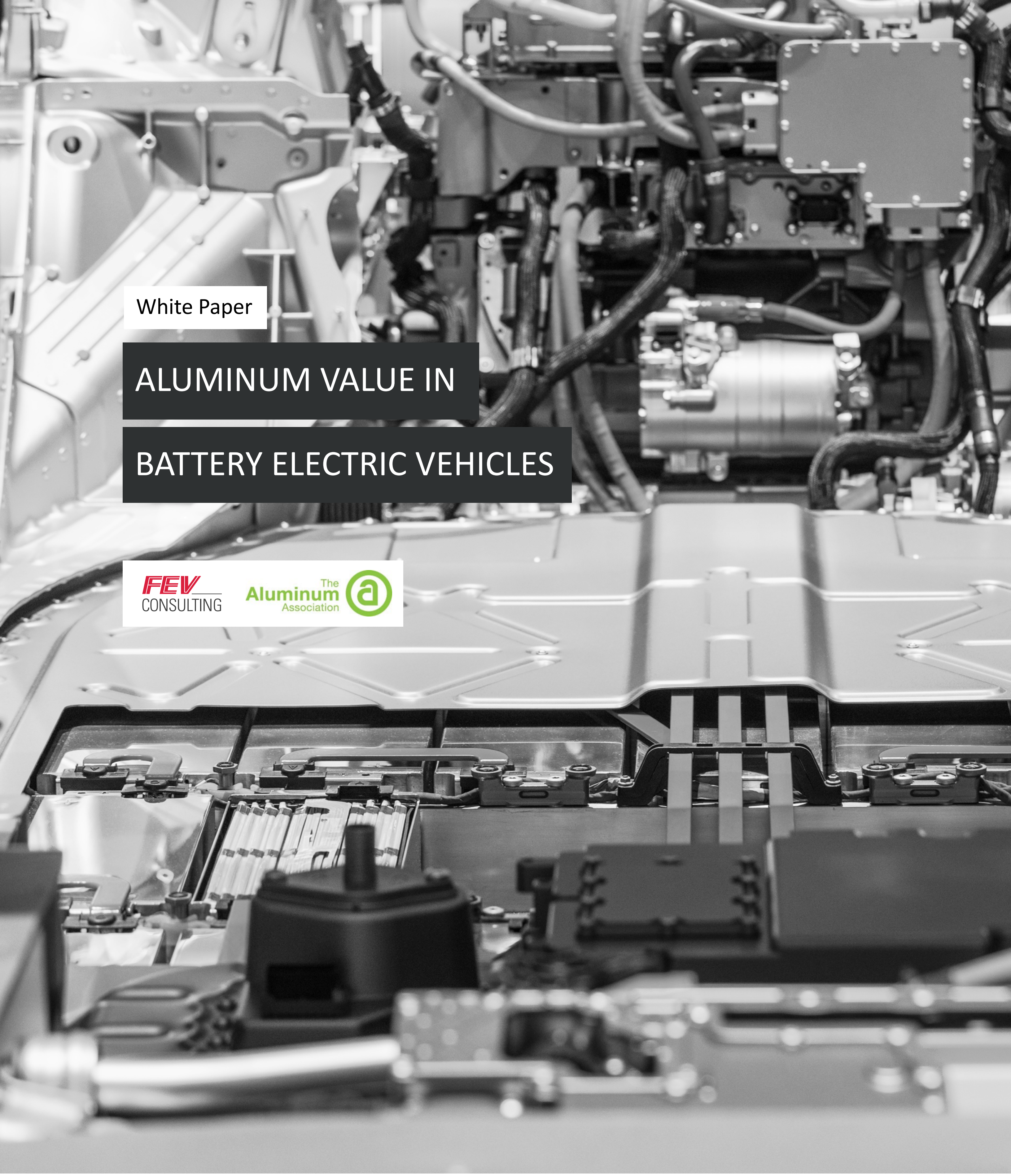

White Paper

ALUMINUM VALUE IN BATTERY ELECTRIC VEHICLES

FEV CONSULTING

The Aluminum Association

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Prepared for

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The Value of Aluminum Light Weighting in Battery Electric Vehicles

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ABSTRACT

FEV Consulting, Inc. conducted a study, funded by The Aluminum Association's Aluminum Transportation Group, to determine the impact of expected improvements in battery and electric powertrain cost and efficiency on the economic attractiveness of aluminum light weighting solutions. The study identified three vehicle classes, a small City vehicle, a midsize Family Crossover vehicle, and a large Pickup Truck, to represent a significant cross section of today's vehicles and considered current trends in aluminum weight reduction magnitude and cost, aluminum application, consumer BEV range and performance expectations, and battery and powertrain cost and efficiency to determine if aluminum solutions will remain viable throughout the current decade. The results of this study indicate that today's battery electric vehicles contain more aluminum than their internal combustion engine counterparts of similar size and mission, that aluminum content increases with increasing battery electric vehicle size and performance expectations, and that aluminum light weighting will continue to remain economically attractive as expected as battery and electric powertrain cost and efficiency improve over the current decade.

BACKGROUND

The value of light weighting with aluminum in internal combustion engine (ICE) vehicles is well understood. Substitution of heavier materials with lightweight aluminum provides fuel economy improvement that can, in many cases, be much more cost effective than powertrain improvements needed to attain a similar fuel economy improvement. Aluminum is now used widely in the construction of internal combustion powertrain vehicles, particularly in those which are larger and more luxury/performance-oriented where meeting fuel economy and emissions regulations is much more challenging.

The light weighting cost dynamics in battery electric vehicles (BEVs) are significantly different than those for ICE vehicles. BEVs carry gasoline-equivalent fuel economy ratings that are already significantly above those of all global governmental regulating agencies. Driving range, rather than emissions or fuel economy, often becomes the deciding factor for light weighting in BEVs. If the cost of reducing vehicle weight to achieve a target driving range is less than the cost of adding batteries for energy storage, light weighting will be preferred.

The decision to light weight BEVs is much more complicated than simply trading battery cost for light weighting cost. Adding batteries adds weight to BEVs, reducing their performance and requiring increases in the size and cost of the powertrain and suspension systems to maintain performance. Adding batteries takes up additional space in the vehicle, and this additional space may be limited or unavailable. The cost and storage density of automotive battery systems are continuously improving and the light weighting cost dynamics for BEVs of the future will be significantly different than those for BEVs of today. Finally, fuel economy and emissions regulations are often assessed on the manufacturer's whole fleet, meaning that equivalent fuel economy improvements made on BEVs could have profound impact on the need to improve fuel economy and emissions in other ICE vehicles in the manufacturer's fleet.

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The Aluminum Association therefore commissioned FEV Consulting, Inc. to conduct a study to better define how these complex dynamics affect the value of light weighting with aluminum in battery electric vehicles of today and in the future.

PROCEDURE

The study proceeded in three tasks.

Task 1 – Specify Three BEVs

FEV began their study by first defining three individual BEVs to represent the full range of vehicle types expected to enter the light vehicle parc in the coming decade. The vehicle types chosen include the following:

- City vehicle, a compact, 4-door hatchback sedan;
- Family Crossover vehicle, a mid-size 4-door hatchback CUV; and
- Pick-Up Truck, a full-size, full-frame 4-door pick-up.

Baseline (2020) materials compositions of main vehicle systems and components and performance measures for each of the three current reference vehicles were set independently by FEV based on their extensive testing and benchmarking of past and current vehicles, both ICE and BEV. Targets for 2025 and 2030 performance measures were established from trends observed by FEV in their past and current testing and benchmarking of light vehicles.

Baseline materials compositions were established from FEV internal benchmarking data. The City vehicle used data from the Hyundai Ioniq and Volkswagen ID.3 BEVs. The Family Crossover vehicle used data from the Ford Mustang Mach-E and Audi E-Tron. The Pickup Truck used data from the Ford F-150 (as a proxy for the F-150 Lightning) and Rivian R1T.

Key performance measures addressed for 2020, 2025, and 2030 vehicles include Vehicle Weight (lbs.), 0-60 MPH Acceleration Time (s), Top Speed (mph), Battery Capacity (kWh), E-Drive Range (mi), and Average Gasoline Equivalent Fuel Economy (MPGe).

Task 2 – Analyze Material Substitutions

FEV next applied their own vehicle technology evolution roadmaps to key vehicle systems and materials. Materials being used in the various systems of the three vehicle types today were examined and the potentials for replacing materials in each of the key systems and components in the 2025 and 2030 vehicle were evaluated. Aluminum was substituted into components not already made of aluminum only where the substitution was deemed appropriate from design and performance considerations. Observations of real-world trends in aluminum application in each of the three vehicle types were taken into consideration when selecting components for additional aluminum substitution.

Task 3 – Weight, Cost, and BEV Efficiency Impact

The weight, cost, and BEV fleet average fuel economy impact of aluminum substitution were determined by incrementally increasing the substitution by aluminum in target components in each of the three vehicle classes in each of the three scenarios (2020, 2025, 2030). Aluminum penetration was increased in 5% increments from the baseline vehicle up to 100%. Battery and electric drive motor size were adjusted to keep performance constant at levels chosen for each vehicle class in each scenario. In all three vehicle classes (City, Family Crossover, Pick-up Truck) and in all three scenarios (2020, 2025, 2030), initial aluminum substitutions resulted in an overall decrease in vehicle cost. Optimum aluminum content was defined by the level of aluminum content at which overall vehicle cost reached a minimum.

RESULTS

Task 1 – Specify Three BEVs

Baseline (2020), 2025, and 2030 performance targets for the City vehicle, Family Crossover vehicle, and Pickup Truck are shown in Figures 1 – 3. Weight, range, and equivalent fuel economy are expected to improve over this time period, but FEV expects consumers to put increasing emphasis on range and cost over speed and acceleration and these latter two measures were allowed to decrease slightly over time to reduce overall vehicle cost.

Figure 4 shows expected improvements in battery technology over the study period. Battery storage density is expected to improve from 200 Wh/kg today with nickel-cobalt-aluminum oxide (NCA) and nickel-manganese-cobalt (NMC) cathodes to about 250 Wh/kg in 2025. Solid-state lithium metal anode technology is expected to further improve storage density to 300 Wh/kg by 2030. Lithium-sulfur technology, if successful, should increase storage density to 400 Wh/kg by 2035. Battery and e-motor costs, respectively, are expected to improve from \$119/kWh and \$5.50/kW in 2025 to \$102/kWh and \$2.30/kW in 2030.

Figure 5 shows expected changes in powertrain and vehicle type over the study period. BEVs are expected to grow from 2% of the fleet in 2020, to 8% in 2025 and 20% in 2030. City vehicles make up the bulk of BEVs in the sales fleet today, but the Family Crossover vehicle is expected to dominate in 2030. The expected evolution of average fleet fuel economy across all powertrain types, e.g., ICE, hybrid, BEV, etc., is shown in Figure 6. Average fleet fuel economy is expected to reach 55 mpg in 2030, driven by both electrification penetration and improvements in overall powertrain efficiency. This analysis is used as a baseline in Task 3 to compare with estimated changes to MPG based on increased aluminum substitution in BEVs.

Task 2 – Analyze Material Substitutions

The baseline (status quo) compositional distributions of materials in the three representative vehicle classes today (2020) and those expected in 2025 and 2030 are shown in Figures 7-9. These distributions were developed under the assumption that weight reduction will be driven primarily by the need to reduce battery size to attain range at an affordable price, and on factors presumed by FEV to drive materials adoption based on current and anticipated future trends. The weight and cost implications of additional aluminum substitutions beyond these changes will be assessed in the following section. FEV also evaluated over 40 components that were not aluminum in the baseline configurations for their potential to be further light weighted by aluminum substitution. Twenty of these parts were selected for application consideration based on the cost effectiveness of their weight reduction potential; design and performance considerations were also part of the selection criteria. The 20 parts selected for additional light weighting and the BEV segment for which they were considered are shown in Figure 10. These parts were selected primarily on the basis of their weight reduction potential and the cost-effectiveness of their weight reduction. Inputs to this selection process were drawn on a component-level basis from FEV's extensive proprietary database of material and manufacturing costs. Generally, the selected parts had light weighting cost efficiencies of $3/pound of weight saved or lower. Aluminum content increases as vehicle size increases primarily driven by the lower price sensitivity in the larger vehicles and the need to keep battery costs down as size increases.

Examples of parts chosen for light weighting with aluminum in the City, Family Crossover, and Pickup Truck vehicles are shown in futures 11, 12, and 13, respectively.

Task 3 – Weight, Cost, and BEV Efficiency Impact

The net cost of aluminum substitution in the representative vehicles in 2025 and 2030 is shown in Figure 14. For all three representative vehicles, increasing aluminum content from the baseline or status quo configuration resulted in a reduction in overall vehicle cost. Furthermore, the aluminum content for lowest overall vehicle cost increased in 2030 over 2025 for all three vehicles.

For the City vehicle in 2025, an optimal cost savings of $62 per vehicle was achieved at 25% aluminum content. Components substituted with aluminum include skid plates, rotor end plates, front and rear BIW floor, doors, seats, and cross car beams. Total weight reduction was 124.5 kg. The average cost per kg of weight saved at this level was $3.76. In 2030, optimal cost savings of $74 per vehicle was achieved at 28% aluminum content. Additional parts converted to aluminum were the front suspension. Total weight reduced by aluminum substitution in 2030 was 128.7 kg. The average cost per kg of weight saved at this level was $ 3.14.

For the Family Crossover vehicle in 2025, an optimal cost savings of $74 per vehicle was achieved at 25% aluminum content. Parts converted to aluminum include the battery housing, rotor end plates, BIW mid floor, body side outers, doors, and front calipers. Total weight removed by these substitutions was 142.8 pounds. The average cost per kg of weight saved at this level was $3.74. In 2030, optimal cost savings of $76 per vehicle was achieved at 42% aluminum content. Additional parts converted to aluminum in 2030 include skid plates, front and rear BIW floor, and seats. Total weight reduction from all substitutions in 2030 was 171.9 kg. The average cost per kg of weight saved at this level was $5.08.

For the Pickup Truck in 2025, an optimal cost savings of $102 per vehicle was achieved at 35% aluminum content. Parts converted to aluminum include the battery housing, BIW mid floor, BIW front and rear floor, front calipers, and seats. Total weight reduction from these substitutions was 156.2 kg. The average cost per kg of weight saved at this level was $5.81. In 2030, the optimal cost savings of $74 per vehicle was achieved at 50% aluminum content. Additional parts converted to aluminum in 2030 include skid plates, upper firewall, front bumper and crush cans, front suspension, and front and rear subframes. Total weight reduction from all substitutions in 2030 was 264.2 kg. The average cost per kg of weight saved at this level was $6.05.

Figure 15 shows the influence of additional BEV light weighting on overall fleet fuel economy. The additional weight reductions coming from light weighting the three vehicle classes over the baseline or status quo scenario increased overall hypothetical fleet fuel economy from 37.6 to 38.9 MPG in 2025 and from 55.3 to 57.3 MPG in 2030. This represents fleet fuel economy improvements of 3% and 4%, respectively, in 2025 and 2030.

DISCUSSION

It is widely understood that in today's ICE-powered vehicles, larger and more performance-oriented vehicles exhibit a higher overall aluminum content than smaller vehicles. This is driven by several factors, including higher performance expectations, greater challenges in meeting fuel economy regulations in heavier vehicles, and a higher price point that reduces price (cost) sensitivity.

The same drivers responsible for the aluminum content trend in ICE vehicles will also apply to BEVs. In addition, the expectations for range and power increase significantly with size in BEVs, making the tradeoff between weight and battery size/cost more economically attractive for aluminum. We therefore expect, confirmed by the results of this study, that the trend toward increased aluminum content with increased size will continue in BEVs.

This study also shows that today's BEVs have a larger aluminum content than their ICE counterparts of similar size and mission. This trend is driven primarily by the lower cost of aluminum light weighting solutions relative to the cost of the batteries they eliminate. However, this tradeoff could shift significantly if the cost of BEV batteries falls faster than the cost of the offsetting aluminum solutions. This potential was a significant reason for the conduct of this study.

This study further shows that the economic attractiveness of aluminum light weighting solutions in BEVs will persist into the future despite expected improvements in battery cost and storage density. In fact, the study suggests that the attractiveness of aluminum will actually increase over the next decade. In all three vehicles and in both the 2025 and 2030 time horizons, vehicle cost decreased as aluminum share initially increased, indicating that increasing aluminum content beyond today's levels will further decrease BEV cost both today and in the future. This trend is driven largely by increases in consumer demands for greater range over time.

Finally, this study suggests that aluminum light weighting solutions will have even greater benefit when the entire fleet is considered. The Authors clearly recognize that carmakers do not make material selection decisions on the basis of a single vehicle, but rather on the basis of their impact on the overall vehicle production fleet. The equivalent fuel economy improvements provided by the individual vehicles in this study improved the overall fuel economy of a hypothetical fleet significantly (i.e., 3-4%). If the fleet is already at its sales volume-averaged fuel economy mandate, the additional improvements coming from the application of additional aluminum light weighting would allow the manufacturer to remove costly fuel economy improvement technologies from other vehicles. On the other hand, if the fleet is not yet attaining its mandated average fuel economy, the improvements from the aluminum light weighting applications could be used to avoid costly fuel economy improvement technology additions elsewhere in the fleet. Either way, the economic benefits of fuel economy improvements from aluminum light weighting will be further enhanced by the broader fleet impacts, making aluminum light weighting even more robust against improvements in battery technology beyond those anticipated in this study.

The impacts of these BEV light weighting cost improvements on the total life cycle carbon footprint of the representative vehicles was beyond the scope of this current study. However, The Aluminum Association has launched such a study and its results will be available in late 2022.

Despite this study's encouraging results, the aluminum industry is cautioned to guard against complacency and continue to drive up the value of its aluminum solutions. To this end, The Aluminum Association's Aluminum Transportation Group recently prepared and published an updated roadmap outlining the technologies needed to further enhance aluminum's light weighting value in the transportation industry. This roadmap along with a detailed report of the study outlined above, can be obtained from The Aluminum Association's Aluminum Transportation Group's website at www.drivealuminum.org

CONCLUSIONS

1. The aluminum content of today's battery electric vehicles is greater than their internal combustion engine powertrain counterparts of similar size and mission.
2. The aluminum content of today's battery electric vehicles increases with increasing vehicle size and performance expectations.
3. Despite expected improvements in battery cost and storage density, aluminum light weighting solutions are expected to remain economically attractive for at least the next decade.
4. Light weighting battery electric vehicles with aluminum provides additional economic benefits when the entire sales fleet is considered, creating additional economic benefit and further increasing the economic viability of aluminum light weighting.

ACKNOWLEDGEMENTS

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BEV SPECIFICATION AND PERFORMANCE TARGETS BY VEHICLE TYPE – (CURRENT)

» STATUS QUO SCENARIO (FEV EXPECTATION)

SPECIFICATIONS	City vehicle	Family crossover	Pickup truck
Vehicle weight (lbs)	3,632	4,645	6,193
Acceleration (0-60 Mph in seconds)	7.4	5.5	4.4
Top speed (mph)	95	111	125
Battery capacity (kWh)	55	76	165
E-drive range (miles)	200	300	400
Average MPG(e)	123	100	82

Figure 1. 2020 performance targets for the three BEV classes.

BEV SPECIFICATION AND PERFORMANCE TARGETS BY VEHICLE TYPE – (2025)

» STATUS QUO SCENARIO (FEV EXPECTATION)

SPECIFICATIONS	City vehicle	Family crossover	Pickup truck
Vehicle weight (lbs)	3,352	4,147	5,536
Acceleration (0-60 Mph in seconds)	8.7	6.3	5.5
Top speed (mph)	90	106	113
Battery capacity (kWh)	61	91	176
E-drive range (miles)	250	350	450
Average MPG(e)	138	114	86

Figure 2. 2025 performance targets for the three BEV classes.

BEV SPECIFICATION AND PERFORMANCE TARGETS BY VEHICLE TYPE – (2030)

» STATUS QUO SCENARIO (FEV EXPECTATION)

SPECIFICATIONS	City vehicle	Family crossover	Pickup truck
Vehicle weight (lbs)	3,072	3,649	4,879
Acceleration (0-60 Mph in seconds)	10.0	7.0	6.5
Top speed (mph)	84	101	101
Battery capacity (kWh)	67	105	186
E-drive range (miles)	300	400	500
Average MPG(e)	151	128	91

Figure 3. 2030 performance targets for the three BEV classes.

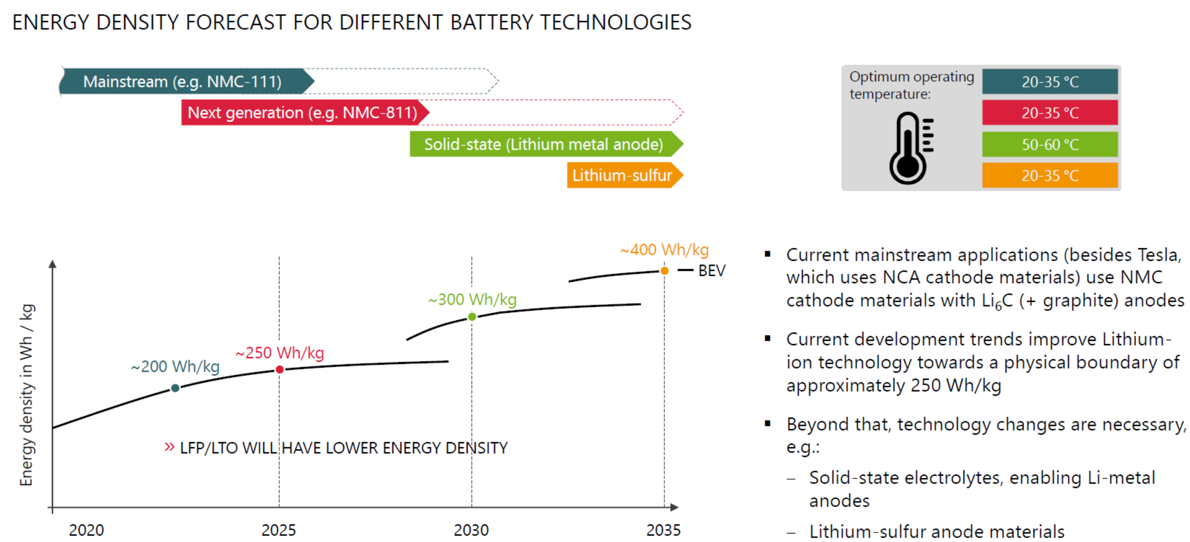

Figure 4. Expected improvements in battery Technology.

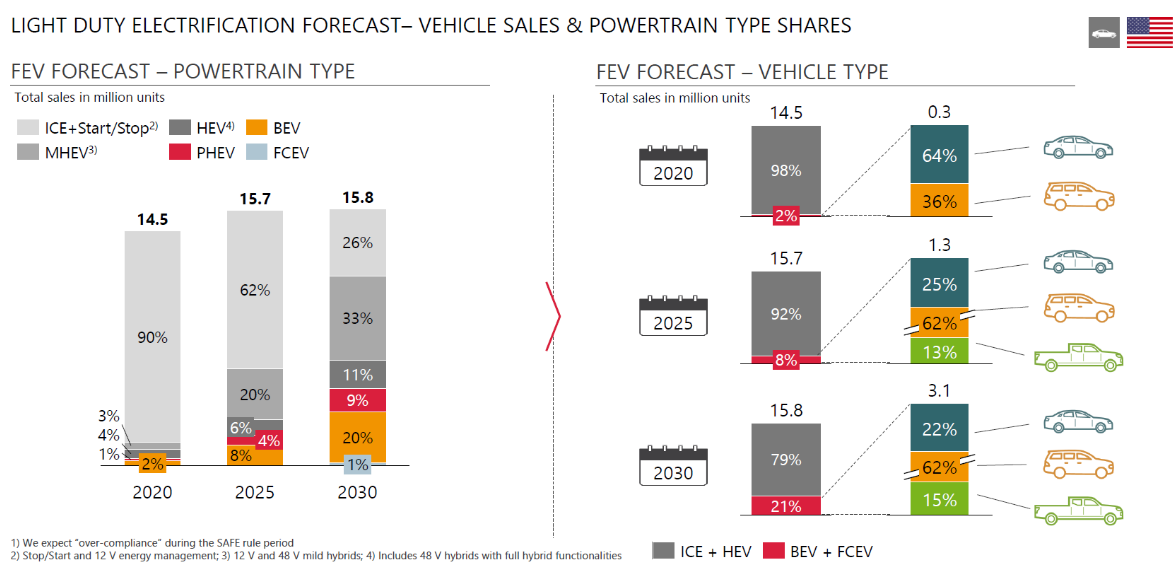

Figure 5. Expected powertrain and vehicle type mix.

AVERAGE FLEET FUEL ECONOMY BY VEHICLE SEGMENT – ALL POWERTRAIN TYPES (MPG)

	2020	Δ	2025	Δ	2030
City vehicle	38.7	29%	49.7	48%	73.8
Family crossover	25.0	51%	37.6	52%	57.3
Pickup truck	19.1	36%	25.9	34%	34.7
Total avg. fleet fuel economy	26.9	40%	37.6	47%	55.3

Figure 6. Expected improvements in overall fleet fuel economy.

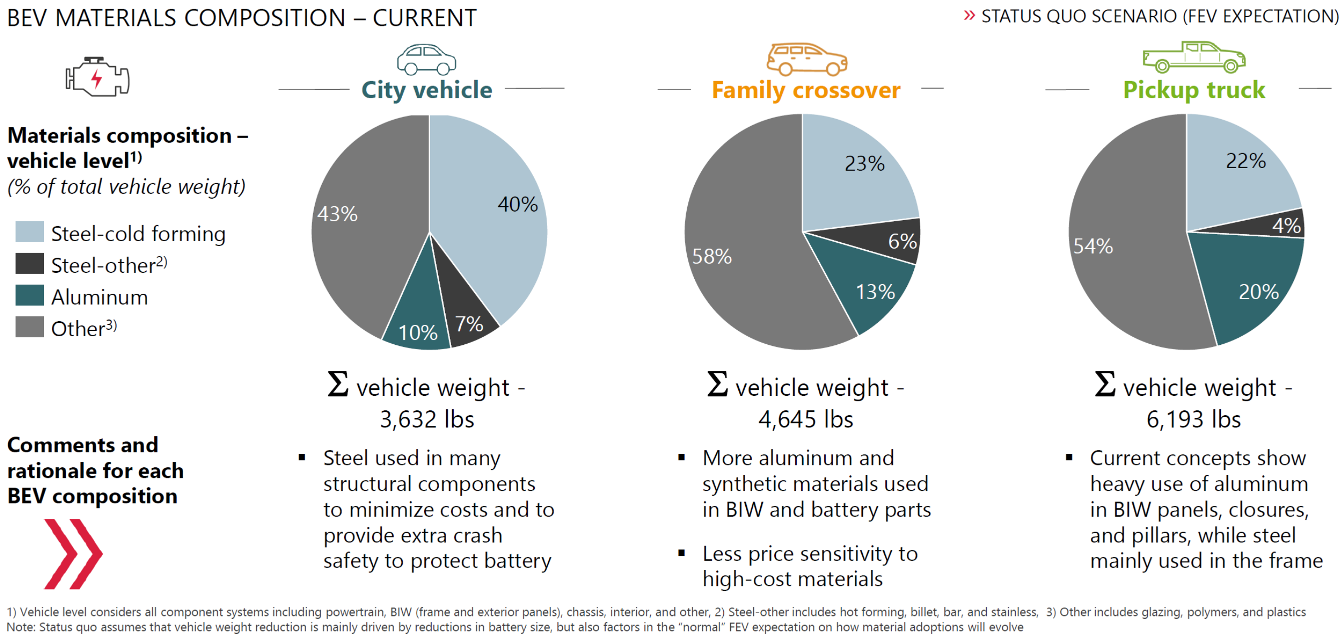

Figure 7. Typical materials composition in representative baseline vehicle classes today (2020).

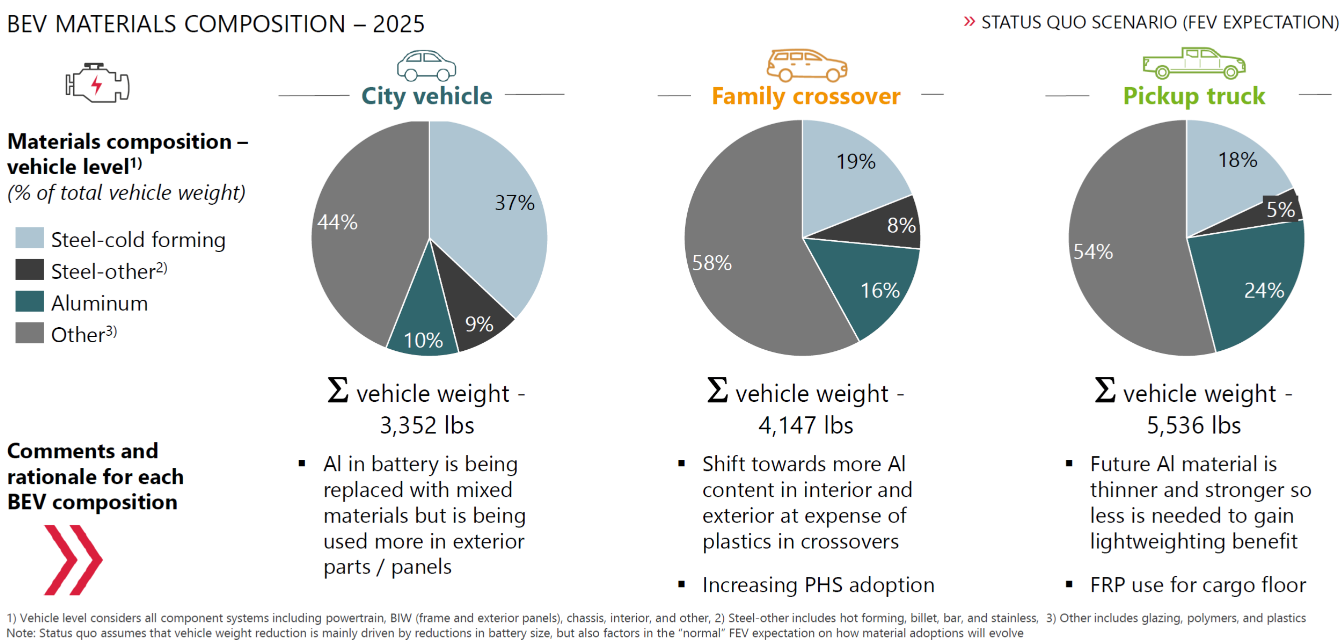

Figure 8. Expected materials composition in representative baseline vehicle classes in 2025.

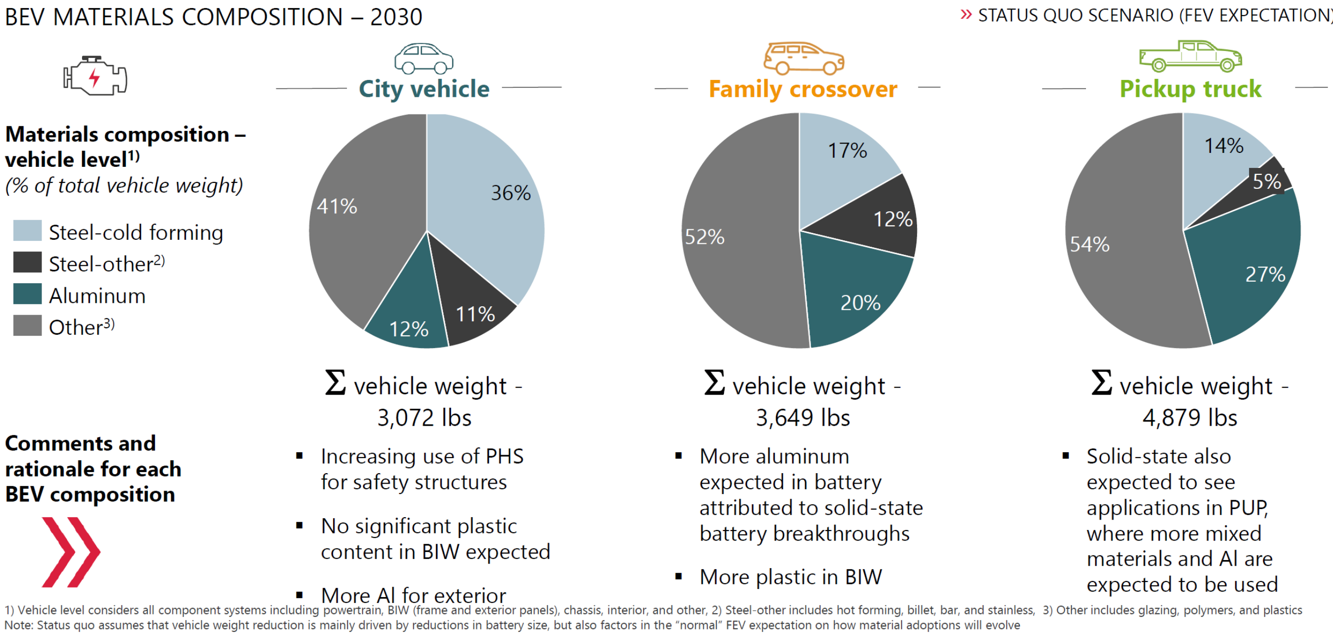

Figure 9. Expected materials composition in representative baseline vehicle classes in 2030.

ALUMINUM SUBSTITUTION OPTIONS SELECTED FOR EACH BEV TYPE

» USED IN THE SENSITVITY ANALYSIS

#	Component	Sub-system	BEV segment
1	Battery module cell housing	HV battery	Family crossover, Pickup truck
2	Skid plates	HV battery	City vehicle, Family crossover, Pickup truck
3	Rotor end plates	E-motor	City vehicle, Family crossover, Pickup truck
4	Planetary carrier	Transmission	City vehicle, Family crossover, Pickup truck
5	Driveshaft (RWD)	Transmission	Family crossover, Pickup truck
6	Bulkhead / firewall (upper)	BIW	Family crossover, Pickup truck
7	Bulkhead / firewall (lower)	BIW	Family crossover, Pickup truck
8	Floor sheet	BIW	Family crossover, Pickup truck
9	Front / rear floor area	BIW	City vehicle, Family crossover, Pickup truck
10	Body side outer	BIW	Family crossover
11	Bumper beam	Exterior	Pickup truck
12	Fenders	Exterior	City vehicle
13	Doors	Exterior	City vehicle, Family crossover
14/15	Suspension system (Fr & Rr)	Chassis	Pickup truck
16/17	Subframes (Fr & Rr)	Chassis	City vehicle, Pickup truck
18	Front calipers (L & R)	Brakes	Family crossover, Pickup truck
19	Seat	Interior	City vehicle, Family crossover, Pickup truck
20	Cross car beam	Interior	City vehicle

Not every part is analyzed for each BEV – application potential and cost / benefit are not equal across segments. Thus, a different sub-set of this list is selected for each BEV based on various prioritization criteria (cost / lb saved, engineering feasibility, etc.)

Figure 10. Applications chosen for additional aluminum substitution beyond the baseline configuration and the BEV segments to which they were applied.

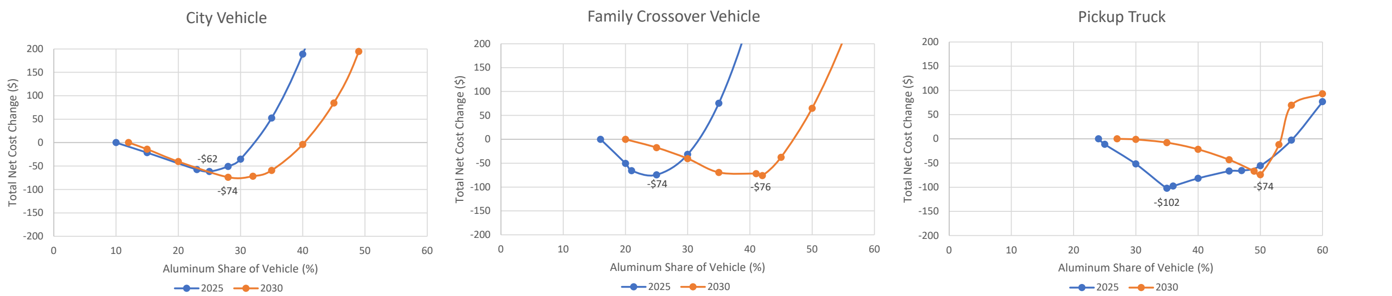

Figure 11. Net cost impact of aluminum substitution in the representative vehicles.

AVERAGE FLEET FUEL ECONOMY BY VEHICLE SEGMENT (MPG) » SUBSTITUTION SCENARIO

	2020	Δ	2025	Δ	2030
City vehicle	38.7	31%	50.6	50%	76.1
Family crossover	25.0	58%	39.6	51%	59.8
Pickup truck	19.1	37%	26.1	37%	35.6
Total avg. fleet fuel economy	26.9	45%	38.9 ⬆ *3%*	47%	57.3 ⬆ *4%*
Vs. baseline (“status quo”)	26.9	40%	37.6	47%	55.3

3% - 4%
Increase

Figure 12. Influence of increased aluminum light weighting in the BEVs on overall fleet fuel economy.

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