramp down of the cell, module, and EAM credits. The totals for the “low-end” market response for these same two cases are ~$52/kWh up to 2029 and ~$0.6/kWh after MY2033.

Figure 9 indicates that Ni/Mn PHEVs and BEVS have the potential to achieve a total, “full” credit of ~$54/kWh through MY2029 (see Table 41 in the Appendix). The maximum credit drops to ~$1.8/kWh by MY2033 due to the 45X ramp down. The “low-end” totals for these same two cases are ~$49/kWh up to MY2029 and ~$0.7/kWh after MY2033.

Figure 10 shows that LFP PHEVs and BEVs have the potential to achieve a total, “full” credit of ~$50/kWh through MY2029 (see Table 42 in the Appendix). The maximum credit drops to ~$0.5/kWh by MY2033 due to the 45X ramp down. The “low-end” totals for these same two cases are ~$48/kWh up to MY2029 and ~$0.3/kWh after MY2033.

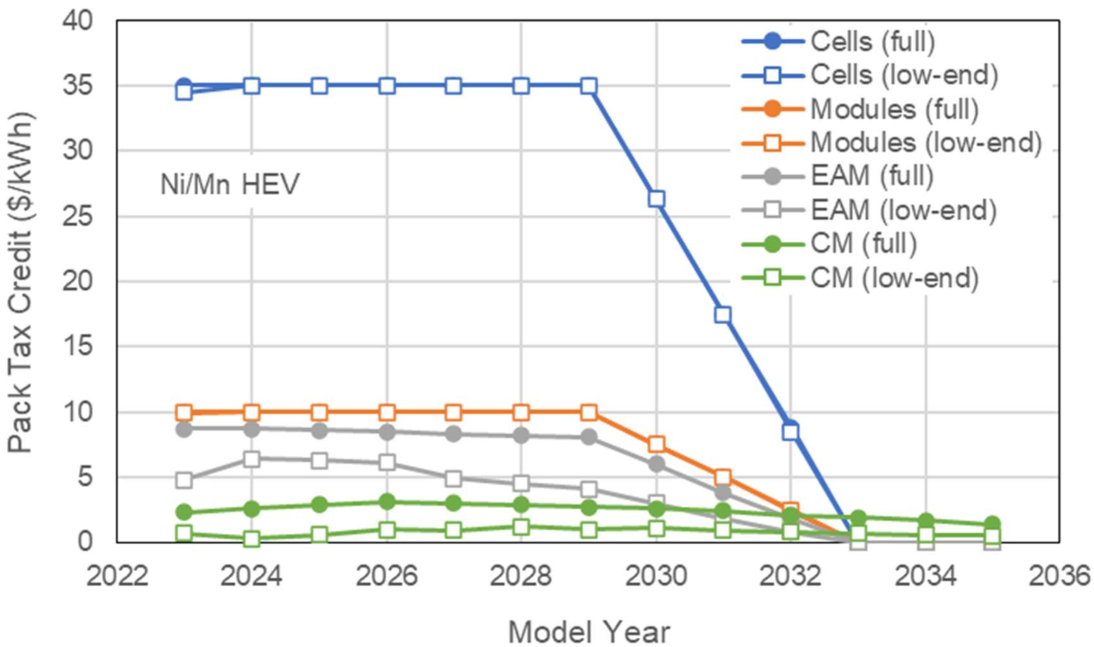

Figure 8. Estimated tax credits ($/kWh$_{rated,2023}$) for Ni/Mn HEV packs under 45X. “Full” refers to full market response, i.e., availability, of domestic U.S. supply (i.e., packs are eligible for 100% of credits) and “low-end” refers to the share of the U.S. market that can be supplied domestically based on announcements available as of the time of analysis (see Appendix A6 for details). EAM and CM refer to electrode active materials and critical minerals tax credits, respectively.

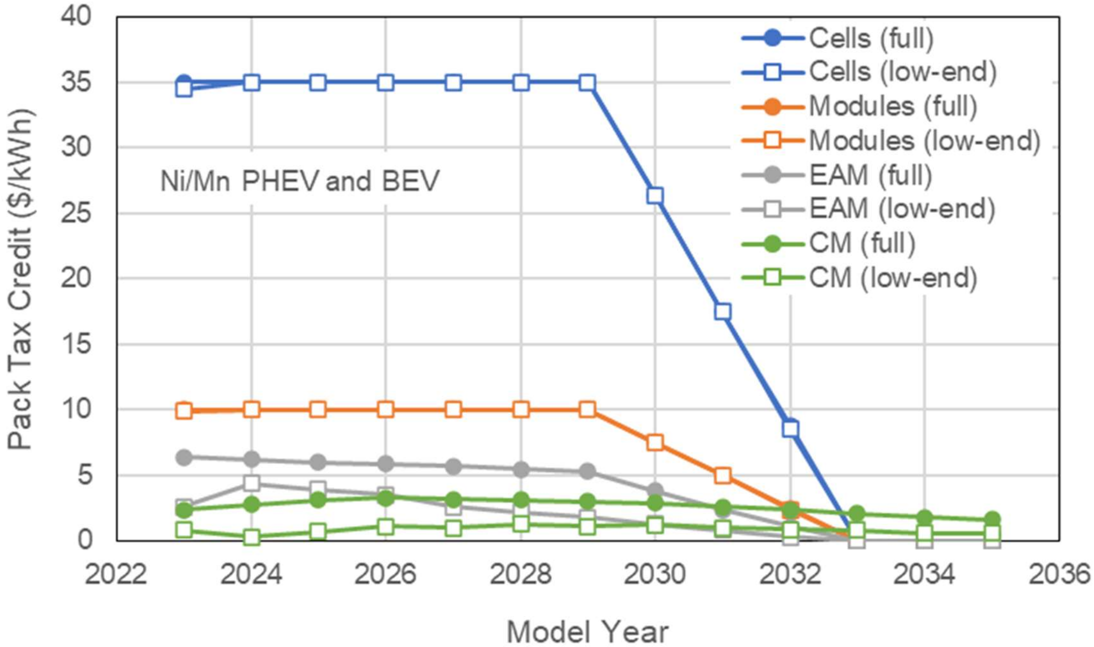

Figure 9. Estimated tax credits ($/kWh_{rated,2023}$) for Ni/Mn PHEV and BEV packs under 45X. "Full" refers to full market response, i.e., availability, of domestic U.S. supply (i.e., packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market that can be supplied domestically based on announcements available as of the time of analysis (see Appendix A6 for details). EAM and CM refer to electrode active materials and critical minerals tax credits, respectively.

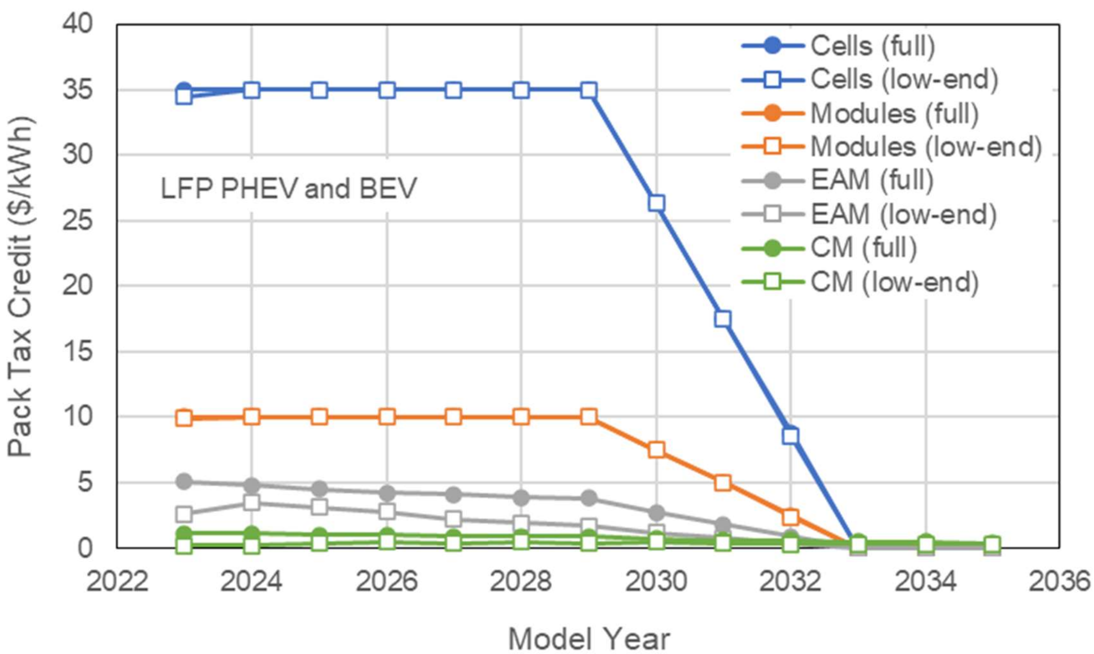

Figure 10. Estimated tax credits ($/kWh_{rated,2023}$) for LFP PHEV and BEV packs under 45X. "Full" refers to full market response, i.e., availability, of domestic U.S. supply (i.e., packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market that can be supplied domestically based on announcements available as of the time of analysis (see Appendix A6 for details). EAM and CM refer to electrode active materials and critical minerals tax credits, respectively.

The 45X tax credits were also incorporated into the volume-averaged pack cost calculations for PHEVs and BEVs (see previous section for details). The influence of three groupings of 45X credits is shown in Figure 11. The first grouping incorporates only the cell and module credits for the low-end case (open triangles in the figure). Note that the full and low-end responses for this grouping are nearly identical because the smallest low-end response is 97% (see Table 39 in Appendix A6). Therefore, this grouping reflects both cases (full and low-end) with negligible difference. The next grouping incorporates all credits, including electrode active materials and critical minerals at the low-end market response (solid triangles). The final grouping includes all credits at full market response (solid squares). Overall, the volume averaged pack cost has the potential to reach a minimum value of \$55.6/kWh in MY2029 for a full market response and \$60.5/kWh for the low-end response. The ramp down of the cell, module, and EAM credits beginning in 2030 will have a significant impact on the cost, raising it to ~91/kWh by MY2033 for both cases.

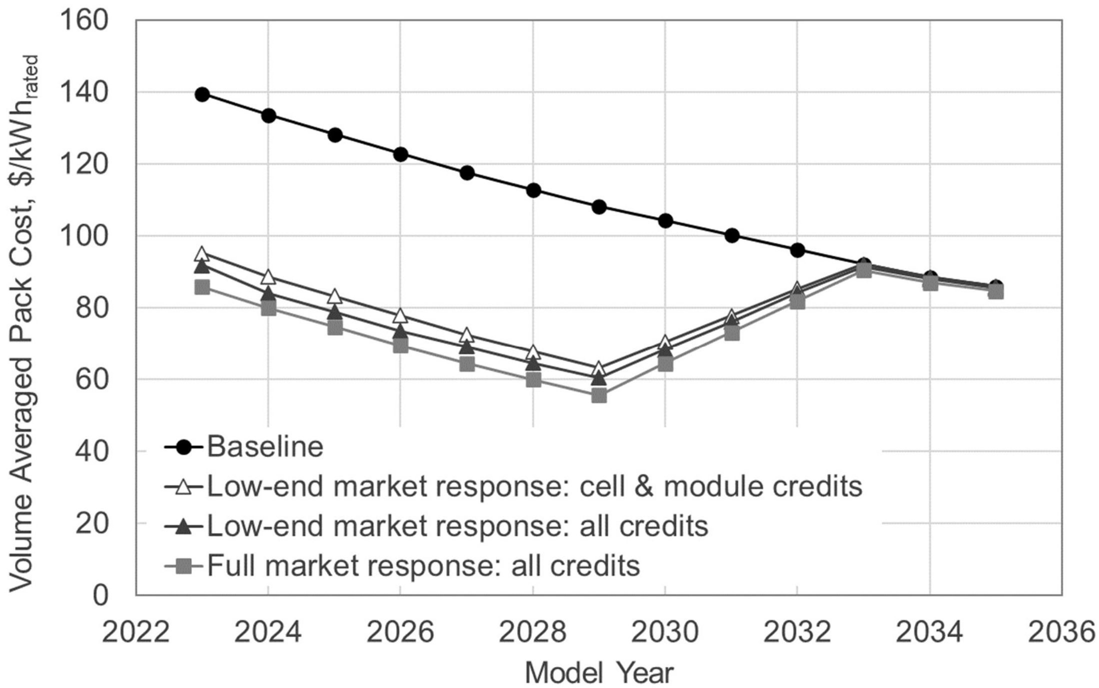

Figure 11. Impact of 45X tax credits on volume averaged pack cost (\$/kWh$_{rated,2023}$).

Calculation Sensitivities

Sensitivity – MY2023 Cost with NMC811 vs. NMC622 as the Cathode Active Material

Some of the EV batteries available in the market in MY2023 use NMC811 as the cathode active material (BloombergNEF, 2023; Sanders, 2023), while the CAM selected as the dominant material in this analysis is NMC622. To address the question of the effect of NMC811 on a pack cost, a series of simulations were run by using NMC811 (and its associated properties and price), while keeping all other MY2023 specifications unchanged. Figure 12 compares the pack costs with NMC622 and NMC811, for all the batteries for BEV light duty (LD) vehicle, i.e., EVs only. The trends for both chemistries show a cost reduction trend for bigger batteries (higher kWh), where the slope gets increasingly shallow at higher kWh. The difference is less than $0.5/kWh for all kWhs, with the exception at 90 kWh where it was highest at $1/kWh. While the NMC811 offers higher specific capacity and higher voltage (compared to NMC622), it has a higher material price, and results in the net higher pack cost.

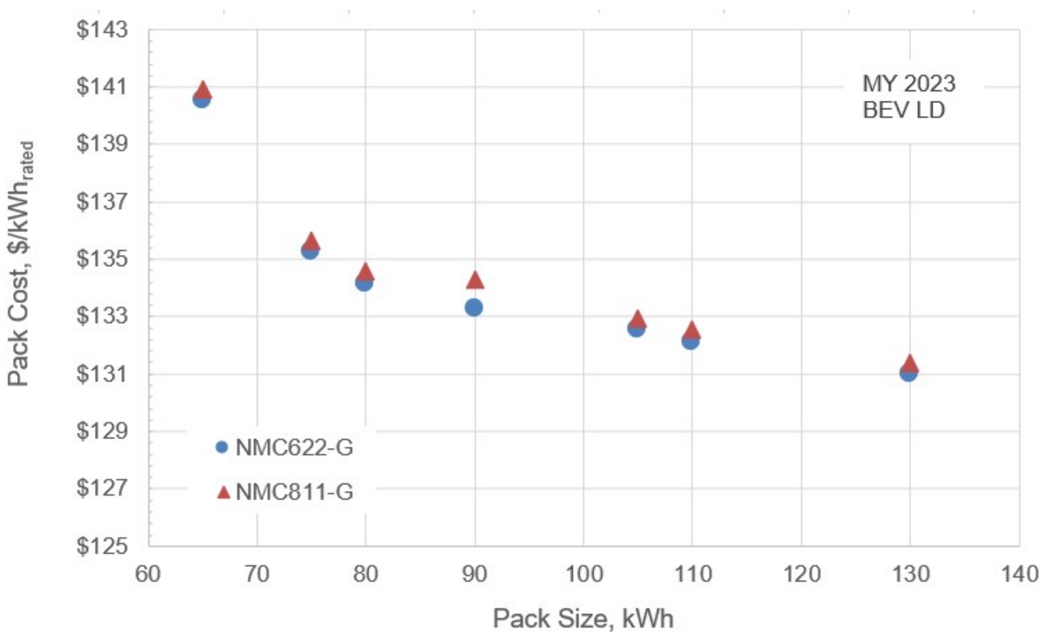

Figure 12. Comparison of pack costs for MY2023 with NMC622 and NMC811 as the cathode active material.

Sensitivity – Production Volume
Cost reduction from economies of scale is calculated according to Equation (3),

$$Cost = Cost_{reference}\left(\frac{Vol}{Vol_{reference}}\right)^{p} \tag{3}$$

Where, the desired cost is determined from the ratio of the actual to the reference production volume, raised to the power p. This cost equation is applied separately for all the processing steps in the plant, for the cell plant size which determines the amount of materials that are purchased, and the number of packs that are produced per year in the plant. As described in an earlier section, the cell plant size (GWh) and pack volumes were specified for each model year in the development of the consolidated cost curve.

Current cell plants around the world appear to have been optimized at above 35 GWh and the learning curve is relatively flat. Large cell plants are feasible because similar cells can be produced in large volume and then used to configure packs of different energy storage capacities (kWh). This was investigated by plotting the pack cost as a function of the annual pack production volume. Figure 13 plots the results for MY2023 vehicles with both NiMn and LFP chemistries and different pack energies. BEV pack costs change less than a $1/kWh above 200 thousand packs per year, while the smaller packs in PHEVs and HEVs show greater sensitivity.

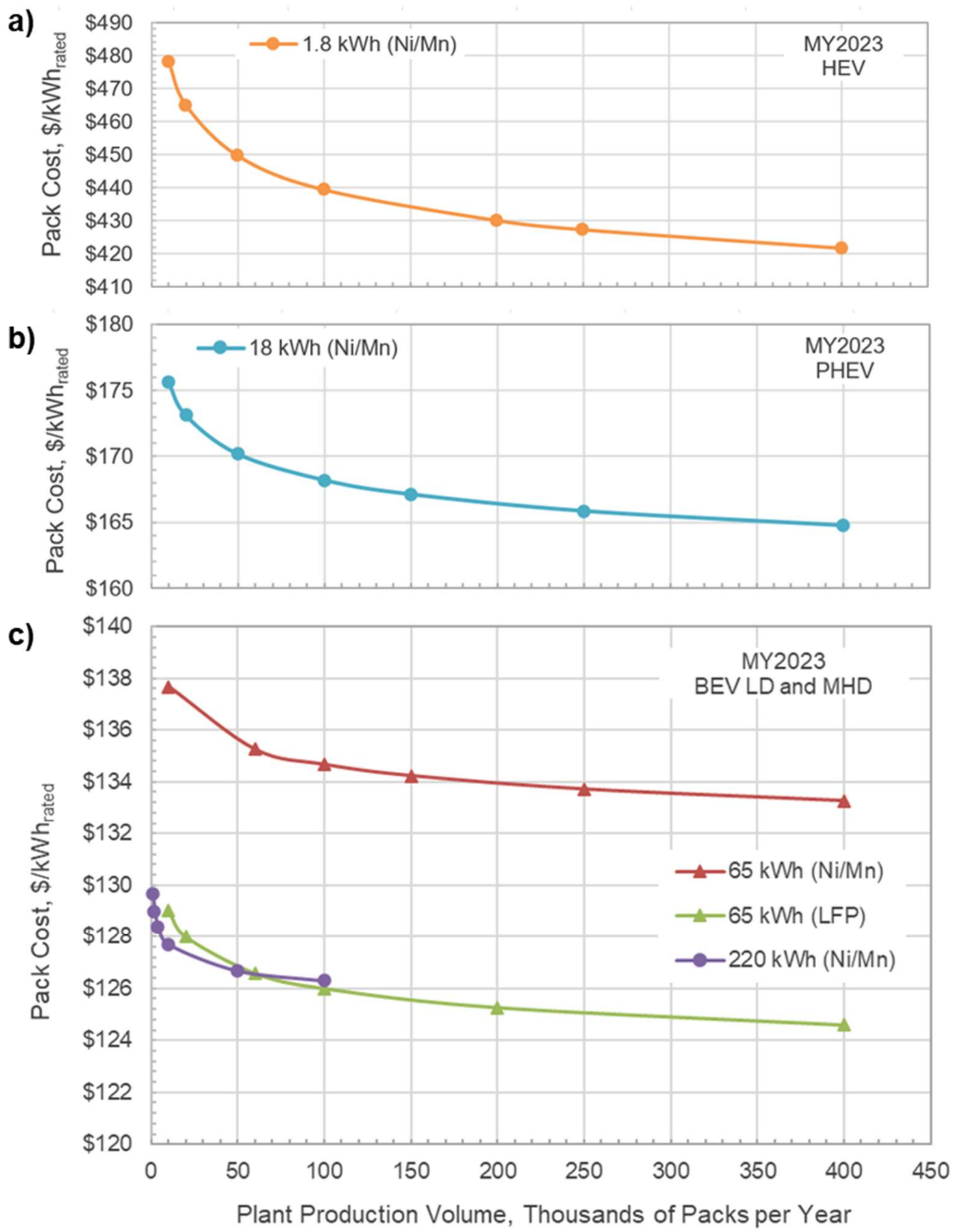

Figure 13. Effect of pack production volume in a plant on the pack cost ($\$/kWh_{rated,2023}$) for a) HEVs, b) PHEV, and c) BEVs. MY2023 with Cell plant capacity of 35 GWh.

Sensitivity – Raw Materials Prices

The price of the active materials has a large impact on the cost of the packs. For instance, the cathode active materials can contribute over 40% of the total pack cost (see Appendix A2). The price of the active materials through MY2035 were estimated from market research reports (Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Sanders, 2023); however, these projections may be impacted by future, unforeseen changes in the supply and demand of the raw materials. Figure 14a shows what might happen if the raw materials' prices remain at MY2023 values and all pack costs were based on the MY2023 price of the active materials. Solid symbols and dotted trendlines refer to calculations assuming 2023 prices. Open symbols and dashed trendlines refer to calculations with forecasted prices. The spread in costs for a given MY for a pack chemistry (LFP or Ni/Mn) is related to the plotting of four different pack sizes for each MY. Details on the inputs can be found in Appendix A7. Figure 14b quantifies the change in cost between forecasted and MY2023 active material prices. Overall, Figure 14b shows that maintaining MY2023 values will increase the LFP cost by \$4-\$10/kWh and the Ni/Mn cost by \$3-8/kWh. The maximum increase in LFP cost will be ~\$10/kWh by MY2035. This is due to the cathode and anode active material prices increasing from \$9.5 to \$13/kg and \$9.1 to \$11/kg, respectively. The maximum increase in Ni/Mn cost will be \$7.7/kWh in MY2030. This is due to the cathode NMC95 and graphite/silicon (G/Si) prices increasing from \$31.3 to \$36.1/kg and \$11.3 to \$13/kg, respectively.

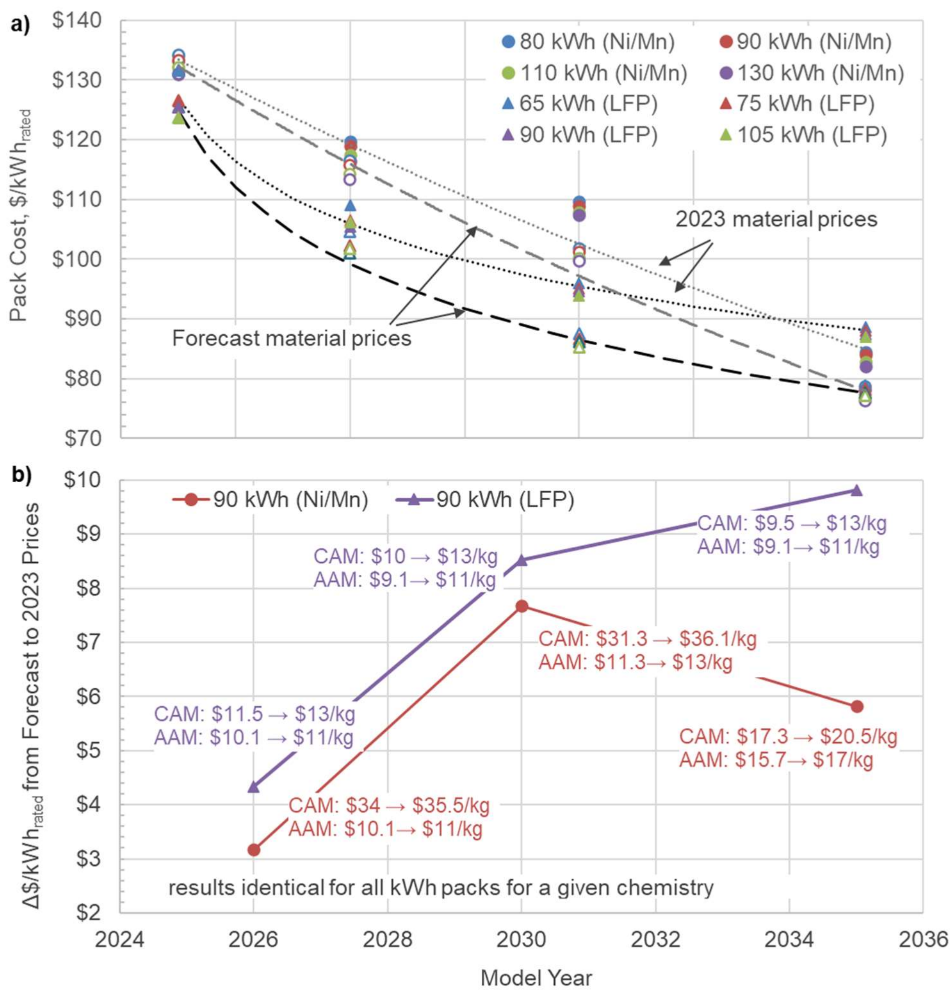

Figure 14. a) Pack costs (\$/$kWh_{rated,2023}$) assuming 2023 (solid symbols, dotted trendlines) and forecasted (open symbols, dashed trend lines) active material prices for Ni/Mn (circles, grey trend lines) and LFP (triangles, black trendlines) packs. b) Change in pack cost from forecasted to 2023 active material prices for 90 kWh packs. Results in b) apply to all kWh packs in a). CAM: cathode active material, AAM: anode active material.

Sensitivity – Fast Charge

Fast charging a pack requires the ability of the cell (particularly the anode layer) to process a large current during the charging period. For short durations the incoming current can be as high as 5-8 times average discharge rate (full discharge in 3 hours, referred to as a C/3 rate) (Ahmed S. , et al., 2017). This high current can initiate several degradation mechanisms (Raj, Rodrigues, & Abraham, 2020; Rodrigues, Shkrob, Colclasure, & Abraham, 2020) and is addressed through electrode design and charging protocols (Song J. , et al., 2021; Usseglio-Viretta, et al., 2020).

The effect of charge times on the design of the electrodes, assuming a well-developed charging protocol, translates to a lower loading of the active material, which in turn increases the ratio of inactive (current collectors, separators, and others) to electrode active materials (EAM) and, therefore, the cost of the cell and pack. Figure 15 plots the effect of charge times on the pack cost and shows that packs with charge times of 25 minutes or more cost ~$135/kWh for a 90 kWh pack and ~$143/kWh for a 65 kWh pack. Below 25 minutes, the cost begins to increase. For a 15-minute chart time, the cost rises to ~$144/kWh and ~$151/kWh, for the 90 and 65 kWh packs, respectively.

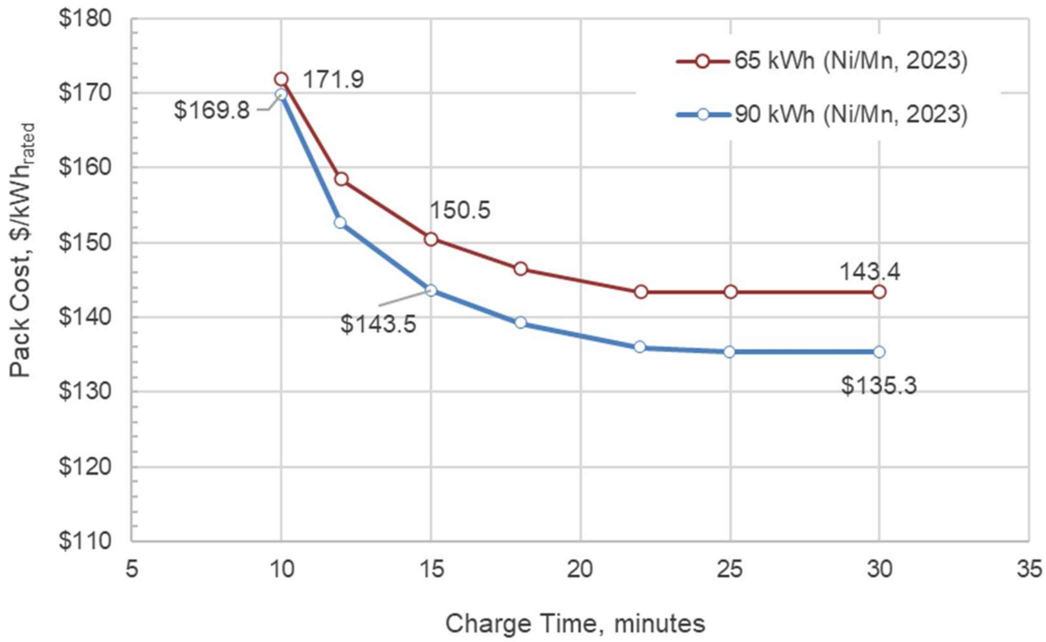

Figure 15. Pack cost ($/kWh$_{rated,2023}$) as a function of charging time, for a 65 kWh and 90 kWh NMC622-Graphite pack for MY2023.

Table 14. Pack costs as a function of charging times.

Charge Time, min	30	15	10
Cost (65 kWh), $/kWh	143	151	172
Δ% w.r.t. 30 min	-	+4.95%	+19.9%
Cost (90 kWh), $/kWh	135	144	170
Δ% w.r.t. 30 min	-	+6.67%	+25.5%

Sensitivity – Labor Rate

The labor rate assumed for the hourly workers in the manufacturing plant can have an impact on the total pack cost. The sensitivity of the pack cost to the labor rate was studied by re-running the BatPaC simulations with the labor rate doubled (from $25/hr[1]) to $50/hr[2]. The resulting data was used to generate correlation constants in Equation (1) for the new dataset. Table 15 provides a comparison of the correlation constants for the two cases ($25 and $50/hr.). Figure 16 shows how the data and correlation outputs change with labor rate.

Table 15. Constants for pack cost ($/kWh$_{rated,2023}$) correlations given in equation 1 for $25/hr. and $50/hr. labor rates.

	Ni/Mn (HEV, ≤5 kWh)		**Ni/Mn (PHEV, EV)**		**LFP (PHEV, EV)**	
	$25/hr.	**$50/hr.**	**$25/hr.**	**$50/hr.**	**$25/hr.**	**$50/hr.**
A	119.3	122.9	124.5	128.9	115.7	120.6
B	492.4	509.6	1071	1480	1141	1535
C	0.7667	0.7649	1.068	1.164	1.138	1.148
D	4.131	4.443	4.617	5.278	9.489	10.04
E	0.01352	0.01018	-0.005038	-0.01290	-0.08312	-0.08346

In Figure 16, squares and solid lines represent the base case of $25/hr., while circles and dashed lines represent the $50/hr case. The results indicate that doubling the labor rate can increase the pack cost by up to ~$10/kWh depending on the model year, pack size, and pack chemistry. For larger packs (>25 kWh), the figure shows that larger increases are observed for LFP packs, which tend to have higher labor due to the need to process more materials per kWh. The lower energy content (Wh/g) of LFP requires bigger cells and production costs to achieve the same pack energy (kWh) as nickel/manganese containing cathodes.

[1] Authors' estimate of average U.S. labor rate for battery manufacturing as of August 2023.

[2] $50/hr case was analyzed to capture ongoing labor negotiations during Fall 2023.

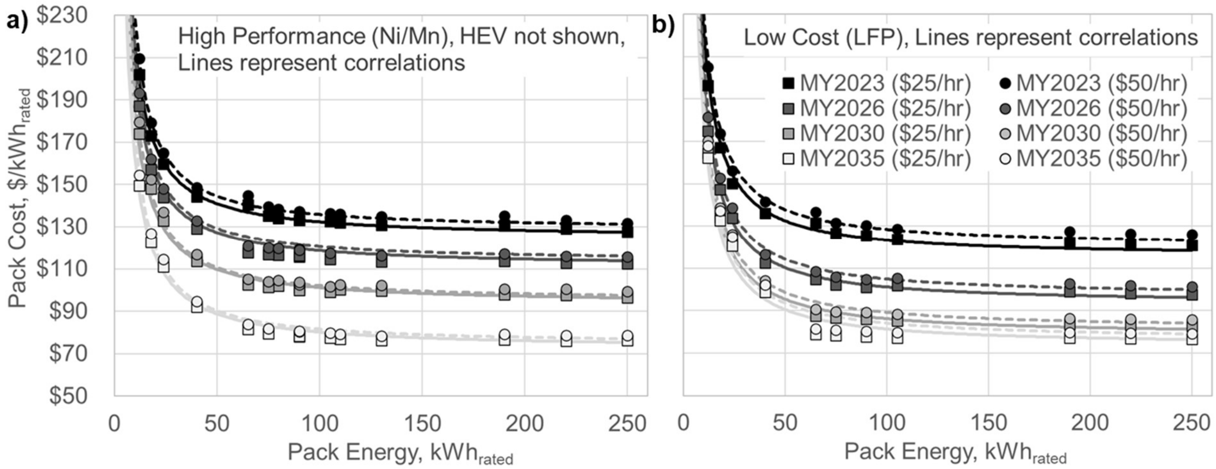

Figure 16. Comparison of pack cost ($\$/kWh_{rated,2023}$) between full BatPaC simulations (symbols) and correlations in equation 1 (lines) for a) high performance (Ni/Mn) and b) low cost (LFP) packs. Squares and solid lines are the baseline simulations which assume labor rate of $25/hr, while circles and dashed lines assume a labor rate of $50/hr.

The impact of labor rate on the results is further exemplified in Table 16 and Table 17, which provide outputs from the correlations for selected pack sizes. Table 16 shows that doubling the labor rate may increase the cost of high performance (Ni/Mn) packs by 1-7%, depending on the model year and pack size. The absolute cost of HEVs is impacted the most (~$20/kWh) because they have more, smaller cells for a given kWh, which results in higher labor costs. The percent change in cost is not the highest for HEVs (~3%) due to the higher total base cost. 10 kWh packs, which reflect PHEVs, have the highest percent change (~6.5%) and the second highest absolute change (~$13/kWh). Larger, 100 kWh packs, which reflect BEVs, have the lowest percent (~2%) and absolute cost (~$2/kWh) changes. These trends are related to increasing cell size and reducing cell quantity per kWh as the pack kWh increases.

Table 17 shows that doubling the labor rate may increase the cost of LFP packs by 3-4%, depending on the model year and pack size. 10 kWh packs have absolute changes of ~$8/kWh, while larger, 100 kWh packs have changes of ~$3/kWh.

Table 16. Outputs from correlations for three pack sizes for high performance (Ni/Mn) packs. The first two columns under each pack size provide the $\$/kWh_{rated,2023}$ output from correlations developed assuming $25/hr. and $50/hr. labor rates. The third column is the percent increase in pack cost from $25/hr. to $50/hr.

	1 kWh (HEV)			**10 kWh (PHEV)**			**100 kWh (BEV)**		
Model Year	**$25/hr.**	**$50/hr.**	**%**	**$25/hr.**	**$50/hr.**	**%**	**$25/hr.**	**$50/hr.**	**%**
2023	611.7	632.4	3.4%	216.1	230.2	6.6%	132.3	135.8	2.6%
2026	598.8	618.7	3.3%	202.4	215.0	6.2%	118.7	120.6	1.6%
2030	579.9	599.1	3.3%	184.9	196.5	6.3%	101.2	102.1	0.9%
2035	553.4	572.2	3.4%	163.9	176.0	7.4%	80.2	81.6	1.7%

Table 17. Outputs from correlations for two pack sizes for low cost (LFP) packs. The first two columns under each pack size provide the $/kWh$_{rated,2023}$ output from correlations developed assuming $25/hr. and $50/hr. labor rates. The third column is the percent increase in pack cost from $25/hr. to $50/hr.

	10 kWh (PHEV)			100 kWh (BEV)		
Model Year	**$25/hr.**	**$50/hr.**	**%**	**$25/hr.**	**$50/hr.**	**%**
2023	220.6	229.8	4.2%	123.3	128.4	4.1%
2026	198.4	206.3	4.0%	101.1	104.9	3.7%
2030	183.5	190.6	3.9%	86.2	89.2	3.5%
2035	178.6	185.5	3.9%	81.3	84.1	3.4%

Summary and Conclusions

Under guidance of the Department of Energy, EPA, and NHTSA managers, a study was conducted to estimate the current and future cost of battery packs for electric vehicles. The pack costs were calculated with Argonne's BatPaC tool for twenty categories of vehicles representing hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and full battery electric vehicles (BEV) for both light duty (LD) and medium/heavy duty vehicles (MHD). The cost of battery packs was calculated for four discrete model years (MY2023, MY2026, MY2030, and MY2035) by applying bottom-up assumptions into the BatPaC tool for cell chemistry, cell design, cell size, pack design, production volumes, and material prices. The Appendix provides many details of the methodology, supporting data, and other analyses, including the cost breakdown and the pack mass and volume projections for the different model years.

HEVs were estimated to have a model year 2023 (MY2023) cost of $430 to $570/kWh, which will reduce by ~20% by MY2035. High performance PHEVs made from nickel and manganese containing cathodes (Ni/Mn) were estimated to have MY2023 costs between $145 to $175/kWh with a 25% to 35% reduction in cost by MY2035. PHEVs made from lithium iron phosphate (LFP) cathodes were estimated to have MY2023 costs between $145 to $200/kWh, which will reduce by 17% to 27% by MY2035. Ni/Mn BEVs for LD and MHD vehicles had a MY2023 pack cost of $130 to $140/kWh and are estimated to decrease by ~40% by MY2035. LFP BEV packs had a MY2023 cost of $120 to $130/kWh and were also estimated to have a ~40% cost reduction by MY2035. The ranges in the cost and reduction numbers above reflect variations in the pack size (kWh) within a broad vehicle category.

The resulting costs were then used to produce a correlation for estimating the pack cost as a function of pack size (kWh) and model year. This correlation was used to produce a consolidated battery cost curve for light-, medium- and heavy-duty PHEVs and BEVs within the United States. The cost curve was derived by weighting the pack costs with projections for the number of new vehicles to be sold between MY2023 to MY2035. The cost curve showed that the volume averaged pack cost of PHEVs and BEVs in the United States was ~$140/kWh for MY2023, which is estimated to drop by ~39% to $86/kWh in MY2035 through a combination of technology advances and economies of scale. Modifications were also made to the estimated costs to reflect possible production incentives for a projection of U.S. manufacturers as of November 2023 per Internal Revenue Code Section 45X (Internal Revenue Service, 2023). Application of these credits was shown to enable a further reduction of the cost to a low of ~$56/kWh in 2029.

In addition, several sensitivity studies were conducted to explore the influence of further parameter modification on pack cost. First, the use of NMC811 (instead of NMC622) as the cathode active material for MY2023 was shown to have a negligible impact on pack cost. Second, changes in the pack production volume were shown to mainly have any significant impact on cost if the production volume is less than 100,000 packs per year. For instance, decreasing the production rate from 400,000 to 100,000 packs only increases the cost of HEVs, PHEVs, and BEVs by ~$20/kWh (4.5%), $3/kWh (1.8%), and $2/kWh (1.6%), respectively. Third, stagnant prices of raw materials could increase future pack costs by $3 to $10/kWh depending on the model year and pack chemistry. Fourth, charging times down to 25 minutes were shown to have a minimal impact on pack cost. Further decreasing the charging time to 15 minutes could result in a 5% to 7% increase in pack cost. Finally, doubling the production worker wage rate from $25/hr to $50/hr was shown to increase pack cost by 1% to 7%. These sensitivities suggest that the pack costs reported herein may be impacted by temporal uncertainties in technology successes and market directions. Therefore, it is recommended that these projected costs be compared with actual market data on an annual basis, and the underlying assumptions be updated to reflect the technology and market.

Definitions of Terms

AAM – Anode active material

BatPaC – Battery Performance and Cost

BEV – Battery electric vehicle

BEV250 – Battery electric vehicle w/ a target 250-mile range

BEV300 – Battery electric vehicle w/ a target 300-mile range

BMS – Battery management system

CAM – Cathode active material

CM – Critical mineral 45X tax credit

EAM – Electrode active material 45X tax credit

EPA – Environmental Protection Agency

GSA – General, sales, and administration

HEV – Hybrid electric vehicle

IRA – Inflation Reduction Act

IRS – Internal Revenue Service

LD – Light duty

LFP – Lithium iron phosphate ($LiFePO_4$)

LMNO – Lithium manganese nickel oxide ($LiMn_{1.5}Ni_{0.5}O_2$)

MHD – Medium/heavy duty

MY – Model year

NHTSA – National Highway Traffic Safety Administration

Ni/Mn – Nickel and manganese containing cathodes

NMC622 – Lithium nickel manganese cobalt oxide ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$)

NMC811 – Lithium nickel manganese cobalt oxide ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$)

NMC95 – Lithium nickel manganese cobalt oxide ($LiNi_{0.95}Mn_{0.025}Co_{0.025}O_2$)

NREL – National Renewable Energy Laboratory

PHEV – Plug-in hybrid electric vehicle

VO – Variable overhead

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Appendix

A1. Tabulated Results

The table below provides the tabulated results for the BatPaC simulations run using the input parameters given in Tables 1-12. These results are shown in graphical form in Figures 1 to 5.

Table 18. Pack Cost ($/kWh) from BatPaC simulations

kWh / kW	Vehicle	Chem.	2023	2026	2030	2035
1.2 / 48	HEV	Ni/Mn	567.08	553.61	537.05	453.50
1.8 / 70	HEV	Ni/Mn	430.11	417.92	402.74	335.48
12 / 100	PHEV Compact (Ni/Mn)	Ni/Mn	202.01	187.11	174.15	149.41
12 / 100	PHEV Compact (LFP)	LFP	196.44	174.80	164.49	162.30
18 / 150	PHEV Midsize (Ni/Mn)	Ni/Mn	173.12	157.19	147.99	122.74
18 / 150	PHEV Midsize (LFP)	LFP	166.99	147.22	134.01	132.61
24 / 200	PHEV Midsize SUV (Ni/Mn)	Ni/Mn	159.76	143.88	133.05	111.08
24 / 200	PHEV Midsize SUV (LFP)	LFP	150.03	133.65	121.72	120.56
40 / 250	PHEV Pickup (Ni/Mn)	Ni/Mn	144.19	129.22	113.76	92.03
40 / 250	PHEV Pickup (LFP)	LFP	136.20	112.51	100.79	98.62
65 / 125	BEV250 Compact	Ni/Mn	140.55	117.69	102.63	81.44
65 / 125	BEV250 Compact	LFP	131.59	104.68	87.58	78.84
75 / 165	BEV250 Midsize	Ni/Mn	135.25	116.89	101.49	79.49
75 / 165	BEV250 Midsize	LFP	126.59	102.18	86.64	78.27
80 / 130	BEV300 Compact	Ni/Mn	134.17	116.50	101.86	78.62
90 / 200	BEV250 Midsize SUV, BEV300 Midsize	Ni/Mn	133.28	116.28	100.04	78.36
90 / 200	BEV250 Midsize SUV	LFP	125.46	101.09	86.17	77.63
105 / 260	BEV250 Pickup	Ni/Mn	132.54	114.51	99.13	77.63
105 / 260	BEV250 Pickup	LFP	123.73	101.81	85.33	77.21
110 / 210	BEV300 Midsize SUV	Ni/Mn	132.13	114.21	100.10	76.95
130 / 270	BEV300 Pickup	Ni/Mn	130.99	113.27	99.64	76.25
190 / 380	BEV MHD	Ni/Mn	130.76	113.78	97.79	76.69
190 / 380	BEV MHD	LFP	122.29	98.92	83.40	77.19
220 / 440	BEV MHD	Ni/Mn	128.99	112.82	97.63	76.16
220 / 440	BEV MHD	LFP	121.35	98.15	83.07	76.90
250 / 500	BEV MHD	Ni/Mn	127.61	112.42	96.52	76.35
250 / 500	BEV MHD	LFP	120.91	97.56	82.73	76.62

A2. Selected Cost Breakdowns

This section contains cost breakdowns for several selected packs. The assumptions that go into the baseline cost calculations are given in Table 19. Further details can be found in the BatPaC manual and the latest version of BatPaC (Knehr K. W., Kubal, Nelson, & Ahmed, 2022).

Table 19. Description of baseline cost calculations.

Cost Component	Assumptions
Materials	Actives, separators, electrolyte, etc.
Purchased Items	Terminals, connectors, packaging, etc.
BMS	Battery management system (BMS)
Energy	$0.05/kWh
Depreciation	10-year lifetime for process equipment, 15 years for building equipment, 20 for building and land
Labor-related	$25/hr. × (1.4 for VO) × (1.25 for GSA)
Other Variable Overhead (VO)	2% of fixed capital investment
Other General, Sales, and Administration (GSA)	0.75% of fixed capital investment
Research & Development (R&D)	35% of depreciation
Financing	0.75% of total capital investment
Profits	5% of total capital investment
Warranty	5.6% of total pack cost

A2.1. Selected HEV Cost Breakdown

Table 20. Cost breakdown for the 1.8 kWh HEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	107.6	100.9	90.6	63.7	25.0%	24.1%	22.5%	19.0%
Purchased Items	147.6	146.6	145.8	125.9	34.3%	35.1%	36.2%	37.5%
BMS	60.7	60.7	60.7	55.2	14.1%	14.5%	15.1%	16.5%
Energy	4.3	4.1	3.9	3.4	1.0%	1.0%	1.0%	1.0%
Depreciation	26.1	25.0	24.1	20.7	6.1%	6.0%	6.0%	6.2%
Labor-related	14.6	13.8	13.2	11.7	3.4%	3.3%	3.3%	3.5%
Other Variable Overhead	7.4	7.1	6.9	5.9	1.7%	1.7%	1.7%	1.8%
Other GSA	4.6	4.4	4.3	3.7	1.1%	1.1%	1.1%	1.1%
R&D	9.1	8.8	8.4	7.2	2.1%	2.1%	2.1%	2.2%
Financing	3.3	3.2	3.1	2.6	0.8%	0.8%	0.8%	0.8%
Profits	22.0	21.2	20.4	17.5	5.1%	5.1%	5.1%	5.2%
Warranty	22.8	22.2	21.4	17.8	5.3%	5.3%	5.3%	5.3%
Total	430.1	417.9	402.7	335.5	100.0%	100.0%	100.0%	100.0%

A2.2. Selected PHEV Cost Breakdowns

Table 21. Cost breakdown for the high performance (Ni/Mn) 24 kWh PHEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	80.7	72.1	64.0	47.5	50.5%	50.1%	48.1%	42.8%
Purchased Items	23.8	21.7	21.2	19.4	14.9%	15.1%	16.0%	17.5%
BMS	17.9	17.0	16.5	15.9	11.2%	11.8%	12.4%	14.3%
Energy	1.8	1.6	1.6	1.5	1.1%	1.1%	1.2%	1.4%
Depreciation	7.8	7.0	6.8	6.3	4.9%	4.9%	5.1%	5.7%
Labor-related	5.3	4.2	3.9	3.6	3.3%	2.9%	2.9%	3.2%
Other Variable Overhead	2.2	1.9	1.9	1.7	1.3%	1.3%	1.4%	1.6%
Other GSA	1.3	1.2	1.2	1.1	0.8%	0.8%	0.9%	1.0%
R&D	2.7	2.5	2.4	2.2	1.7%	1.7%	1.8%	2.0%
Financing	1.0	0.9	0.9	0.8	0.6%	0.6%	0.7%	0.7%
Profits	6.7	6.0	5.8	5.2	4.2%	4.2%	4.3%	4.7%
Warranty	8.5	7.6	7.1	5.9	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*159.8*	*143.9*	*133.0*	*111.1*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 22. Breakdown of materials costs in high performance (Ni/Mn) 24 kWh PHEV pack.

	$/kWh				% of total material cost			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Cathode Active Materials	54.39	51.54	44.33	29.96	67.4%	71.5%	69.3%	63.1%
Anode Active Materials	10.54	7.63	5.82	3.97	13.1%	10.6%	9.1%	8.4%
Positive Current Collector	0.83	0.67	0.80	0.76	1.0%	0.9%	1.3%	1.6%
Negative Current Collector	5.23	4.24	5.05	4.81	6.5%	5.9%	7.9%	10.1%
Separators	3.56	2.88	3.43	3.29	4.4%	4.0%	5.4%	6.9%
Electrolyte	3.64	2.91	2.52	2.33	4.5%	4.0%	3.9%	4.9%
Carbon and Binder	2.52	2.21	2.02	2.38	3.1%	3.1%	3.2%	5.0%
Total of Materials Only Costs	*80.7*	*72.1*	*64.0*	*47.5*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 23. Cost breakdown for the low cost (LFP) 24 kWh PHEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	67.2	55.6	47.6	46.6	44.8%	41.6%	39.1%	38.6%
Purchased Items	23.0	24.0	23.6	23.6	15.3%	18.0%	19.4%	19.6%
BMS	19.0	17.7	17.2	17.2	12.6%	13.3%	14.1%	14.3%
Energy	2.1	1.9	1.8	1.8	1.4%	1.4%	1.4%	1.5%
Depreciation	9.1	8.2	7.6	7.6	6.0%	6.1%	6.3%	6.3%
Labor-related	6.0	4.9	4.2	4.2	4.0%	3.7%	3.5%	3.5%
Other Variable Overhead	2.5	2.3	2.1	2.1	1.7%	1.7%	1.7%	1.7%
Other GSA	1.6	1.4	1.3	1.3	1.0%	1.1%	1.1%	1.1%
R&D	3.2	2.9	2.7	2.7	2.1%	2.1%	2.2%	2.2%
Financing	1.1	1.0	0.9	0.9	0.7%	0.8%	0.8%	0.8%
Profits	7.4	6.7	6.2	6.2	5.0%	5.0%	5.1%	5.1%
Warranty	8.0	7.1	6.5	6.4	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*150.0*	*133.6*	*121.7*	*120.6*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 24. Breakdown of materials costs in low cost (LFP) 24 kWh PHEV pack.

	$/kWh				% of total material cost			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Cathode Active Materials	29.95	25.74	21.70	20.62	44.6%	46.3%	45.5%	44.3%
Anode Active Materials	11.65	8.35	7.30	7.30	17.3%	15.0%	15.3%	15.7%
Positive Current Collector	1.45	1.18	0.97	0.97	2.2%	2.1%	2.0%	2.1%
Negative Current Collector	9.11	7.43	6.10	6.10	13.6%	13.4%	12.8%	13.1%
Separators	6.30	5.11	4.18	4.18	9.4%	9.2%	8.8%	9.0%
Electrolyte	5.35	4.55	4.29	4.29	8.0%	8.2%	9.0%	9.2%
Carbon and Binder	3.37	3.21	3.11	3.11	5.0%	5.8%	6.5%	6.7%
Total of Materials Only Costs	*67.2*	*55.6*	*47.6*	*46.6*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

A2.3. Selected Light Duty (LD) BEV Cost Breakdowns

Table 25. Cost breakdown for the high performance (Ni/Mn) 75 kWh BEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	81.0	72.0	61.2	44.7	59.9%	61.6%	60.3%	56.2%
Purchased Items	15.2	11.6	10.6	8.8	11.2%	9.9%	10.4%	11.1%
BMS	5.3	5.1	4.9	4.5	4.0%	4.3%	4.8%	5.7%
Energy	1.7	1.5	1.4	1.3	1.3%	1.3%	1.4%	1.7%
Depreciation	7.5	6.3	5.6	5.0	5.6%	5.4%	5.5%	6.3%
Labor-related	4.2	3.2	2.7	2.3	3.1%	2.7%	2.6%	2.9%
Other Variable Overhead	2.1	1.7	1.5	1.4	1.5%	1.5%	1.5%	1.7%
Other GSA	1.3	1.1	1.0	0.9	0.9%	0.9%	0.9%	1.1%
R&D	2.6	2.2	2.0	1.7	1.9%	1.9%	1.9%	2.2%
Financing	0.9	0.8	0.7	0.6	0.7%	0.7%	0.7%	0.8%
Profits	6.2	5.2	4.6	4.0	4.6%	4.5%	4.6%	5.1%
Warranty	7.2	6.2	5.4	4.2	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*135.3*	*116.9*	*101.5*	*79.5*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 26. Breakdown of materials costs in high performance (Ni/Mn) 75 kWh BEV pack.

	$/kWh				% of total material cost			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Cathode Active Materials	54.38	51.58	44.57	30.15	67.2%	71.6%	72.8%	67.5%
Anode Active Materials	10.59	7.69	5.88	4.00	13.1%	10.7%	9.6%	9.0%
Positive Current Collector	0.85	0.66	0.55	0.50	1.1%	0.9%	0.9%	1.1%
Negative Current Collector	5.39	4.17	3.48	3.20	6.7%	5.8%	5.7%	7.2%
Separators	3.58	2.83	2.36	2.25	4.4%	3.9%	3.9%	5.0%
Electrolyte	3.65	2.91	2.37	2.18	4.5%	4.0%	3.9%	4.9%
Carbon and Binder	2.52	2.22	2.03	2.39	3.1%	3.1%	3.3%	5.4%
Total of Materials Only Costs	*81.0*	*72.0*	*61.2*	*44.7*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 27. Cost breakdown for the low cost (LFP) 75 kWh BEV pack.

	$/kWh				**% of pack total**			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	67.6	55.5	47.2	44.5	53.4%	54.4%	54.4%	56.9%
Purchased Items	16.5	11.6	9.7	8.9	13.0%	11.4%	11.2%	11.4%
BMS	5.5	5.2	4.9	2.0	4.3%	5.1%	5.6%	2.6%
Energy	2.0	1.7	1.6	1.5	1.6%	1.7%	1.8%	1.9%
Depreciation	8.6	7.0	5.8	5.3	6.8%	6.8%	6.7%	6.8%
Labor-related	5.0	3.7	3.0	2.7	4.0%	3.7%	3.4%	3.4%
Other Variable Overhead	2.3	1.9	1.6	1.5	1.9%	1.9%	1.8%	1.9%
Other GSA	1.5	1.2	1.0	0.9	1.2%	1.2%	1.1%	1.2%
R&D	3.0	2.4	2.0	1.9	2.4%	2.4%	2.3%	2.4%
Financing	1.0	0.8	0.7	0.6	0.8%	0.8%	0.8%	0.8%
Profits	6.9	5.6	4.6	4.2	5.4%	5.4%	5.4%	5.4%
Warranty	6.7	5.4	4.6	4.2	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*126.6*	*102.2*	*86.6*	*78.3*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 28. Breakdown of materials costs in low cost (LFP) 75 kWh BEV pack.

	$/kWh				**% of total material cost**			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Cathode Active Materials	29.95	25.76	21.75	20.78	44.3%	46.4%	46.1%	46.7%
Anode Active Materials	11.70	8.38	7.29	7.33	17.3%	15.1%	15.5%	16.5%
Positive Current Collector	1.49	1.18	0.92	0.77	2.2%	2.1%	2.0%	1.7%
Negative Current Collector	9.36	7.38	5.78	4.87	13.9%	13.3%	12.3%	10.9%
Separators	6.33	5.12	4.04	3.43	9.4%	9.2%	8.6%	7.7%
Electrolyte	5.36	4.55	4.27	4.19	7.9%	8.2%	9.0%	9.4%
Carbon and Binder	3.37	3.21	3.12	3.14	5.0%	5.8%	6.6%	7.0%
Total of Materials Only Costs	*67.6*	*55.5*	*47.2*	*44.5*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

A2.4. Selected Medium-Heavy Duty (MHD) BEV Cost Breakdowns

Table 29. Cost breakdown for the high performance (Ni/Mn) 220 kWh BEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	81.0	72.0	61.2	44.7	62.8%	63.8%	62.7%	58.7%
Purchased Items	12.9	10.5	9.0	7.7	10.0%	9.3%	9.2%	10.1%
BMS	2.6	2.5	2.9	2.7	2.0%	2.2%	3.0%	3.5%
Energy	1.7	1.5	1.4	1.3	1.3%	1.3%	1.4%	1.8%
Depreciation	7.2	6.2	5.5	4.9	5.6%	5.5%	5.7%	6.5%
Labor-related	4.2	3.3	2.8	2.4	3.2%	2.9%	2.8%	3.2%
Other Variable Overhead	2.0	1.7	1.5	1.3	1.5%	1.5%	1.5%	1.8%
Other GSA	1.2	1.1	0.9	0.8	1.0%	0.9%	1.0%	1.1%
R&D	2.5	2.2	1.9	1.7	2.0%	1.9%	2.0%	2.3%
Financing	0.9	0.8	0.7	0.6	0.7%	0.7%	0.7%	0.8%
Profits	6.0	5.1	4.5	4.0	4.6%	4.6%	4.7%	5.2%
Warranty	6.8	6.0	5.2	4.0	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*129.0*	*112.8*	*97.6*	*76.2*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 30. Cost breakdown for the low cost (LFP) 220 kWh BEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	67.6	55.5	47.2	44.5	55.7%	56.6%	56.8%	57.9%
Purchased Items	14.7	10.4	8.4	7.9	12.2%	10.6%	10.1%	10.3%
BMS	2.7	3.1	2.9	2.0	2.2%	3.1%	3.5%	2.6%
Energy	2.0	1.7	1.6	1.5	1.7%	1.8%	1.9%	1.9%
Depreciation	8.4	6.8	5.8	5.3	6.9%	6.9%	6.9%	6.9%
Labor-related	5.1	3.9	3.1	2.7	4.2%	3.9%	3.7%	3.5%
Other Variable Overhead (VO)	2.3	1.8	1.6	1.4	1.9%	1.9%	1.9%	1.9%
Other GSA	1.4	1.2	1.0	0.9	1.2%	1.2%	1.2%	1.2%
R&D	2.9	2.4	2.0	1.8	2.4%	2.4%	2.4%	2.4%
Financing	1.0	0.8	0.7	0.6	0.8%	0.8%	0.8%	0.8%
Profits	6.7	5.4	4.6	4.2	5.5%	5.5%	5.5%	5.4%
Warranty	6.4	5.2	4.4	4.1	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*121.3*	*98.2*	*83.1*	*76.9*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

A3. Specific Energy (Wh/kg) Results and Correlations

Correlations were also developed for the specific energy (Wh/kg) of the packs simulated in this work. The correlations had the following functional form:

$$\dot{E}_{pack} = 1000\left[A + \frac{B}{x^C} - D(y-2023)e^{E(y-2023)}\right]^{-1} \quad \text{(A1)}$$

where *x* is the pack energy in kWh and *y* is the model year. A, B, C, D, and E are constants given in Table 31. The agreement between the equation and the data is shown in Figure 17.

Table 31. Constants for Wh/kg correlation given in Equation A1.

Constant in Eq. A1	High Performance (Ni/Mn) (HEV, ≤5 kWh)	High Performance (Ni/Mn) (PHEV, EV)	Low Cost (LFP) (PHEV, EV)
A	5.220	5.266	6.602
B	13.398	20.60	25.62
C	0.941	1.129	1.016
D	0.359	0.3537	0.3597
E	-0.081	-0.08158	-0.09757

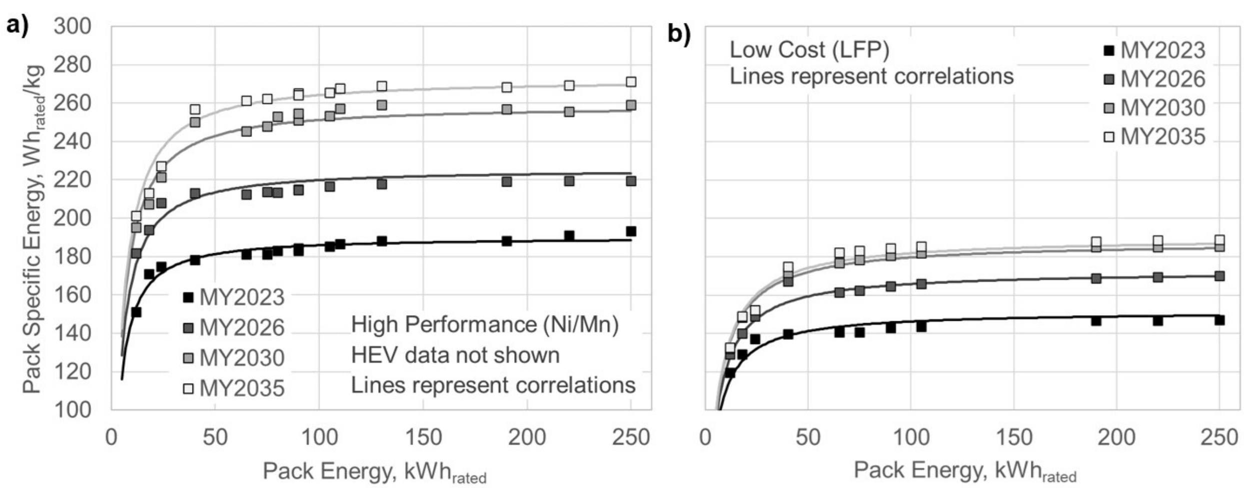

Figure 17. Comparison of specific energy (Wh/kg) between full BatPaC simulations (symbols) and correlations in equation A1 (lines) for a) high performance (Ni/Mn) and b) low cost (LFP) packs.

A4. Energy Density (Wh/L) Results and Correlations

Correlations were also developed for the energy density (Wh/L) of the packs simulated in this work. The correlations had the following functional form:

$$\hat{E}_{pack} = 1000\left[A + \frac{B}{x^C} - D(y-2023)e^{E(y-2023)}\right]^{-1} \quad \text{(A2)}$$

where x is the pack energy in kWh and y is the model year. A, B, C, D, and E are constants given in Table 32. The agreement between the equation and the data is shown in Figure 18. The slight underpredictions for larger packs in MY2035 result in a maximum error of 7% at 220 kWh for the Ni/Mn packs.

Table 32. Constants for Wh/L correlation given in Equation A2.

Constant in Eq. A2	High Performance (Ni/Mn) (HEV, ≤5 kWh)	High Performance (Ni/Mn) (PHEV, EV)	Low Cost (LFP) (PHEV, EV)
A	2.930	3.057	3.844
B	12.616	130.4	54.03
C	0.967	1.888	1.402
D	0.179	0.1902	0.2608
E	-0.04298	-0.05076	-0.09607

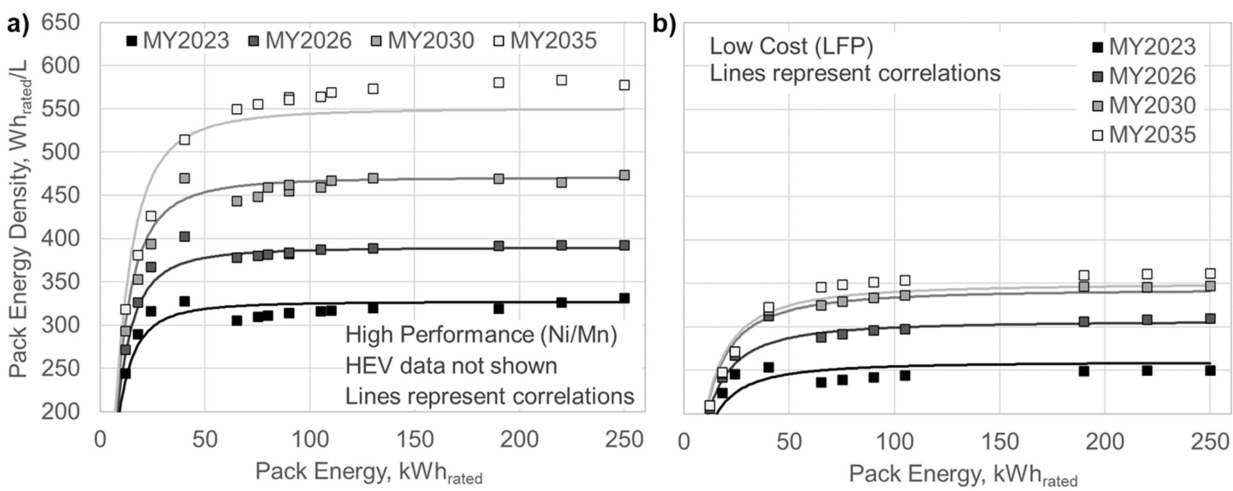

Figure 18. Comparison of energy density (Wh/L) between full BatPaC simulations (symbols) and correlations in equation A2 (lines) for a) high performance (Ni/Mn) and b) low cost (LFP) packs.

A5. Details for Estimating the Volume Averaged Cost of PHEV and BEV Packs in the U.S.

The volume averaged pack cost of PHEVs and BEVs was determined by first segmenting the U.S. vehicle fleet into the twenty-four vehicles shown in Table 33. The volume averaged cost of packs in the U.S. fleet was estimated each year using Equation (2) in the main text, which is repeated here as follows:

$$C_{fleet} = \frac{\sum_{v=1}^{v=24} C_v N_v}{\sum_{v=1}^{v=24} N_v} \quad (2)$$

where C_{fleet} is the volume averaged cost in $/kWh, C_v is the cost of each vehicle, *v*, in $/kWh, and N_v is the number of vehicles, *v*, sold each year. The summations are evaluated for vehicles, *v*, from 1 to 24 to represent the twenty-four vehicles listed in Table 33. The determination of N_v and C_v is explained in detail in the remainder of this section.

Table 33. Vehicles used to segment U.S. fleet in volume average pack cost calculation.

Vehicle, *v*	Type	Class	Chemistry
1	LD BEV	Compact	Ni/Mn
2	LD BEV	Midsize	Ni/Mn
3	LD BEV	Small SUV	Ni/Mn
4	LD BEV	Midsize SUV	Ni/Mn
5	LD BEV	Pickup	Ni/Mn
6	MHD BEV	MHD	Ni/Mn
7	LD BEV	Compact	LFP
8	LD BEV	Midsize	LFP
9	LD BEV	Small SUV	LFP
10	LD BEV	Midsize SUV	LFP
11	LD BEV	Pickup	LFP
12	MHD BEV	MHD	LFP
13	LD PHEV	Compact	Ni/Mn
14	LD PHEV	Midsize	Ni/Mn
15	LD PHEV	Small SUV	Ni/Mn
16	LD PHEV	Midsize SUV	Ni/Mn
17	LD PHEV	Pickup	Ni/Mn
18	MHD PHEV	MHD	Ni/Mn
19	LD PHEV	Compact	LFP
20	LD PHEV	Midsize	LFP
21	LD PHEV	Small SUV	LFP
22	LD PHEV	Midsize SUV	LFP
23	LD PHEV	Pickup	LFP
24	MHD PHEV	MHD	LFP

A5.1. Pack Sales for Each Year (N_v)

The number of vehicles sold each year (N_v) was estimated for each vehicle type based on the workflow shown in Figure 19.

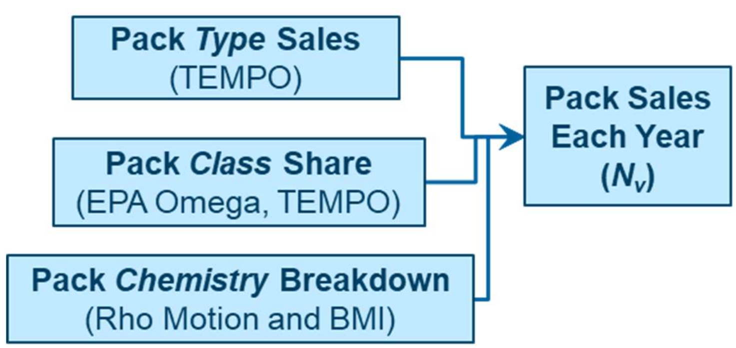

Figure 19. Workflow used to determine pack sales per year for each vehicle (N_v).

First, the total sales of PHEVs and BEVs was estimated for each year using the NREL TEMPO model (Muratori, et al., Forthcoming). Then, the EPA OMEGA model was used to estimate the percent breakdown of each class for each year for light duty vehicles (United States Environmental Protection Agency, 2023). This breakdown is shown in Figure 20a. The same breakdown was assumed for both LD PHEVs and LD BEVs. The number of MHD vehicles was estimated using the TEMPO model. Next, the fraction of packs using LFP or Ni/Mn chemistries was estimated using forecasts from Rho Motion and Benchmark Minerals Intelligence data (Benchmark Minerals Intelligence, 2023; Rho Motion, 2023). The Ni/Mn chemistry was assumed to include NCA cells due to similarities in cost. The estimated fraction is given in Figure 20b. The same fraction of LFP and Ni/Mn packs was assumed for all vehicle types (PHEV or BEV) and classes (Compact, Midsize, Small SUV, Midsize SUV, Pickup, and MHD). These three sets of information (type, class share, and chemistry breakdown) were used to determine N_v for each vehicle and each model year. Figure 21 shows the results for all twenty-four vehicles listed in Table 33.

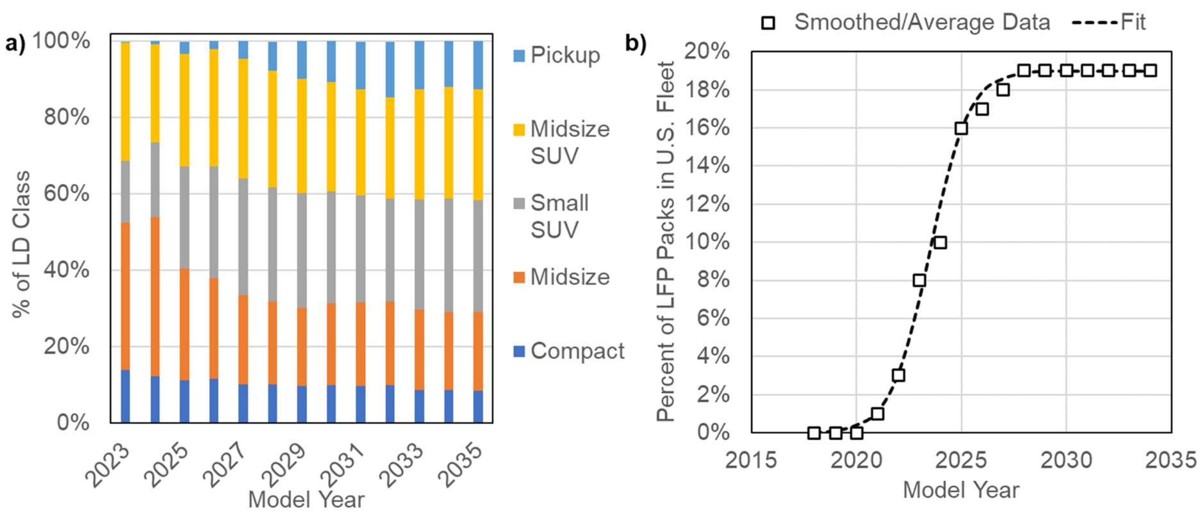

Figure 20. a) Estimated percent breakdown of vehicles based on class [data courtesy of Charbel Mansour, Paul Phillips, Ehsan Islam, and Aymeric Rousseau (Argonne)]. b) Estimated percentage of LFP packs in U.S. fleet [data courtesy of Jessica Suda (NHTSA) and Mike Safoutin (EPA)].

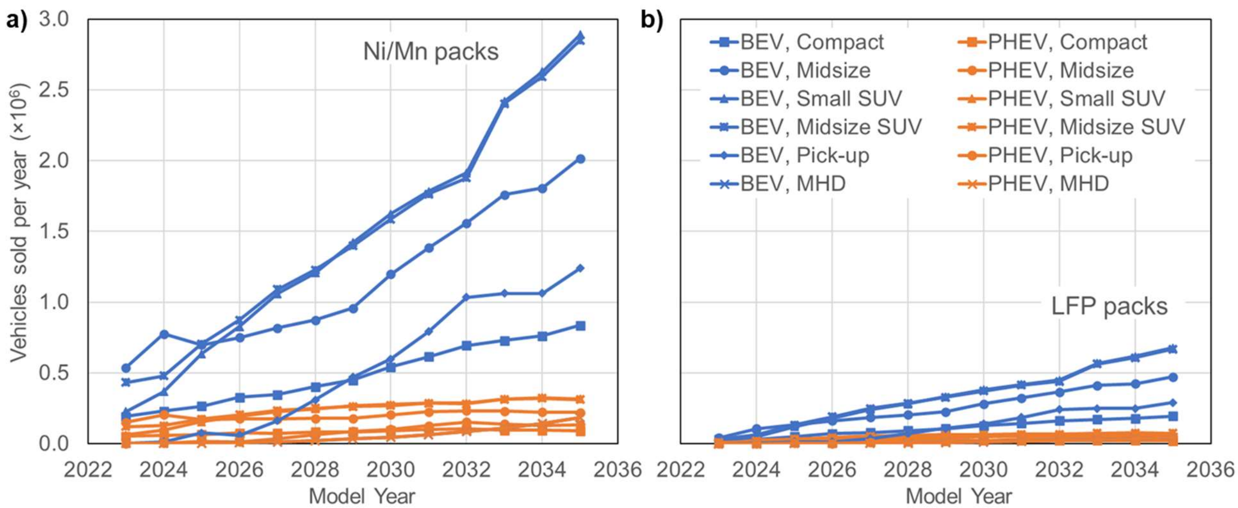

Figure 21. Number of packs sold per year (N_v) for each of the 24 vehicles in Table 33 organized into a) Ni/Mn and b) LFP packs [total packs per year courtesy of Catherine Ledna (NREL)].

A5.2. Pack Cost for Each Year (C_v)

The cost of each vehicle pack for each model year (C_v) was determined using the workflow shown in Figure 22.

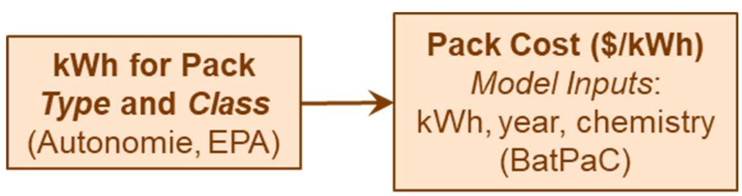

Figure 22. Workflow used to determine pack cost (C_v).

First, a representative pack energy, in kWh, was estimated for each vehicle and each year using the Argonne Autonomie model for LD vehicles and the EPA OMEGA model for MHD vehicles (see Figure 23) (Islam, et al., 2023; United States Environmental Protection Agency, 2023). The same values were used for both Ni/Mn and LFP packs. The pack energy and model year were then used as inputs into the correlations in Equation (1) in the main text to calculate the pack cost. The results of the calculations are shown in Figure 24. The cost values (C_v) in Figure 24 were combined with the sales values (N_v) in Figure 21 to determine the volume weighted average using Equation (2). The results are shown in Figure 7 in the main text.

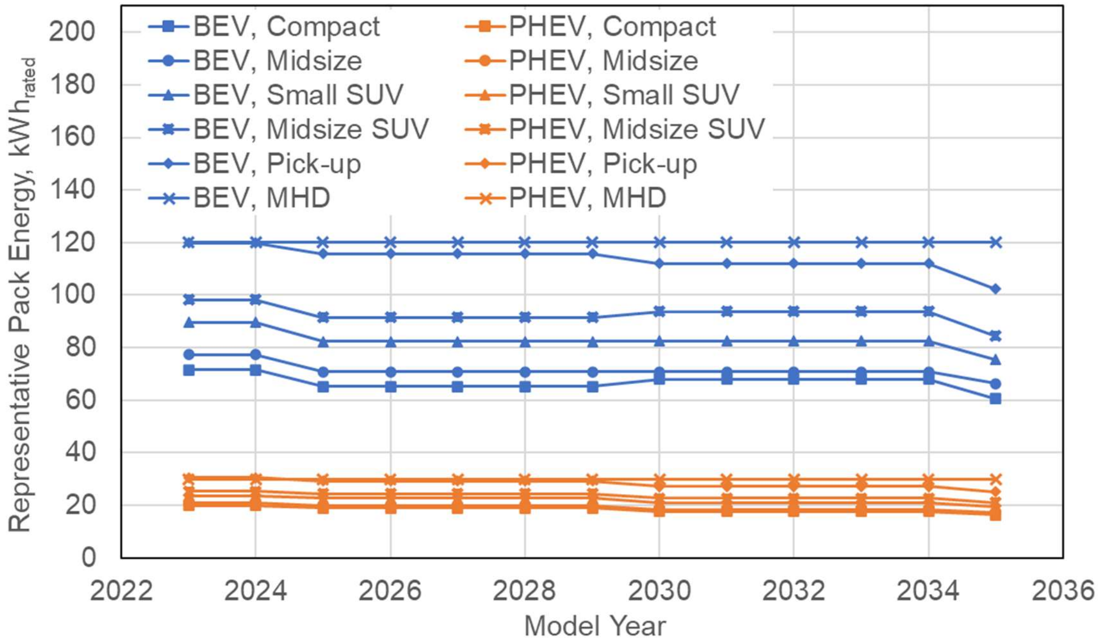

Figure 23. Representative pack energy used to estimate pack costs for all vehicles [data courtesy of Charbel Mansour, Paul Phillips, Ehsan Islam, and Aymeric Rousseau (Argonne National Laboratory)].

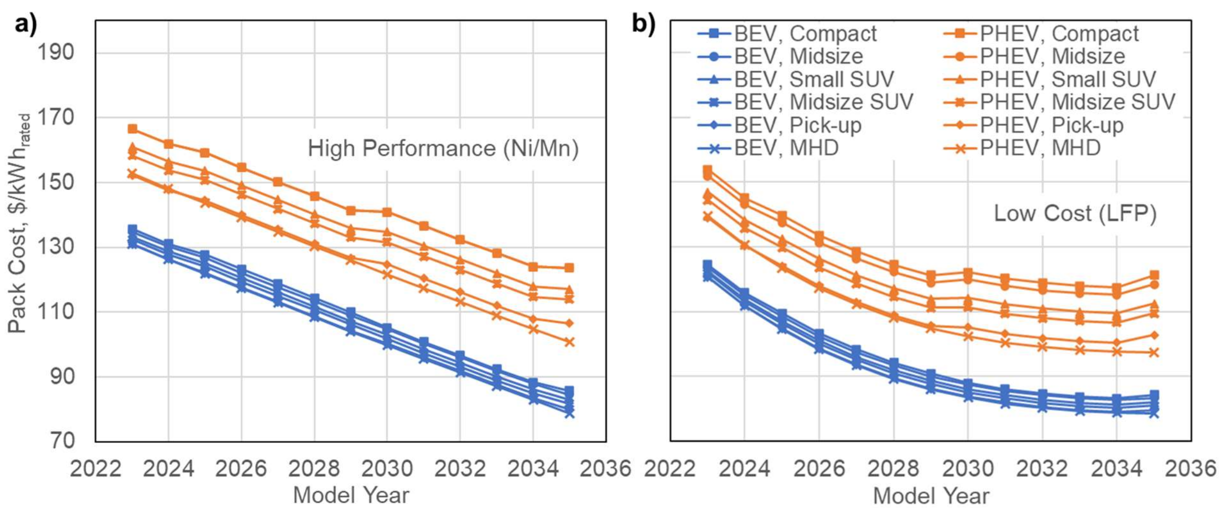

Figure 24. Pack costs (C_v) for a) Ni/Mn and b) LFP packs used in calculation of volume average cost curve.

A6. Details of 45X Analysis

The following tables were used for estimating the impact of the 45X tax credit on pack cost. The tax credits were determined by first estimating the $/kWh contribution of each component to the pack (Table 34 to Table 36). Next, tax credits were applied at each component based on the 45X credit (Table 37 and Table 38) and estimates for the eligibility of components based on announced production capacities (Table 39). The results of the analysis can be found in (Table 40 to Table 42). Tax credits were calculated for the same three vehicle categories used to generate the correlations in Equation 1 in the main text – *i.e.,* Ni/Mn HEV, Ni/Mn PHEV/BEV, and LFP PHEV/BEV. A comparison of tax credit calculations for multiple vehicles within these categories resulted in very small differences within a given category (data now shown). The HEV breakdowns (Table 34) are based on the 1.8-kWh pack. The Ni/Mn (Table 35) and LFP (Table 36) PHEV and BEV breakdowns are based on a 75-kWh pack.

Table 34. Mass (kg/kWh) and cost ($/kg) breakdowns for components in Ni/Mn HEV packs. Data is generated from BatPaC and used in 45X calculations. Values are interpolated for model years between these cases.

	Mass Breakdown (kg/kWh)				**Cost Breakdowns ($/kg)**			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
CAM[a]	1.31	1.18	1.09	1.37	31.90	34.00	31.30	17.30
AAM[a]	0.84	0.80	0.79	0.66	10.00	9.00	8.00	8.00
Separator	0.17	0.17	0.17	0.11	70.60	70.60	70.60	70.60
Electrolyte	0.74	0.70	0.68	0.60	8.33	8.33	8.33	8.33
Copper Foil	1.81	1.81	1.80	1.18	8.90	8.90	8.90	8.90
Aluminum Foil	0.68	0.68	0.67	0.44	3.70	3.70	3.70	3.70
Lithium[b]	0.10	0.09	0.08	0.06	90.78	186.00	144.00	136.50
Nickel[c]	0.48	0.57	0.62	0.22	20.09	19.19	20.53	21.42
Cobalt[c]	0.16	0.07	0.02	0.00	23.78	44.71	64.69	75.15
Manganese[c]	0.15	0.07	0.02	0.62	3.07	3.07	3.07	3.07

[a]CAM: cathode active material, AAM: anode active material, [b]metal contained in hydroxide, carbonate, or electrolyte salt (electrolyte ~2% of total lithium), [c]metal contained in sulphate.

Table 35. Mass (kg/kWh) and cost ($/kg) breakdowns for components in Ni/Mn PHEV & BEV packs. Data is generated from BatPaC and used in 45X calculations. Values are interpolated for model years between these cases.

	Mass Breakdown (kg/kWh)				**Cost Breakdowns ($/kg)**			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
CAM[a]	1.42	1.30	1.24	1.54	31.90	34.00	31.30	17.30
AAM[a]	0.89	0.65	0.45	0.23	10.00	10.05	11.30	15.70
Separator	0.04	0.04	0.03	0.03	70.60	70.60	70.60	70.60
Electrolyte	0.39	0.31	0.26	0.20	8.33	8.33	8.33	8.33
Copper Foil	0.32	0.25	0.21	0.08	8.90	8.90	8.90	8.90
Aluminum Foil	0.14	0.11	0.09	0.09	3.70	3.70	3.70	3.70
Lithium[b]	0.10	0.09	0.09	0.06	90.78	186.00	144.00	136.50
Nickel[c]	0.52	0.63	0.71	0.25	20.09	19.19	20.53	21.42
Cobalt[c]	0.17	0.08	0.02	0.00	23.78	44.71	64.69	75.15
Manganese[c]	0.16	0.07	0.02	0.69	3.07	3.07	3.07	3.07

[a]CAM: cathode active material, AAM: anode active material, [b]metal contained in hydroxide, carbonate, or electrolyte salt (electrolyte ~2% of total lithium), [c]metal contained in sulphate.

Table 36. Mass (kg/kWh) and cost ($/kg) breakdowns for components in LFP PHEV & BEV packs. Data is generated from BatPaC and used in 45X calculations. Values are interpolated for model years between these cases.

	Mass Breakdown (kg/kWh)				**Cost Breakdowns ($/kg)**			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
CAM[a]	1.93	1.94	1.94	1.96	13.00	11.50	10.00	9.50
AAM[a]	0.98	0.72	0.72	0.72	10.00	9.00	8.00	8.00
Separator	0.08	0.07	0.05	0.05	70.60	70.60	70.60	70.60
Electrolyte	0.57	0.50	0.48	0.47	8.33	8.33	8.33	8.33
Copper Foil	0.55	0.45	0.36	0.30	8.90	8.90	8.90	8.90
Aluminum Foil	0.24	0.19	0.16	0.13	3.70	3.70	3.70	3.70
Lithium[b]	0.09	0.09	0.09	0.09	85.76	72.36	53.60	50.25
Iron[c]	0.68	0.69	0.69	0.69	5.02	5.02	5.02	5.02

[a]CAM: cathode active material, AAM: anode active material, [b]metal contained in hydroxide, carbonate, or electrolyte salt (electrolyte ~2% of total lithium), [c]metal contained in phosphate.

Table 37. 45X tax credits for modules, cells, and electrode active materials (EAM) [data estimated per definition proposed by IRS (Internal Revenue Service, 2023)].

	Modules ($/kWh)	Cells ($/kWh)	CAM[a] (%)	AAM[a] (%)	Separator (%)	Electrolyte (%)	Cu Foil (%)	Al Foil (%)	Li[b] (%)	Ni[b] (%)	Co[b] (%)	Mn[b] (%)	Fe[b] (%)
2023	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2024	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2025	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2026	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2027	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2028	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2029	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2030	7.5	26.25	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%
2031	5	17.5	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
2032	2.5	8.75	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
2033	0	0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2034	0	0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2035	0	0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

[a]CAM: cathode active material, AAM: anode active material, [b]metal salt/oxide used in battery

Table 38. 45X tax credits for critical minerals (CM) [data estimated per definitions proposed by IRS (Internal Revenue Service, 2023)]. Elements refer to lithium carbonate/hydroxide and nickel/cobalt/manganese sulfates.

	Lithium	Nickel	Cobalt	Manganese
2023	10%	10%	10%	10%
2024	10%	10%	10%	10%
2025	10%	10%	10%	10%
2026	10%	10%	10%	10%
2027	10%	10%	10%	10%
2028	10%	10%	10%	10%
2029	10%	10%	10%	10%
2030	10%	10%	10%	10%
2031	10%	10%	10%	10%
2032	10%	10%	10%	10%
2033	10%	10%	10%	10%
2034	10%	10%	10%	10%
2035	10%	10%	10%	10%

Table 39. Low-end market response of U.S. domestic supply chain. Calculated as share of U.S. demand met from November 2023 market announcements [data courtesy of David Gohlke, Tisi Barlock, and Jarod Kelly (Argonne)].

	Modules	Cells	CAM[a]	AAM[a]	Separator	Electrolyte	Cu Foil	Al Foil	Li[b]	Ni[c]	Co[c]	Mn[c]	Fe[c]
2023	99%	99%	31%	45%	52%	100%	100%	100%	6%	56%	36%	36%	31%
2024	100%	100%	67%	75%	47%	100%	100%	100%	3%	16%	27%	27%	67%
2025	100%	100%	60%	55%	79%	100%	100%	100%	28%	14%	19%	19%	60%
2026	100%	100%	55%	51%	83%	100%	100%	100%	51%	10%	16%	16%	55%
2027	100%	100%	38%	43%	55%	100%	100%	100%	49%	8%	29%	29%	38%
2028	100%	100%	32%	40%	44%	100%	100%	100%	70%	7%	39%	39%	32%
2029	100%	100%	27%	34%	35%	100%	100%	100%	66%	6%	36%	36%	27%
2030	100%	100%	26%	32%	32%	100%	100%	100%	81%	6%	34%	34%	26%
2031	100%	100%	24%	30%	30%	100%	100%	100%	74%	6%	31%	31%	24%
2032	97%	97%	22%	28%	28%	94%	100%	100%	67%	10%	28%	28%	22%
2033	100%	100%	24%	30%	29%	99%	100%	100%	61%	11%	28%	28%	24%
2034	98%	98%	23%	28%	28%	94%	100%	100%	55%	10%	26%	26%	23%
2035	98%	98%	23%	28%	28%	94%	100%	100%	56%	11%	27%	27%	23%

[a]CAM: cathode active material, AAM: anode active material, [b]metal contained in hydroxide or carbonate, [c]metal contained in sulphate or phosphate.

Table 40. Estimated tax credits ($/kWh) for Ni/Mn HEV packs. "Full" refers to full market response of domestic U.S. supply (packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market for packs that can be supplied domestically based on announcements as of November 2023.

	Modules		Cells		EAM[a]		CM[b]		Total	
	Full	**Low-end**	**Full**	**Low-end**	**Full**	**Low-end**	**Full**	**Low-end**	**Full**	**Low-end**
2023	10.0	9.9	35.0	34.5	8.7	4.8	2.3	0.7	56.0	49.9
2024	10.0	10.0	35.0	35.0	8.7	6.4	2.6	0.3	56.3	51.7
2025	10.0	10.0	35.0	35.0	8.6	6.3	2.9	0.6	56.5	51.9
2026	10.0	10.0	35.0	35.0	8.5	6.1	3.1	1.0	56.6	52.1
2027	10.0	10.0	35.0	35.0	8.3	4.9	3.0	0.9	56.3	50.9
2028	10.0	10.0	35.0	35.0	8.2	4.5	2.9	1.2	56.1	50.7
2029	10.0	10.0	35.0	35.0	8.1	4.1	2.7	1.0	55.8	50.1
2030	7.5	7.5	26.3	26.3	6.0	3.0	2.6	1.1	42.3	37.8
2031	5.0	5.0	17.5	17.5	3.8	1.8	2.4	0.9	28.7	25.3
2032	2.5	2.4	8.8	8.5	1.8	0.8	2.1	0.8	15.2	12.6
2033	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.7	1.9	0.7
2034	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.6	1.7	0.6
2035	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.5	1.4	0.5

[a]EAM: electrode active materials, [b]CM: critical materials.

Table 41. Estimated tax credits ($/kWh) for Ni/Mn PHEV and BEV packs. "Full" refers to full market response of domestic U.S. supply (packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market for packs that can be supplied domestically based on announcements as of November 2023.

	Modules		Cells		EAM[a]		CM[b]		Total	
	Full	Low-end	Full	Low-end	Full	Low-end	Full	Low-end	Full	Low-end
2023	10.0	9.9	35.0	34.5	6.4	2.6	2.4	0.8	53.8	47.8
2024	10.0	10.0	35.0	35.0	6.2	4.4	2.8	0.3	54.1	49.7
2025	10.0	10.0	35.0	35.0	6.0	3.9	3.1	0.7	54.2	49.5
2026	10.0	10.0	35.0	35.0	5.9	3.5	3.3	1.1	54.2	49.6
2027	10.0	10.0	35.0	35.0	5.7	2.6	3.2	1.0	53.9	48.6
2028	10.0	10.0	35.0	35.0	5.5	2.2	3.1	1.3	53.6	48.4
2029	10.0	10.0	35.0	35.0	5.3	1.8	3.0	1.1	53.3	47.9
2030	7.5	7.5	26.3	26.3	3.8	1.3	2.9	1.2	40.4	36.2
2031	5.0	5.0	17.5	17.5	2.4	0.8	2.6	1.0	27.5	24.3
2032	2.5	2.4	8.8	8.5	1.1	0.3	2.4	0.9	14.7	12.1
2033	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.8	2.1	0.8
2034	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.6	1.8	0.6
2035	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.6	1.6	0.6

[a]EAM: electrode active materials, [b]CM: critical materials.

Table 42. Estimated tax credits ($/kWh) for LFP PHEV and BEV packs. "Full" refers to full market response of domestic U.S. supply (packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market for packs that can be supplied domestically based on announcements as of November 2023.

	Modules		Cells		EAM[a]		CM[b]		Total	
	Full	Low-end	Full	Low-end	Full	Low-end	Full	Low-end	Full	Low-end
2023	10.0	9.9	35.0	34.5	5.1	2.6	1.1	0.2	51.2	47.1
2024	10.0	10.0	35.0	35.0	4.8	3.5	1.1	0.2	50.9	48.8
2025	10.0	10.0	35.0	35.0	4.5	3.1	1.0	0.4	50.5	48.5
2026	10.0	10.0	35.0	35.0	4.2	2.8	1.0	0.5	50.2	48.3
2027	10.0	10.0	35.0	35.0	4.1	2.2	0.9	0.4	50.0	47.6
2028	10.0	10.0	35.0	35.0	3.9	1.9	0.9	0.5	49.8	47.4
2029	10.0	10.0	35.0	35.0	3.8	1.7	0.9	0.4	49.7	47.1
2030	7.5	7.5	26.3	26.3	2.7	1.2	0.7	0.5	37.2	35.4
2031	5.0	5.0	17.5	17.5	1.8	0.8	0.6	0.4	25.0	23.6
2032	2.5	2.4	8.8	8.5	0.9	0.4	0.6	0.3	12.7	11.6
2033	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.5	0.3
2034	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.5	0.3
2035	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.3	0.4	0.3

[a]EAM: electrode active materials, [b]CM: critical materials.

A7. Raw Materials Prices

Table 43 provides the raw material price estimates used in the calculations (Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Intercalation, Ltd., 2023; Ballif, Haug, Boccard, Verlinden, & Hahn, 2022; Sanders, 2023). Table 44 provides the cathode active material (CAM) prices calculated from the raw materials. The prices include manufacturing costs and margin. The bold CAM prices refer to forecasted values used in the main study. The italicized values refer to the 2023 prices used in the sensitivity study. Table 45 provides the values for the anode active materials (AAM). Several of the 5% Si cases are bold because they are used in all LFP packs after 2026.

Table 43. Raw materials prices for each model year

		Price ($/kg)			
Precursor	**Purity**	**2023**	**2026**	**2030**	**2035**
$NiSO_4{\cdot}6H_2O$	battery grade, 22.4 wt.% Ni	4.5	4.3	4.6	4.8
$CoSO_4{\cdot}7H_2O$	battery grade, 20.5 wt.% Co	5	9.4	13.6	15.8
$MnSO_4{\cdot}H_2O$	battery grade, 32.5 wt.% Mn	1	1	1	1
Li_2CO_3	battery grade, 99.5% Li_2CO_3	34	29	22	20.75
Li_2CO_3	Industrial grade, 99% Li_2CO_3	32	27	20	18.75
$LiOH{\cdot}H_2O$	battery grade, 57.0% LiOH	36	31	24	22.75
Graphite	natural/synthetic blend	10	9	8	8
Silicon	engineered material	30	30	30	30

*Table 44. Cathode active material (CAM) prices used in simulations. ****bold***** indicates forecasted prices used in simulations. *italicized* indicates 2023 values used in sensitivity study.*

CAM	2023	2026	2030	2035
NMC622	***31.9***	32.2	32.3	33.4
NMC811	*35.5*	**34.0**	32.7	33.2
NMC95	*36.1*	33.5	**31.3**	31.4
LMNO	*20.5*	19.0	17.5	**17.3**
LFP	***13***	**11.5**	**10.0**	**9.5**

*Table 45. Anode active material (AAM) prices used in simulations. ****bold***** indicates forecasted prices used in simulations. *italicized* indicates 2023 values used in sensitivity study. The low cost (LFP) cells used 5% Si in 2026, 2030 and 2035.*

AAM	2023	2026	2030	2035
G	***10***	9.0	8.0	8.0
95% G, 5% Si	*11*	**10.1**	**9.1**	**9.1**
85% G, 15% Si	*13*	12.2	**11.3**	11.3
65% G, 35% Si	*17*	16.4	15.7	**15.7**

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