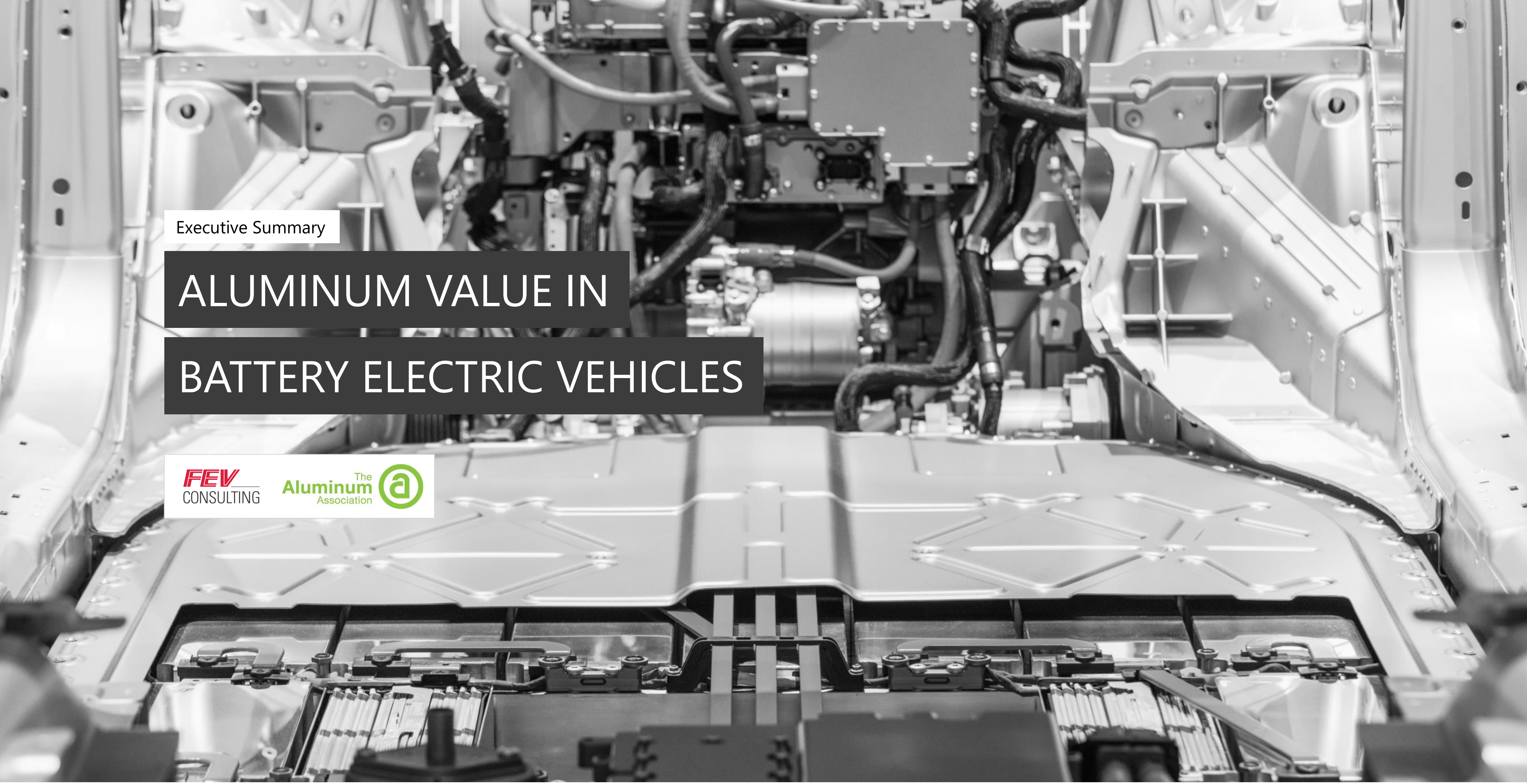

Executive Summary

ALUMINUM VALUE IN BATTERY ELECTRIC VEHICLES

2022

Prepared for **THE ALUMINUM ASSOCIATION**

FEV
CONSULTING

ALUMINUM VALUE IN BATTERY ELECTRIC VEHICLES

PREPARED FOR

THE ALUMINUM ASSOCIATION

EXECUTIVE SUMMARY

The Aluminum Association

OBJECTIVES

- The Aluminum Association, the industry’s leading voice in Washington, DC, providing global standards, industry statistics and expert knowledge to member companies and policy makers, considered the following as it set out to investigate and quantify the value of mass reductions achievable through aluminum substitution for steel in battery electric vehicles (BEVs):
  - The cost tradeoff of aluminum light weighting against the cost of batteries and traction motors for vehicles of equivalent performance
  - The impact of battery packaging and performance degradation in a heavier, steel-intensive BEV
  - The value of aluminum weight reduction in a mixed fleet of BEV and ICE vehicles
  - The impact of a growing number of BEVs in a mixed fleet of BEV and ICE vehicles on the value of weight reduction in all vehicles
- Cost impact of material substitutions should be made at a high system level, beginning with a baseline structure and then substituted by other materials; electrified powertrain to be adjusted to maintain constant vehicle performance
- Costs to be calculated based on today’s economics and projections to 2025 and 2030
- Different vehicle types to be considered

List of abbreviations from study

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AA	Aluminum Association
AC	Air conditioning / cooling
AHSS	Advanced high strength steel
Al.	Aluminum
AM	Additive manufacturing
ASM	Asynchronous motors
AWD	All wheel drive
BEV	Battery electric vehicle
BIW	Body in white
BMS	Battery management system
CCB	Cross car beam
CFRP	Carbon fiber reinforced polymer
D&C	Doors & closures
ECU	Electronic control unit
EPCU	Electric power control unit
Ext.	Extrusion
Fr&Rr	Front & rear
FRP	Fiber reinforced plastic
GFRP	Glass fiber reinforced polymer
HSS	High strength steel
HV	High voltage
ICE	Internal combustion engine
L&R	Left & right
LSS	Low strength steel
Mag.	Magnesium
Misc.	Miscellaneous
NdFeB	Neodymium magnet
NVH	Noise, vibration, and harshness
OBCM	On-board charger module
PEC	Power electronic center
PHS	Press hardened steel
PM	Powder metal
PMSM	Permanent magnet synchronous motor
PUP	Pickup truck
RWD	Rear wheel drive
UHSS	Ultra-high strength steel

FEV implemented a four-step approach to analyze value of aluminum in BEVs

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PROJECT APPROACH

1 SPECIFY THREE BEVS

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  - City vehicle
  - Family crossover
  - Pick-up truck
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- Baseline current vehicle structure & composition (e.g., materials used for main systems and components)
- Share FEV forecasts for 2025 and 2030 by 3 vehicle types; baseline fleet avg. fuel economy

2 ANALYZE MATERIAL SUBSTITUTIONS

- Share FEV technology roadmaps for key vehicle systems and materials
- Examine materials being used in the 3 BEVs defined in Task 1
- Analyze potential options for aluminum replacing some of the materials being used for the main systems and components
- Define the 3 BEVs for 2025 and 2030 with aluminum substitutions

3 WEIGHT, COST, AND BEV EFFICIENCY IMPACT

- Analyze impact of weight due to aluminum substitution on the BEVs defined for 2025 & 2030
- Based on performance targets defined in ask 1, e.g., resize battery due to weight reduction
- Calculate cost impact due to reduction in battery, motor size etc.
- Calculate BEV fleet average fuel efficiency improvement

4 TOTAL FLEET MPG AND RECOMMENDATIONS

- Calculate total fleet average fuel economy improvement
- Analyze cost vs.
  - fleet average fuel economy improvement
- Quantify value of aluminum substitution
- Recommend BEVs segments with best balance between cost and improvement in
  - fleet average fuel economy
- Summarize BEVs aluminum content targets for 2025 & 2030

Task 1: Specify three BEVs for analysis

PROJECT APPROACH

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KEY TAKEAWAYS / NOTES

Improvements in energy density, range, and overall weight reduction expected for all specified BEVs thru 2030

Three BEVs are specified as a baseline for this study:

City vehicle

Family crossover

Pickup truck

Expected specifications, weights, and performance targets are defined for the three BEV types for “current”, 2025, and 2030

This represents the “status quo” or baseline scenario, which assumes natural market adoption of lightweight materials and overall decline in vehicle weight over time

Expected performance improvements in areas such as range are attributed to vehicle weight reduction but improvements in battery technology through 2030 is also a main driving factor

We have defined BEV specifications, weights, and performance targets for the three vehicle types in today’s market

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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

Expected targets by 2025 include lower overall weight and increases in battery energy density, range, and vehicle efficiency for all three BEV types

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

Weight reduction and energy density continue to improve; performance (e.g., speed) is less of a differentiator as more BEVs are used for fleets (mobility)

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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

KEY TAKEAWAYS / NOTES

Current materials composition was estimated for three BEV segments using benchmark data from four BEV examples

Hyundai IONIQ and VW ID.3 BOM data was used to estimate current material composition for a representative city vehicle BEV

Mach-E benchmark data cross-checked with E-tron data was used to estimate the current material composition for a representative family crossover BEV

Ford-F150 benchmark data was used as a proxy for the F-150 Lightning, and averaged with various Rivian data points to estimate current pickup (PUP) BEV composition

In current market, family crossover and PUP BEVs are estimated to have highest aluminum content due to customers’ lower price sensitivity and demand for higher performance targets in these segments, which increased aluminum content helps achieve

This trend is expected to continue in the future materials composition, which is estimated based on FEV’s expected view and roadmaps on materials technology

Crossover and PUP with highest estimated aluminum content due to lower price sensitivity in these segments and higher use in BIW and battery components

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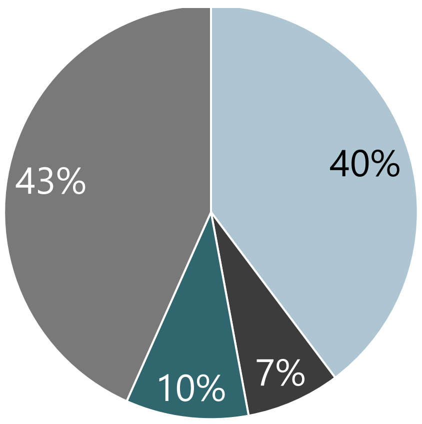
BEV MATERIALS COMPOSITION – CURRENT

» STATUS QUO SCENARIO (FEV EXPECTATION)

Materials composition – vehicle level1)
(% of total vehicle weight)

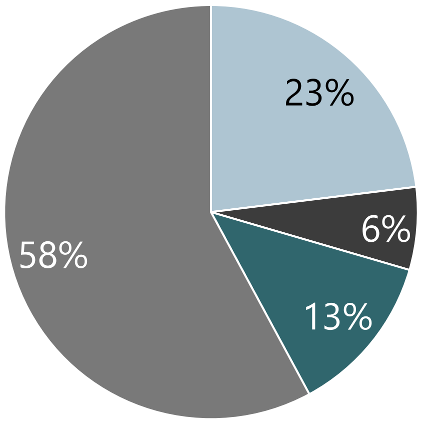
- ■ Steel-cold forming
- ■ Steel-other2)
- ■ Aluminum
- ■ Other3)

City vehicle



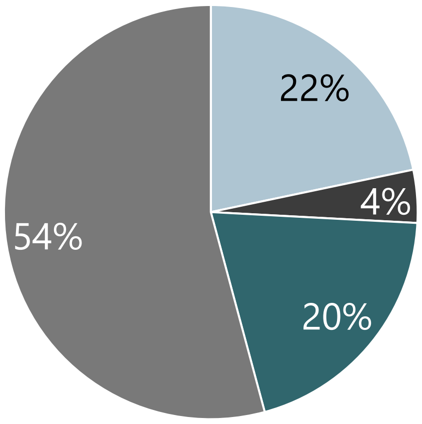
Σ vehicle weight - 3,632 lbs

Family crossover



Σ vehicle weight - 4,645 lbs

Pickup truck



Σ vehicle weight - 6,193 lbs

Comments and rationale for each BEV composition

City vehicle:

- Steel used in many structural components to minimize costs and to provide extra crash safety to protect battery

Family crossover:

- More aluminum and synthetic materials used in BIW and battery parts
- Less price sensitivity to high-cost materials

Pickup truck:

- Current concepts show heavy use of aluminum in BIW panels, closures, and pillars, while steel mainly used in the frame

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1) Vehicle level considers all component systems including powertrain, BIW (frame and exterior panels), chassis, interior, and other, 2) Steel-other includes hot forming, billet, bar, and stainless, 3) Other includes glazing, polymers, and plastics

Note: Status quo assumes that vehicle weight reduction is mainly driven by reductions in battery size, but also factors in the "normal" FEV expectation on how material adoptions will evolve

Absolute weight of PHS and aluminum increase or remain roughly constant in all three BEV segments with further drop in composites and steel-cold forming

BEV MATERIALS COMPOSITION – 2030

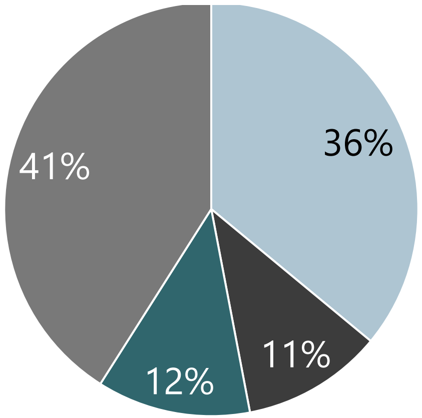
» STATUS QUO SCENARIO (FEV EXPECTATION)

Materials composition – vehicle level[1]
(% of total vehicle weight)

- ▨ Steel-cold forming
- ■ Steel-other[2]
- 🟦 Aluminum
- ■ Other[3]

Comments and rationale for each BEV composition

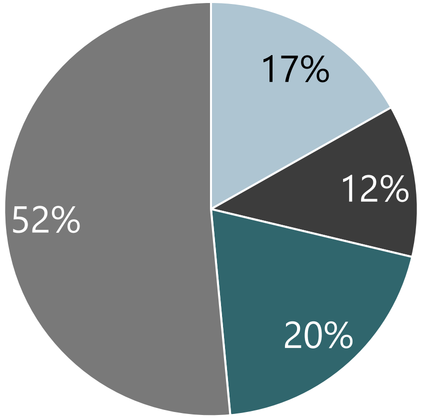
City vehicle



Σ vehicle weight - 3,072 lbs

- Increasing use of PHS for safety structures
- No significant plastic content in BIW expected
- More aluminum for exterior

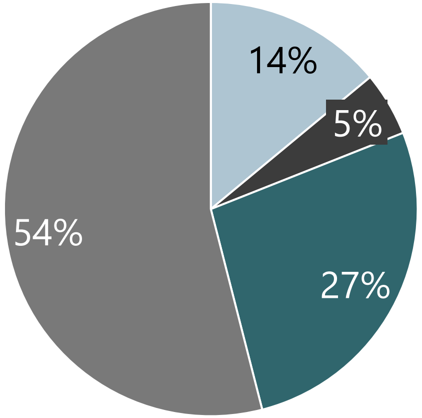
Family crossover



Σ vehicle weight - 3,649 lbs

- More aluminum expected in battery attributed to solid-state battery breakthroughs
- More plastic in BIW

Pickup truck



Σ vehicle weight - 4,879 lbs

- Solid-state also expected to see applications in PUP, where more mixed materials and aluminum are expected to be used

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1) Vehicle level considers all component systems including powertrain, BIW (frame and exterior panels), chassis, interior, and other, 2) Steel-other includes hot forming, billet, bar, and stainless, 3) Other includes glazing, polymers, and plastics

Note: Status quo assumes that vehicle weight reduction is mainly driven by reductions in battery size, but also factors in the "normal" FEV expectation on how material adoptions will evolve

Task 2: FEV view on future materials trends and identification of substitution opportunities for aluminum (replacing steel) in the three BEV types

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  - fleet average fuel economy
- Summarize BEVs aluminum content targets for 2025 & 2030

In future, we expect most BEV components to be mainly comprised of mixed materials (Al., steel, composites) rather than one dominant material type

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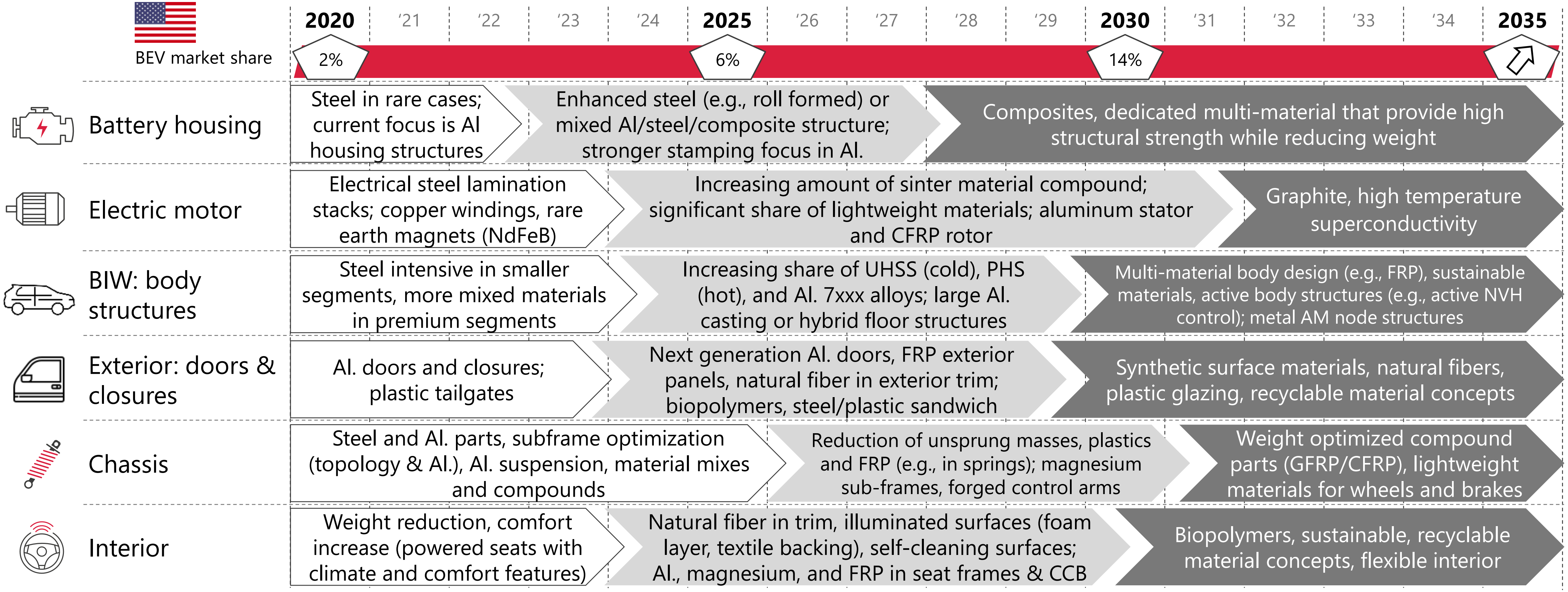
TECHNOLOGY ROADMAP – BEV MATERIALS TRENDS SUMMARY



	Current technology focus	Next generation technology focus	Future technology focus
Battery housing	Steel in rare cases; current focus is Al housing structures	Enhanced steel (e.g., roll formed) or mixed Al/steel/composite structure; stronger stamping focus in Al.	Composites, dedicated multi-material that provide high structural strength while reducing weight
Electric motor	Electrical steel lamination stacks; copper windings, rare earth magnets (NdFeB)	Increasing amount of sinter material compound; significant share of lightweight materials; aluminum stator and CFRP rotor	Graphite, high temperature superconductivity
BIW: body structures	Steel intensive in smaller segments, more mixed materials in premium segments	Increasing share of UHSS (cold), PHS (hot), and Al. 7xxx alloys; large Al. casting or hybrid floor structures	Multi-material body design (e.g., FRP), sustainable materials, active body structures (e.g., active NVH control); metal AM node structures
Exterior: doors & closures	Al. doors and closures; plastic tailgates	Next generation Al. doors, FRP exterior panels, natural fiber in exterior trim; biopolymers, steel/plastic sandwich	Synthetic surface materials, natural fibers, plastic glazing, recyclable material concepts
Chassis	Steel and Al. parts, subframe optimization (topology & Al.), Al. suspension, material mixes and compounds	Reduction of unsprung masses, plastics and FRP (e.g., in springs); magnesium sub-frames, forged control arms	Weight optimized compound parts (GFRP/CFRP), lightweight materials for wheels and brakes
Interior	Weight reduction, comfort increase (powered seats with climate and comfort features)	Natural fiber in trim, illuminated surfaces (foam layer, textile backing), self-cleaning surfaces; Al., magnesium, and FRP in seat frames & CCB	Biopolymers, sustainable, recyclable material concepts, flexible interior

Current technology focus
Next generation technology focus
Future technology focus

KEY TAKEAWAYS / NOTES

From FEV benchmark data, aluminum content is observed to increase with performance and size, and is higher in BEV vs ICE equivalents

Material breakdown examples and estimations have been provided for Hyundai IONIQ, VW ID.3, Ford Mustang Mach-E, and Ford F-150 Lighting (estimations based on F-150 data)

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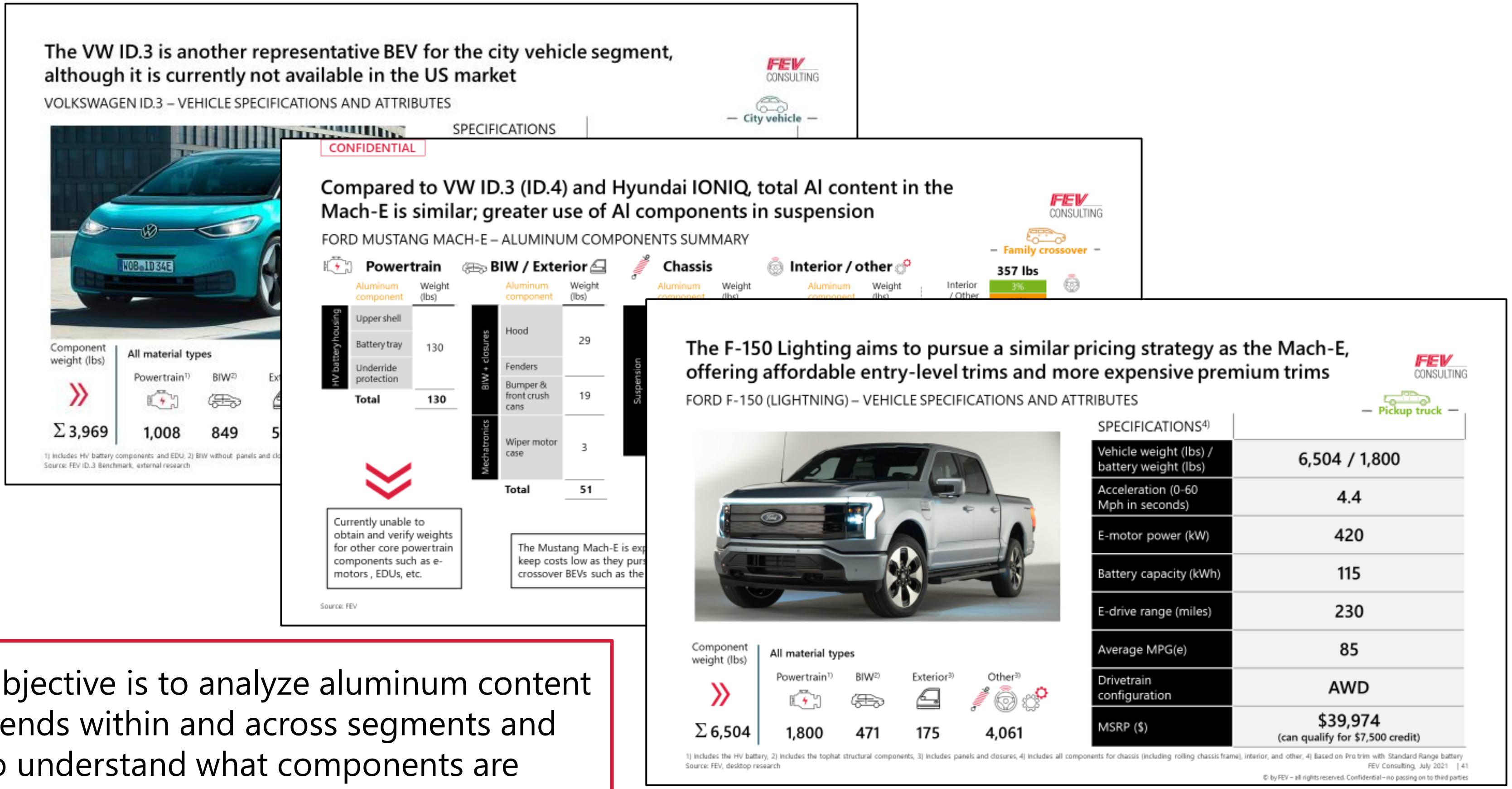

The VW ID.3 is another representative BEV for the city vehicle segment, although it is currently not available in the US market

VOLKSWAGEN ID.3 – VEHICLE SPECIFICATIONS AND ATTRIBUTES

City vehicle

SPECIFICATIONS

Component weight (lbs)	All material types		
	Powertrain[1]	BIW[2]	Ex
Σ 3,969	1,008	849	5

1) Includes HV battery components and EDU, 2) BIW without panels and cl

Source: FEV ID.3 Benchmark, external research

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Compared to VW ID.3 (ID.4) and Hyundai IONIQ, total Al content in the Mach-E is similar; greater use of Al components in suspension

FORD MUSTANG MACH-E – ALUMINUM COMPONENTS SUMMARY

Family crossover

357 lbs

Interior / Other 3%

Powertrain

	Aluminum component	Weight (lbs)
HV battery housing	Upper shell	130
	Battery tray	
	Underride protection	
	Total	**130**

Currently unable to obtain and verify weights for other core powertrain components such as e-motors , EDUs, etc.

BIW / Exterior

	Aluminum component	Weight (lbs)
BIW + closures	Hood	29
	Fenders	
	Bumper & front crush cans	19
Mechatronics	Wiper motor case	3
	Total	**51**

The Mustang Mach-E is exp keep costs low as they purs crossover BEVs such as the

Chassis

Aluminum component | Weight (lbs)

Suspension

Interior / other

Aluminum component | Weight (lbs)

Source: FEV

The F-150 Lighting aims to pursue a similar pricing strategy as the Mach-E, offering affordable entry-level trims and more expensive premium trims

FORD F-150 (LIGHTNING) – VEHICLE SPECIFICATIONS AND ATTRIBUTES

Pickup truck

SPECIFICATIONS[4]	
Vehicle weight (lbs) / battery weight (lbs)	6,504 / 1,800
Acceleration (0-60 Mph in seconds)	4.4
E-motor power (kW)	420
Battery capacity (kWh)	115
E-drive range (miles)	230
Average MPG(e)	85
Drivetrain configuration	AWD
MSRP ($)	$39,974 (can qualify for $7,500 credit)

Component weight (lbs)	All material types			
	Powertrain[1]	BIW[2]	Exterior[3]	Other[3]
Σ 6,504	1,800	471	175	4,061

1) Includes the HV battery, 2) Includes the tophat structural components, 3) Includes panels and closures, 4) Includes all components for chassis (including rolling chassis frame), interior, and other, 4) Based on Pro trim with Standard Range battery

Source: FEV, desktop research

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Objective is to analyze aluminum content trends within and across segments and to understand what components are currently used as aluminum and what could be promising in the future

From FEV benchmarks, aluminum content in BEVs increases in segments with larger vehicle size, higher price class, and performance requirements

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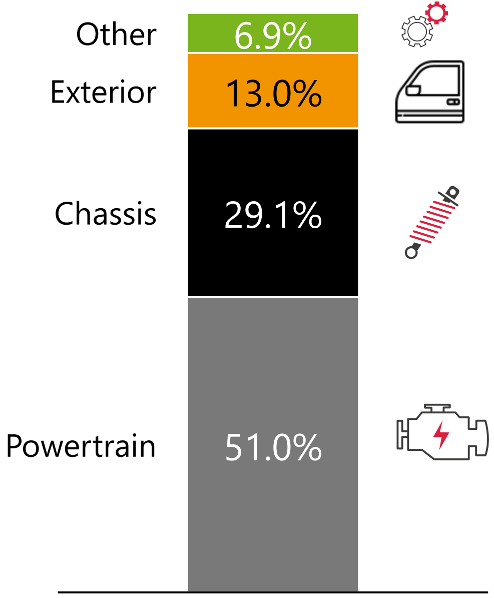
SEGMENT COMPARISON – BEV ALUMINUM CONTENT (CURRENT MARKET)

» FEV ESTIMATES & BENCHMARK DATA

City vehicle

346 lbs

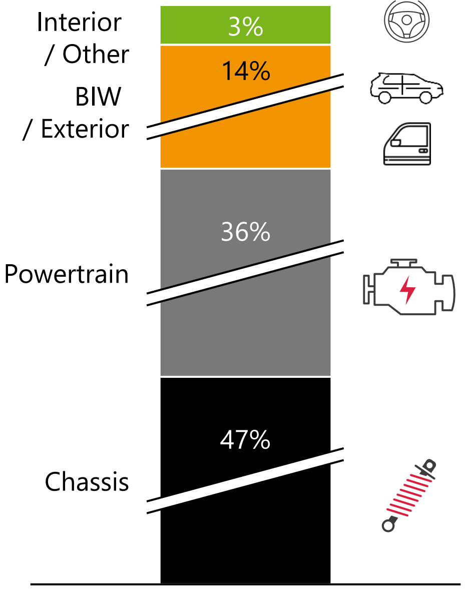


Al. content by component system

IONIQ

Family crossover

357 lbs



Al. content by component system

Mach-E

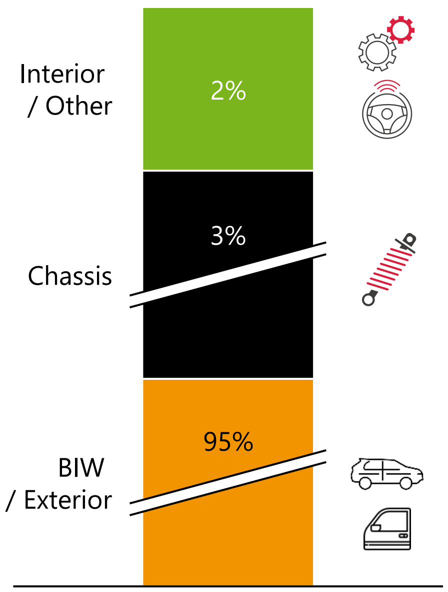
640lbs

BIW
Bulkhead firewall
Front / rear floor area
Floor sheet

i-Pace

Pickup truck

646 lbs



Al. content by component system

Lightning

Aluminum components in the IONIQ battery system (cell, BMS, etc.), exterior and chassis offset the lost aluminum content from Elantra ICE parts (blocks, heads, etc.)

PASSENGER CAR COMPARISON: MATERIALS SHIFT FROM ICE TO BEV

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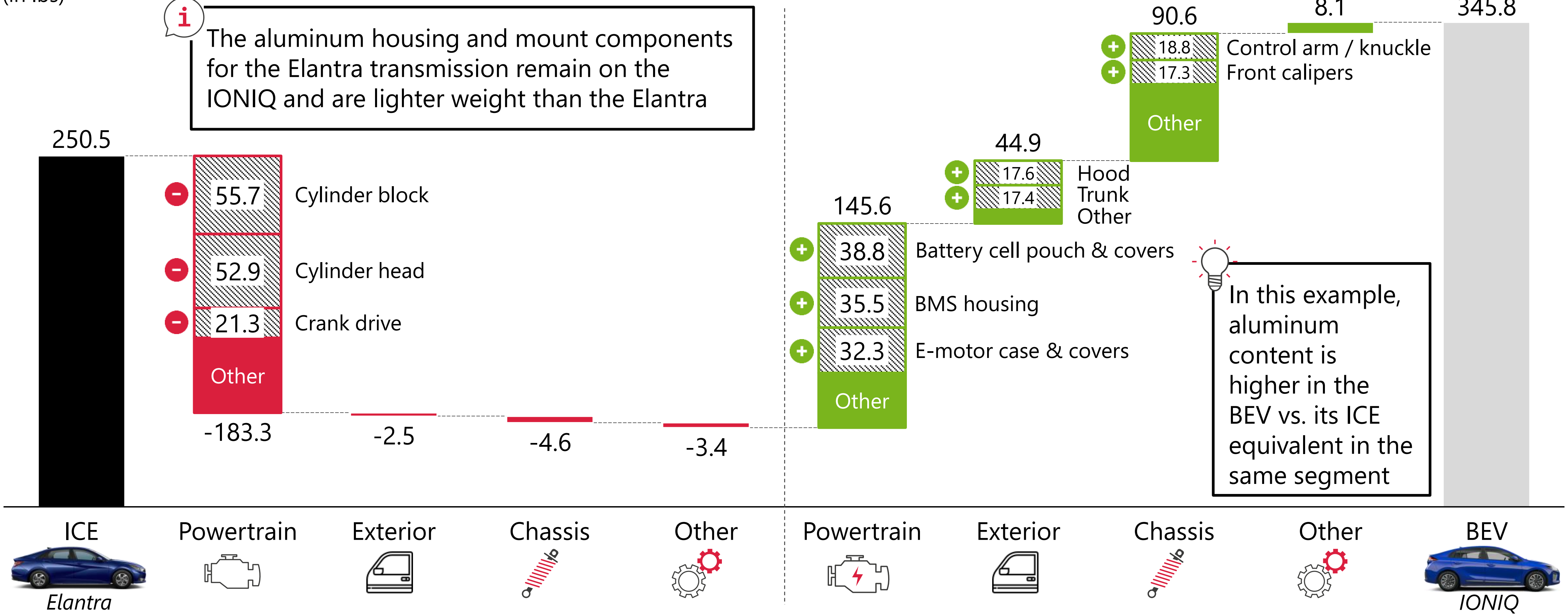
— City vehicle —

Aluminum content shift from Elantra to IONIQ
(in lbs)



The aluminum housing and mount components for the Elantra transmission remain on the IONIQ and are lighter weight than the Elantra

In this example, aluminum content is higher in the BEV vs. its ICE equivalent in the same segment

⊖ = Al. components that are eliminated moving from Elantra to IONIQ

⊕ = Al. components unique to IONIQ or was a non-Al. component in the Elantra

Task 3: Analyze the weight, cost and MPGe impact on the three BEV types with increased aluminum content via aluminum component substitutions

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KEY TAKEAWAYS / NOTES

Sensitivity analysis to show the impact on BEV weight with increased aluminum in a “substitution scenario”

“Aggressive” aluminum adoption is now assumed with aluminum substituting steel, at different levels for each BEV segment in 2025 and 2030

Material costs increase with more aluminum, but can be potentially offset by the reduction in the battery and e-motor size (kWh and kW respectively) since vehicle mass is reduced, but only in a certain threshold of aluminum share will provide net cost savings for each BEV

Sensitivity tables can show the optimal point of aluminum share in the vehicle and vehicle mass that yields the highest cost savings based on a reduction in battery capacity and required e-motor power

- Aluminum share of up to 100% is tested for each BEV, but on average, the added aluminum material cost starts to outweigh the cost reduction in battery and e-motor between 30% - 50%

The reduction in battery and e-motor size comes from reduction in vehicle mass as a result of increasing aluminum in this scenario

- The model calculates, from WLTP drive cycle data, the required battery and e-motor size from at a specific vehicle mass for each BEV

FEV internally assessed >40 components for potential to be used as aluminum substitutions (vs. steel) for each BEV type in 2025 and 2030; 20 were selected

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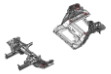
ALUMINUM SUBSTITUTION OPTIONS SELECTED FOR EACH BEV TYPE

» USED IN THE SENSITIVITY ANALYSIS

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

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.)

Adding aluminum suspension system (Fr) further reduces overall vehicle weight by ~10 lbs and slightly increases the cost / lb of weight saved vs. 2025

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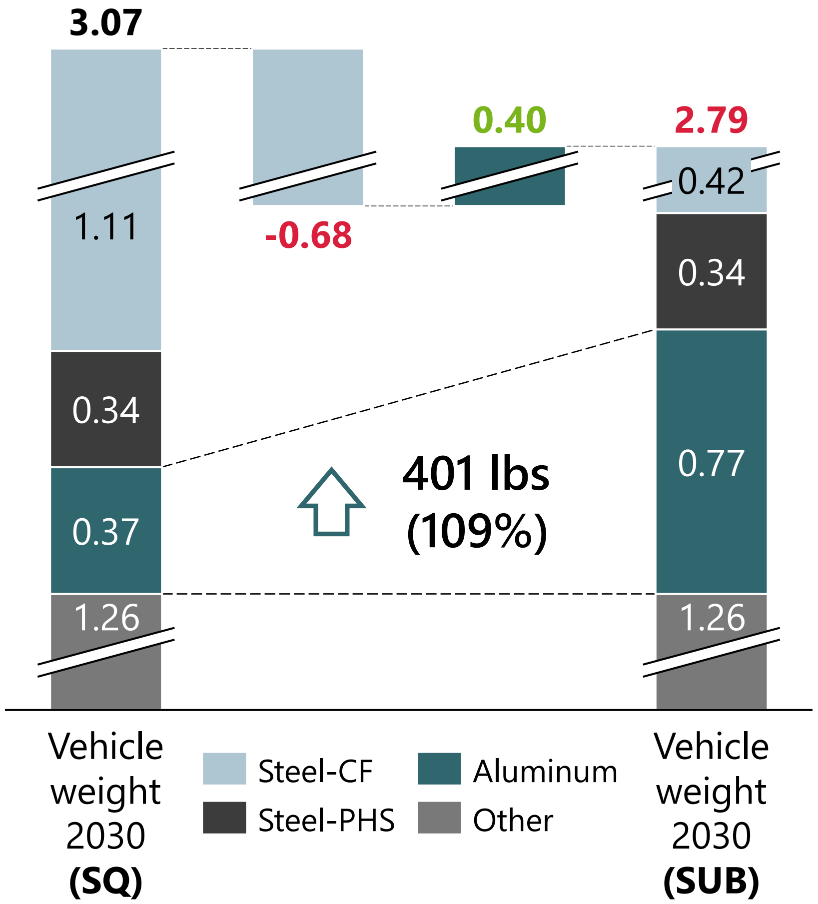
» SUBSTITUTION SCENARIO

— City vehicle —

MATERIALS SHIFT WITH ALUMINUM SUBSTITUTIONS - 2030

Material content shift with increased lightweighting (in lbs, thousands)



Selected components	Weight per vehicle (lb) / Δ net weight savings			Cost per vehicle ($) / Δ net cost savings		
	Steel	Al.	Δ	Steel	Al.	Δ
Skid plates	101.1	58.4	-42.7	166.8	234.9	+68.1
Rotor end plates	1.9	1.1	-0.8	2.9	2.6	-0.3
Front / rear floor area	303.2	176.9	-126.4	463.9	622.4	+158.5
Doors	134.1	78.2	-55.9	257.2	333,4	+65.7
Seat	108.4	64.5	-43.9	207.9	272.8	+55.9
Cross car beam	11.3	7.0	-4.3	21.8	30.2	+7.3
Suspension system (Fr)	24.3	14.5	-9.8	30.6	58.7	+28.1
Total	**684.3**	**400.5**	**-283.8**	**$1,083.1**	**$1,467.9**	**$383.3**

i The same components from 2025 are added and remaining components are reevaluated for 2030 and selected based on prioritization criteria1)

1.35
$/lb weight reduction

28% Al. share

Like the 2025 city vehicle BEV, substituting steel for aluminum results in net cost savings at 15% through 40% aluminum vehicle share

BEV ALUMINUM SUBSTITUTION SENSITIVITY ANALYSIS - 2030

» SUBSTITUTION SCENARIO

— **City vehicle** —

Vehicle content		Battery and E-motor sizing		Net lightweighting cost per vehicle 1)($)			
Al share of vehicle (%)	**Vehicle weight (lbs)**	**Battery capacity (kWh)**	**E-motor power (kW)**	**Aluminum net cost**	**Battery savings**	**E-motor savings**	**Total net cost**
12%	3072.0	67.0	120.9	0.0	0.0	0.0	-
15%	3017.4	66.2	118.8	73.7	-83.2	-4.8	-14.2
20%	2926.4	64.8	115.3	196.6	-224.4	-12.9	-40.6
FEV 28%	2788.2	62.8	110.1	383.1	-432.2	-24.8	-74.0
32%	2718.8	61.6	107.2	508.4	-548.8	-31.5	-71.9
35%	2676.1	60.9	105.3	598.7	-622.3	-35.7	-59.4
40%	2604.9	59.7	102.2	785.7	-746.7	-42.9	-3.9
45%	2533.8						84.6
49%	2475.2						194.5
55%	2368.1	55.4	91.3				443.5
60%	2277.1	53.6	86.8				698.7
65%	2186.0	51.8	82.1				998.2
70%	2095.0	49.9	77.2				1341.3
75%	2004.0	47.9	72.2	3789.6	-1950.3	-112.0	1727.3
80%	1913.0	45.8	66.8	4442.5	-2162.9	-124.2	2155.4
85%	1821.9	43.6	61.3	5147.2	-2385.5	-137.0	2624.7
90%	1730.9	41.3	55.4	5903.8	-2619.3	-150.4	3134.1
95%	1639.9	38.9	49.3	6712.3	-2865.4	-164.6	3682.3
100%	1548.9	36.4	42.8	7572.6	-3125.2	-179.5	4268.0

Max Al. share estimated when only replacing steel

Adding aluminum decreases overall cost of vehicle at aluminum share of **15% - 40%**. In this range, aluminum remains attractive versus increasing battery capacity and using steel as the main vehicle material

Point that provides the maximum net cost savings at a given aluminum share and vehicle weight

- **Status quo** city vehicle has **12%** aluminum share and is used as the starting point here for the sensitivity table
- Max. net cost savings point reached at **28%** aluminum share of vehicle using prioritized aluminum substitutions
- Net cost savings continues up to **40%** aluminum share
- Max. aluminum share possible in this model with **only steel** substitution at **~49%** - CFRP and other materials make up remainder

FEV Assessment of potential **aluminum substitutions** for **city vehicle BEVs in 2030** estimates an average **28% Al. share @ $74 cost savings per vehicle** is possible to meet performance targets and is the **optimal point**

Battery price: **102** $/kWh

E-motor price: **2.3** $/kW

Range: **300** miles

FEV estimated feasible cost savings point

Note: Net cost of aluminum substitution = sum of Al vs. steel cost differential for all steel parts substituted with Al + (Battery kWh delta X battery $/kWh price) + (E-motor kW delta X e-motor kW price)

1) All figures in each column are cumulative of the previous rows

In the 2030 family crossover BEV, substituting steel for aluminum results in net cost savings of at least 25% through 45% aluminum vehicle share

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BEV ALUMINUM SUBSTITUTION SENSITIVITY ANALYSIS - 2030

» SUBSTITUTION SCENARIO

– **Family crossover** –

Vehicle content		Battery and E-motor sizing		Net lightweighting cost per vehicle[1] ($)			
Al share of vehicle (%)	**Vehicle weight (lbs)**	**Battery capacity (kWh)**	**E-motor power (kW)**	**Aluminum net cost**	**Battery savings**	**E-motor savings**	**Total net cost**
20%	3649.0	105.0	200.1				-
25%	3557.8	102.9	195.2	204.7	-210.8	-11.3	-17.36
30%	3466.6	100.8	190.1	409.5	-427.0	-22.9	-40.42
35%	3375.4	98.6	185.0	614.2	-648.8	-34.8	-69.46
41%	[illegible]	[illegible]	179.7	849.0	-874.1	-46.9	-72.00
42%	[illegible]	[illegible]	179.1	872.1	-899.8	-48.3	-76.0
45%	[illegible]	[illegible]	175.6	1069.1	-1050.3	-56.4	-37.59
50%	3111.4	92.3	170.0	1424.9	-1290.4	-69.3	65.14
55%	3020.2	89.9	164.2	[illegible]	[illegible]	[illegible]	207.50
60%	2929.0	87.4	158.3	[illegible]	[illegible]	[illegible]	389.04
65%	2837.8	84.9	152.1	[illegible]	[illegible]	[illegible]	609.27
70%	2746.6	82.2	145.8	[illegible]	[illegible]	[illegible]	867.65
75%	2655.4	79.5	139.3	[illegible]	[illegible]	[illegible]	1163.59
80%	2564.2	76.6	132.5	[illegible]	[illegible]	[illegible]	1496.45
85%	2473.0	73.7	125.5	5232.6	-3195.6	-171.6	1865.49
90%	2381.8	70.6	118.3	5964.8	-3506.6	-188.3	2269.92
95%	2290.6	67.5	110.7	6744.0	-3829.5	-205.6	2708.84
100%	2199.4	64.2	102.9	7570.2	-4165.3	-223.6	3181.27

FEV

Max Al share estimated when only replacing steel

Adding aluminum decreases overall cost of vehicle at Al. share of **25% - 45%**. In this range, aluminum remains attractive versus increasing battery capacity and using steel as the main vehicle material

Point that provides the maximum net cost savings at a given aluminum share and vehicle weight

- **Status quo** family crossover BEV has **20%** aluminum share in 2030 and is used as the baseline for this table
- Max. net cost savings point reached at **42%** aluminum share of vehicle
- Net cost savings continues up to **45%** aluminum share
- Max. Aluminum share of vehicle with **only steel** substitution estimated at **~42%** - CFRP and other materials make up remainder

FEV

Assessment of potential **aluminum substitutions** for **family crossover BEVs in 2030** estimates achieving the net cost savings point of **41% Al. share @ ~$72 cost savings per vehicle** is feasible

Battery price: **102** $/kWh

E-motor price: **2.3** $/kW

Range: **400** miles

FEV estimated feasible cost savings point

Note: Net cost of aluminum substitution = sum of Al vs. steel cost differential for all steel parts substituted with Al + (Battery kWh delta X battery $/kWh price) + (E-motor kW delta X e-motor kW price)

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1) All figures in each column are cumulative of the previous rows

In 2030, pickup truck (PUP) BEV aluminum net cost savings extends to 53% vehicle share, the highest share with savings than the other BEV segments

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BEV ALUMINUM SUBSTITUTION SENSITIVITY ANALYSIS - 2030

» SUBSTITUTION SCENARIO

— **Pickup truck** —

Vehicle content		Battery and E-motor sizing		Net lightweighting cost per vehicle[1] ($)			
Al share of vehicle (%)	**Vehicle weight (lbs)**	**Battery capacity (kWh)**	**E-motor power (kW)**	**Aluminum net cost**	**Battery savings**	**E-motor savings**	**Total net cost**
27%	4879.0	186.0	286.7	0.0	0.0	0.0	
30%	4812.5	184.3	282.9	182.9	-175.5	-8.8	-1.4
35%	4701.8	181.4	276.5	487.8	-472.1	-23.6	-7.9
40%	4591.0	178.4	269.9	792.6	-775.6	-38.8	-21.8
45%	4480.3	175.3	263.1	1097.5	-1086.5	-54.4	-43.4
49%	4391.6	172.8	257.6	1341.4	-1341.4	-67.1	-67.1
50%	4369.5	172.2	256.1	1402.4	-1406.4	-70.4	-74.4
53%	[illegible]	[illegible]	253.4	1599.6	-1534.9	-76.8	-12.1
55%	[illegible]	[illegible]	251.4	1685.4	-1585.9	-81.3	69.2
60%	[illegible]	[illegible]	244.3	2048.6	-1909.2	-97.5	92.9
65%	4049.7	164.4	236.9	[illegible]	[illegible]	[illegible]	133.1
70%	3938.9	161.0	229.2	[illegible]	[illegible]	[illegible]	188.3
75%	3828.1	157.4	221.3	[illegible]	[illegible]	[illegible]	257.8
80%	3717.4	153.8	213.2	[illegible]	[illegible]	[illegible]	341.1
85%	3606.6	150.0	204.9	[illegible]	[illegible]	[illegible]	437.5
90%	3495.9	146.1	196.3	[illegible]	[illegible]	[illegible]	546.3
95%	3385.1	142.1	187.4	5372.0	-4527.8	-228.5	666.7
100%	3274.3	138.0	178.2	5945.9	-4949.5	-249.6	797.8

FEV

Max Al. share estimated when only replacing steel

Adding aluminum decreases overall cost of vehicle at Al. share of **30% - 60%**. In this range, aluminum remains attractive versus increasing battery capacity and using steel as the main vehicle material

Point that provides the maximum net cost savings at a given aluminum share and vehicle weight

- **Status quo** PUP has **27%** Al. share and is the point that has the maximum net cost savings
- Net cost savings continues up to **53%** Al. share
- Max. aluminum share possible in this model, with **only steel** substitution, at **~55%** - CFRP and other materials make up remainder
- Further net savings when substituting composite materials for aluminum might be possible

FEV

Assessment of potential **aluminum substitutions** for **pickup truck BEVs in 2030** estimates achieving the optimal net cost savings point of **50% Al. share @ ~$74 cost savings per vehicle** is likely feasible

Battery price: **102** $/kWh

E-motor price: **2.3** $/kW

Range: **500** miles

FEV estimated feasible cost savings point

Note: Net cost of aluminum substitution = sum of Al vs. steel cost differential for all steel parts substituted with Al + (Battery kWh delta X battery $/kWh price) + (E-motor kW delta X e-motor kW price)

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1) All figures in each column are cumulative of the previous rows

For some aluminum parts, cost declines as scale increases, driving further aluminum substitution, but costs expected to increase significantly at higher aluminum levels

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LIGHTWEIGHTING IMPACT OVERVIEW ON BEVS – SCENARIO COMPARISON: 2030

» AT THE MAX NET COST SAVINGS POINT

	Net cost of Al. adoption[1]	**Vehicle weight (lbs)**		**Aluminum weight (lbs)**		**Battery capacity (kWh)**		**E-motor power (kW)**		**Fleet avg. efficiency (MPGe)**	
		SQ	**SUB**	**SQ**	**SUB**	**SQ**	**SUB**	**SQ**	**SUB**	**SQ**	**SUB**
City vehicle	**-$74 (28% share)**	3,072	↓ 2,788	369	↑ 769	67	↓ 63	121	↓ 110	151	↑ 161
Family crossover	**-$76 (42% share)**	3,649	↓ 3,261	730	↑ 1,363	105	↓ 96	200	↓ 179	128	↑ 140
Pickup truck	**-$74 (50% share)**	4,879	↓ 4,369	1,317	↑ 2,185	186	↓ 172	287	↓ 256	91	↑ 98
ℹ	**-$74 Avg. net Al. cost savings**[1]	*More aggressive Al. adoption in long-term as costs decline w/ volume*		*Use of larger Al. parts (floor sheets, etc.) expected for all BEVs*		*Increased sensitivity in battery and E-motor size as vehicle mass further drops for all BEVs despite increase in range requirements*				*Larger gains in average BEV fleet MPGe with lower mass*	

Battery price: **102** $/kWh

E-motor price: **2.3** $/kW

Net cost of Al. formula = **Sum of Al. vs. steel or "other" cost differential for all parts selected** + **Battery kWh delta X battery $/kWh price** + **E-motor kW delta X e-motor kW price**

Note: SQ = status quo scenario (baseline, SUB = substitution scenario with more aggressive aluminum adoption by adding new aluminum components prioritized for each BEV

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[1] $ per vehicle at the maximum net cost savings point in the SUB scenario : the cost difference from increase aluminum substitution vs. the resizing of the battery and e-motor

E-motor power and battery capacity decline each year for all BEVs compared to the "status quo" scenario despite assumed increases in range requirements

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

» SUBSTITUTION SCENARIO

Parameters that changed in the substitution scenario[1)]

SPECIFICATIONS	City vehicle	Family crossover	Pickup truck
Vehicle weight (lbs.)	2,788	3,261	4,369
Acceleration (0-60 Mph in seconds)	10.0	7.0	6.5
E-drive range (miles)	300	400	500
Battery capacity (kWh)	63	96	172
E-motor power (kW)	110	179	256
Average efficiency (MPGe)	161	140	98
Aluminum share of vehicle (%)	28%	42%	50%

1) These parameters are the result of the aluminum share at the maximum net cost savings point, for a given % share of Al. content

With exception of PUP, net cost of aluminum will begin to increase greater than size reduction savings as steel vehicle content nears 0% share

BEV MATERIALS COMPOSITION – 2030

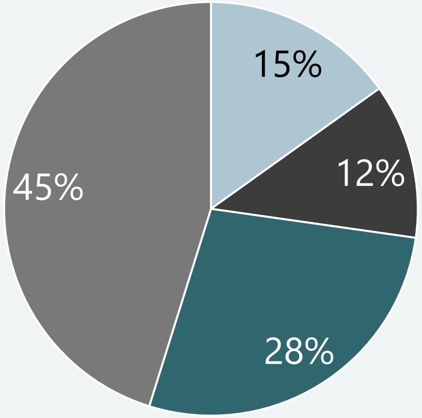
» SUBSTITUTION SCENARIO

Materials composition – vehicle level[1]
(% of total vehicle weight)

- ▨ Steel-cold forming
- ■ Steel-other[2]
- 🟩 Aluminum
- ▨ Other[3]

Trend of increasing Al. content from small to large BEVs (city vehicle to PUP) is expected to continue through 2030

City vehicle

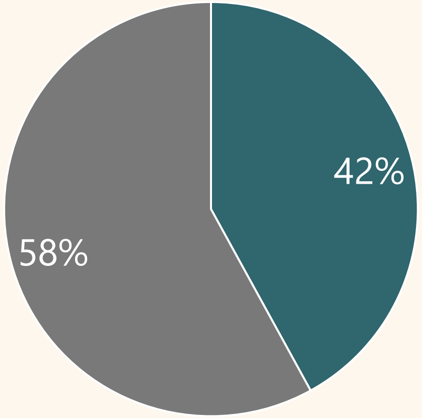


Σ vehicle weight - 2,788 lbs

Σ Aluminum weight - 769 lbs

Δ vs. status quo – 130%

Family crossover

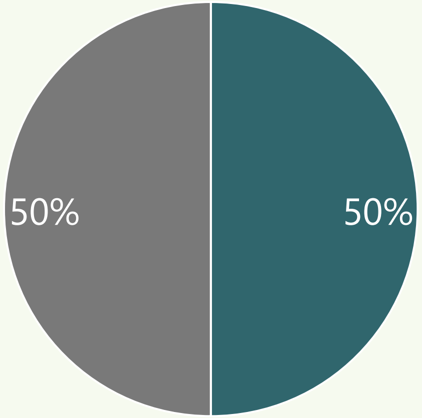


Σ vehicle weight - 3,261 lbs

Σ Aluminum weight - 1,363 lbs

Δ vs. status quo – 87%

Pickup truck



Σ vehicle weight - 4,369 lbs

Σ Aluminum weight - 2,185 lbs

Δ vs. status quo – 66%

1) Vehicle level considers all component systems including powertrain, BIW (frame and exterior panels), chassis, interior, and other, 2) Steel-other includes hot forming, billet, bar, and stainless, 3) Other includes glazing, polymers, and plastics

Note: Status quo assumes that vehicle weight reduction is mainly driven by reductions in battery size, but also factors in the "normal" FEV expectation on how material adoptions will evolve

Task 4: Analyze average efficiency impact on the BEV fleet and overall vehicle fleet at specific points of aluminum share and cost per weight saved

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PROJECT APPROACH

1 SPECIFY THREE BEVS

- Define 3 BEV types
  - City vehicle
  - Family crossover
  - Pick-up truck
- Specify performance targets for the vehicles (today, 2025, 2030)
- Baseline current vehicle structure & composition (e.g. materials used for main systems and components)
- Share FEV forecasts for 2025 and 2030 by 3 vehicle types; baseline fleet avg. fuel economy

2 ANALYZE MATERIAL SUBSTITUTIONS

- Share FEV technology roadmaps for key vehicle systems and materials
- Examine materials being used in the 3 BEVs defined in task 1
- Analyze potential options for aluminum replacing some of the materials being used for the main systems and components
- Define the 3 BEVs for 2025 and 2030 with aluminum substitutions

3 WEIGHT, COST, AND BEV EFFICIENCY IMPACT

- Analyze impact of weight due to aluminum substitution on the BEVs defined for 2025 & 2030
- Based on performance targets defined in task 1, e.g. resize battery due to weight reduction
- Calculate cost impact due to reduction in battery, motor size etc.
- Calculate BEV fleet average fuel efficiency improvement

4 TOTAL FLEET MPG AND RECOMMENDATIONS

- Calculate total fleet average fuel economy improvement
- Analyze cost vs.
  - fleet average fuel economy improvement
- Quantify value of aluminum substitution
- Recommend BEVs segments with best balance between cost and improvement in
  - fleet average fuel economy
- Summarize BEVs aluminum content targets for 2025 & 2030

KEY TAKEAWAYS / NOTES

Objective is to recommend optimal point in each BEV segment with best balance between cost and average efficiency (MPG / MPGe)

Average fleet efficiency is calculated at each point of aluminum vehicle share for each BEV type; the optimal aluminum savings point per vehicle is chosen for overall fleet MPG

City vehicle **Family crossover** **Pickup truck**

$$\text{Overall vehicle fleet efficiency} = \Sigma\left(\text{Market share forecast for city vehicle} \times \text{Weighted avg. fuel economy of city vehicle fleet}\ f\left(\text{Powertrain share forecast for city vehicle} \times \text{Powertrain type MPG estimate for city vehicle}\right)\ldots\right.$$

In 2025, choosing the MPGe at the optimal savings point for each BEV type yields an overall vehicle fleet efficiency of 38.9 MPG (all powertrain types)

- This contrasts with 37.6 MPG in the status quo scenario, an increase of ~3%

In 2030, the optimal aluminum savings point per vehicle is ~$74-$76 for all three BEV types with an estimated BEV efficiency of at least ~100 MPGe up to ~160 MPGe

- Together this improves the overall vehicle fleet efficiency to 57.3 MPG vs. 55.3 in the status quo scenario, an increase of ~4%

Aluminum content at optimal point results in average net savings of $75 per vehicle, improving OEMs’ fleet efficiency average by ~3-4% by 2030

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

The optimal aluminum savings point per vehicle is ~$74-$76 for all three BEV types with an estimated efficiency of at least ~100 MPGe up to ~160 MPGe

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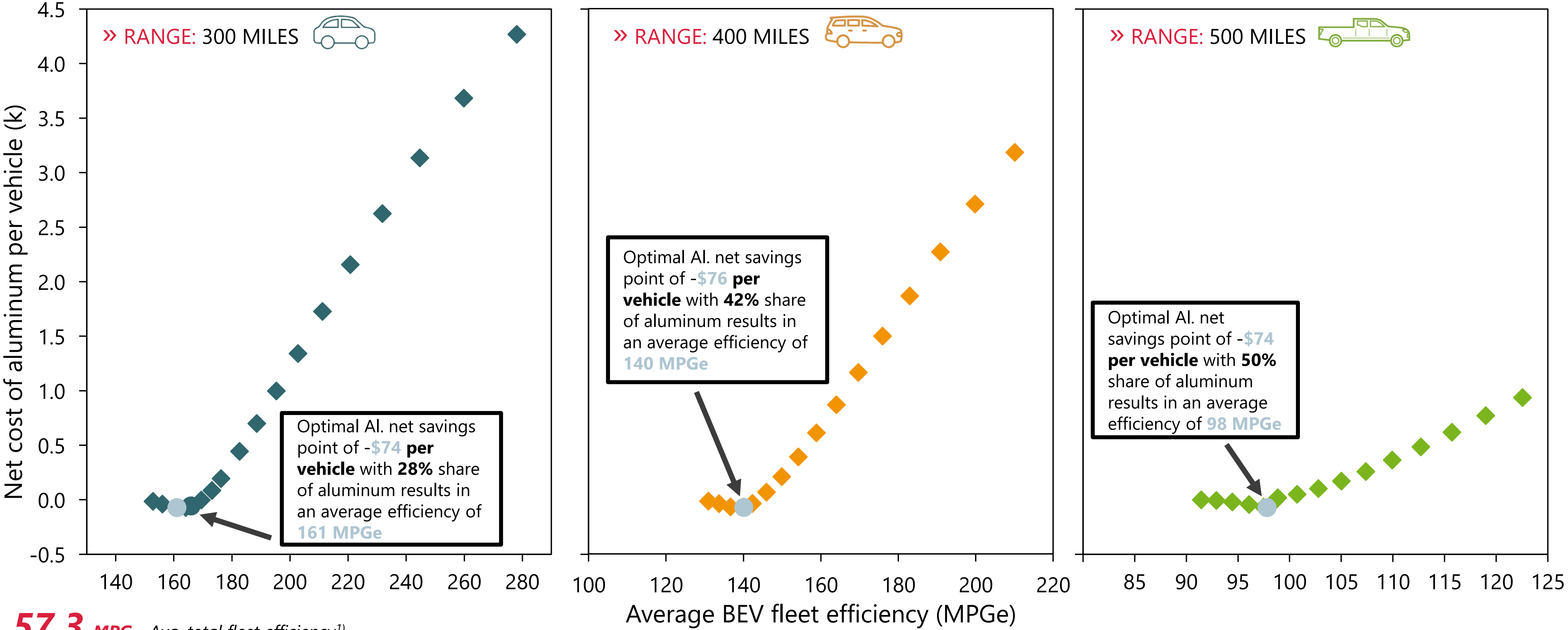
AVERAGE BEV FLEET EFFICIENCY (MPGE) VS NET COST OF ALUMINUM PER VEHICLE - 2030

At each specific point of aluminum share in vehicle



Optimal Al. net savings point of -$74 **per vehicle** with **28%** share of aluminum results in an average efficiency of 161 MPGe

Optimal Al. net savings point of -$76 **per vehicle** with **42%** share of aluminum results in an average efficiency of 140 MPGe

Optimal Al. net savings point of -$74 **per vehicle** with **50%** share of aluminum results in an average efficiency of 98 MPGe

57.3 MPG - *Avg. total fleet efficiency*[1)]

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1) Weighted avg. of all powertrain types when factoring in the new BEV MPGe at the optimal Al. savings point
Note: all graphs are set to same y-axis scale

RECOMMENDATIONS

All three BEVs yield a net savings for both 2025 and 2030 up to a certain point of aluminum share in the vehicle and within a specific $/lb weight saved

The optimal net savings point should be targeted for each BEV. The “FEV aluminum point” is typically at a lower aluminum share than the optimal point, but is considered the most feasible, so this should at least serve as a minimum target and can be achieved with the aluminum substitution mix for each BEV as analyzed in Task 3

- In 2025, an optimal net savings point of ~**$62** per vehicle at **25%** Al. share can be achieved if the average cost per pound of weight saved ($/lb weight saved) of the Al. substitutions is **$1.71**
- In 2030, an optimal net savings point of ~**$74** per vehicle at **28%** Al. share can be achieved if the average $/lb weight saved of the prioritized Al. substitutions is **$1.35** (this is also the FEV point)

- In 2025, an optimal net savings point of ~**$74** per vehicle at **25%** Al. share can be achieved if the average $/lb weight saved of the prioritized Al. substitutions is **$2.14**
- In 2030, an optimal net savings point of ~**$76** per vehicle at **42%** Al. share can be achieved if the average $/lb weight saved of the prioritized Al. substitutions is **$2.31** (**41%** is the FEV point)

- In 2025, an optimal net savings point of ~**$102** per vehicle at **35%** Al. share can be achieved if the average $/lb weight saved of the prioritized Al. substitutions is **$2.64**
- In 2030, an optimal net savings point of ~**$74** per vehicle at **50%** Al. share can be achieved if the average $/lb weight saved of the prioritized Al. substitutions is **$2.75** (**53%** is the FEV point)

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