



LDV Electrification Study

Himanshu Saxena, Sawyer D. Stone, Vishnu Nair, Sajit Pillai

March 24, 2022

Roush Advanced Engineering

Agenda

- Market segmentation and powertrain definitions
- Summarized results
 - Comparison of 2030 powertrain costs of BEV Vs ICE
 - Comparison of 2030 powertrain costs of BEV Vs Sales weighted ICE cost from CAFE analysis
 - TCO of ICE Vs battery electric vehicles purchased in 2030
 - Variation of TCO values for ICE and BEVs in different segments
 - Duration for the total cost ownership parity between ICE and BEV
- Incremental powertrain cost calculation for small SUV
- TCO Inputs
- Appendix
 - I Detailed incremental powertrain cost
 - II TCO results
 - III EV Component cost
 - IV TCO inputs

Market Segmentation

ICE and BEV Vehicles Specifications Selected for 2030 TCO Analysis

ICE powertrains for different vehicle segments

Vehicle type	Subclass ANL (EPA CAFE)	Base/ Premium	NA SI/ HCR1	BISG (NA SI/ HCR1)	SI turbo (Turbo 1)	BISG turbo 1	P2 HEV (NA SI/ HCR1)	P2 HEV (turbo 1)	Diesel
Car	Compact (Small) car	Base	●	●			●		
		Premium			●	●		●	
	Midsize (Medium) car	Base	●	●			●		
		Premium			●	●		●	
SUV	Small SUV	Base	●	●			●		
		Premium			●	●		●	
	Midsize (Medium) SUV	Base	●	●			●		
		Premium			●	●		●	
	Large SUV	Base	●	●			●		●
		Premium			●	●		●	●
Pickup	Pickup		●	●			●		●
					●	●		●	●

- Low-cost ICE powertrain
- Medium-cost ICE powertrain
- High-cost ICE powertrain
- Not considered in TCO due to very low market penetration and high cost of emissions compliance

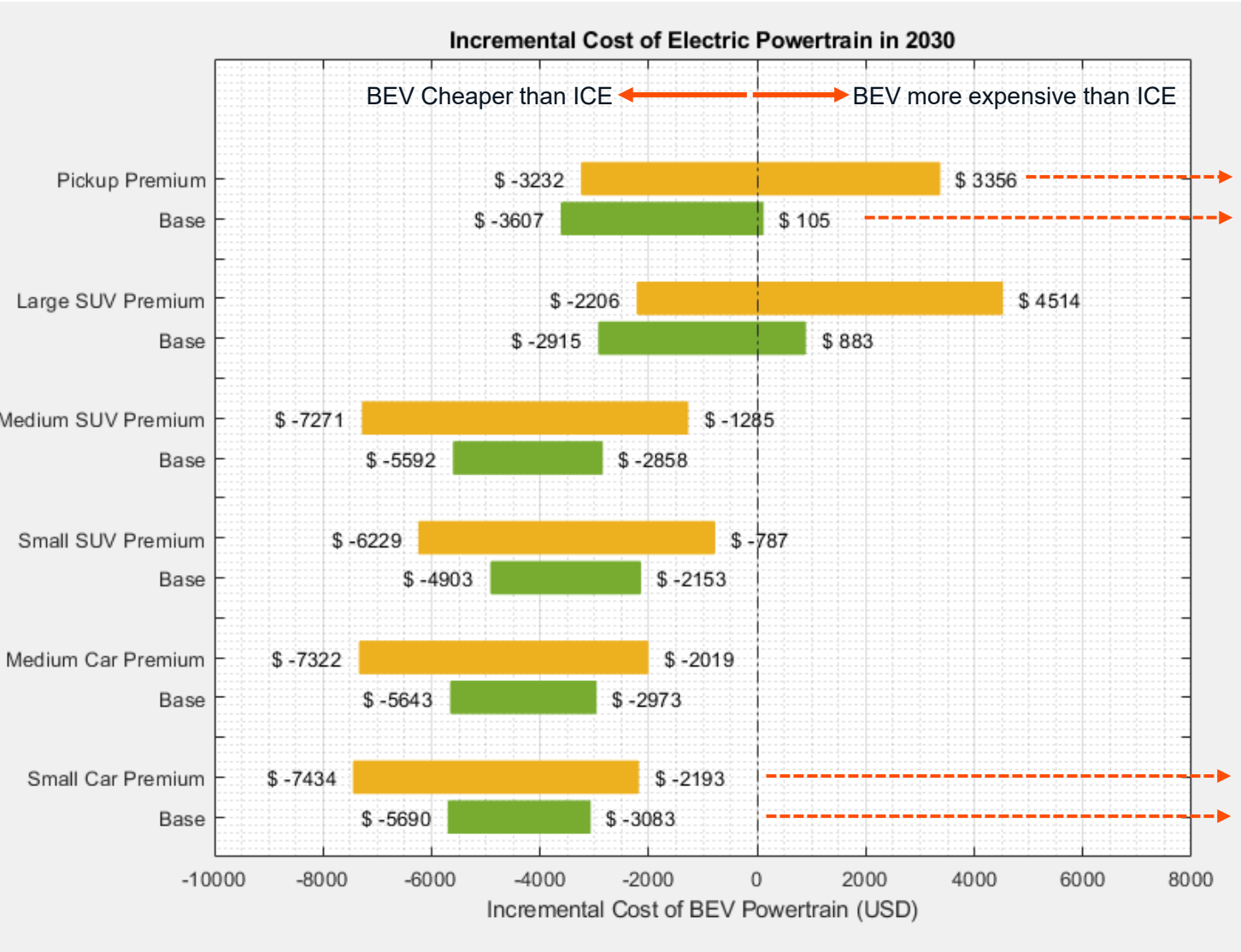
BEV range for different vehicle segments

Vehicle type	Subclass	Base/Premium	Example vehicles (range miles)	Range for study (Miles)
Car	Small car	Base	Chevy Bolt (259)	200
		Premium		300
	Medium car	Base	Nissan Leaf (150 - 226)	200
		Premium	Tesla model 3 (267 - 334) BMW i4 (270 - 301)	300
SUV	Small SUV	Base	Nissan Aria (261) VW ID.4 (240) Kia EV6 (265)	200
		Premium	Tesla Model Y (244-330) Ford Mach E (224 - 314)	300
	Medium SUV	Base	VW ID.4 (240-260) Kia EV6 (265-310)	200
		Premium	Audi E-tron (185 - 250) Tesla Model X (311 - 348) Rivian R1S (316) BMW iX (324)	300
	Large SUV	Base	GMC Hummer EV SUV (329)	300
		Premium/ high towing		400
Pickup	Pickup	Base	Ford F150 lightning (230 - 300) Rivian R1T (314)	300
		Premium/ high towing	Rivian R1T (400)	400

- 2030 BEV low cost LFP battery
- 2030 BEV medium cost NMC battery
- 2030 BEV high cost Best estimate of NMC battery cost * 1.1

Summarized Results

2030 Incremental Powertrain Cost of BEV over ICE



	ICE Powertrain	EV Powertrain
Pickup Truck – Premium	Turbo1, +BISG , +P2 HEV	BEV 400 (LFP, NMC, 1.1*NMC cost)
Base	V8 OHV, +BISG, +P2 HEV	BEV 300 (LFP, NMC, 1.1*NMC cost)
Large SUV – Premium	Turbo1, +BISG , +P2 HEV	BEV 400 (LFP, NMC, 1.1*NMC cost)
Base	V8 OHV, +BISG, +P2 HEV	BEV 300 (LFP, NMC, 1.1*NMC cost)
Medium SUV – Premium	Turbo1, +BISG , +P2 HEV	BEV 300 (LFP, NMC, 1.1*NMC cost)
Base	HCR1+CEGR, +BISG, +P2 HEV	BEV 200 (LFP, NMC, 1.1*NMC cost)
Small SUV – Premium	Turbo1, +BISG , +P2 HEV	BEV 300 (LFP, NMC, 1.1*NMC cost)
Base	HCR1+CEGR, +BISG, +P2 HEV	BEV 200 (LFP, NMC, 1.1*NMC cost)
Medium Car – Premium	Turbo1, +BISG , +P2 HEV	BEV 300 (LFP, NMC, 1.1*NMC cost)
Base	HCR1+CEGR, +BISG, +P2 HEV	BEV 200 (LFP, NMC, 1.1*NMC cost)
Small Car – Premium	Turbo1, +BISG , +P2 HEV	BEV 300 (LFP, NMC, 1.1*NMC cost)
Base	HCR1+CEGR, +BISG, +P2 HEV	BEV 200 (LFP, NMC, 1.1*NMC cost)

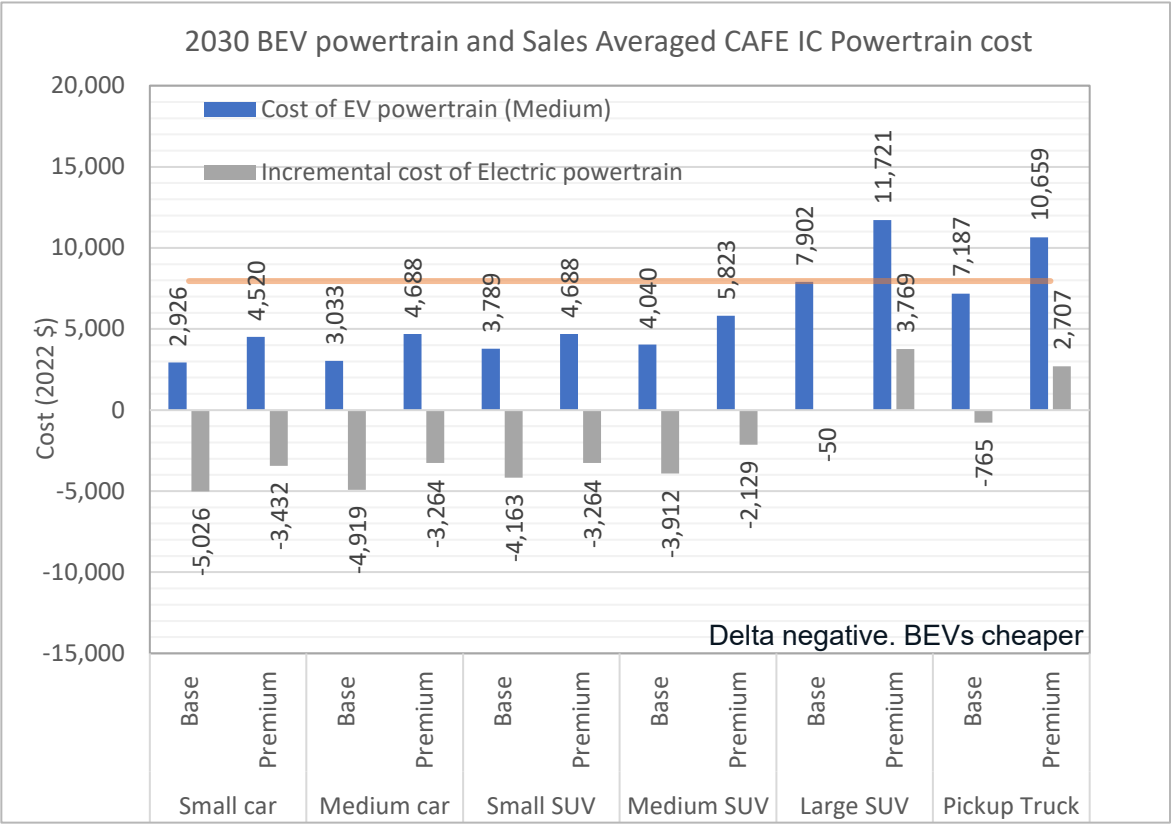
BEVs - Low cost - LFP, Medium Cost - NMC, High Cost - NMC*1.1

See Appendix 1 for detailed breakdown of each segment

2030 Incremental Powertrain Cost of BEV over ICE : Sales Weighted Fleet Average

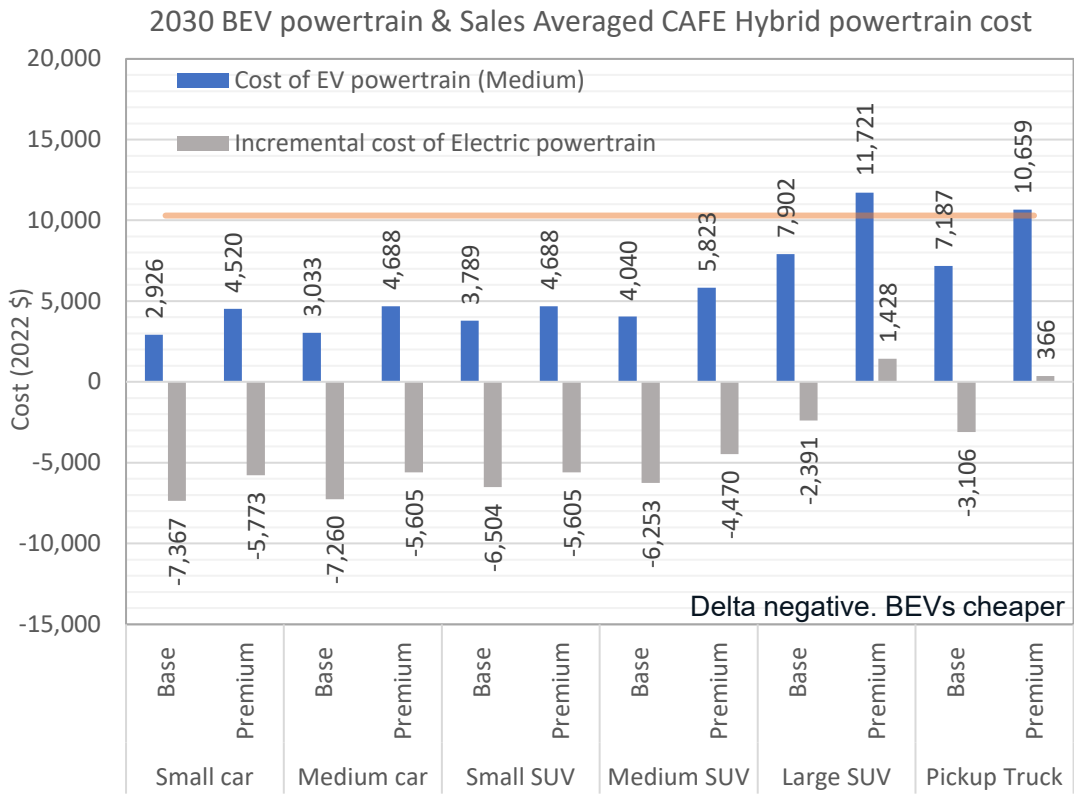
- Compares the projected 2030 BEV powertrain cost (medium cost case) to the 2030 sales averaged cost of ICE powertrain from CAFE “Market Data” file.

Current GHG standards – No change after 2026



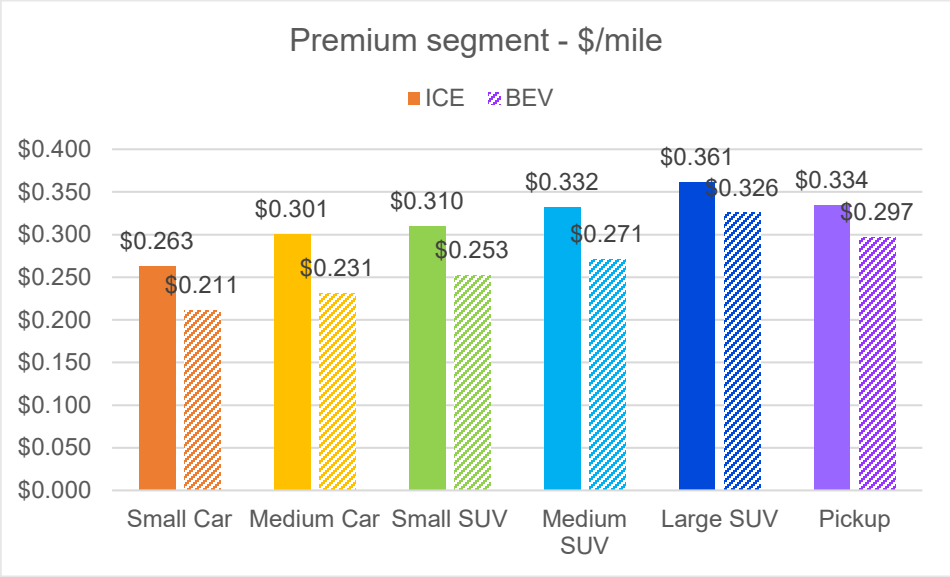
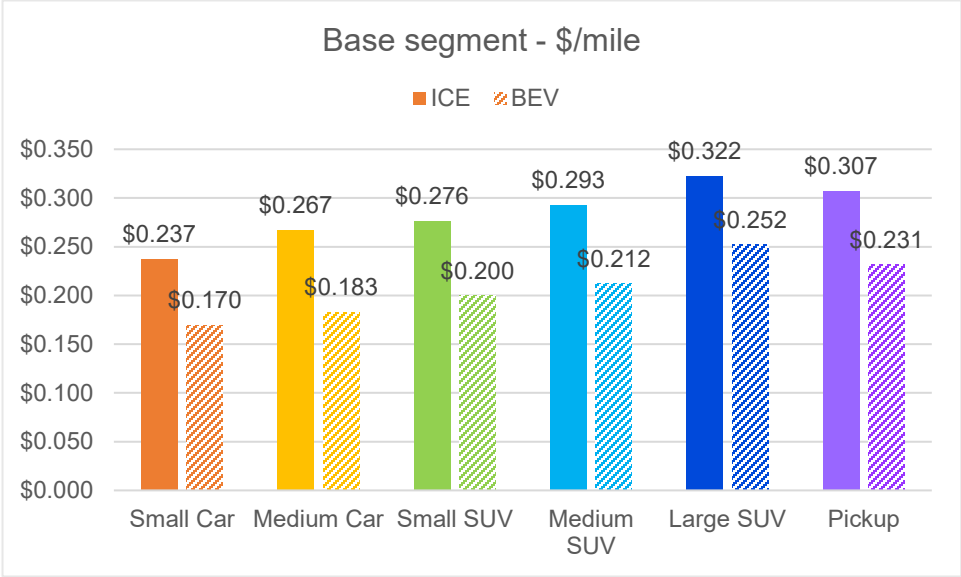
2030 sales weighted ICE powertrain cost – \$ 7,952

Stricter GHG Standards – All vehicles P2 Hybrid Powertrain



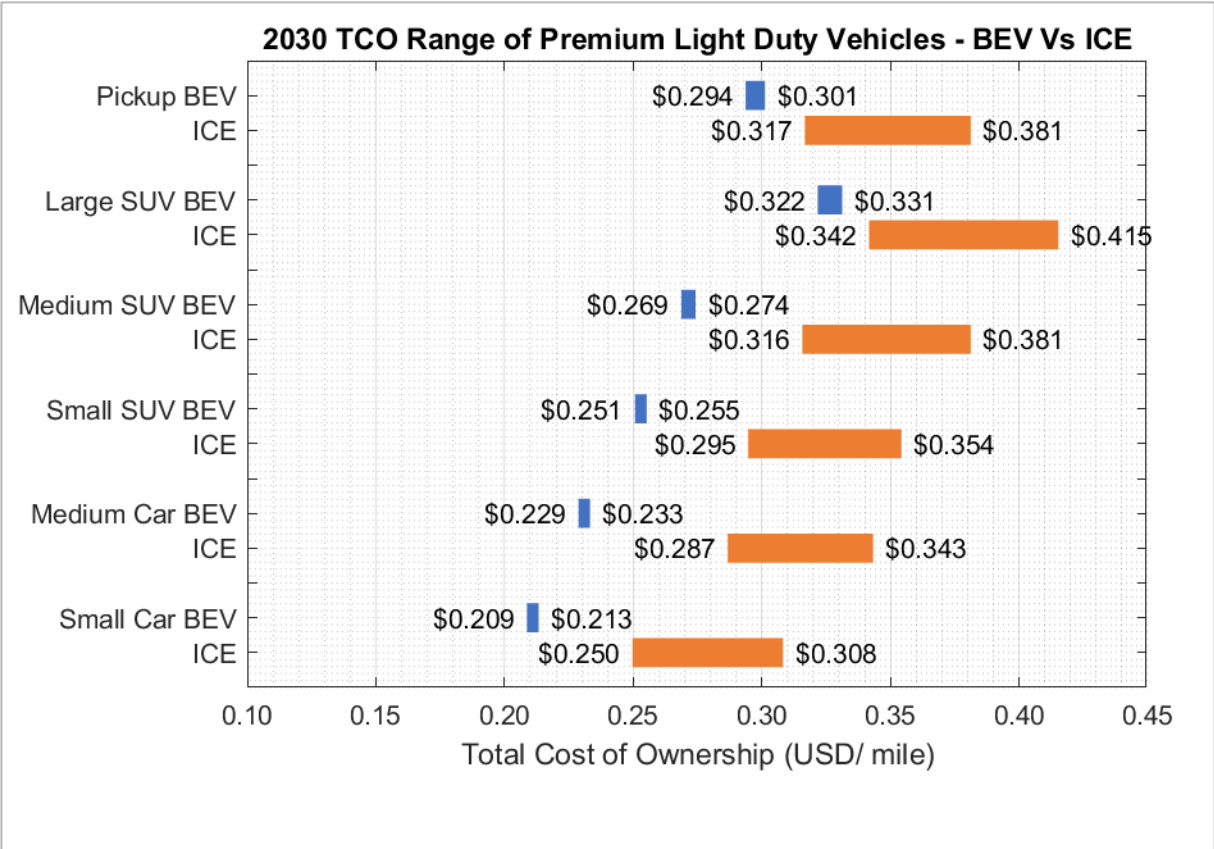
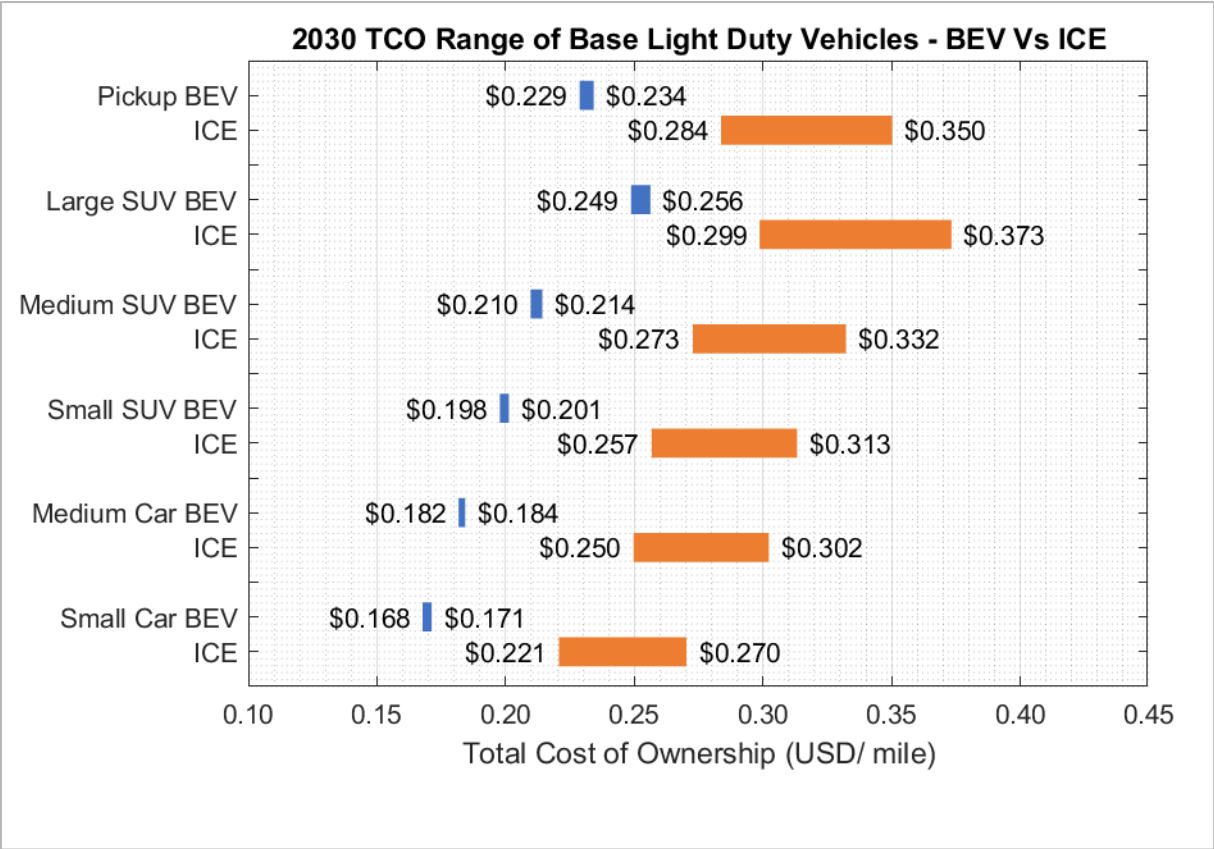
2030 sales weighted ICE P2 HEV powertrain Cost - \$ 10,293

TCO Projections for Vehicles Purchased in 2030 (Medium ICE vs Medium BEV)



Vehicle type	Subclass ANL (EPA CAFE)	Segment	BEV Range (Miles)	ICE efficiency (mpg)	Incremental EV powertrain cost (Medium case) (\$)	Duration (years) for TCO breakeven for vehicle purchased in 2030
Car	Compact (Small) car	Base	200	41	-\$3,785	Immediate
		Premium	300	49	-\$2,891	Immediate
	Midsize (Medium) car	Base	200	38	-\$3,678	Immediate
		Premium	300	44	-\$2,723	Immediate
SUV	Small SUV	Base	200	35	-\$2,922	Immediate
		Premium	300	41	-\$1,588	Immediate
	Midsize (Medium) SUV	Base	200	33	-\$3,654	Immediate
		Premium	300	39	-\$2,143	Immediate
	Large SUV	Base	300	27	-\$102	Immediate
		Premium	400	31	\$3,164	2
Pickup	Pickup	Base	300	27	-\$817	Immediate
		Premium	400	35	\$2,102	1

TCO Projections (\$/mile) - BEV vs ICE for LDVs purchased in 2030



ICE BEV

Cumulative TCO Parity for ICE & BEVs Purchased in 2030

Subclass ANL (EPA CAFE)	Segment	Low-cost BEV vs High-cost ICE	Medium-cost BEV vs Medium-cost ICE	High-cost BEV vs Low-cost ICE
Small car	Base (BEV 200)	Immediate*	Immediate*	Immediate*
	Premium (BEV 300)	Immediate*	Immediate*	Immediate*
Medium car	Base (BEV 200)	Immediate*	Immediate*	Immediate*
	Premium (BEV 300)	Immediate*	Immediate*	Immediate*
Small SUV	Base (BEV 200)	Immediate*	Immediate*	Immediate*
	Premium (BEV 300)	Immediate*	Immediate*	Immediate*
Medium SUV	Base (BEV 200)	Immediate*	Immediate*	Immediate*
	Premium (BEV 300)	Immediate*	Immediate*	Immediate*
Large SUV	Base (BEV 300)	Immediate*	Immediate*	Immediate*
	Premium (BEV 400)	Immediate*	2 years	8 years
Pickup	Base (BEV 300)	Immediate*	Immediate*	Immediate*
	Premium (BEV 400)	Immediate*	1 year	4 years

- *In 2030, for most segments we estimate that:
 - BEVs will be cheaper to purchase
 - TCO gap widens (BEV cheaper) with duration of ownership due to lower electricity and maintenance cost

Calculation of Incremental Powertrain Costs

Small SUV– ICE Vs BEV Powertrain Cost

Powertrain description	Description	Base (USD)			Premium (USD)		
		2022	2030	2035	2022	2030	2035
Conventional SI	HCR1+ CGER+ AT8L3	6,283	6,255	6,254			
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	6,866	6,711	6,697			
Conventional SI Turbo	Turbo 1+ AT8L3	6,461	6,393	6,388	7,178	7,108	7,102
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	6,849	6,697	6,683	7,567	7,411	7,398
Par HEV SI	HCR1+ AT8L3+ P2 Hybrid	8,800	8,570	8,535	9,742	9,504	9,468
Par HEV SI Turbo	Turbo1+ AT8L3+ P2 Hybrid	11,107	10,839	10,799	12,140	11,861	11,821
Conventional CI							
BEV200 - Low		7,942	3,667	3,086	8,422	3,945	3,362
BEV200 - Medium		8,138	3,789	3,185	8,622	4,069	3,464
BEV200 - High		8,782	4,102	3,441	9,280	4,390	3,728
BEV300 - Low		11,422	5,311	4,694	12,245	5,632	4,998
BEV300 - Medium		11,724	5,498	4,857	12,561	5,823	5,165
BEV300 - High		12,717	5,980	5,277	13,600	6,315	5,594

Costs Calculated from EPA Volpe technologies sheet 2021 (Input to CAFE)

BEV costs based on our best estimate of EV component costs

Low cost (green highlight)

Medium (red text)

High cost (pink highlight)

ICE Technology

Cost	Base			Premium		
	2022	2030	2035	2022	2030	2035
Low	HCR1 + CEGR + AT8L3	HCR1 + CEGR + AT8L3	HCR1 + CEGR + AT8L3	Turbo1 + 8spd AT	Turbo1 + AT8L3	Turbo1 + AT8L3
Medium	HCR1 + CEGR + AT8L3	HCR1 + CEGR + AT8L3 + BISG	HCR1 + CEGR + AT8L3 + BISG	Turbo1 + 8spd AT	Turbo1 + 8spd AT + BISG	Turbo1 + AT8L3 + BISG
High	HCR1+CEGR + AT8L3+ P2 HEV	HCR1+CEGR + AT8L3 + P2 HEV	HCR1+CEGR + AT8L3 + P2 HEV	Turbo1 + 8spd AT + P2 HEV	Turbo1 + 8spd AT + P2 HEV	Turbo1 + AT8L3+ P2 HEV

BEV Range and Costs

Cost	Base			Premium		
	2022	2030	2035	2022	2030	2035
Low	BEV 200 - LFP	BEV 200 - LFP	BEV 200 - LFP	BEV 300 – LFP	BEV 300 – LFP	BEV 300 – LFP
Medium	BEV 200 - NMC	BEV 200 - NMC	BEV 200 - NMC	BEV 300 – NMC	BEV 300 – NMC	BEV 300 – NMC
High	BEV 200 – NMC*1.1	BEV 200 – NMC*1.1	BEV 200 – NMC*1.1	BEV 300 – NMC*1.1	BEV 300 – NMC*1.1	BEV 300 – NMC*1.1

Small SUV– ICE Vs BEV Powertrain Cost

Powertrain description	Description	Base (USD)			Premium (USD)		
		2022	2030	2035	2022	2030	2035
Conventional SI	HCR1+ CGER+ AT8L3	6,283	6,255	6,254			
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	6,866	6,711	6,697			
Conventional SI Turbo	Turbo 1+ AT8L3	6,461	6,393	6,388	7,178	7,108	7,102
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	6,849	6,697	6,683	7,567	7,411	7,398
Par HEV SI	HCR1+ AT8L3+ P2 Hybrid	8,800	8,570	8,535	9,742	9,504	9,468
Par HEV SI Turbo	Turbo1+ AT8L3+ P2 Hybrid	11,107	10,839	10,799	12,140	11,861	11,821
Conventional CI							
BEV200 - Low		7,496	4,436	3,746	7,967	4,722	4,031
BEV200 - Medium		8,258	4,877	4,106	8,745	5,172	4,402
BEV200 - High		8,914	5,256	4,415	9,414	5,560	4,721
BEV300 - Low		10,734	6,263	5,533	11,525	6,595	5,847
BEV300 - Medium		11,909	6,940	6,122	12,755	7,286	6,451
BEV300 - High		12,921	7,522	6,630	13,813	7,882	6,971

Low cost (green highlight)

Medium (red text)

High cost (pink highlight)

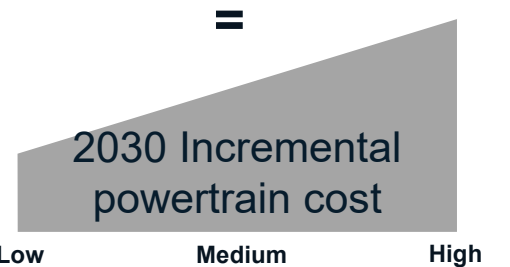
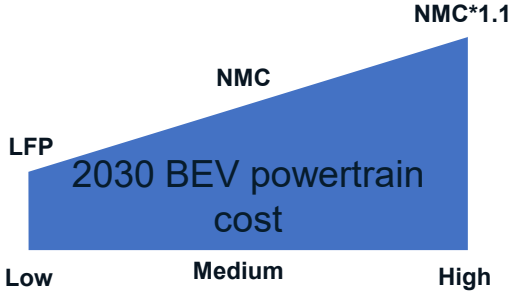
			Base			Premium		
			2022	2030	2035	2022	2030	2035
BEV200	Energy Consumption including charger	Wh/mile	314	240	226	323	246	234
	Battery	KW.hr	58	49	44	59	50	46
	Motor	KW	136	110	105	183	146	140
	Inverter	kW	136	110	105	183	146	140
	Battery usable size	KW.hr	52	44	42	53	45	43
BEV300	Energy Consumption including charger	Wh/mile	329	246	241	340	253	249
	Battery	KW.hr	89	75	73	93	77	74
	Motor	KW	148	115	110	199	153	147
	Inverter	kW	148	115	110	199	153	147
	Battery usable size	KW.hr	80	68	68	84	69	70



BEV specifications from

“A Detailed Vehicle Modeling & Simulation Study
Quantifying Energy Consumption and Cost Reduction of
Advanced Vehicle Technologies Through 2050”
(ANL/ESD-21/10)

ICE Vs BEV Powertrain Cost Comparison Methodology (Small SUV)

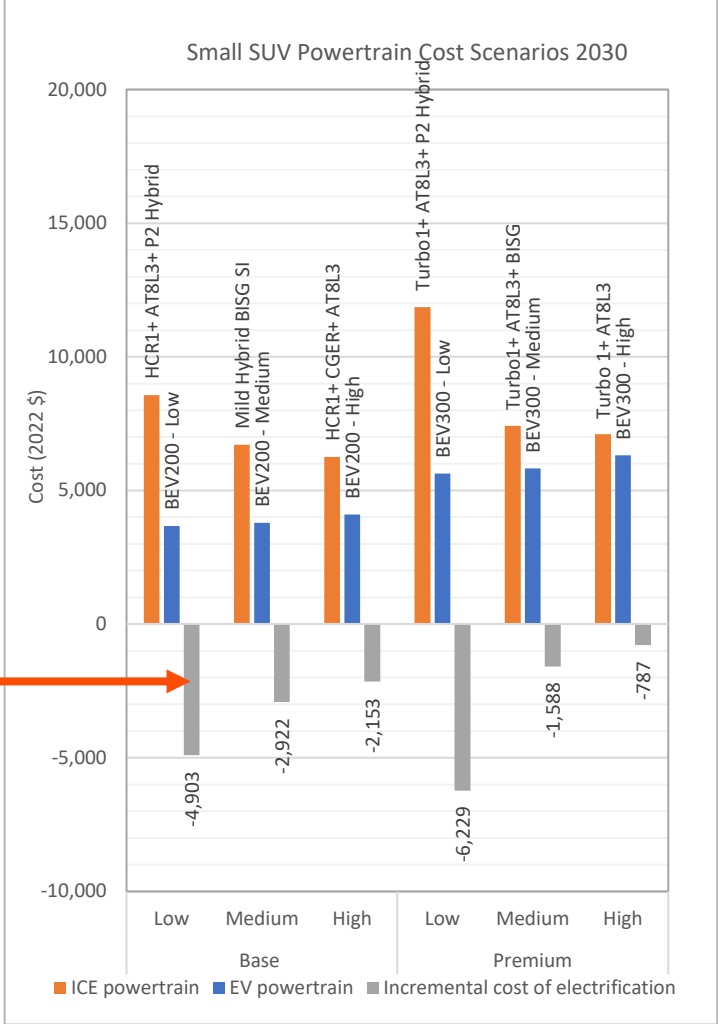


Lowest increase in powertrain cost (2030) when moving from ICE to BEV

Increasing incremental cost of moving to electric powertrain

Highest increase in powertrain cost (2030) when moving from ICE to BEV

ICE powertrain cheaper
→ incremental cost negative



Small SUV– ICE Vs BEV Powertrain Cost

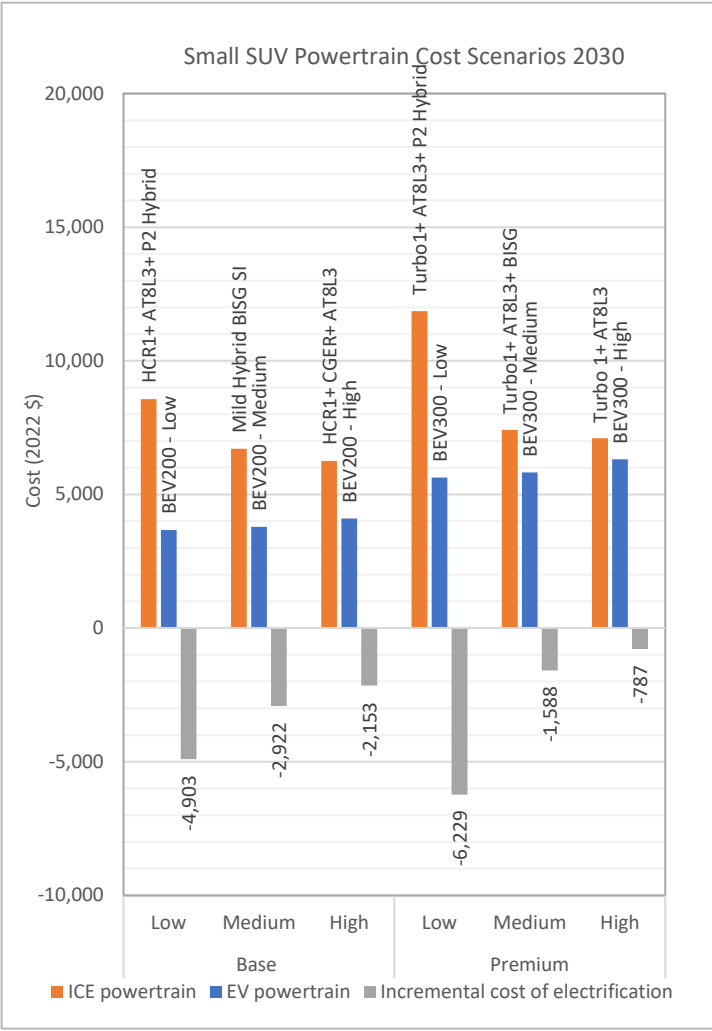
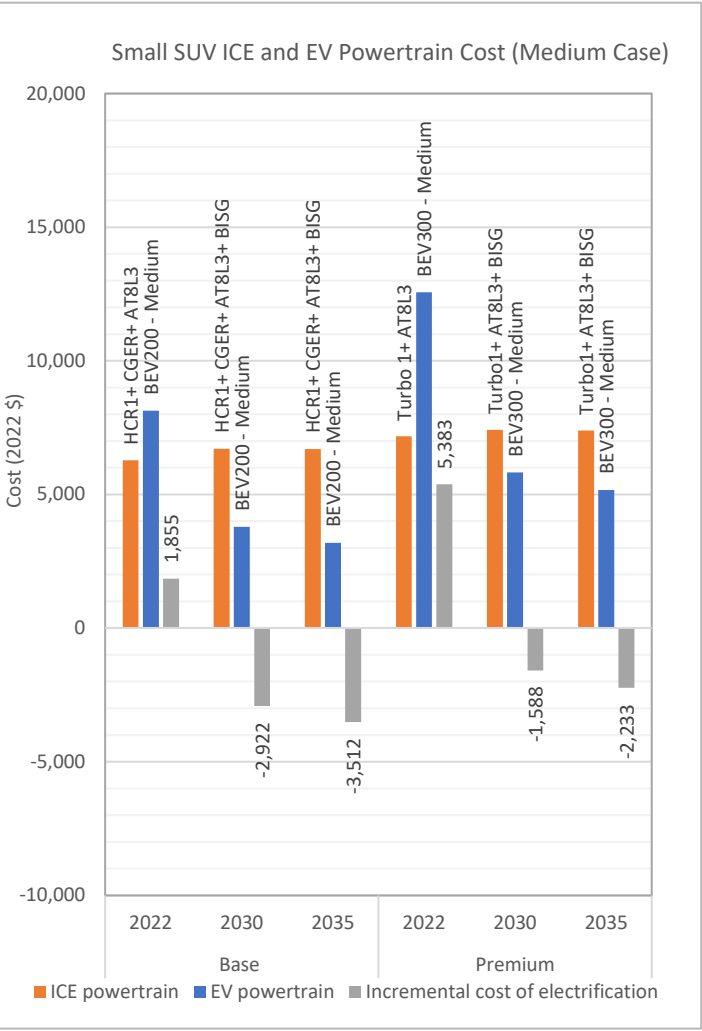
Powertrain description	Description	Base (USD)			Premium (USD)		
		2022	2030	2035	2022	2030	2035
Conventional SI	HCR1+ CGER+ AT8L3	6,283	6,255	6,254			
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	6,866	6,711	6,697			
Conventional SI Turbo	Turbo 1+ AT8L3	6,461	6,393	6,388	7,178	7,108	7,102
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	6,849	6,697	6,683	7,567	7,411	7,398
Par HEV SI	HCR1+ AT8L3+ P2 Hybrid	8,800	8,570	8,535	9,742	9,504	9,468
Par HEV SI Turbo	Turbo1+ AT8L3+ P2 Hybrid	11,107	10,839	10,799	12,140	11,861	11,821
Conventional CI							
BEV200 - Low		7,496	4,436	3,746	7,967	4,722	4,031
BEV200 - Medium		8,258	4,877	4,106	8,745	5,172	4,402
BEV200 - High		8,914	5,256	4,415	9,414	5,560	4,721
BEV300 - Low		10,734	6,263	5,533	11,525	6,595	5,847
BEV300 - Medium		11,909	6,940	6,122	12,755	7,286	6,451
BEV300 - High		12,921	7,522	6,630	13,813	7,882	6,971

Low cost (green highlight)

Medium (red text)

High cost (pink highlight)

			Base			Premium		
			2022	2030	2035	2022	2030	2035
BEV200	Energy Consumption including charger	Wh/mile	314	240	226	323	246	234
	Battery	KW.hr	58	49	44	59	50	46
	Motor	KW	136	110	105	183	146	140
	Inverter	kW	136	110	105	183	146	140
	Battery usable size	KW.hr	52	44	42	53	45	43
BEV300	Energy Consumption including charger	Wh/mile	329	246	241	340	253	249
	Battery	KW.hr	89	75	73	93	77	74
	Motor	KW	148	115	110	199	153	147
	Inverter	kW	148	115	110	199	153	147
	Battery usable size	KW.hr	80	68	68	84	69	70



TCO Analysis

TCO Inputs

- Costs considered
 - Vehicle Glider cost
 - ICE/BEV powertrain cost
 - Fuel/Electricity
 - Maintenance costs
 - BEV charger cost
- Sensitivity
 - Fuel/electricity costs
 - Charging
- Vehicle age – 15 years
- 3% annual discount rate

Category	Vehicle Class	Maintenance cost per mile
ICE	Small Sedan	\$0.088
	Medium Sedan	\$0.104
	Subcompact SUV	\$0.099
	Medium SUV (4WD)	\$0.100
	Midsize Pickup	\$0.099
BEV	Electric Vehicle (all classes)	\$0.077

Maintenance cost from AAA 2021

Segment	Annual VMT (miles)
Cars	15922
SUVs	16234
Pickup trucks	18964

ANL 2021*

Year	Reference case 2021 \$/gal (MEDIUM CASE)	Low oil price 2021 \$/gal (HIGH CASE)	High oil price 2021 \$/gal (LOW CASE)	\$/kWh (MEDIUM CASE)	\$/kWh (HIGH CASE)	\$/kWh (LOW CASE)
2030	2.80	2.07	4.23	0.130	0.130	0.127
2031	2.89	2.16	4.26	0.130	0.131	0.127
2032	2.91	2.17	4.29	0.131	0.131	0.127
2033	2.94	2.20	4.26	0.132	0.132	0.127
2034	2.96	2.21	4.30	0.132	0.133	0.127
2035	2.97	2.24	4.34	0.132	0.133	0.126

EIA AEO 2022

*Burnham, Andrew, et al. Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains. No. ANL/ESD-21/4. Argonne National Lab.(ANL), Argonne, IL US, 2021.

ROUSH[®]

INGENUITY ON DEMAND

Appendix I - Incremental Powertrain Cost Detailed

- Small car
- Medium car
- Small SUV
- Medium SUV
- Large SUV
- Pickup Truck

Small Car – ICE Vs BEV Powertrain Cost

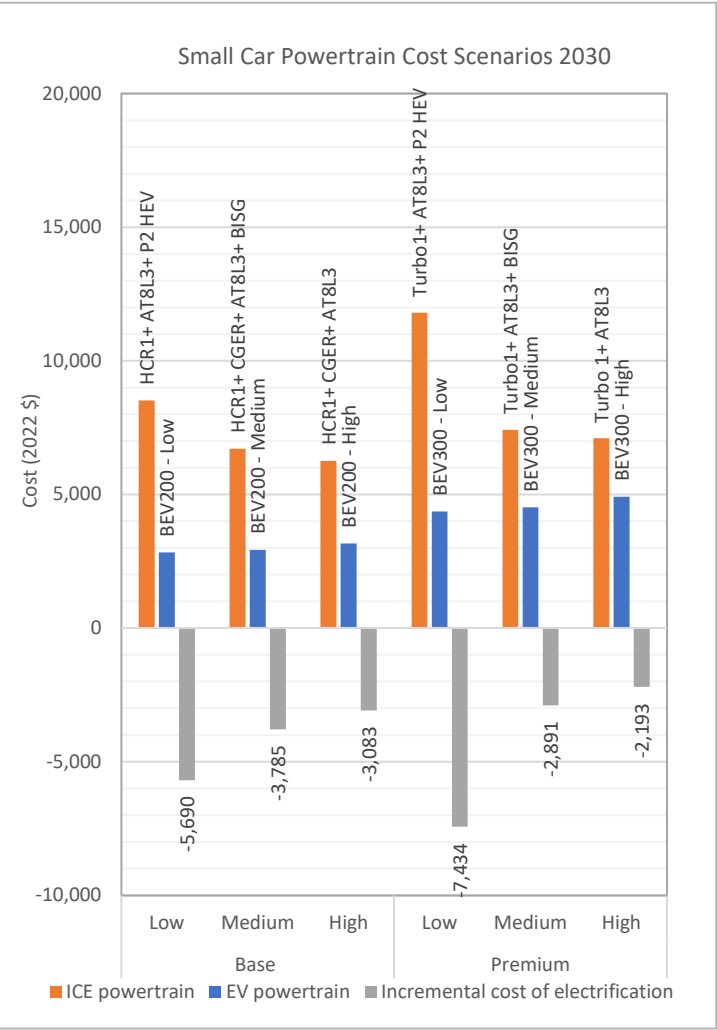
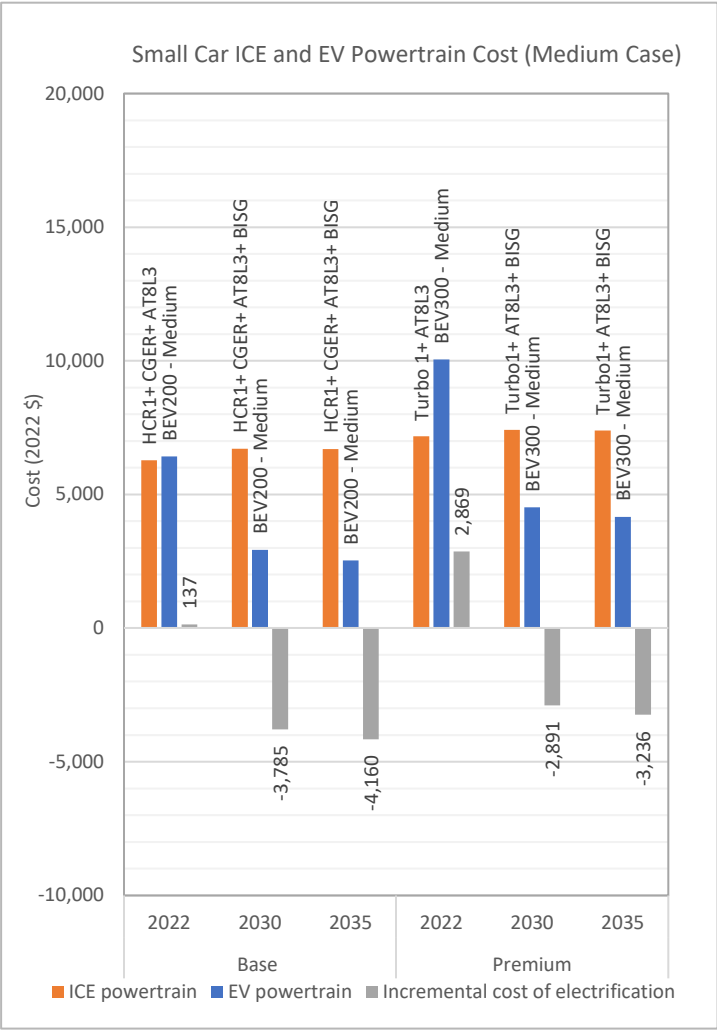
Powertrain description	Description	Base (USD)			Premium (USD)		
		2022	2030	2035	2022	2030	2035
Conventional SI	HCR1+ CGER+ AT8L3	6,283	6,255	6,254			
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	6,866	6,711	6,697			
Conventional SI Turbo	Turbo 1+ AT8L3	6,461	6,393	6,388	7,178	7,108	7,102
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	6,849	6,697	6,683	7,567	7,411	7,398
Par HEV SI	HCR1+ AT8L3+ P2 Hybrid	8,739	8,520	8,486	9,672	9,446	9,411
Par HEV SI Turbo	Turbo1+ AT8L3+ P2 Hybrid	11,046	10,788	10,750	12,070	11,803	11,764
Conventional CI							
BEV200 - Low		6,267	2,830	2,456	6,734	3,091	2,695
BEV200 - Medium		6,420	2,926	2,537	6,894	3,192	2,780
BEV200 - High		6,924	3,172	2,745	7,424	3,452	2,999
BEV300 - Low		9,067	4,122	3,705	9,793	4,368	4,024
BEV300 - Medium		9,306	4,269	3,836	10,047	4,520	4,162
BEV300 - High		10,093	4,648	4,172	10,884	4,909	4,516

Low cost (green highlight)

Medium (red text)

High cost (pink highlight)

			Base			Premium		
			2022	2030	2035	2022	2030	2035
BEV200	Energy Consumption including charger	Wh/mile	245	188	181	257	197	190
	Battery	KW.hr	45	38	36	47	40	38
	Motor	KW	93	76	74	123	99	97
	Inverter	kW	93	76	74	123	99	97
	Battery usable size	KW.hr	41	35	34	43	36	36
BEV300	Energy Consumption including charger	Wh/mile	257	193	192	270	202	203
	Battery	KW.hr	70	59	58	75	61	61
	Motor	KW	101	79	78	133	104	103
	Inverter	kW	101	79	78	133	104	103
	Battery usable size	KW.hr	63	53	55	67	55	58



Medium Car – ICE Vs BEV Powertrain Cost

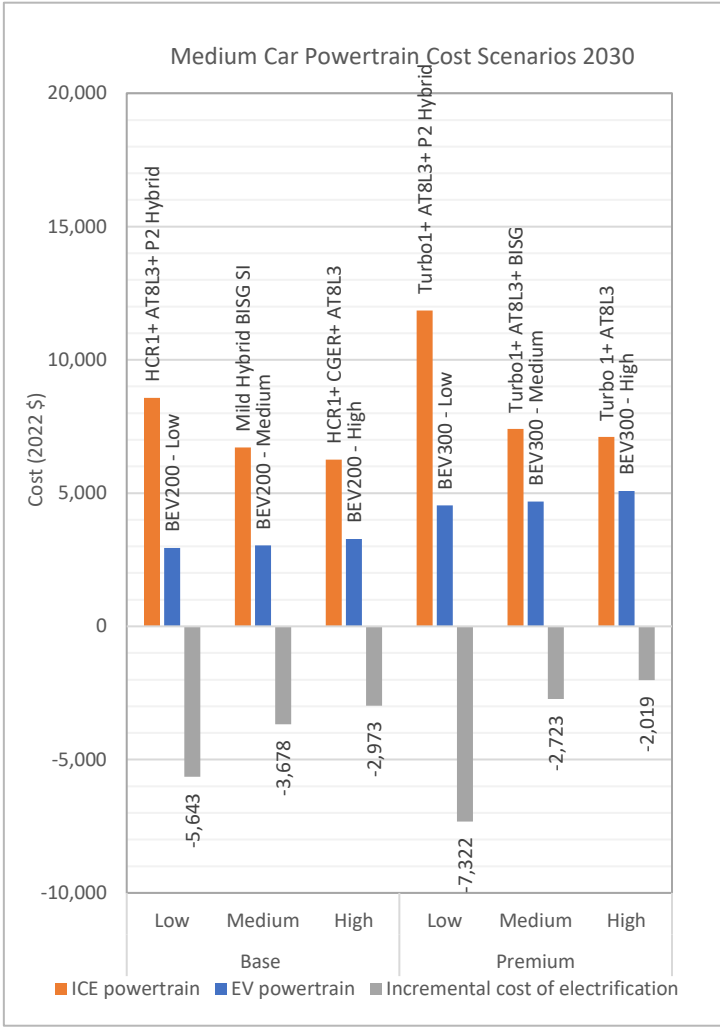
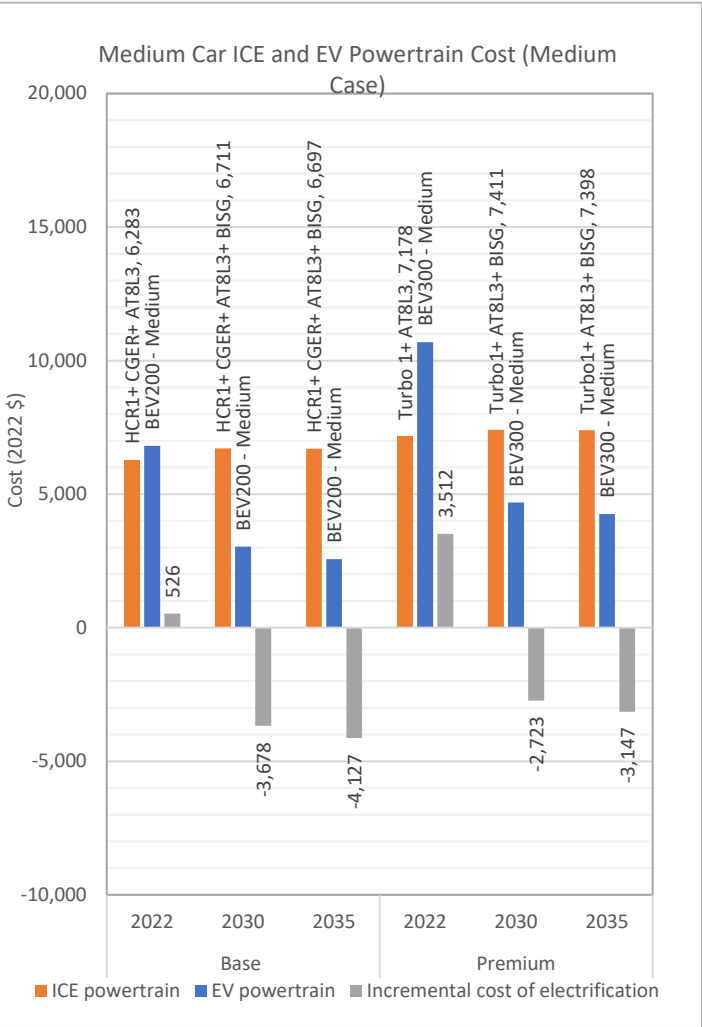
Powertrain description	Description	Base (USD)			Premium (USD)		
		2022	2030	2035	2022	2030	2035
Conventional SI	HCR1+ CGER+ AT8L3	6,283	6,255	6,254			
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	6,866	6,711	6,697			
Conventional SI Turbo	Turbo 1+ AT8L3	6,461	6,393	6,388	7,178	7,108	7,102
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	6,849	6,697	6,683	7,567	7,411	7,398
Par HEV SI	HCR1+ AT8L3+ P2 Hybrid	8,810	8,579	8,543	9,737	9,500	9,463
Par HEV SI Turbo	Turbo1+ AT8L3+ P2 Hybrid	11,117	10,847	10,808	12,135	11,857	11,816
Conventional CI							
BEV200 - Low		6,649	2,936	2,489	7,184	3,229	2,785
BEV200 - Medium		6,809	3,033	2,570	7,351	3,331	2,871
BEV200 - High		7,335	3,283	2,775	7,902	3,594	3,091
BEV300 - Low		9,659	4,246	3,774	10,425	4,535	4,113
BEV300 - Medium		9,911	4,395	3,905	10,690	4,688	4,251
BEV300 - High		10,740	4,779	4,242	11,565	5,083	4,605

Low cost (green highlight)

Medium (red text)

High cost (pink highlight)

			Base			Premium		
			2022	2030	2035	2022	2030	2035
BEV200	Energy Consumption including charger	Wh/mile	256	190	180	268	200	191
	Battery	KW.hr	47	39	36	49	41	38
	Motor	KW	115	88	84	155	119	113
	Inverter	kW	115	88	84	155	119	113
	Battery usable size	KW.hr	42	35	34	44	37	36
BEV300	Energy Consumption including charger	Wh/mile	269	196	193	282	205	203
	Battery	KW.hr	74	60	58	78	62	61
	Motor	KW	125	92	88	169	124	119
	Inverter	kW	125	92	88	169	124	119
	Battery usable size	KW.hr	67	54	55	70	55	58



Small SUV– ICE Vs BEV Powertrain Cost

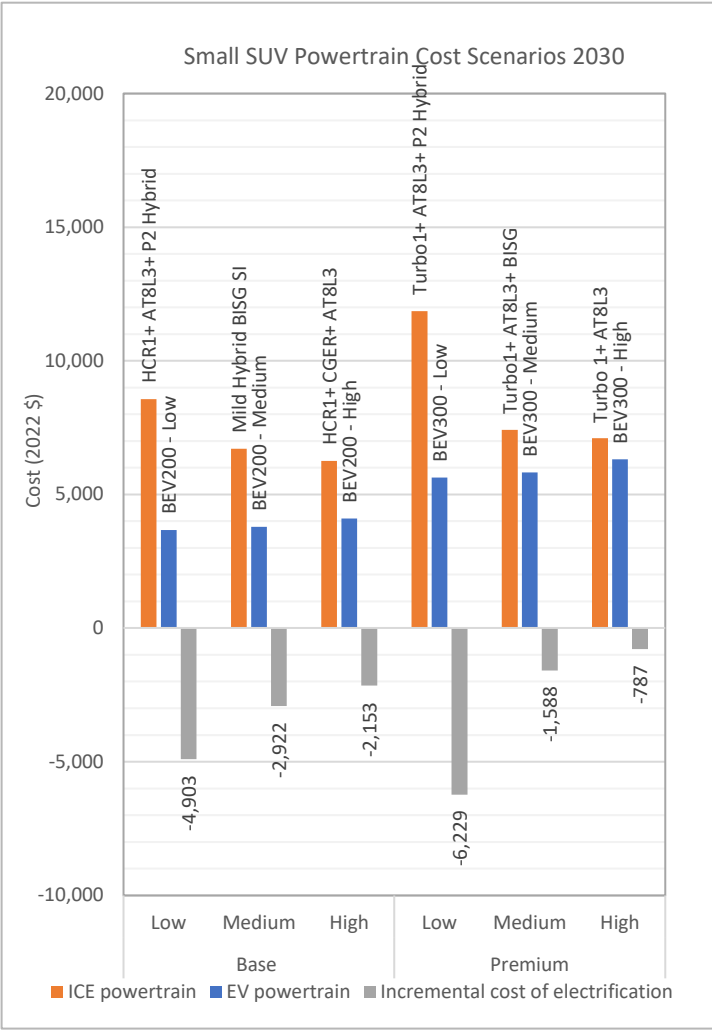
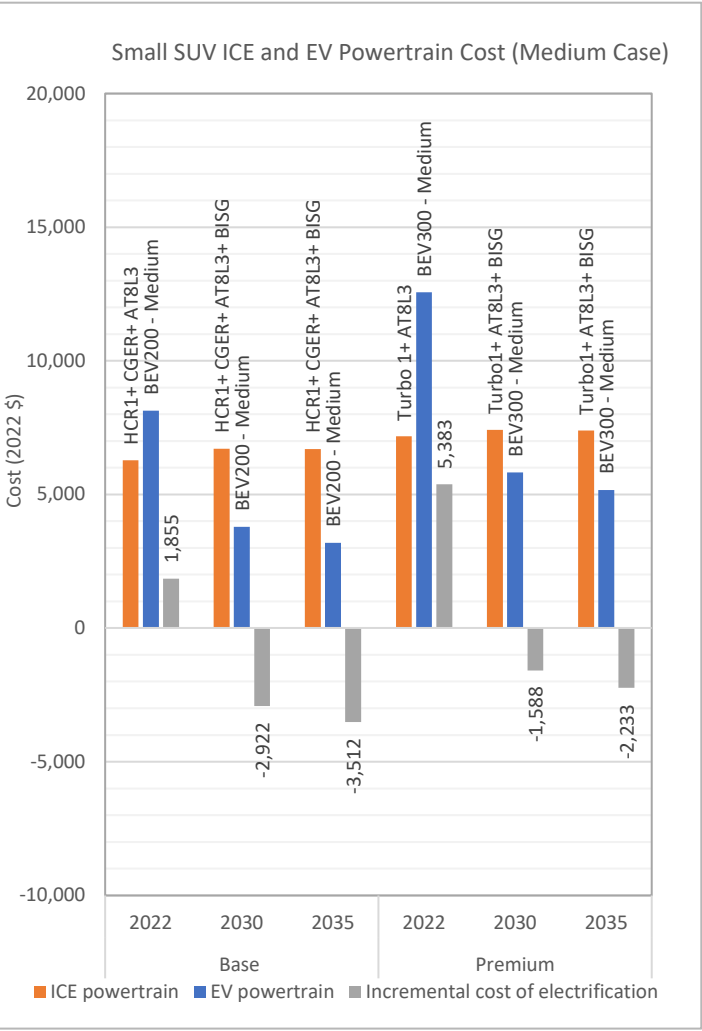
Powertrain description	Description	Base (USD)			Premium (USD)		
		2022	2030	2035	2022	2030	2035
Conventional SI	HCR1+ CGER+ AT8L3	6,283	6,255	6,254			
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	6,866	6,711	6,697			
Conventional SI Turbo	Turbo 1+ AT8L3	6,461	6,393	6,388	7,178	7,108	7,102
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	6,849	6,697	6,683	7,567	7,411	7,398
Par HEV SI	HCR1+ AT8L3+ P2 Hybrid	8,800	8,570	8,535	9,742	9,504	9,468
Par HEV SI Turbo	Turbo1+ AT8L3+ P2 Hybrid	11,107	10,839	10,799	12,140	11,861	11,821
Conventional CI							
BEV200 - Low		7,496	4,436	3,746	7,967	4,722	4,031
BEV200 - Medium		8,258	4,877	4,106	8,745	5,172	4,402
BEV200 - High		8,914	5,256	4,415	9,414	5,560	4,721
BEV300 - Low		10,734	6,263	5,533	11,525	6,595	5,847
BEV300 - Medium		11,909	6,940	6,122	12,755	7,286	6,451
BEV300 - High		12,921	7,522	6,630	13,813	7,882	6,971

Low cost (green highlight)

Medium (red text)

High cost (pink highlight)

			Base			Premium		
			2022	2030	2035	2022	2030	2035
BEV200	Energy Consumption including charger	Wh/mile	314	240	226	323	246	234
	Battery	KW.hr	58	49	44	59	50	46
	Motor	KW	136	110	105	183	146	140
	Inverter	kW	136	110	105	183	146	140
	Battery usable size	KW.hr	52	44	42	53	45	43
BEV300	Energy Consumption including charger	Wh/mile	329	246	241	340	253	249
	Battery	KW.hr	89	75	73	93	77	74
	Motor	KW	148	115	110	199	153	147
	Inverter	kW	148	115	110	199	153	147
	Battery usable size	KW.hr	80	68	68	84	69	70



Medium SUV – ICE Vs BEV Powertrain Cost

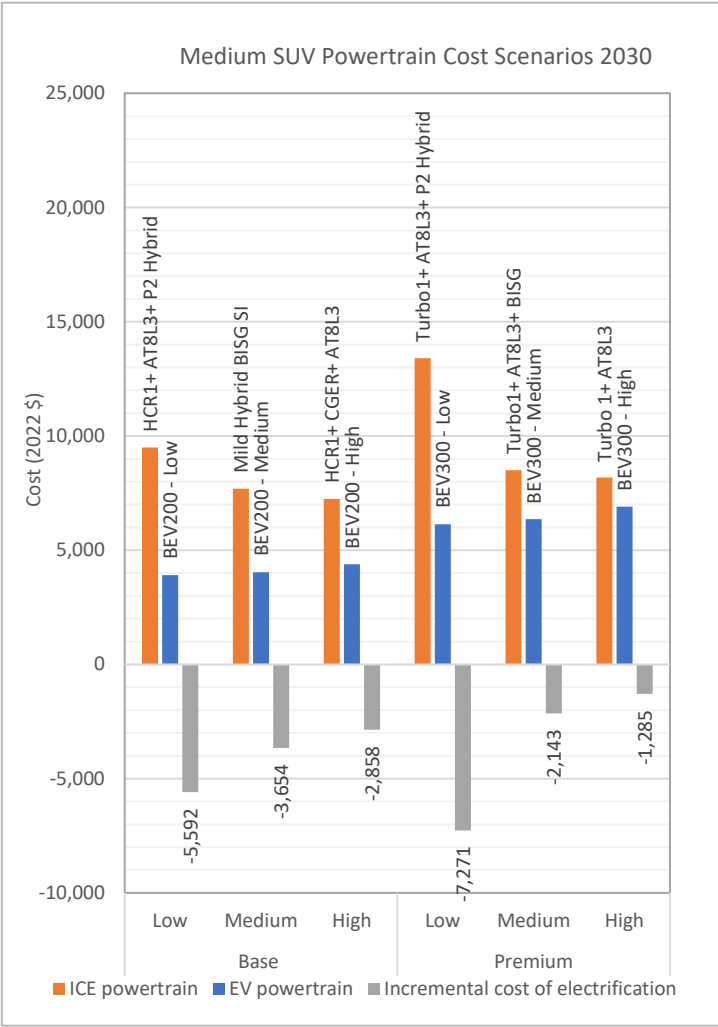
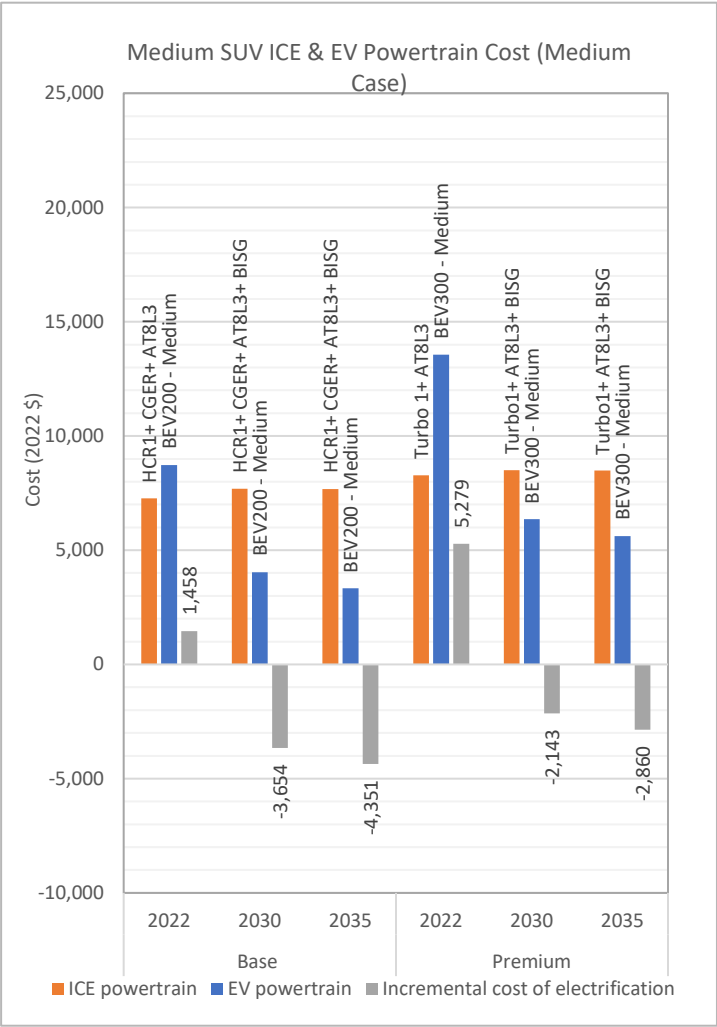
Powertrain description	Description	Base (USD)			Premium (USD)		
		2022	2030	2035	2022	2030	2035
Conventional SI	HCR1+ CGER+ AT8L3	7,266	7,239	7,237			
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	7,848	7,694	7,680			
Conventional SI Turbo	Turbo 1+ AT8L3	7,178	7,108	7,102	8,285	8,194	8,187
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	7,567	7,411	7,398	8,673	8,497	8,482
Par HEV SI	HCR1+ AT8L3+ P2 Hybrid	9,736	9,499	9,463	10,695	10,445	10,407
Par HEV SI Turbo	Turbo1+ AT8L3+ P2 Hybrid	12,134	11,856	11,816	13,732	13,413	13,369
Conventional CI							
BEV200 - Low		8,509	3,907	3,223	9,182	4,269	3,609
BEV200 - Medium		8,723	4,040	3,329	9,406	4,408	3,722
BEV200 - High		9,428	4,381	3,602	10,143	4,764	4,013
BEV300 - Low		12,466	5,703	5,009	13,218	6,142	5,436
BEV300 - Medium		12,802	5,908	5,186	13,564	6,355	5,622
BEV300 - High		13,906	6,432	5,641	14,704	6,902	6,099

Low cost (green highlight)

Medium (red text)

High cost (pink highlight)

			Base			Premium		
			2022	2030	2035	2022	2030	2035
BEV200	Energy Consumption including charger	Wh/mile	345	262	246	360	272	258
	Battery	KW.hr	63	53	47	66	56	50
	Motor	KW	132	105	100	181	143	137
	Inverter	kW	132	105	100	181	143	137
	Battery usable size	KW.hr	57	48	44	59	50	47
BEV300	Energy Consumption including charger	Wh/mile	361	269	262	377	280	275
	Battery	KW.hr	99	82	79	102	85	83
	Motor	KW	144	110	106	198	150	143
	Inverter	kW	144	110	106	198	150	143
	Battery usable size	KW.hr	89	74	74	92	77	78



Large SUV – ICE Vs BEV Powertrain Cost

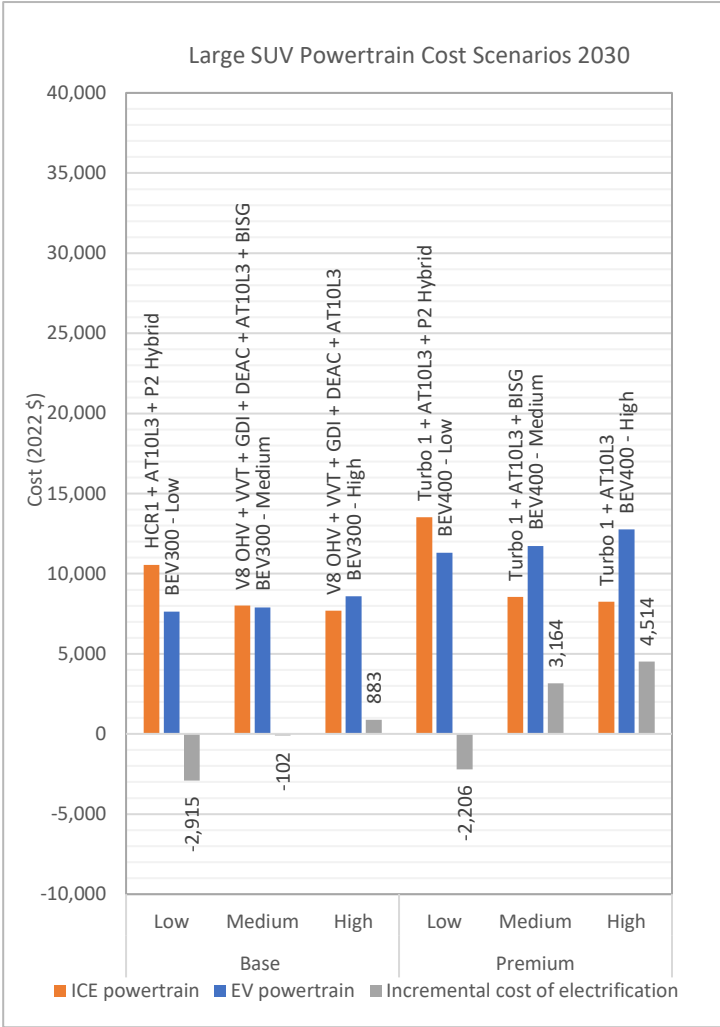
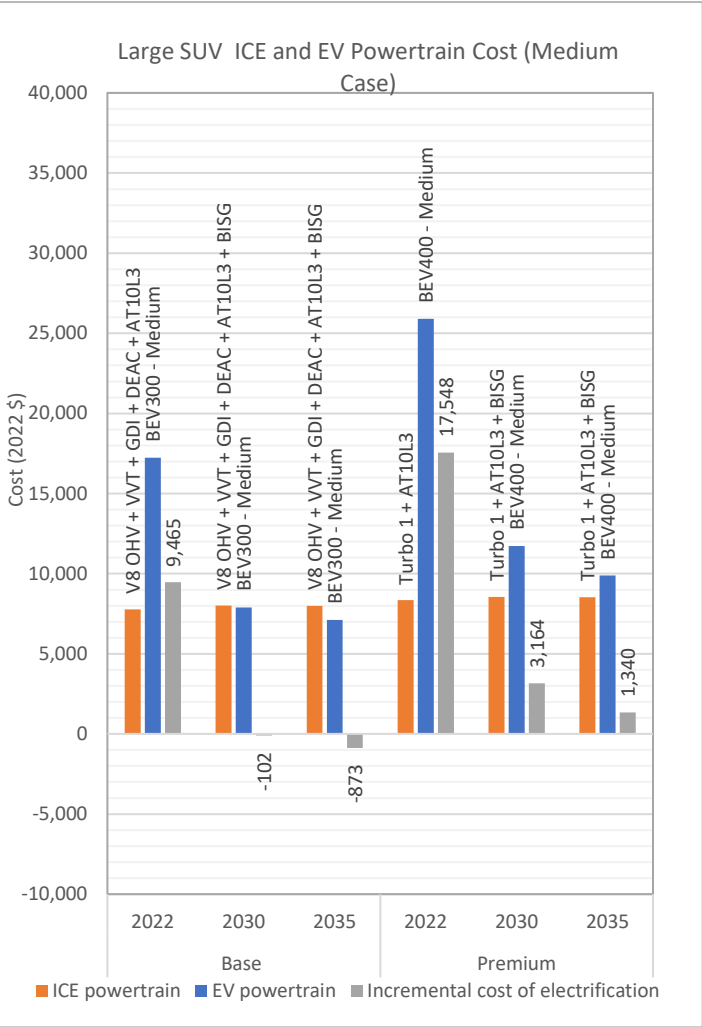
Powertrain description	Description	Base (USD)			Premium (USD)		
		2022	2030	2035	2022	2030	2035
Conventional SI	V8 OHV + AT10L3	7,779	7,700	7,692	7,779	7,700	7,692
Mild Hybrid BISG SI	V8 OHV + AT10L3 + BISG	8,167	8,004	7,987	8,167	8,004	7,987
Conventional SI Turbo	Turbo 1 + AT10L3	8,350	8,253	8,246	8,350	8,253	8,246
Mild Hybrid BISG SI Turbo	Turbo 1 + AT10L3 + BISG	8,739	8,557	8,541	8,739	8,557	8,541
Par HEV SI	HCR1 + AT10L3 + P2 Hybrid	10,819	10,553	10,513	10,819	10,553	10,513
Par HEV SI Turbo	Turbo 1 + AT10L3 + P2 HEV	13,856	13,521	13,475	13,856	13,521	13,475
Conventional CI		12,674	12,443	12,420	12,674	10,104	10,081
BEV300 - Low		16,797	7,637	6,879	17,467	8,043	7,278
BEV300 - Medium		17,244	7,902	7,114	17,929	8,320	7,526
BEV300 - High		18,715	8,583	7,720	19,450	9,033	8,163
BEV400 - Low		23,835	10,596	9,036	25,201	11,314	9,544
BEV400 - Medium		24,495	10,978	9,356	25,899	11,721	9,881
BEV400 - High		26,670	11,961	10,181	28,195	12,767	10,747

Low cost (green highlight)

Medium (red text)

High cost (pink highlight)

			Base			Premium		
			2022	2030	2035	2022	2030	2035
BEV300	Energy Consumption including charger	Wh/mile	486	359	351	507	374	367
	Battery	KW.hr	132	106	105	136	111	110
	Motor	KW	248	186	181	271	204	198
	Inverter	kW	248	186	181	271	204	198
	Battery usable size	KW.hr	119	96	99	123	100	104
BEV400	Energy Consumption including charger	Wh/mile	533	383	358	559	400	375
	Battery	KW.hr	195	153	143	206	163	150
	Motor	KW	276	197	190	301	216	207
	Inverter	kW	276	197	190	301	216	207
	Battery usable size	KW.hr	175	138	134	185	147	141



Pickup Truck– ICE Vs BEV Powertrain Cost

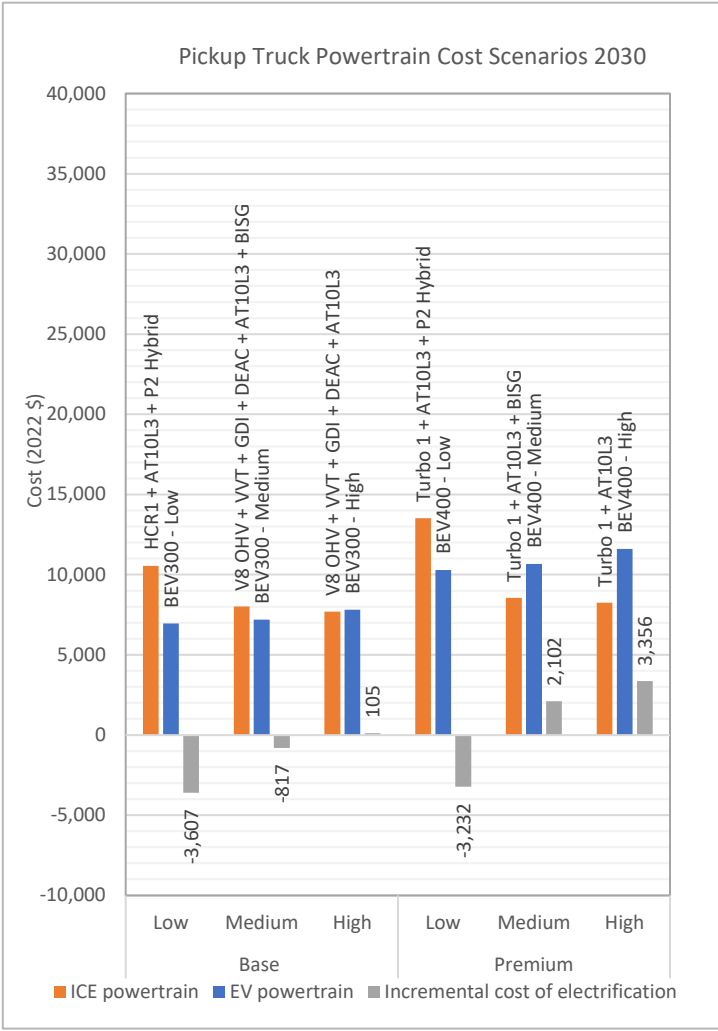
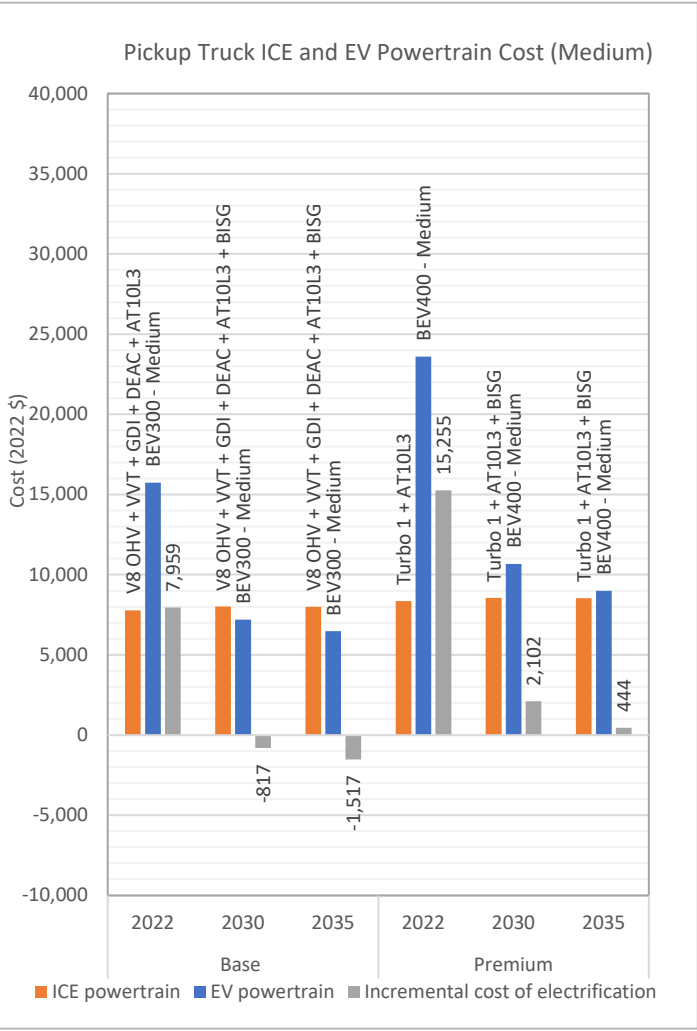
Powertrain description	Description	Base (USD)			Premium (USD)		
		2022	2030	2035	2022	2030	2035
Conventional SI	V8 OHV + AT10L3	7,779	7,700	7,692	7,779	7,700	7,692
Mild Hybrid BISG SI	V8 OHV + AT10L3 + BISG	8,167	8,004	7,987	8,167	8,004	7,987
Conventional SI Turbo	Turbo 1 + AT10L3	8,351	8,254	8,246	8,351	8,254	8,246
Mild Hybrid BISG SI Turbo	Turbo 1 + AT10L3 + BISG	8,739	8,557	8,541	8,739	8,557	8,541
Par HEV SI	HCR1 + AT10L3 + P2 Hybrid	10,819	10,553	10,513	10,819	10,553	10,513
Par HEV SI Turbo	Turbo 1 + AT10L3 + P2 HEV	13,856	13,521	13,475	13,856	13,521	13,475
Conventional CI		12,674	12,443	12,420	12,674	10,104	10,081
BEV300 - Low		15,332	6,946	6,257	15,940	7,314	6,619
BEV300 - Medium		15,738	7,187	6,471	16,360	7,566	6,845
BEV300 - High		17,075	7,806	7,021	17,743	8,214	7,423
BEV400 - Low		21,729	9,636	8,217	22,972	10,289	8,679
BEV400 - Medium		22,330	9,983	8,509	23,606	10,659	8,985
BEV400 - High		24,306	10,876	9,258	25,693	11,610	9,773

Low cost (green highlight)

Medium (red text)

High cost (pink highlight)

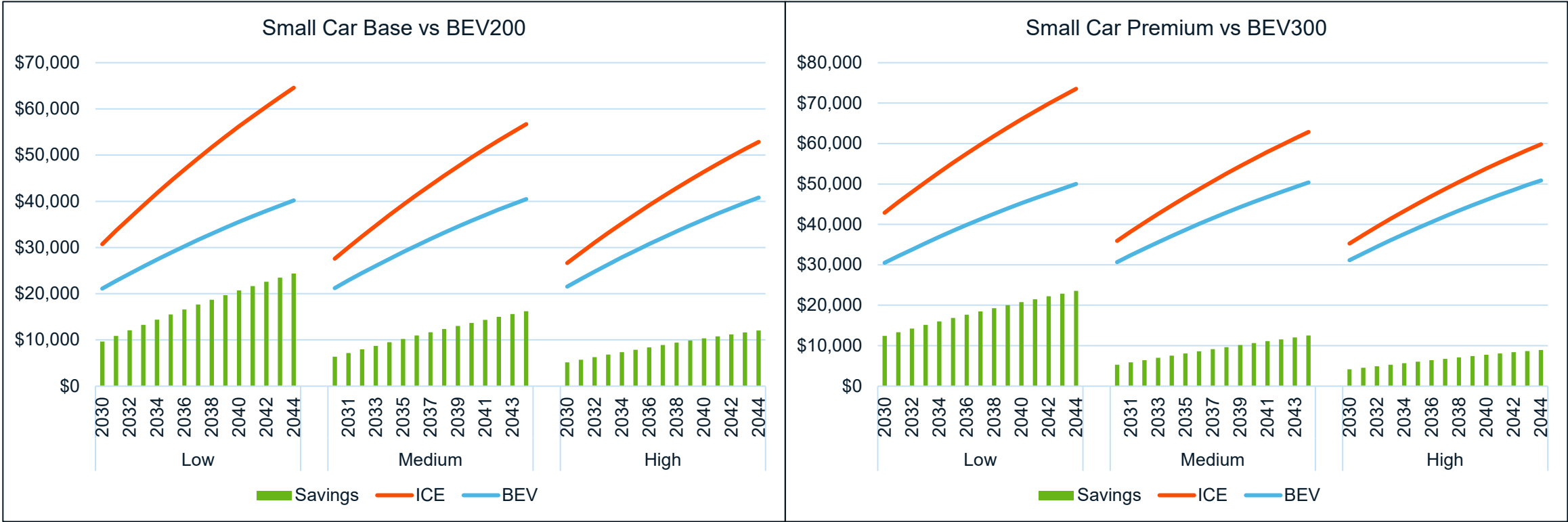
			Base			Premium		
			2022	2030	2035	2022	2030	2035
BEV200	Energy Consumption including charger	Wh/mile	314	240	226	323	246	234
	Battery	KW.hr	58	49	44	59	50	46
	Motor	KW	136	110	105	183	146	140
	Inverter	kW	136	110	105	183	146	140
	Battery usable size	KW.hr	52	44	42	53	45	43
BEV300	Energy Consumption including charger	Wh/mile	329	246	241	340	253	249
	Battery	KW.hr	89	75	73	93	77	74
	Motor	KW	148	115	110	199	153	147
	Inverter	kW	148	115	110	199	153	147
	Battery usable size	KW.hr	80	68	68	84	69	70



Appendix II - TCO Results

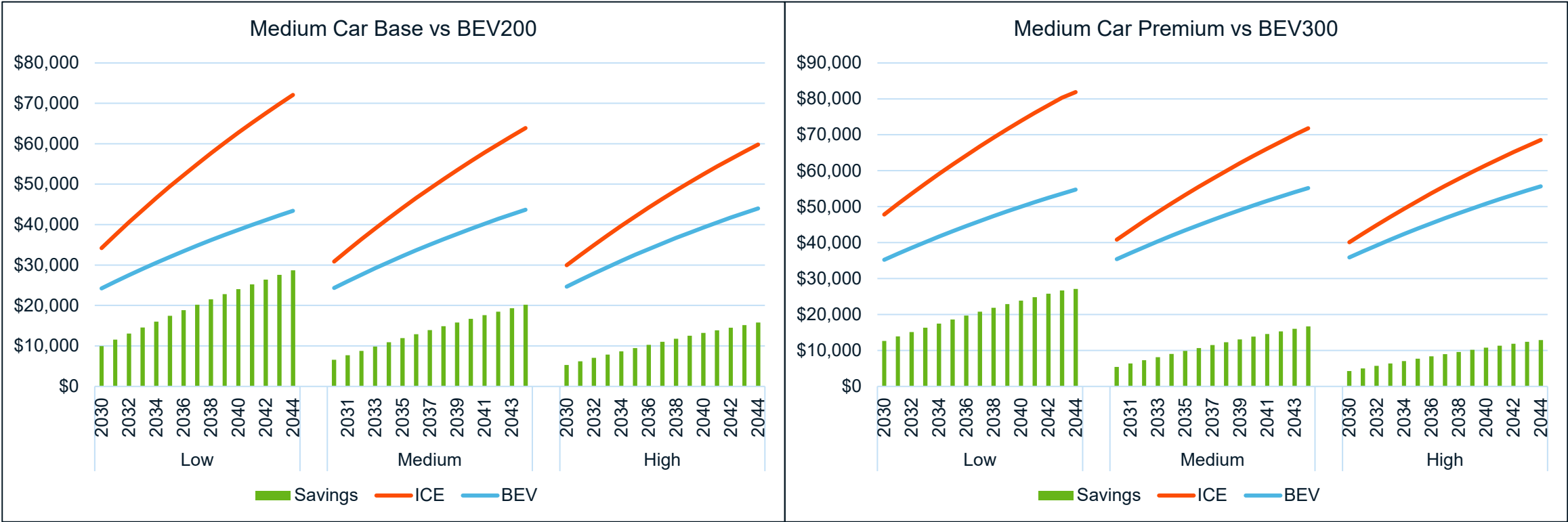
- Small car
- Medium car
- Small SUV
- Medium SUV
- Large SUV
- Pickup Truck

TCO – Small Car (Base/Premium) vs BEV (200/300)



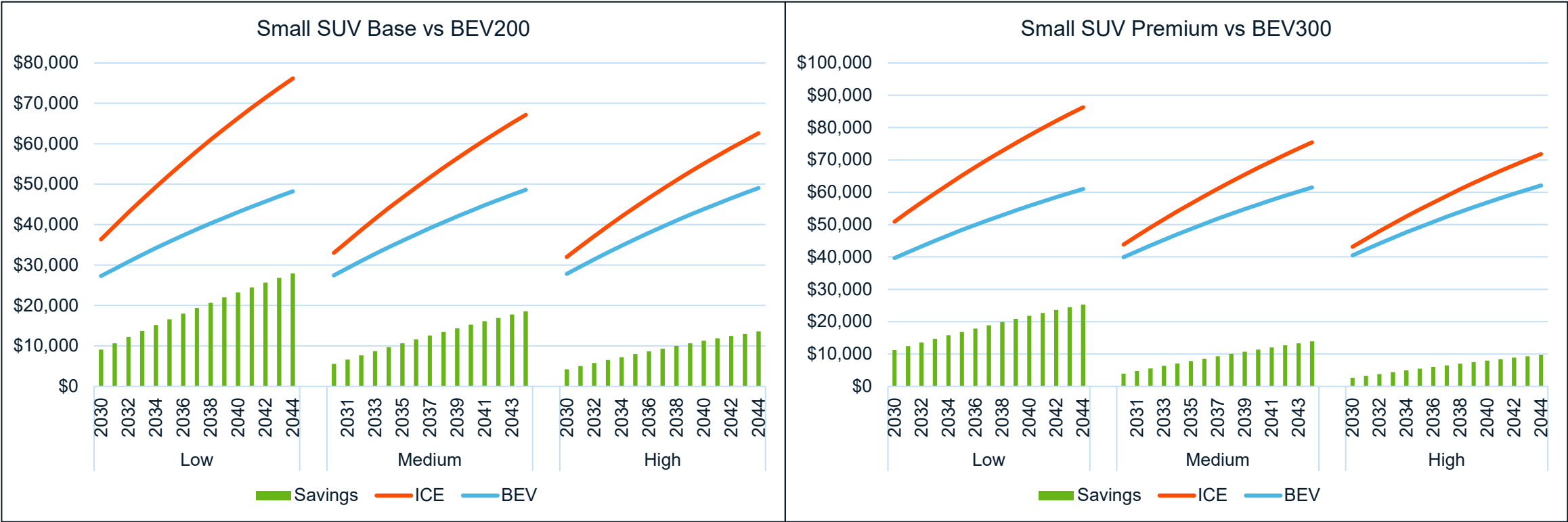
- Low case – Lowest cost BEV vs Highest cost ICE powertrain
- Medium case – Medium cost BEV vs Medium cost ICE powertrain
- High Case – Highest cost BEV vs Lowest cost ICE powertrain

TCO – Medium Car (Base/Premium) vs BEV (200/300)



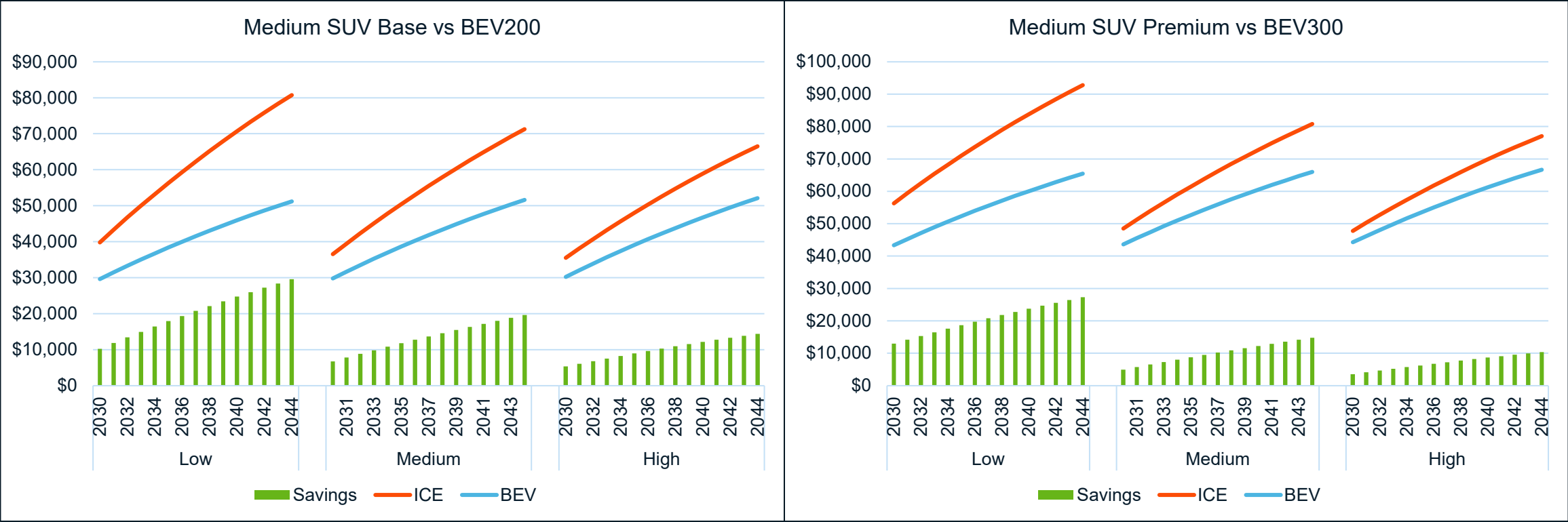
- Low case – Lowest cost BEV vs Highest cost ICE powertrain
- Medium case – Medium cost BEV vs Medium cost ICE powertrain
- High Case – Highest cost BEV vs Lowest cost ICE powertrain

TCO – Small SUV (Base/Premium) vs BEV (200/300)



- Low case – Lowest cost BEV vs Highest cost ICE powertrain
- Medium case – Medium cost BEV vs Medium cost ICE powertrain
- High Case – Highest cost BEV vs Lowest cost ICE powertrain

TCO – Medium SUV (Base/Premium) vs BEV (200/300)



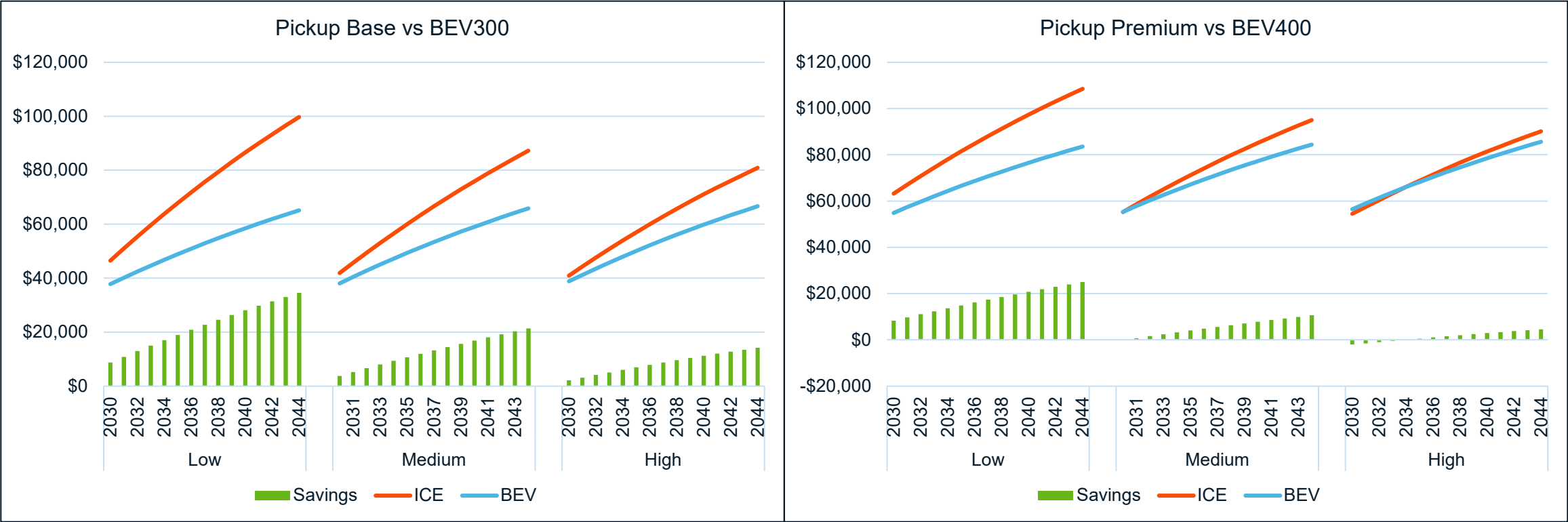
- Low case – Lowest cost BEV vs Highest cost ICE powertrain
- Medium case – Medium cost BEV vs Medium cost ICE powertrain
- High Case – Highest cost BEV vs Lowest cost ICE powertrain

TCO – Large SUV (Base/Premium) vs BEV (300/400)



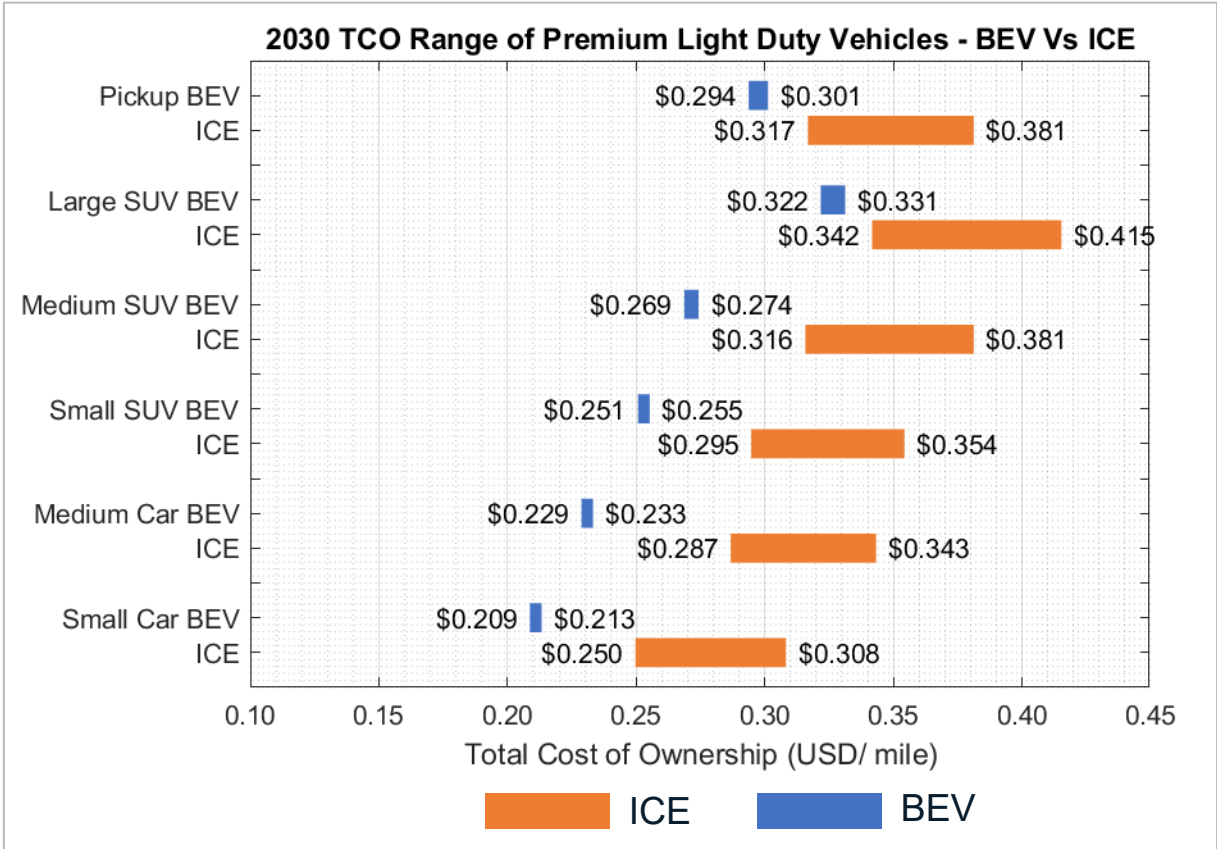
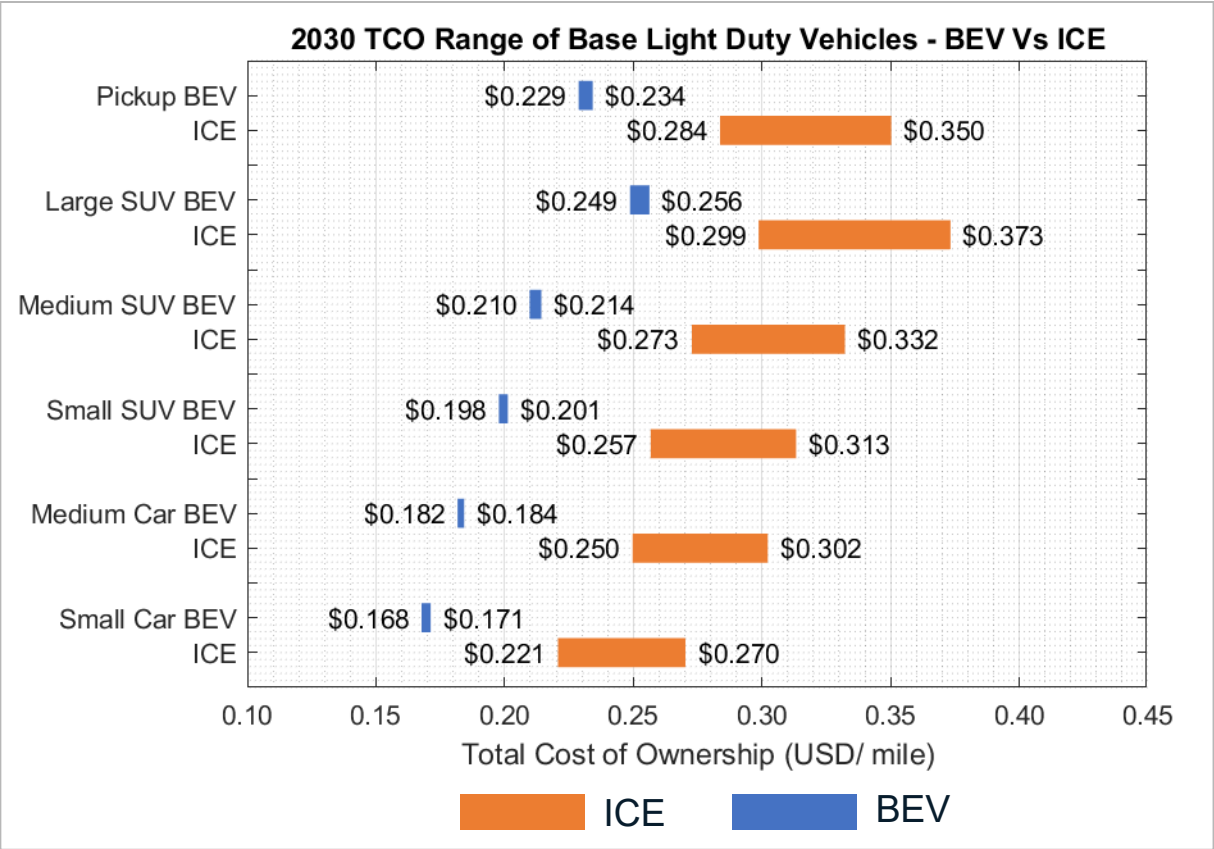
- Low case – Lowest cost BEV vs Highest cost ICE powertrain
- Medium case – Medium cost BEV vs Medium cost ICE powertrain
- High Case – Highest cost BEV vs Lowest cost ICE powertrain

TCO – Pickup (Base/Premium) vs BEV (300/400)



- Low case – Lowest cost BEV vs Highest cost ICE powertrain
- Medium case – Medium cost BEV vs Medium cost ICE powertrain
- High Case – Highest cost BEV vs Lowest cost ICE powertrain

TCO Projections (\$/mile) - BEV vs ICE for LDVs purchased in 2030



	Small Car			Medium Car			Small SUV			Medium SUV			Large SUV			Pickup		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Base Vehicles																		
ICE	\$0.270	\$0.237	\$0.221	\$0.302	\$0.267	\$0.250	\$0.313	\$0.276	\$0.257	\$0.332	\$0.293	\$0.273	\$0.373	\$0.322	\$0.299	\$0.350	\$0.307	\$0.284
BEV	\$0.168	\$0.170	\$0.171	\$0.182	\$0.183	\$0.184	\$0.198	\$0.200	\$0.201	\$0.210	\$0.212	\$0.214	\$0.249	\$0.252	\$0.256	\$0.229	\$0.231	\$0.234
Premium Vehicles																		
ICE	\$0.308	\$0.263	\$0.250	\$0.343	\$0.301	\$0.287	\$0.354	\$0.310	\$0.295	\$0.381	\$0.332	\$0.316	\$0.415	\$0.361	\$0.342	\$0.381	\$0.334	\$0.317
BEV	\$0.209	\$0.211	\$0.213	\$0.229	\$0.231	\$0.233	\$0.251	\$0.253	\$0.255	\$0.269	\$0.271	\$0.274	\$0.322	\$0.326	\$0.331	\$0.294	\$0.297	\$0.301

Appendix III - EV Component Costs

Battery Costing Methodology

		Cost to Build \$/kWh			Cell cost to OEM \$/kWh			OEM cost to build pack \$/kWh	
Year	Plant Size, GWh	NMC811 Cell cost \$/kWh	LFP Cell cost \$/kWh	Supplier Margin (assumed)	NMC811 Cell cost \$/kWh	LFP Cell cost \$/kWh	Cell to Pack multiplier	NMC811 Pack Cost \$/kWh	LFP Pack cost \$/kWh
2022	20	78 ¹	75 ¹	15%	89	87	1.25	112	108
2027	80	59 ^{1,2}	57 ^{1,2}	10%	65	62	1.18	76	74
2030	120	50 ^{1,2}	48 ^{1,2}	10%	55	52	1.18	64	62
2035								58	55

- *Cell:Pack* ratio for 2022 is 80:20 based on BNEF Price Survey 2021
- *Cell:Pack* ratio is assumed to be 85:15 for 2027 and 2030
- Literature ratio² applied to BaTPaC
 - 2030:2020 = 0.66
 - 2027:2020 = 0.78
- The cost estimation for 2035 is a speculation
 - Without considering potentially disruptive technologies as the chemistry may change completely
 - Learning rate may reduce
 - Manufacturing and battery configuration would vastly improve

¹BaTPaC V5.0, 2022

²Mauler, Lukas, et al. "Battery cost forecasting: a review of methods and results with an outlook to 2050." *Energy & Environmental Science* (2021)

EV Component Costs

Case	Component	Unit	2022	2030	2035
BEV component cost low					
	Battery Pack (LFP)	\$/kWh	108.3	61.7	55.5
	Motor	\$/kW	4.0	3.3	3.3
	Inverter	\$/kW	3.5	2.4	2.4
	DC-DC converter	\$/kW	50.0	2.4	2.4
	Onboard charger	\$/kW	50.0	2.4	2.4
BEV component cost reference					
	Battery Pack (NMC)	\$/kWh	111.7	64.2	57.7
	Motor	\$/kW	4.0	3.3	3.3
	Inverter	\$/kW	3.5	2.4	2.4
	DC-DC converter	\$/kW	50.0	2.4	2.4
	Onboard charger	\$/kW	50.0	2.4	2.4
EV component cost high					
	Battery pack (NMC *1.1)	\$/kWh	122.8	70.6	63.5
	Motor	\$/kW	4.0	3.3	3.3
	Inverter	\$/kW	3.5	2.4	2.4
	DC-DC converter	\$/kW	50.0	2.4	2.4
	Onboard charger	\$/kW	50.0	2.4	2.4

Appendix IV - TCO Inputs

TCO Inputs

Category	Vehicle Class	Maintenance cost per mile
ICE	Small Sedan	\$0.088
	Medium Sedan	\$0.104
	Subcompact SUV	\$0.099
	Medium SUV (4WD)	\$0.100
	Midsize Pickup	\$0.099
BEV	Electric Vehicle (all classes)	\$0.077

Maintenance cost from AAA 2021

	Annual VMT (miles)
Cars	15,922
SUVs	16,234
Pickup trucks	18,964

ANL study 2021*

- ICE base price = Vehicle glider + 1.5 x ICE powertrain cost
- BEV base price = Vehicle glider + 1.2 x BEV powertrain cost
- Discount rate of 3%

EIA AEO 2022

Year	Reference case 2021 \$/gal (MEDIUM CASE)	Low oil price 2021 \$/gal (HIGH CASE)	High oil price 2021 \$/gal (LOW CASE)	\$/kWh (MEDIUM CASE)	\$/kWh (HIGH CASE)	\$/kWh (LOW CASE)
2030	2.80	2.07	4.23	0.130	0.130	0.127
2031	2.89	2.16	4.26	0.130	0.131	0.127
2032	2.91	2.17	4.29	0.131	0.131	0.127
2033	2.94	2.20	4.26	0.132	0.132	0.127
2034	2.96	2.21	4.30	0.132	0.133	0.127
2035	2.97	2.24	4.34	0.132	0.133	0.126
2036	2.99	2.25	4.34	0.132	0.133	0.125
2037	3.01	2.26	4.36	0.131	0.132	0.124
2038	3.04	2.27	4.36	0.131	0.132	0.124
2039	3.04	2.26	4.39	0.131	0.132	0.124
2040	3.07	2.25	4.39	0.131	0.132	0.124
2041	3.09	2.24	4.37	0.130	0.132	0.124
2042	3.09	2.24	4.40	0.131	0.132	0.124
2043	3.12	2.24	4.41	0.130	0.131	0.124
2044	3.15	2.25	4.41	0.130	0.131	0.124

*Burnham, Andrew, et al. Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains. No. ANL/ESD-21/4. Argonne National Lab.(ANL), Argonne, IL US, 2021.