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REPORT PEI-1308
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Lifecycle Carbon Analysis and Total Cost of Ownership for 2030 Light Duty Vehicle Fleet

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Executive Summary

The Manufacturers of Emission Controls Association (MECA) had AVL conduct this study because MECA wants to understand the following about the 2030 vehicles in operation (VIO) in the United States of America (US):

- The potential relative market share of various types of vehicles and powertrains in the VIO and how that aligns with greenhouse gas (GHG) emissions goals
- Total cost of ownership (TCO)
- Lifecycle emissions of carbon dioxide (CO_2), nitrogen oxides (NOx), and methane (CH_4)

MECA also wanted to understand the effect of likely carbon intensities of future regional electrical grids on TCO and lifecycle emissions for the 2030 VIO.

For this study, TCO includes both the vehicle first cost and its operating cost over the vehicle life. For the example fleet analyses presented in this report, the vehicle life was assumed to be 12 years at 10,500 miles per year. Similarly, the lifecycle emissions include contributions from the following:

- Well to pump (WTP) emissions for the fuels considered
- Vehicle manufacture (VM) emissions for the vehicles and powertrains considered
- Vehicle operation (VO) or tank to wheels (TTW) emissions over the vehicle life

The overall methodology for the program is outlined in Figure ES.1. AVL used GREET 2020 from the Argonne National Laboratory (ANL) and developed spreadsheet-based Dashboard tools for this study to evaluate the design space. The Dashboard tools support both vehicle-level and fleet-level analyses of the 2030 VIO.

The technology pathways for the 2030 vehicle design space are based on those available in GREET 2020. From those pathways, several vehicle options were chosen for the fleet-level analyses. Three representative vehicle classes were studied: City Sedan, Family SUV, and Pickup Truck. Each vehicle had several powertrain options. Depending on the powertrain type, several fuels were also available for use. In addition to the vehicles and fuels, several regional electrical grids and their corresponding emissions were considered for their effects on the lifecycle emissions for the vehicles. These effects were aggregated into response surface models and embodied into two Dashboards for vehicle-level analysis, Dashboard 1 and Dashboard 2.

Key input factors in Dashboards 1 and 2 for a given combination of vehicle class and powertrain type are fuel prices, charging efficiency, and BEV range (if appropriate). The user interface for Dashboard 1 is shown in Figure ES.2. The Dashboard then returns lifecycle emissions, TCO, and similar results. Dashboard 2 is used to define the vehicles used in the fleet analysis tool, Dashboard 3, which is shown in Figure ES.3.

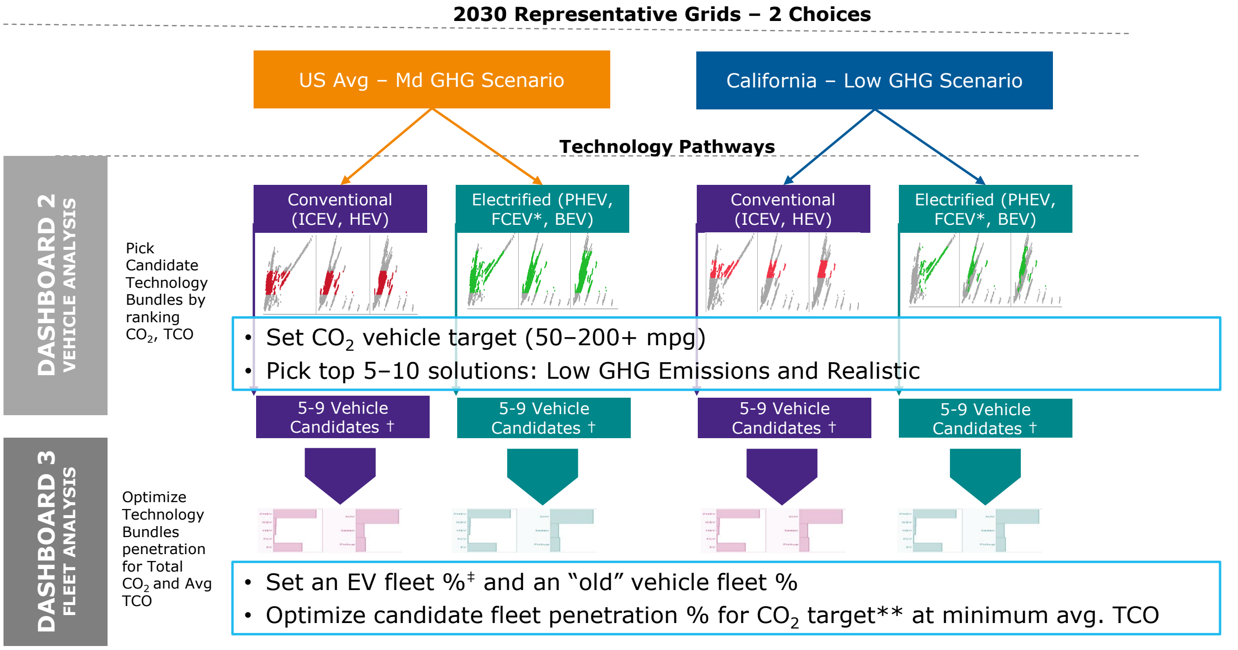
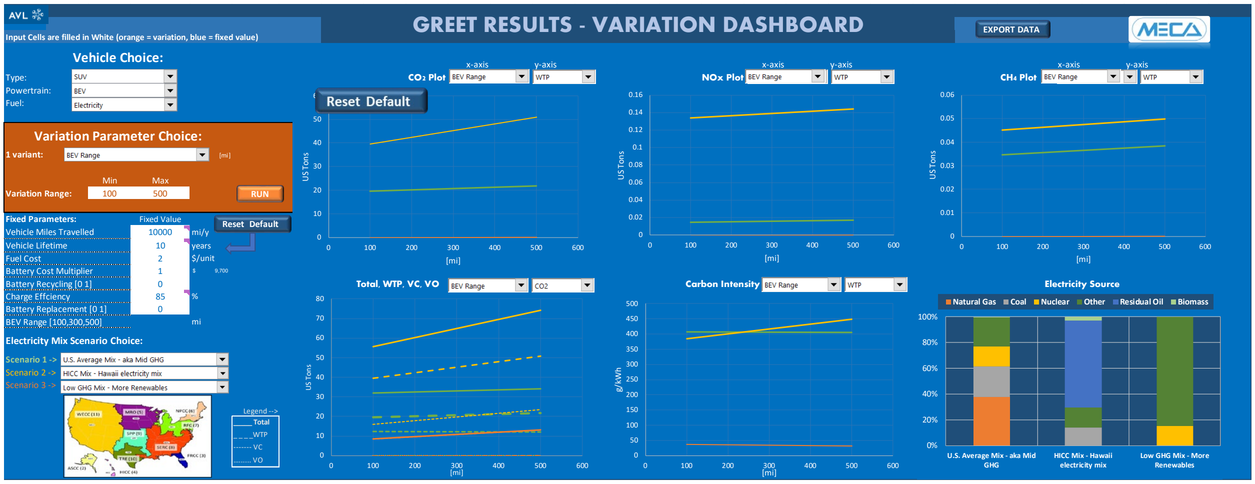


Figure ES.1 – Program methodology concept, including grid scenarios, technology pathways, and Dashboard tools.



Input Cells are filled in White (orange = variation, blue = fixed value)

Vehicle Choice:
Type: SUV
Powertrain: BEV
Fuel: Electricity

Variation Parameter Choice:
1 variant: BEV Range [mi]
Variation Range: Min 100 Max 500

Fixed Parameters:	Fixed Value	
Vehicle Miles Travelled	10000	mi/y
Vehicle Lifetime	10	years
Fuel Cost	2	$/unit
Battery Cost Multiplier	1	$ 9,700
Battery Recycling [0 1]	0	
Charge Effciency	85	%
Battery Replacement [0 1]	0	
BEV Range [100,300,500]		mi

Electricity Mix Scenario Choice:
Scenario 1 -> U.S. Average Mix - aka Mid GHG
Scenario 2 -> HICC Mix - Hawaii electricity mix
Scenario 3 -> Low GHG Mix - More Renewables

Figure ES.2 – Dashboard 1 for single vehicle analysis.

MECA and AVL together defined a Baseline fleet and, from the vehicle candidates identified in the initial analysis, five future fleet scenarios that represented differing levels of technology adoption. The six fleet scenarios considered in this study are the following:

1. Baseline (2019) fleet
2. Low GHG Emissions fleet using conventional vehicles and HEV
3. Low GHG Emissions fleet using highly electrified vehicles (PHEV, FCEV, BEV)
4. MECA Scenario 1 (Technology ready options)
5. MECA Scenario 2 (Moderate technology advancing)
6. MECA Scenario 3 (Aggressive technology advancing)

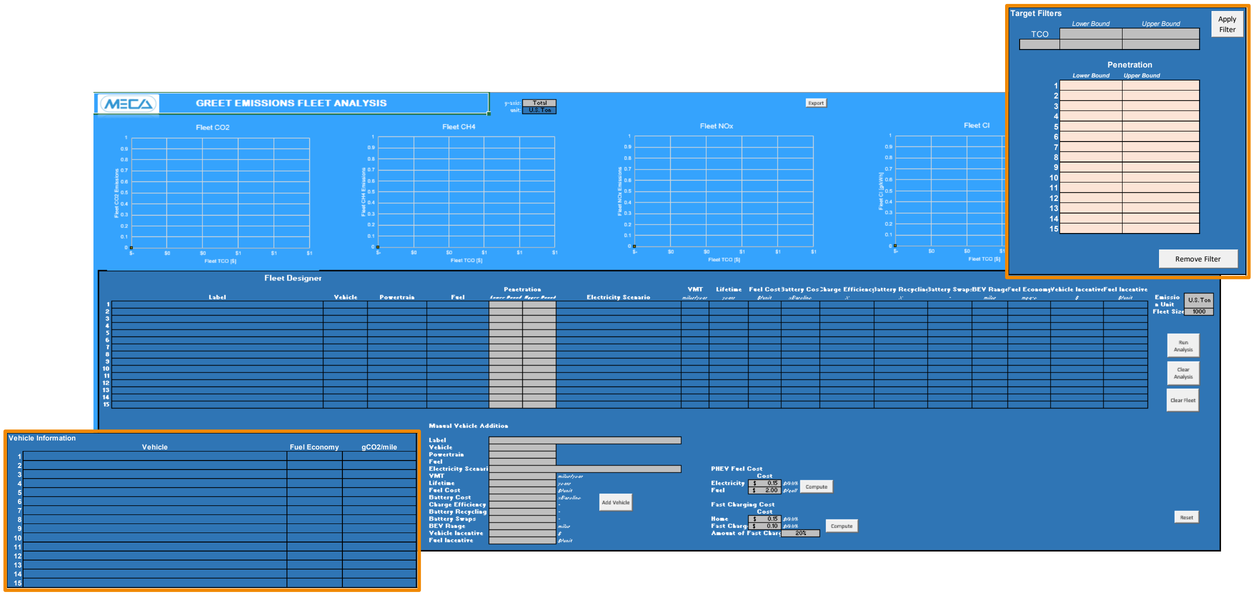


Figure ES.3 – Dashboard 3 for fleet analysis.

Using Dashboard 3, AVL then evaluated how the five future fleet scenarios would affect TCO and lifecycle emissions for new vehicles sold in 2030 and for the overall VIO in 2030. The analysis varies the relative market share of the vehicles, powertrains, and fuels considered within a given fleet scenario to generate a case for analysis. Several of these cases are then aggregated to provide an overall, fleet-level range of estimates of the TCO and lifecycle emissions.

An example of these fleet-level results is shown in Figure ES.4, where the colored point clouds represent different cases within each of three 2030 fleet scenarios. The clouds on the left use the 2030 California (low GHG) electrical grid whereas the ones on the right use the 2030 US Average (medium GHG) electrical grid. MECA and AVL assumed that the 2030 VIO would need to demonstrate a 30% reduction in overall CO_2 emissions to meet the Paris Accord requirements, which is marked by the orange dashed line. Note that there is a weak correlation between TCO and lifecycle CO_2 emissions that is affected by the first cost of the technologies and the expected life or use of the vehicles.

Since the 2030 VIO will include both new vehicles—represented by the point clouds—and older vehicles—represented by the Baseline Fleet average lifecycle CO_2 emissions value of 51.5 US ton calculated for this study—achieving a given level of overall CO_2 emissions reduction puts the onus on the new vehicles to meet the target. As the assumed fraction of old vehicles in the 2030 VIO increases, the CO_2 emissions target for the new vehicles decreases accordingly. The orange dashed line in Figure ES.4 is the new vehicle emissions target when old vehicles are under 10% of the VIO. As the fraction of old vehicles increases in the VIO, the target for the new (2030) vehicles decreases and fewer fleet options within each of the fleet scenarios will support the overall VIO meeting the expected 2030 GHG emissions targets.

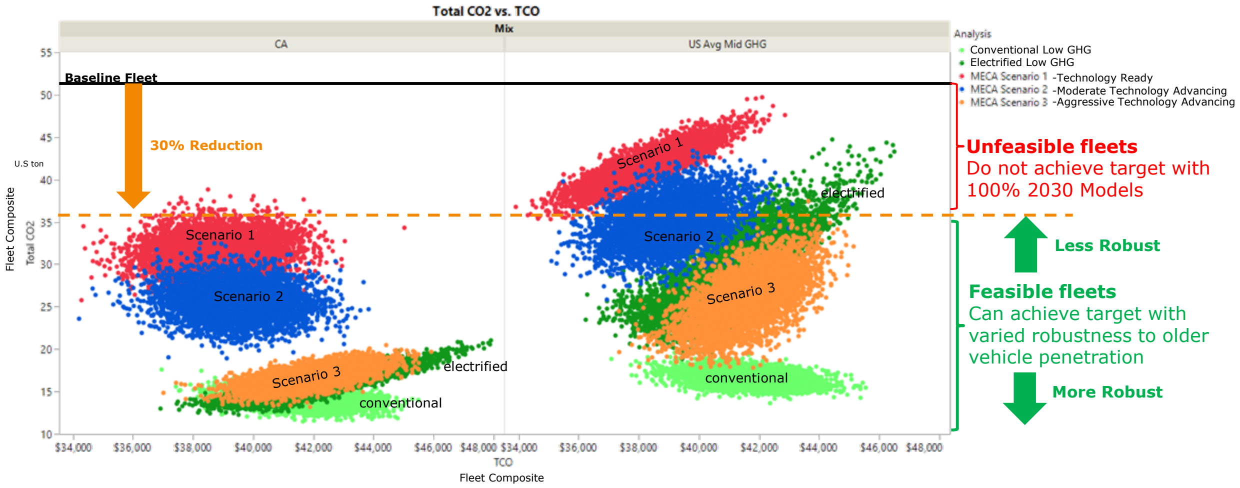


Figure ES.4 – 2030 Fleets comparing the results from the Low GHG Emissions and three MECA Scenario vehicle technology options. Point clouds represent new 2030 vehicles only.

In addition, this analysis did not evaluate how fuels with a lower CO_2 content would affect the emissions of the Baseline (2019) fleet. For example, if fuels with a near-zero well to pump (WTP) CO_2 content become widespread, then the overall fleet lifecycle CO_2 emissions will be correspondingly lower. This effect would allow the future fleet scenarios to be less aggressive with their GHG emissions reduction targets to achieve the net target for the overall 2030 VIO.

In summary, AVL has created a tool set that can be used to evaluate future fleet scenarios and has conducted some initial fleet emissions and TCO scenario analyses with input from MECA. The results suggest that there are multiple future fleet options that can meet expected future fleet emissions targets, for example, as defined by the Paris Accord or by the US Government. The study also demonstrates that the fleet fraction and emissions level of legacy vehicles within the VIO will influence the level of emissions reduction needed by new vehicles to meet an overall emissions target for the VIO. This suggests that any CO_2 reductions that are achieved by legacy vehicles in the transition years to 2030 will build in fleet robustness needed to ensure that ultimate CO_2 emission reduction goals from transportation are met. The fleet analyses also incorporated TCO into the results. Thus, the future fleets can be assessed based on their overall benefits, not just on their technology or emissions benefits.

Contents

List of Tables

List of Figures

1. Introduction

1.1. Background

The Manufacturers of Emission Controls Association (MECA) contracted AVL to conduct a study of lifecycle emissions and the total cost of ownership (TCO) for light-duty vehicles (LDV) in the US market. AVL constructed a baseline fleet and compared that against several scenarios for 2030 [1].

To complete the study, AVL developed a well to wheels dataset for the vehicle and fuel matrix shown in Table 2.1 that included carbon dioxide (CO_2), nitrogen oxides (NOx), and methane (CH_4) emissions. Carbon dioxide and methane are both greenhouse gases (GHG), where methane is 25 times as potent a GHG as CO_2, and NOx is a key criteria pollutant that is formed as a by-product of combustion [2].

AVL also investigated variations and uncertainties within the emissions and TCO analyses, and then aggregated the generated data into a set of Dashboards. These Dashboards, which are described further in Section 2.5, support both vehicle-level and fleet-level analysis of the 2030 scenarios. Three Dashboards were created for this project: Dashboard 1 is for stand-alone vehicle analysis, whereas Dashboard 2 is for vehicle analysis that populates the fleet analyses conducted by Dashboard 3.

This report documents the background of the study, its technical methodology, the analyses conducted, and the results for the 2030 fleet scenarios.

1.2. Project Objectives

For the projected US Fleet of Vehicles in Operation (VIO) in 2030, MECA wants to understand the following:

- Likely vehicle configurations for 2030 US VIO
- TCO including both
    - Vehicle first cost
    - Vehicle operating cost over life
- Lifecycle carbon analysis (LCA), including contributions from
    - Net CO_2 content of fuel from well to pump (WTP)
    - Vehicle manufacture
    - Vehicle generation of CO_2 from operation over life
- Additional lifecycle emissions estimates for NOx and methane
- Likely electrical grid carbon intensities for 2030 and their effect on TCO, LCA, and other lifecycle emissions

2. Technical Methodology

For this program, AVL and MECA defined a design space for the 2030 VIO. This section describes the design space, the various analysis inputs, and the assumptions needed to bound the analysis. AVL used GREET 2020 to evaluate the lifecycle emissions over the design space, processed those results, and then integrated them into Dashboards. These Dashboards, described further in Section 2.5, were used to conduct the vehicle- and fleet-level studies described in Section 3.

2.1. Toolchain

Two main tools were used in this study to generate the results. The first main tool was GREET, which is a LCA tool developed by Argonne National Laboratory (ANL) [3, 4]. MECA and AVL agreed to use GREET as-is for this study and agreed to not create extensions where the study design space was not contained within the GREET design space. Further assumptions about how GREET was used are discussed in Section 2.4.

AVL developed a set of tools—the Dashboards—to conduct single-vehicle analyses and the fleet analyses. The overall toolchain is illustrated in Figure 2.1, where the technology pathways are generated using GREET.

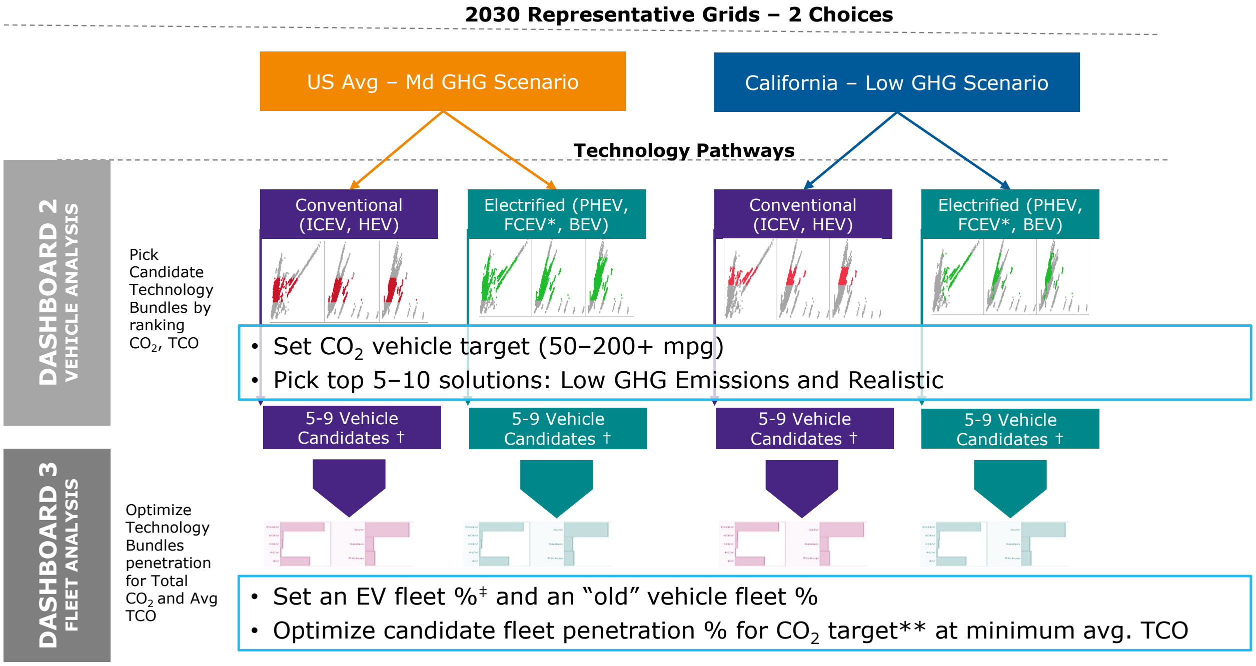


Figure 2.1 – Program methodology concept, including grid scenarios, technology pathways, and Dashboard tools.

2.2. Design Space Definition

The overall design space considered in this project was broad. Three main classes of vehicles were studied: City Sedan (“Sedan”), Family SUV (“SUV”), and Pickup Truck (“Pickup”). These vehicle classes are as defined in GREET 2020. Each vehicle had several powertrain options and where appropriate, the vehicle–powertrain combination had a set of fuels to choose from. Table 2.1 shows the complete matrix of vehicles, powertrains, and fuels considered in this study. The specific combinations that were considered in the study are marked with an “X”. Options listed in teal or combinations in teal boxes in Table 2.1 were added during the study.

In addition to the vehicle and fuel combinations, AVL also initially considered 19 different electricity scenarios for 2030[1], each of which had associated CO_2, NOx, and methane emissions. The electricity scenarios have the largest effect on WTP CO_2 emissions, especially for battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) powertrains where the vehicles are recharged by the grid.

An example of WTP CO_2 emissions on a grams per mile basis is shown in Table 2.2 for the SUV BEV, and the electrical grid understandably has the primary effect on those emissions. However, as shown in Table 2.3 for the SUV with the internal combustion engine vehicle powertrain (ICEV), the electrical grid scenario only has a secondary effect on WTP CO_2 emissions and the primary effect is the carbon intensity of the fuel type [1, 5].

The electricity scenario grid-level GHG affects CO_2 emissions from its three main constituents: WTP, vehicle manufacturing, and vehicle operation (VO, a.k.a. tank to wheels, TTW). MECA and AVL agreed to narrow the design space to only include two grid scenarios that would reasonably represent the main 2030 grid options. The two 2030 grid scenarios chosen are the California (low GHG) scenario and the US Average scenario, also labeled as “MidGHG” in Table 2.2 and Table 2.3.

It is also possible to make comparisons between the SUV ICEV and SUV PHEV, as shown in Table 2.4. Here, the SUV PHEV CO_2 emissions are affected both by the fuel type and by the electricity scenario. In fact, electricity scenarios with high CO_2 emissions, such as the Hawaiian grid scenario, can overwhelm the WTP CO_2 emissions of the fuel for the ICEV.

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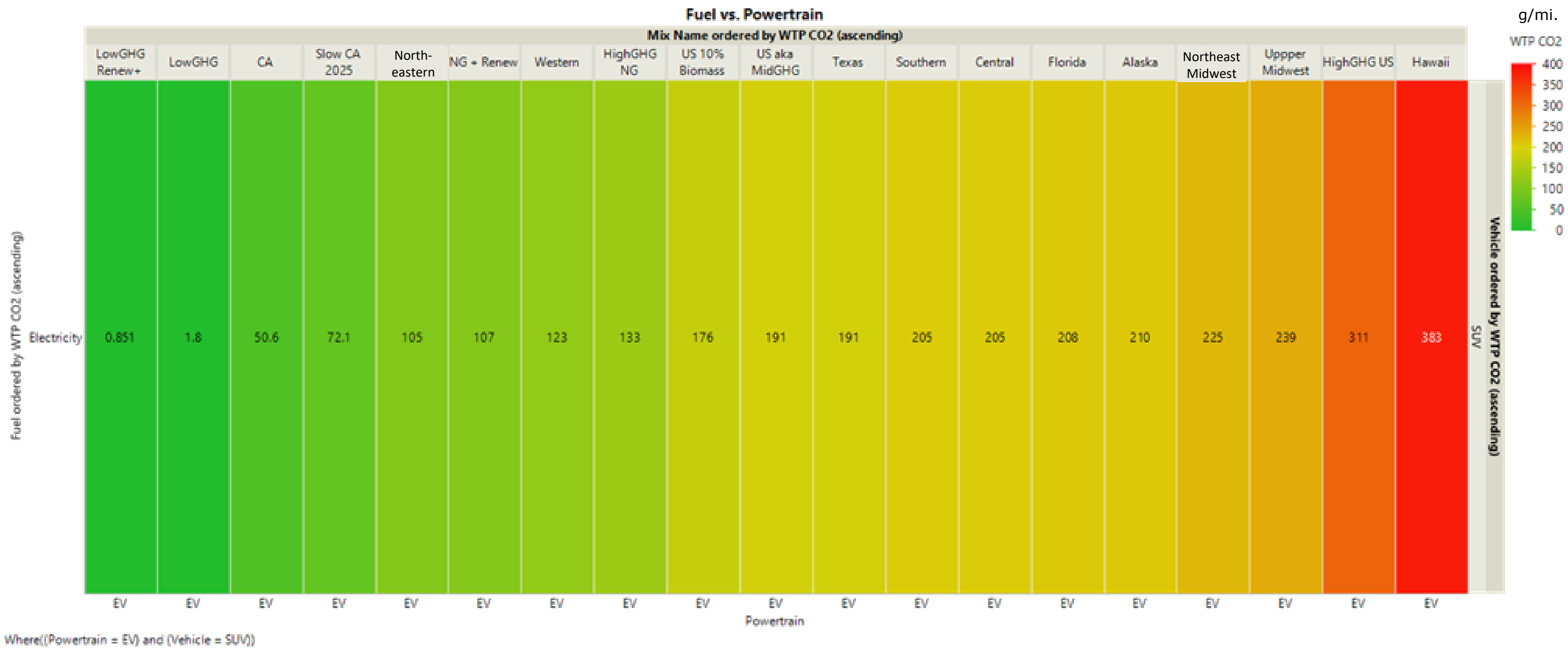
[1] The electricity scenarios are described further in Appendix B, Electricity Scenarios and Generation Mix.

Table 2.1 – Vehicle, powertrain, and fuel matrix for study. Options and combinations marked in teal were added during the study.

												19 Grid Power Scenarios	
Vehicles	**E10**	**E85**	**B20**	**Renewable Diesel**	**Renewable Gasoline**	**E-Gasoline**	**E-Diesel**	**RNG**	**CNG**	**Renewable H_2**	**High GHG H_2**	**High GHG**	**Avg GHG**	**Low GHG**
City ICE Sedan	X	X			X	X								
City BEV Sedan 100, 300, 400 mi												X	X	X
City HEV Sedan	X				X	X								
Family ICE SUV	X	X	X	X	X	X	X	X	X					
Family HEV SUV	X	X	X	X	X	X	X							
Family PHEV SUV	X	X	X	X	X	X	X	X	X					
Family BEV SUV 100, 300, 400, 500 mi												X	X	X
Family FCEV SUV										X	X			
Pickup ICE	X	X	X	X	X	X	X	X	X					
Pickup HEV	X	X	X	X	X	X	X	X	X					
Pickup BEV 100, 300, 400, 500 mi												X	X	X
Pickup FCEV										X	X			

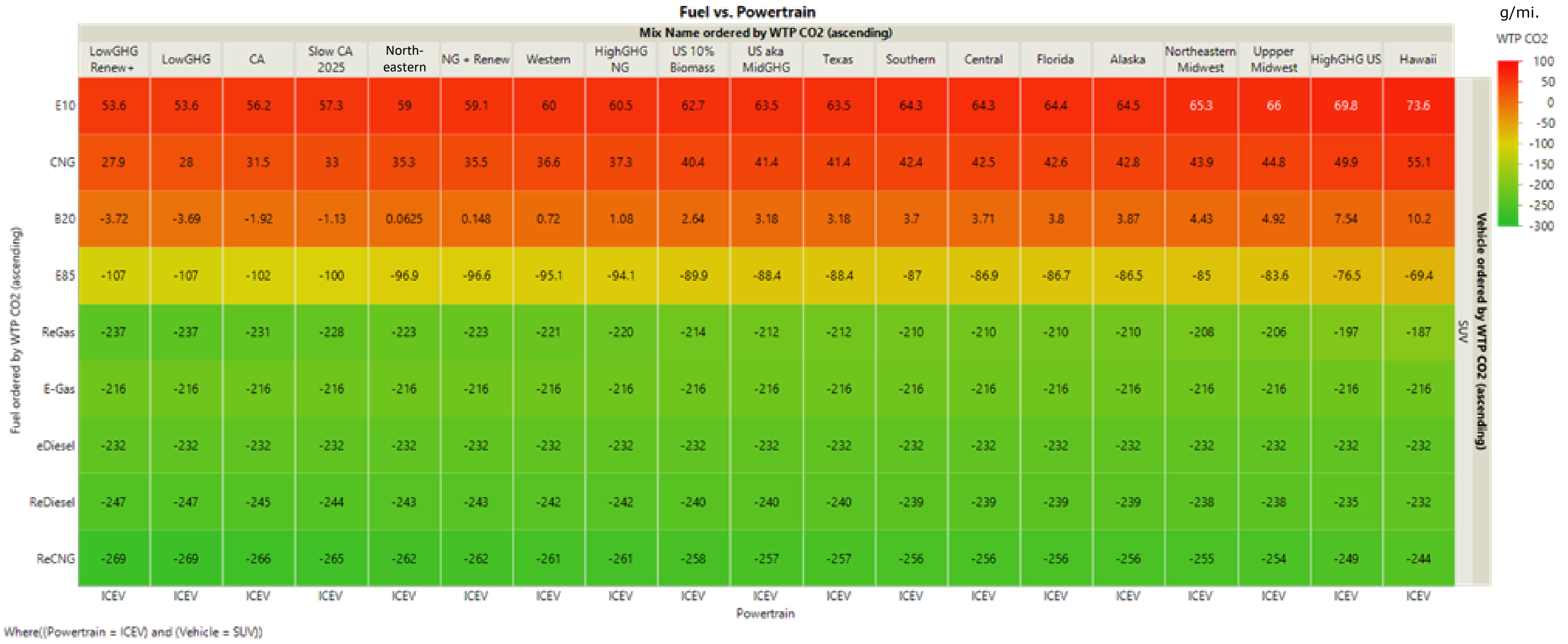
Table 2.2 – Well to pump CO_2 emissions from each of 19 electrical grid scenarios for the SUV BEV on a gram per mile basis.



	LowGHG Renew+	LowGHG	CA	Slow CA 2025	North-eastern	NG + Renew	Western	HighGHG NG	US 10% Biomass	US aka MidGHG	Texas	Southern	Central	Florida	Alaska	Northeast Midwest	Uppper Midwest	HighGHG US	Hawaii
Electricity	0.851	1.8	50.6	72.1	105	107	123	133	176	191	191	205	205	208	210	225	239	311	383
	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV

Where((Powertrain = EV) and (Vehicle = SUV))

Table 2.3 – Well to pump CO_2 emissions from each of 19 electrical grid scenarios for the SUV ICEV on a gram per mile basis.



Fuel vs. Powertrain

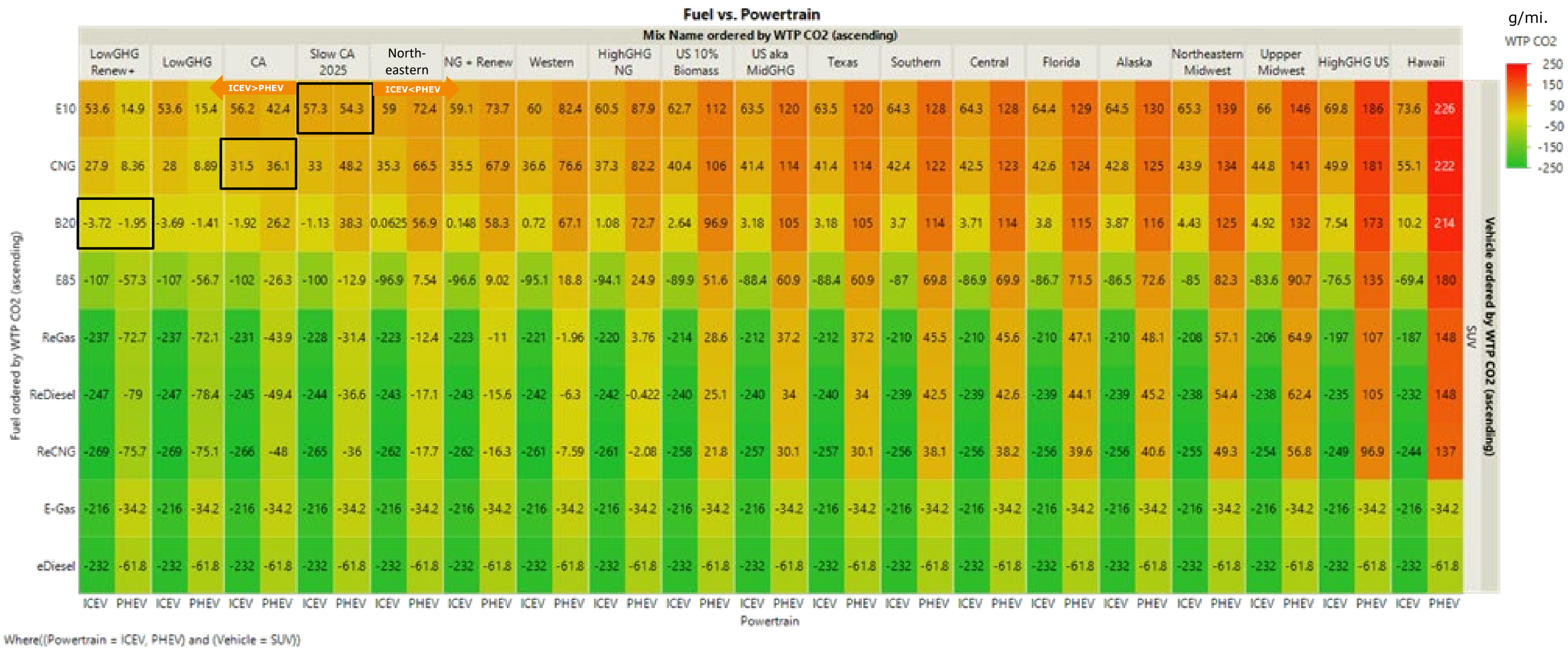
Mix Name ordered by WTP CO2 (ascending)

Fuel ordered by WTP CO2 (ascending)	LowGHG Renew+	LowGHG	CA	Slow CA 2025	North-eastern	NG + Renew	Western	HighGHG NG	US 10% Biomass	US aka MidGHG	Texas	Southern	Central	Florida	Alaska	Northeastern Midwest	Uppper Midwest	HighGHG US	Hawaii
E10	53.6	53.6	56.2	57.3	59	59.1	60	60.5	62.7	63.5	63.5	64.3	64.3	64.4	64.5	65.3	66	69.8	73.6
CNG	27.9	28	31.5	33	35.3	35.5	36.6	37.3	40.4	41.4	41.4	42.4	42.5	42.6	42.8	43.9	44.8	49.9	55.1
B20	-3.72	-3.69	-1.92	-1.13	0.0625	0.148	0.72	1.08	2.64	3.18	3.18	3.7	3.71	3.8	3.87	4.43	4.92	7.54	10.2
E85	-107	-107	-102	-100	-96.9	-96.6	-95.1	-94.1	-89.9	-88.4	-88.4	-87	-86.9	-86.7	-86.5	-85	-83.6	-76.5	-69.4
ReGas	-237	-237	-231	-228	-223	-223	-221	-220	-214	-212	-212	-210	-210	-210	-210	-208	-206	-197	-187
E-Gas	-216	-216	-216	-216	-216	-216	-216	-216	-216	-216	-216	-216	-216	-216	-216	-216	-216	-216	-216
eDiesel	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232
ReDiesel	-247	-247	-245	-244	-243	-243	-242	-242	-240	-240	-240	-239	-239	-239	-239	-238	-238	-235	-232
ReCNG	-269	-269	-266	-265	-262	-262	-261	-261	-258	-257	-257	-256	-256	-256	-256	-255	-254	-249	-244
Powertrain	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV	ICEV

Where((Powertrain = ICEV) and (Vehicle = SUV))

Table 2.4 – Summary comparison of well to pump CO_2 emissions from each of 19 electrical grid scenarios for the SUV ICEV and SUV PHEV on a gram per mile basis.

ICEV promote CO2 removal for eFuels and renewable fuels while PHEV loses advantage when electricity grid is poor



Fuel vs. Powertrain

Mix Name ordered by WTP CO2 (ascending)

Fuel ordered by WTP CO2 (ascending)	LowGHG Renew+		LowGHG		CA		Slow CA 2025		North-eastern		NG + Renew		Western		HighGHG NG		US 10% Biomass		US aka MidGHG	
Powertrain	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV
E10	53.6	14.9	53.6	15.4	56.2	42.4	57.3	54.3	59	72.4	59.1	73.7	60	82.4	60.5	87.9	62.7	112	63.5	120
CNG	27.9	8.36	28	8.89	31.5	36.1	33	48.2	35.3	66.5	35.5	67.9	36.6	76.6	37.3	82.2	40.4	106	41.4	114
B20	-3.72	-1.95	-3.69	-1.41	-1.92	26.2	-1.13	38.3	0.0625	56.9	0.148	58.3	0.72	67.1	1.08	72.7	2.64	96.9	3.18	105
E85	-107	-57.3	-107	-56.7	-102	-26.3	-100	-12.9	-96.9	7.54	-96.6	9.02	-95.1	18.8	-94.1	24.9	-89.9	51.6	-88.4	60.9
ReGas	-237	-72.7	-237	-72.1	-231	-43.9	-228	-31.4	-223	-12.4	-223	-11	-221	-1.96	-220	3.76	-214	28.6	-212	37.2
ReDiesel	-247	-79	-247	-78.4	-245	-49.4	-244	-36.6	-243	-17.1	-243	-15.6	-242	-6.3	-242	-0.422	-240	25.1	-240	34
ReCNG	-269	-75.7	-269	-75.1	-266	-48	-265	-36	-262	-17.7	-262	-16.3	-261	-7.59	-261	-2.08	-258	21.8	-257	30.1
E-Gas	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2
eDiesel	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8

Fuel ordered by WTP CO2 (ascending)	Texas		Southern		Central		Florida		Alaska		Northeastern Midwest		Uppper Midwest		HighGHG US		Hawaii	
Powertrain	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV	ICEV	PHEV
E10	63.5	120	64.3	128	64.3	128	64.4	129	64.5	130	65.3	139	66	146	69.8	186	73.6	226
CNG	41.4	114	42.4	122	42.5	123	42.6	124	42.8	125	43.9	134	44.8	141	49.9	181	55.1	222
B20	3.18	105	3.7	114	3.71	114	3.8	115	3.87	116	4.43	125	4.92	132	7.54	173	10.2	214
E85	-88.4	60.9	-87	69.8	-86.9	69.9	-86.7	71.5	-86.5	72.6	-85	82.3	-83.6	90.7	-76.5	135	-69.4	180
ReGas	-212	37.2	-210	45.5	-210	45.6	-210	47.1	-210	48.1	-208	57.1	-206	64.9	-197	107	-187	148
ReDiesel	-240	34	-239	42.5	-239	42.6	-239	44.1	-239	45.2	-238	54.4	-238	62.4	-235	105	-232	148
ReCNG	-257	30.1	-256	38.1	-256	38.2	-256	39.6	-256	40.6	-255	49.3	-254	56.8	-249	96.9	-244	137
E-Gas	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2	-216	-34.2
eDiesel	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8	-232	-61.8

Where((Powertrain = ICEV, PHEV) and (Vehicle = SUV))

Figure 2.1 shows the high-level technology options considered for the program after the design space was constrained by agreement with MECA and AVL. The two grid scenarios and the two vehicle scenarios—conventional and electrified—led to four sets of vehicle candidates.

For the electrified vehicle (EV) fleet, the 2030 fleet was assumed to have not more than 5% fuel cell-electric vehicles (FCEV). Each of the vehicle candidate sets have at least two candidate vehicles per vehicle type (Sedan, SUV, or Pickup Truck). The EV fleet fraction was estimated based on California's targets for 2030, and, likewise, the fleet CO_2 target for 2030 assumed that a 30% reduction from the 2019 baseline would be needed to meet the Paris Accord targets for overall GHG emissions. Since the technical work was completed, the Biden Administration has set a target of 50–52% reduction in GHG by 2030 compared to 2005, so a reduction from 5,999 million metric tons of CO_2 in 2005 to ≈2,950 million metric tons [6]. Since the net U.S. emissions in 2019 were 5,138 million metric tons of CO_2, this suggests that a 42–43% reduction target might be more appropriate.

2.3. Analysis Inputs

For the Pickup Truck BEV, the powertrain components were sized based on performance metrics. The vehicle was modeled and then simulated traversing a comprehensive drive cycle until the battery was depleted. The model results then indicated the battery capacity or size needed for a given achieved range, as shown in Figure 2.2. GREET 2020 only provides emissions estimates for BEV with a 100-mile or 300-mile range; therefore, battery sizes for ranges in between those two ranges were estimated using a linear interpolation, as shown by the black dashed line in Figure 2.2. For a BEV range above 300 miles, an offset is applied that is based on the error (shown in red) between the linear fit extrapolated beyond 300 miles and the polynomial fit (shown by a blue dashed line) derived from the simulation results.

Other parameters that can be varied in the Dashboards are shown in Table 2.5, along with the ranges allowed in the Dashboards. AVL used specific values of these parameters to build up the fleet scenarios described further in Section 3.4.

The fuel prices used for the TCO calculations are shown in Table 2.6. The renewable diesel and gasoline costs are taken from estimates by the United States Department of Energy (DOE) [7]. The other fuel costs, such as those for E10 or E85, are taken from typical pump prices from 2019. Fuel prices in 2030 were assumed to be the same as 2019 prices in real terms, based on the historical trends over the last 30 years [8]. Note that all of these prices can be adjusted in the Dashboards that were used to generate the example results in this study to reflect updated forecasts of future fuel prices. The Dashboards are described in Sections 3.2 and 3.4.

E-Diesel and E-Gasoline costs will be strongly influenced by the input cost of the hydrogen needed to make them[2]. One gallon of e-fuel needs nearly 2 kg of hydrogen, so if hydrogen production costs are $2.00/kg in 2030 then the hydrogen content contributes $4.00/gal. to the e-fuel cost. AVL and MECA agreed that some sort of subsidy or incentive would be in place in 2030 to get the pricing to a competitive level of $3.50/gal.

For electricity costs, AVL and MECA assumed that BEV and PHEV would use fast charging for 20% of energy stored over the vehicle life and home charging for 80%. The fast-charging cost is assumed to be $0.35/kW·h, and the home charging costs are $0.167/kW·h in California and $0.131/kW·h elsewhere in the US [9]. These rates were then averaged to provide the effective charging costs listed in Table 2.6. Note also that one kilogram of hydrogen is about one gallon of gasoline equivalent (GGE).

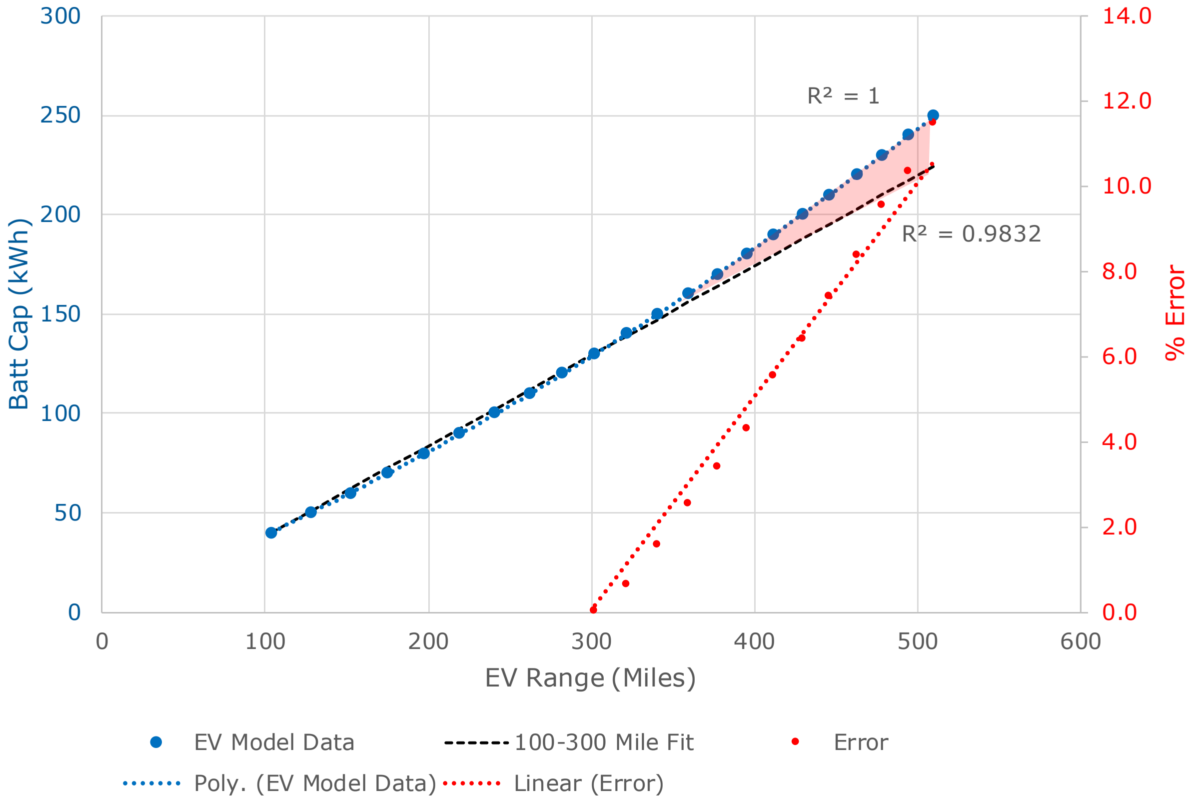


Figure 2.2 – Battery capacity in kW·h needed for a given BEV range in mi.

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[2] An extended discussion of electro-fuels or e-fuels may be found in Appendix C.

Table 2.5 – Variation parameters summary.

Variable	Type	Target Effect	Range	Variation
Vehicle Miles Traveled (VMT, mi.)	Vehicle input	TCO and Total Emissions (post-GREET)	5,000–20,000 mi./yr.	Continuous variable
Years of Operation (YOO, yr.)	Vehicle input	TCO and Total Emissions (post-GREET)	5–15 yr.	Continuous variable
Vehicle Fraction of Fleet (%)	Vehicle level in fleet	TCO and Total Emissions (post GREET)	0-100%	Continuous variable
Fuel Cost ($)	User defined	Overall Fleet Emissions, Total incentive accumulation in Fleet Dashboard	$ User Range	Continuous variable
Electricity Mix	GREET scenario	TCO	19 Scenarios	Discrete sets
Battery Swap	Vehicle input	GREET Emissions	0 or 1	Discrete options
EV Range (mi.)	Vehicle input	TCO and GREET Emissions for PHEV and BEV	100, 300, 400, 500 mi.	Discrete options
Battery Recycling	GREET input	TCO and GREET Emissions for BEV	0 or 1 (100%)	Discrete options
Charging Efficiency (%)	GREET input	TCO and GREET Emissions for PHEV and BEV	70–95%	Continuous variable
Battery Cost Multiplier	User defined	GREET Emissions for PHEV and BEV	User Range	Continuous variable
Incentives ($)	User defined	TCO for PHEV and BEV	$ User Range	Continuous variable

Table 2.6 – Fuel prices used for TCO calculations. Prices shown are for 2030 but in 2019$.

Fuel	Price	Unit
E10	2.22	$/gal.
E85	1.99	$/gal.
B20	2.50	$/gal.
Renewable Diesel	3.50	$/gal.
Renewable Gasoline	3.50	$/gal.
E-Diesel	3.50	$/gal.
E-Gasoline	3.50	$/gal.
RNG	2.15	$/GGE
CNG	2.15	$/GGE
Electricity (US Avg.)	0.175	$/kW·h
Electricity (Calif. Avg.)	0.204	$/kW·h
Renewable H_2	4.00	$/kg
High GHG H_2	4.00	$/kg

2.4. Study Assumptions

AVL and MECA made several assumptions to help bound the study, as described in this section. One part of the work that needed some bounds was the TCO analysis, which used industry-standard methods and an AVL database of component and vehicle-level costs.

For the TCO analysis, the first cost is assumed to be the cost to the vehicle owner. Likewise, the operating costs are costs to the vehicle owner and include both fuel and maintenance costs over the vehicle lifetime. AVL assumed that the fuel prices in Table 2.6 will be constant in real terms from 2019 through 2030, which is based on the trend in constant-dollar fuel prices over the previous decade.

All vehicle types are assumed to have a lifetime of 12 years, which matches the 2019 Baseline average vehicle age in the VIO [10]. This assumption means that the average age of vehicles in the VIO in 2030 will also be about 12 years. For all vehicles, the annual vehicle miles traveled (VMT) is assumed to be 10,500 mi./year, which is based on the state-by-state VMT values shown in Figure 2.3 [11]. Note that these parameters can be varied in the Dashboards should one wish to look at a longer or shorter vehicle life or more or fewer VMT in a year.

There are several assumptions specific to BEV and PHEV and their larger battery packs, including the following:

- The battery pack lasts for the lifetime of the vehicle, thus, there are no battery pack swaps during the vehicle life.
- There is no recycling of the battery pack at end of life that might offset the lifecycle GHG emissions.
- The charging efficiency is 85% [12].
- The default range for the BEV Sedan is 300 miles.
- The default range for the BEV SUV or Pickup is 400 miles.

It was further assumed that by 2030 there would no longer be any incentives applied to the first cost of a vehicle with a low GHG emissions powertrain.

Several assumptions were also made for the use of GREET in this study. The vehicle configurations chosen were based on what was available in GREET. Fuels in the matrix shown in Table 2.1 were mapped to the closest option available in GREET.

For the TTW emissions estimates in GREET, AVL used the existing calculations in GREET for distillate gasoline (E10) and Fischer–Tropsch (FT) diesel fuel. The model includes GHG—both carbon dioxide and methane—and the criteria pollutant NOx.

For the WTP emissions, AVL used the closest approximation available in GREET. For example, AVL assumed that hydrogen gas (H_2) is generated by renewable energy electrolysis at a central plant and that the hydrogen is not liquefied because of the energy cost for liquefaction.

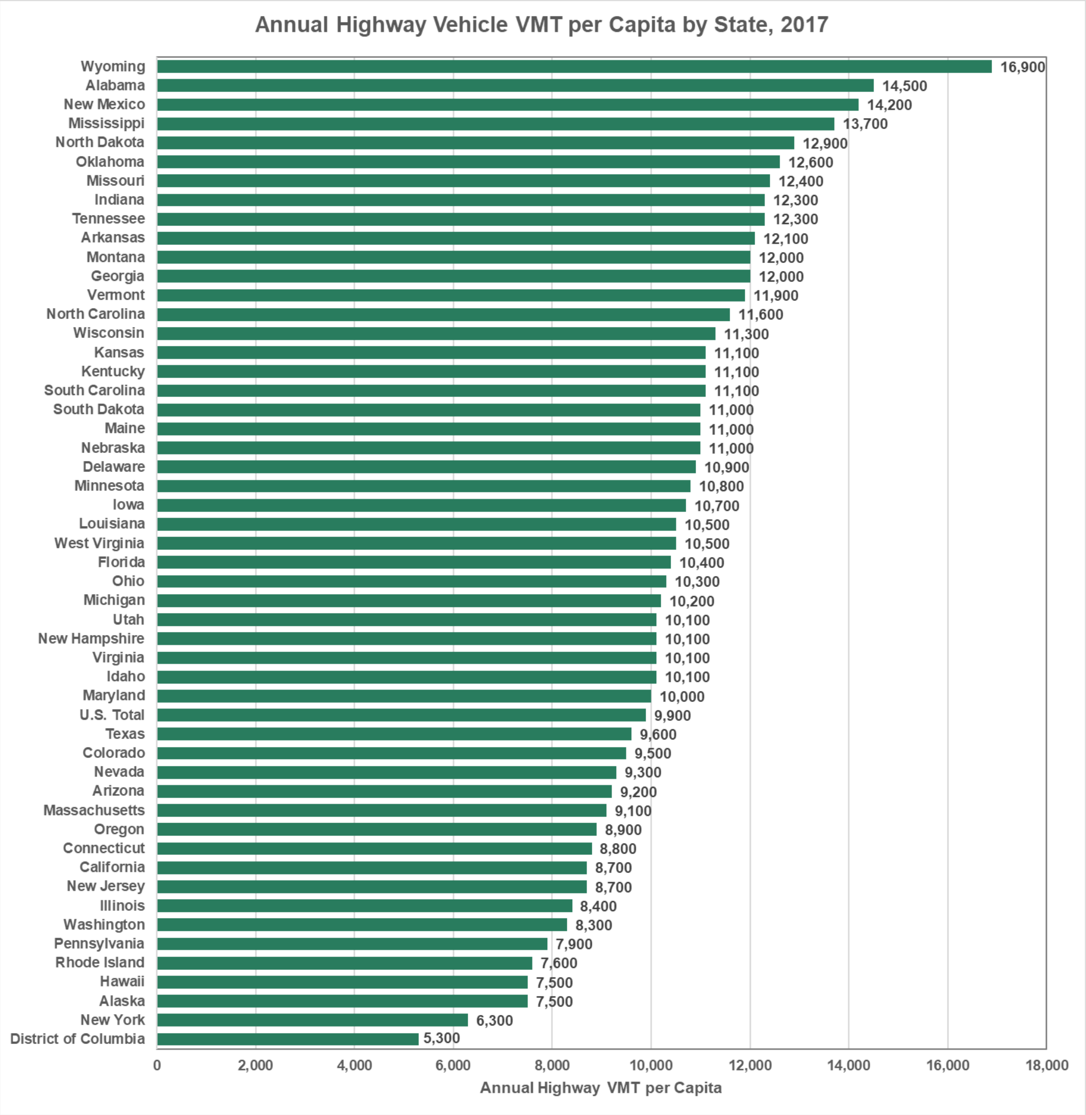


Figure 2.3 – Annual VMT per capita by state from 2017 [11].

In the case of electro-fuels, also known as e-fuels, the hydrogen gas used to make the fuels is generated at the same facility as where the e-fuels are produced so that there are no GHG emissions associated with the transport of the hydrogen. For e-gasoline, AVL assumed that the fuel provides a CO_2 credit to the feedstock equal to 75% of the TTW CO_2 emissions estimate. Similarly, for e-diesel, AVL assumed that the CO_2 credit to the feedstock equaled 90% of the TTW CO_2. The difference in the two CO_2 credit levels reflects that the Mobil methanol to gasoline process is less efficient than the FT process used to make e-diesel.

AVL recognizes that these assumed CO_2 credit levels are conservative estimates, and that the actual benefit could be closer to 100% of the TTW CO_2 emissions. This benefit depends on the energy inputs needed to manufacture the fuel and to transport it to fueling stations. AVL recommends that these fuels be included in a future update of GREET as they grow in interest. In addition, MECA and AVL assumed that some sort of subsidy or incentive would need to be in place in 2030 to keep the e-fuel costs per gallon competitive with other pump fuels.

2.5. Dashboards

AVL developed three tools for this study: Dashboards 1, 2, and 3. Dashboard 1 is a stand-alone tool that uses results from the GREET analysis over the agreed design space to evaluate individual vehicle cases for their lifecycle GHG emissions and TCO. Dashboard 2 is like Dashboard 1 in that it evaluates vehicle cases, but here Dashboard 2 is used to populate the vehicles used in the fleet analysis. Dashboard 3 is used for the fleet analysis.

A screenshot of Dashboard 1 is shown in Figure 2.4. Dashboard 1 is a spreadsheet-based tool where the user can select the vehicle, powertrain, and fuel type. Other parameters can be selected, and one parameter can be varied over a range of values. In the screenshot in Figure 2.4, for example, the variation parameter is BEV range. These selections are then used to calculate and display results plots.

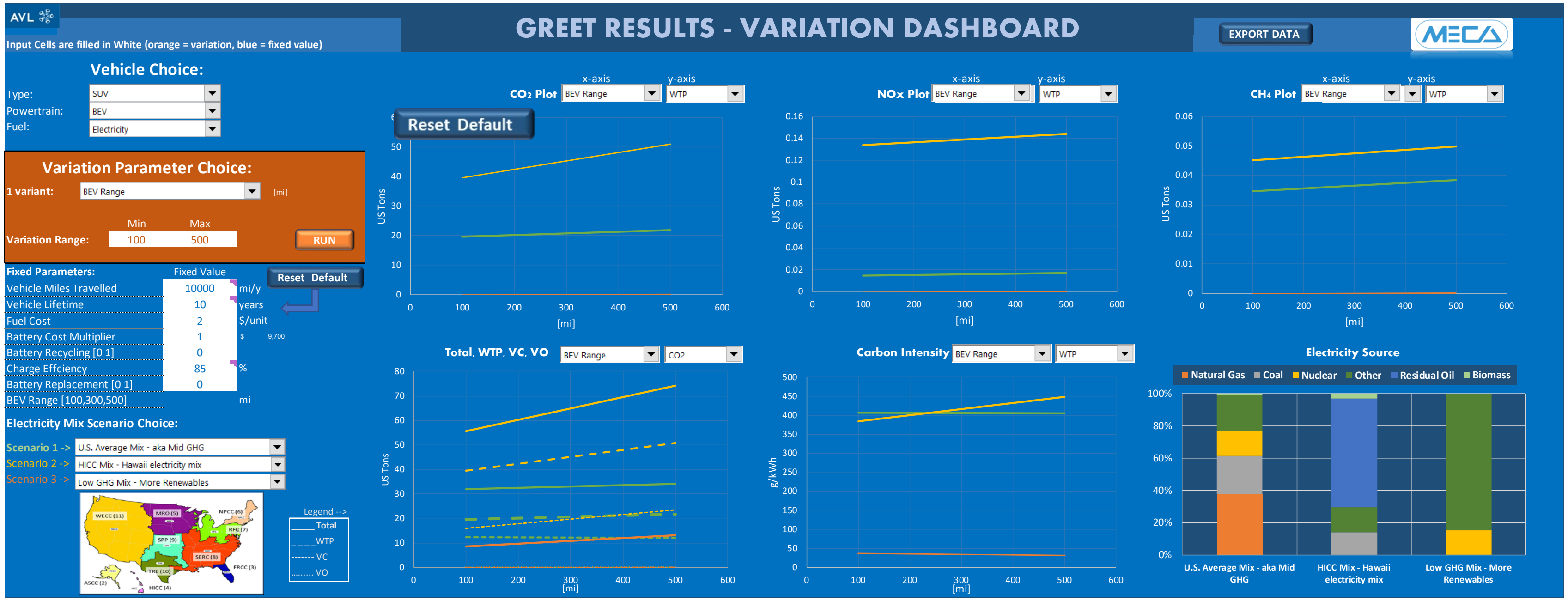
Input factors for Dashboard 1 and 2 used in the study are as follows:

- Fuel prices for each of the fuels considered, as shown in Table 2.6
- Charging efficiency, which is nominally 85%.
- BEV range of 300 miles for sedans and 400 miles for pickups and SUVs.
- Battery pack recycling was not considered.
- Battery modules or packs are not replaced during the vehicle life considered.

The assumption to neglect battery pack recycling is based on the current 2020 situation, where there is a low population of EVs at end of life, and few recycling facilities for lithium-ion batteries.

For Dashboard 3, a main input factor was the market penetration of the candidate 2030 new vehicle fleets as a fraction of the 2030 VIO.

These Dashboards were used to pick candidate technology bundles for each of the three vehicle types. Bundles were ranked by life-cycle CO_2 emissions and by TCO. The five solutions with the lowest life-cycle CO_2 emissions were grouped into a best-technology or “Low GHG Emissions” set. MECA and AVL also selected three other vehicle solution sets. The fleets used in this study are described further in Section 3.3.



AVL

GREET RESULTS - VARIATION DASHBOARD

Input Cells are filled in White (orange = variation, blue = fixed value)

Vehicle Choice:

Type: SUV
Powertrain: BEV
Fuel: Electricity

Variation Parameter Choice:

1 variant: BEV Range [mi]

	Min	Max
Variation Range:	100	500

Fixed Parameters:	Fixed Value	
Vehicle Miles Travelled	10000	mi/y
Vehicle Lifetime	10	years
Fuel Cost	2	$/unit
Battery Cost Multiplier	1	$ 9,700
Battery Recycling [0 1]	0	
Charge Effciency	85	%
Battery Replacement [0 1]	0	
BEV Range [100,300,500]		mi

Electricity Mix Scenario Choice:

Scenario 1 -> U.S. Average Mix - aka Mid GHG
Scenario 2 -> HICC Mix - Hawaii electricity mix
Scenario 3 -> Low GHG Mix - More Renewables

Figure 2.4 – Dashboard 1 for single vehicle analysis.

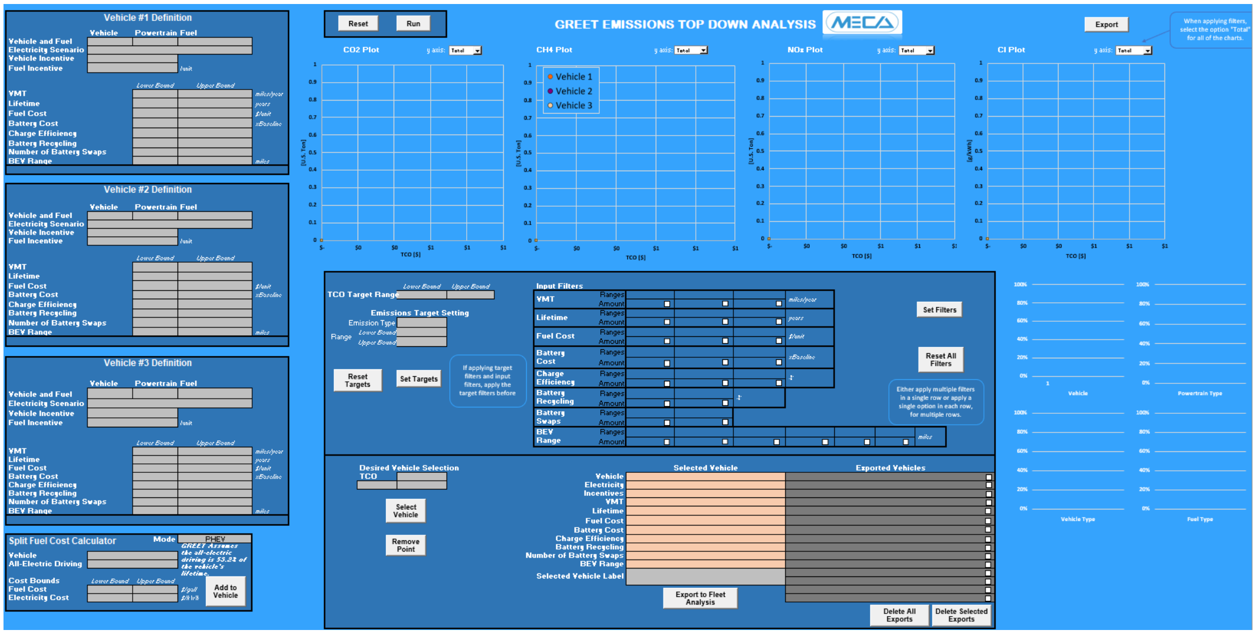


Figure 2.5 – Dashboard 2 for vehicle analyses to populate the fleet analysis.

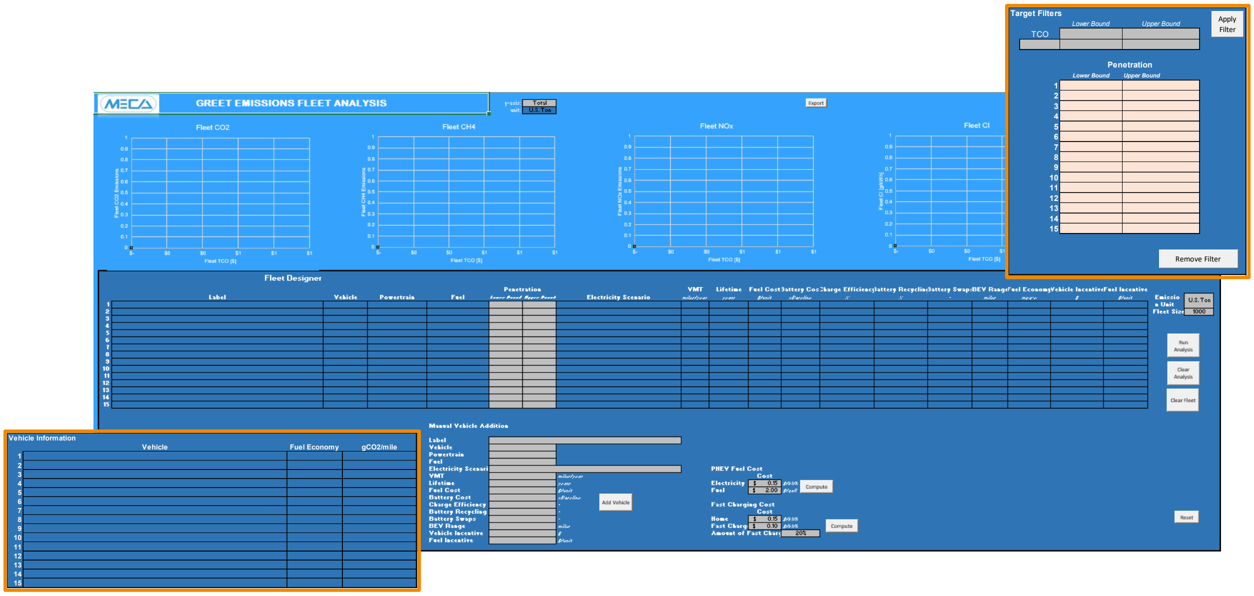


Figure 2.6 – Dashboard 3 for fleet analysis.

3. Analyses and Results

This section describes the various analyses that went into the study and discusses the study results. The initial simulations in GREET were used to populate the design space, then the vehicle analysis Dashboards were used. Finally, Dashboard 2 was used to populate the fleet vehicle and technology mixes for the fleet analyses described in Section 3.4.

The following three CO_2 emissions sources that contribute to overall vehicle-level lifecycle GHG emissions are considered in this study:

- Fuel, on a WTP basis
- Vehicle manufacturing
- Vehicle operation

3.1. GREET Simulations over Design Space

GREET simulations were used to populate the overall design space as defined by the vehicle matrix of powertrains and fuels shown in Table 2.1, by the 19 electricity mix scenarios, and by the following variations in GREET parameters for BEV and PHEV:

- Vehicle range for BEV
- Charging efficiency
- Battery replacement
- Battery recycling

To fully sample the design space, a total of 12,900 runs were executed in GREET. These results allowed over 500 regression models to be created by the AVL team, and these models were then populated into the Dashboards developed for the study. The results from each run included the CO_2, NOx, and CH_4 emissions estimates as calculated by GREET.

The GREET results can be used to show how the varied input parameters can affect the lifecycle CO_2 emissions. For example, Figure 3.1 shows the effects of fuels and charging efficiency on the WTP emissions for the SUV PHEV. The four electricity scenarios shown span the full range of WTP lifecycle CO_2 emissions from lowest (LowGHG Renew) to highest (Hawaii). Understandably, as charging efficiency improves, the WTP CO_2 emissions decrease since there is less waste. Likewise, the WTP CO_2 emissions are strongly influenced by the electricity scenario.

As for vehicle operation, the CO_2 emissions for vehicles with internal combustion engines (ICEs) show that the powertrain efficiency and fuel choice will both influence the in-use emissions from these vehicles. This is true for all three vehicle types studied: the Sedan, shown in Figure 3.2; the SUV, shown in Figure 3.3; and the Pickup Truck, shown in Figure 3.4.

The CO_2 emissions from the electricity scenarios were used to calculate the CO_2 emissions associated with vehicle manufacture. Note that vehicle manufacture is not evenly distributed across the US. Instead, it is clustered in a few states largely in the

Midwest and South. Likewise, the GREET results were also used to calculate the CO_2 emissions from vehicle operation for each of the vehicle, powertrain, and fuel combinations considered.

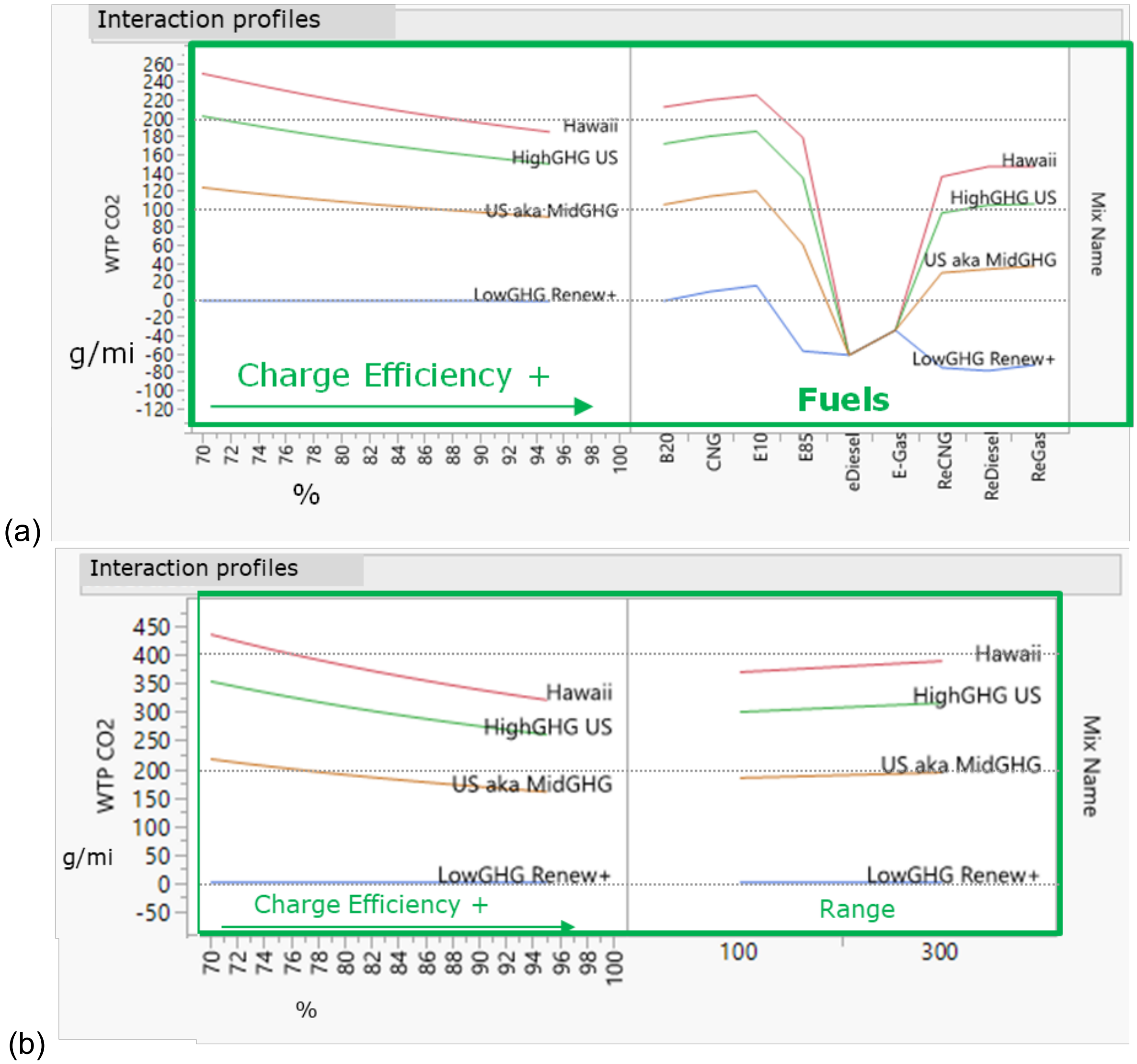


Figure 3.1 – Effect of charging efficiency on well to pump (WTP) CO_2 emissions for the SUV PHEV using four representative electricity scenarios: (a) Effect of fuels and (b) Effect of EV range.

Finally, the contributions to CO_2 emissions from WTP, vehicle manufacturing, and TTW can be summed into the total CO_2 emissions for each combination of vehicle, powertrain, and fuel included in the design space, as shown in Figure 3.5 and Figure 3.7 for the US Average grid and Figure 3.6 for the California grid. Note that these three plots are on slightly different scales.

The vehicle mixes in Figure 3.5 and Figure 3.6 are all based on the SUV and the results in both figures compare lifecycle CO_2 emissions for the FCEV, HEV, and ICEV powertrains. The FCEV and HEV are charge-sustaining hybrids, so their lifecycle CO_2 emissions are an indirect function of the electricity scenario. In transitioning from the US

Average grid in Figure 3.5 to the California grid in Figure 3.6, the lifecycle CO_2 emissions contributions from WTP and vehicle manufacture are cut by about a third. Nevertheless, the CO_2 emissions from vehicle operation are only slightly lower.

Figure 3.7 shows the effects of the various fuels on the SUV PHEV and BEV total CO_2 emissions for one grid scenario, the US Average (mid-GHG) mix. Here, the variations shown by the box plots come from variations in the four parameters listed on the figure. The effect of charging efficiency on WTP CO_2 emissions, for example, is shown in Figure 3.1. Additionally, the BEV with the US Average electricity mix from Figure 3.7 has a nominal emissions value of 250 g CO_2/mi., which is only slightly better than HEVs using B20 or E10. Moreover, it is worse (higher) than HEV or ICEV using more sustainable fuels.

AVL also calculated emissions coverage matrices across all 19 electricity scenarios. Variations were included for the four key parameters of this study: BEV range, battery charging efficiency, battery replacement during vehicle life, and battery recycling at end of life. More detail on these results is included in Appendix D.

AVL also looked at the effects of the fuel and electricity grid scenarios on the WTP contribution to lifecycle NOx and methane emissions. These results are described in more detail in Appendix D, and are based on how GREET handles these emissions for both WTP and vehicle operation emissions [3, 4, 13, 14].

Note that VMT, vehicle life, and cost variations are not parameters considered in GREET. They are only applied within the Dashboards, as described in Sections 3.2 and 3.4.

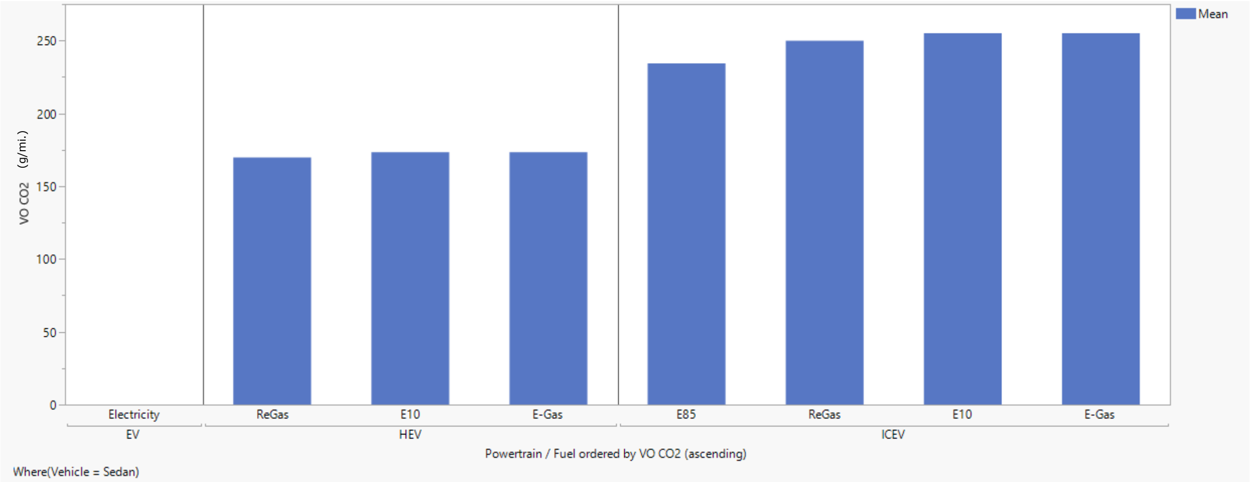


Figure 3.2 – Mean CO_2 emissions from vehicle operation for the Sedan, with powertrain and fuel combinations ranked by increasing mean emissions.

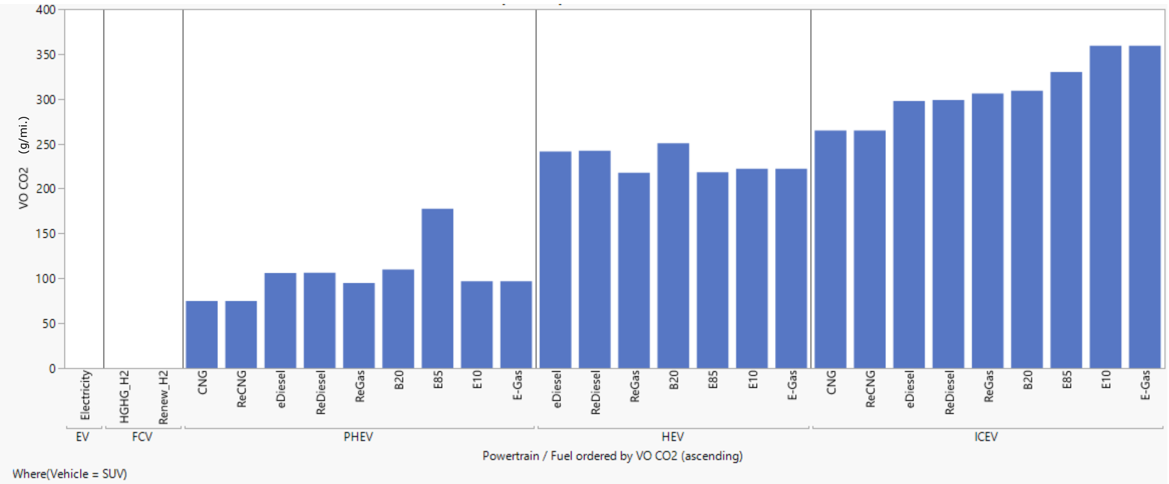


Figure 3.3 – Mean CO_2 emissions from vehicle operation for the SUV, with powertrain and fuel combinations ranked by increasing mean emissions.

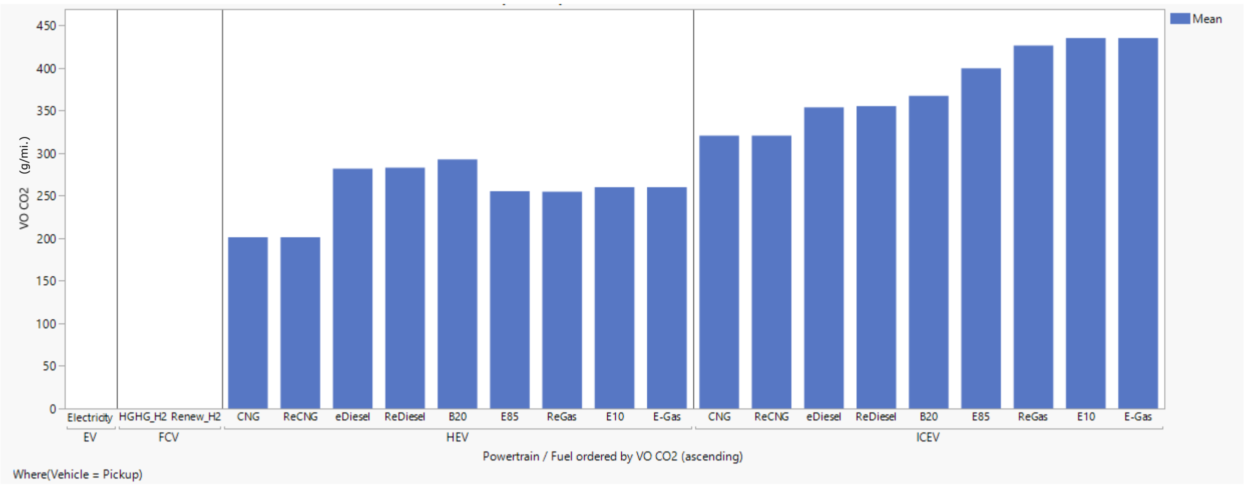


Figure 3.4 – Mean CO_2 emissions from vehicle operation for the Pickup Truck, with powertrain and fuel combinations ranked by increasing mean emissions.

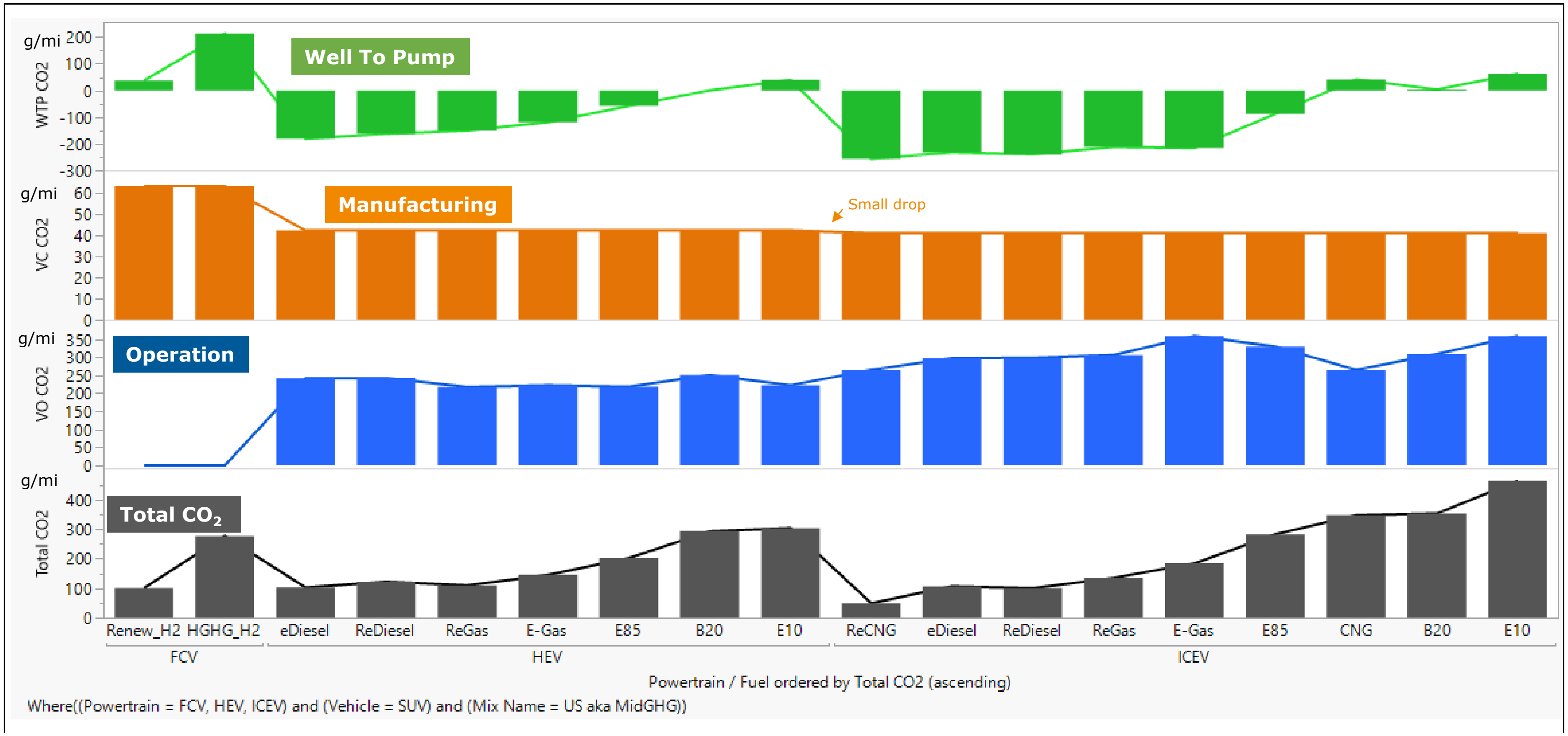


Figure 3.5 – Mean total CO_2 emissions from total lifecycle for the SUV ICEV, HEV, and FCEV using the 2030 US Averaged electricity mix.

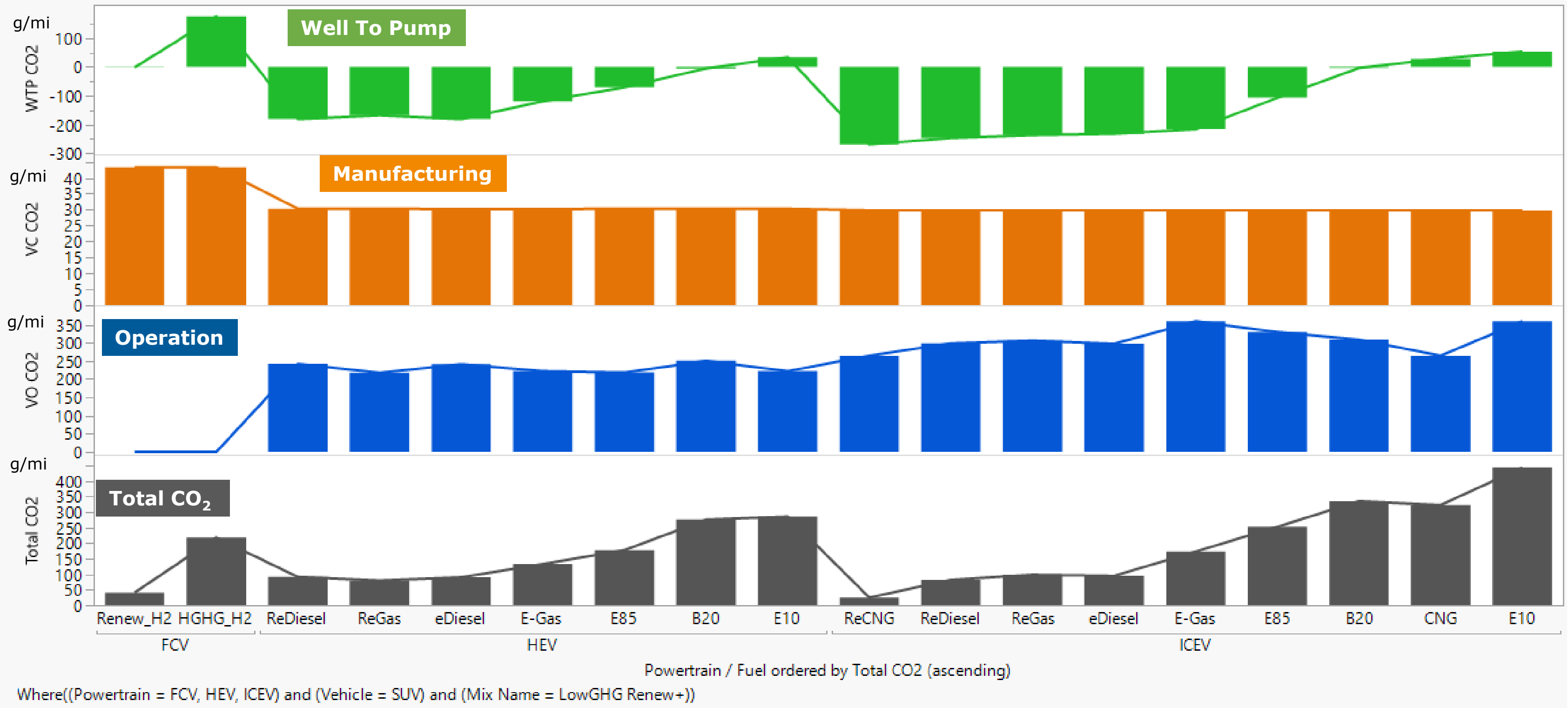
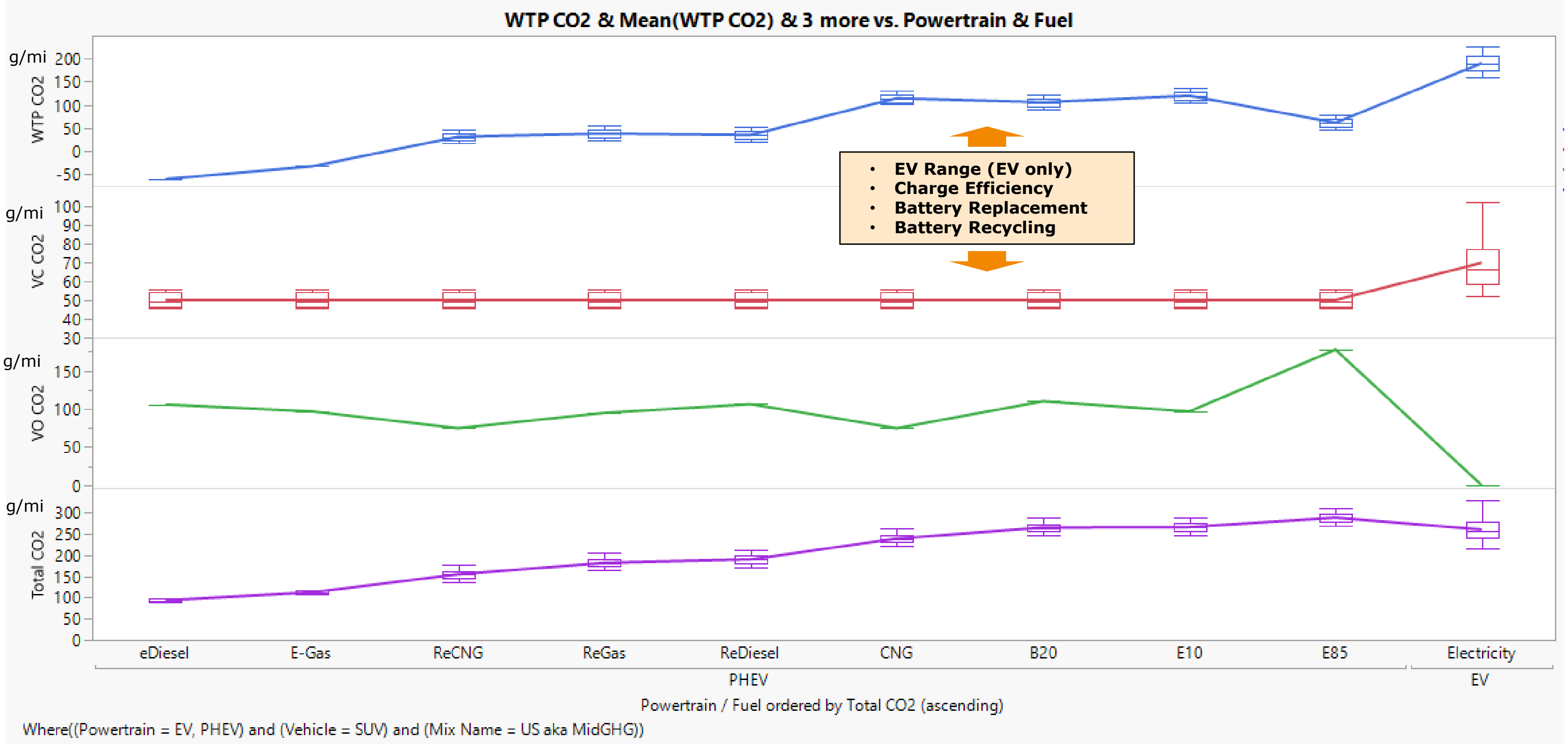


Figure 3.6 – Mean total CO_2 emissions from total lifecycle for the SUV ICEV, HEV, and FCEV using the 2030 California electricity mix.



- **EV Range (EV only)**
- **Charge Efficiency**
- **Battery Replacement**
- **Battery Recycling**

Where((Powertrain = EV, PHEV) and (Vehicle = SUV) and (Mix Name = US aka MidGHG))

Figure 3.7 – Constituent and total CO_2 emissions estimates for the SUV PHEV and BEV using the US Average electricity scenario.

3.2. Vehicle Analysis – Dashboards 1 and 2

Dashboard 1 was used to assess individual vehicle cases. In this study, Dashboard 1 was mostly used by AVL to check the data quality and to confirm that the results were sensible. Dashboard 1 was delivered to MECA for their use.

Dashboard 2 was used to generate the vehicle-level data that populated the fleet for the analyses using Dashboard 3. Using the assumptions from Section 2.4, AVL varied fuel prices as follows to help populate the analyzed design space for TCO:

- Hydrocarbon fuels: \$1/gal. to \$5/gal.
- Hydrogen: \$2/kg to \$13/kg
- Electricity: \$0.01/kW·h to \$0.50/kW·h

3.3. Definition of Fleets for This Study

AVL used results from Dashboard 2 to calculate the lifecycle GHG emissions and TCO from the range of vehicle options considered. For this analysis AVL uses “Conventional” to refer to vehicles with ICEs and to charge-sustaining HEVs. The “Highly Electrified” options include BEVs, FCEVs, and PHEVs. BEVs and PHEVs use energy stored in the vehicle battery during normal driving. The FCEV is assumed to be a charge-sustaining hybrid configuration but uses a hydrogen-fueled PEM fuel cell as the main on-vehicle power source.

The initial scenario analysis to help define the fleets used GREET to assess the sensitivity of TCO results to the various input factors shown in Table 2.5. The Sedan, SUV, and Pickup Truck vehicle options were assessed and ranked from highest CO_2 emissions to lowest by fuel type, as shown in Figure 3.8 and Figure 3.9. In addition, the analysis calculated ranges of values for TCO, which are shown by the whisker plots for each of the three vehicle types. Figure 3.8 shows the results using the 2030 US Average electrical grid, whereas Figure 3.9 shows the results using the 2030 California electrical grid. For all three vehicle types, the BEV version produces higher lifecycle CO_2 emissions than most of the other configurations. This is a result of the higher emissions in vehicle manufacture and in the WTP burden of a higher GHG emitting electrical grid.

AVL evaluated selected Conventional and Highly Electrified technology options for each of the three vehicle classes as shown in Figure 3.10 and Figure 3.11. AVL sorted the results from each vehicle technology option by lifecycle GHG emissions and then selected the five options for each vehicle class that had the lowest emissions without regard to TCO. These options are listed in Table 3.1.

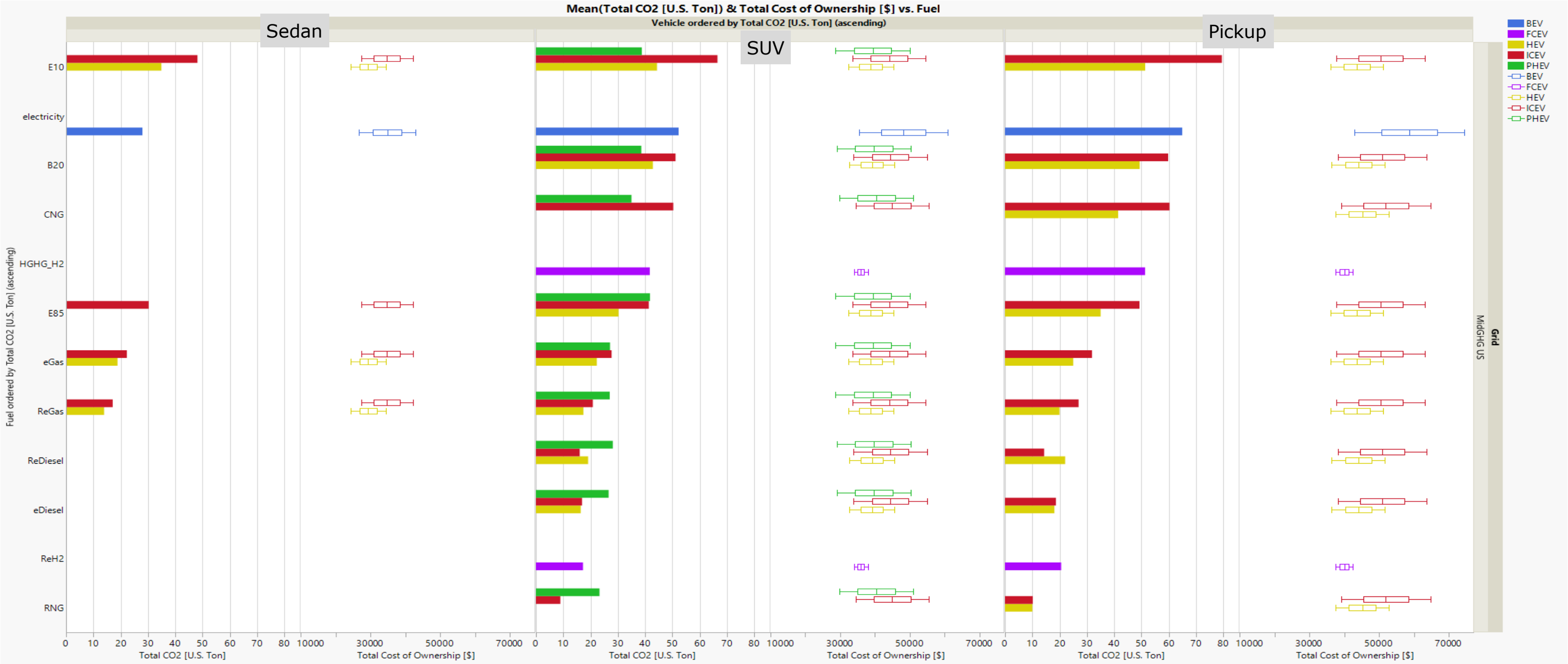


Figure 3.8 – Fleet options with 2030 US Average electrical grid.

Figure 3.9 – Fleet options with 2030 California electrical grid.

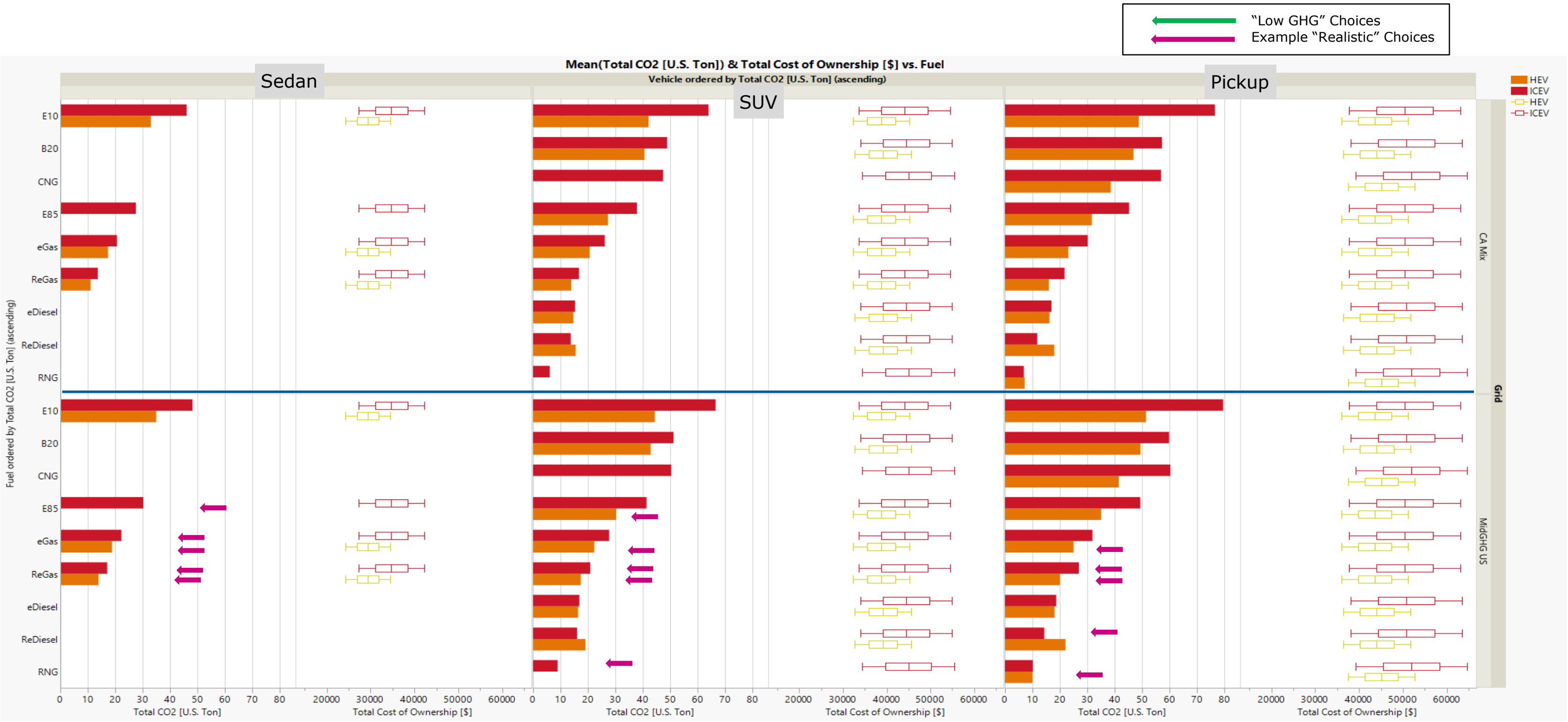


Figure 3.10 – Conventional fleet options for both 2030 grid mixes. Vehicles are ordered by total lifecycle CO_2. Green arrows mark Low GHG Emissions fleet choices; the magenta arrows mark options that balance emissions and TCO.

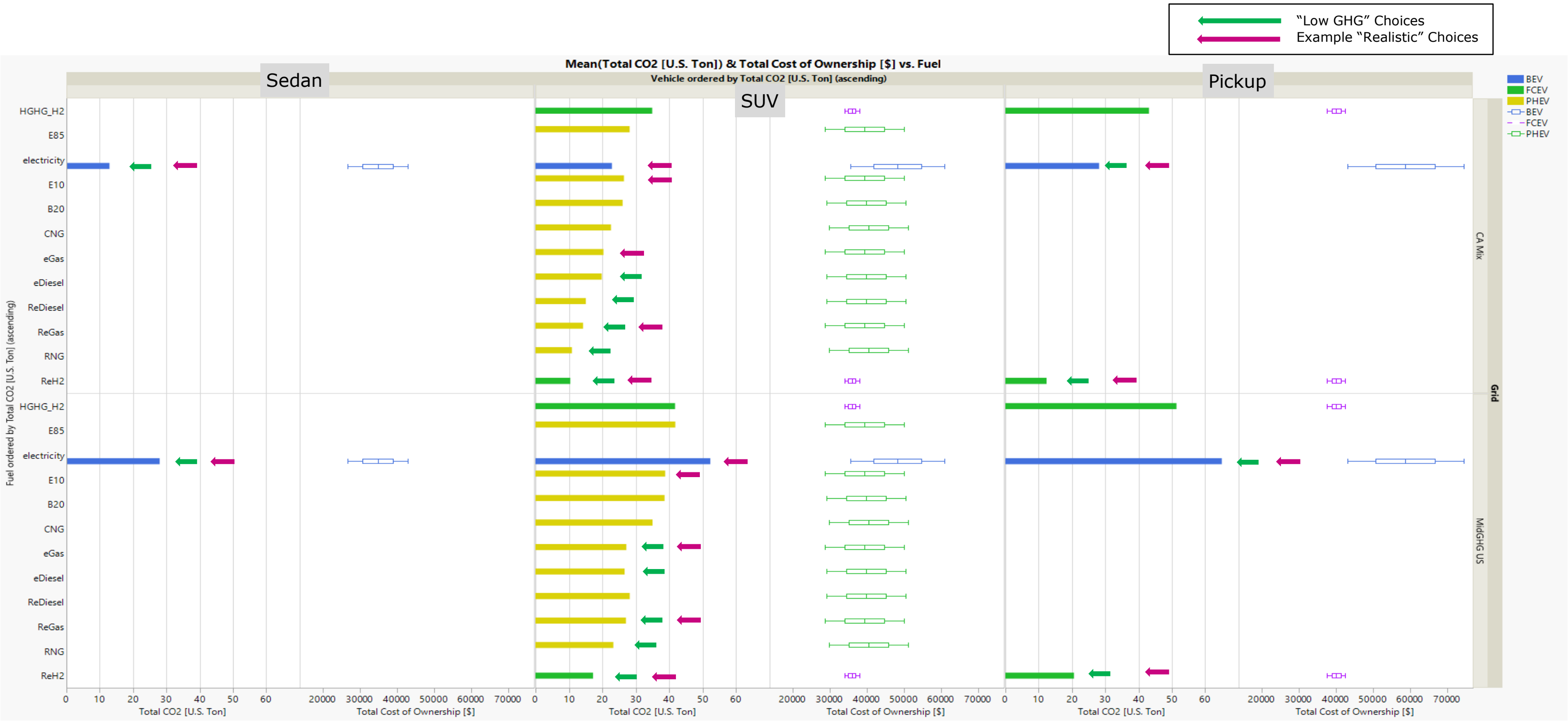


Figure 3.11 – Highly electrified fleet options for both 2030 grid mixes. Vehicles are ordered by total lifecycle CO$_2$. Green arrows mark Low GHG Emissions fleet choices; the magenta arrows mark options that balance emissions and TCO.

Table 3.1 – Low GHG Emissions Vehicle fleet options for analysis.

	Conventional	Electrified
Sedans	ICE E85	BEV-300
	ICE e-gasoline	
	HEV e-gasoline	
	ICE renewable gasoline	
	HEV renewable gasoline	
SUVs	HEV renewable gasoline	BEV-400
	ICE e-diesel	PHEV E10
	HEV e-diesel	PHEV e-gasoline
	ICE renewable diesel	PHEV renewable gasoline
	ICE RNG	FCEV renewable H_2
Pickups	HEV e-gasoline	BEV-400
	ICE renewable gasoline	FCEV renewable H_2
	HEV renewable gasoline	
	ICE renewable diesel	
	HEV RNG	

MECA also reviewed the aggregated Dashboard 2 results and created three fleet scenarios that represented increasing levels of technology uptake. As shown in Table 3.2, Scenario 1 represents a modest improvement in vehicle technology packages from the 2019 baseline, whereas Scenario 3 uses advanced vehicle technologies and fuels to try to improve fleet-level emissions. In all three cases, MECA balanced their consideration of TCO with lifecycle GHG emissions.

Table 3.2 – MECA proposed fleet scenarios, where technology content increases from Scenario 1 to Scenario 3.

	Scenario 1	Scenario 2	Scenario 3
Sedans	HEV E10	HEV E10	HEV renewable gasoline
	ICE E85	ICE E85	HEV e-gasoline
	BEV-300	HEV renewable gasoline	BEV-300
		BEV-300	
SUVs & Pickups	HEV E10	HEV E85	ICE RNG (SUV only)
	HEV E85	HEV renewable gasoline	HEV RNG (Pickup only
	PHEV E10 (SUV only)	HEV renewable diesel (Pickup only)	HEV renewable gasoline
	HEV B20 (Pickup only)	PHEV E10 (SUV only)	HEV renewable diesel (Pickup only)
	BEV-400	HEV B20 (Pickup only)	HEV e-gasoline
		BEV-400	HEV e-diesel (Pickup only)
			FCEV renewable H_2
			BEV-400

3.4. Fleet Analysis – Dashboard 3

The main inputs to Dashboard 3 are the vehicles evaluated in Dashboard 2. The most important parameter unique to Dashboard 3 is the market penetration, or market share, ranges that are defined for each of the vehicles in the fleet. This bound was used, for example, to cap the maximum market share of FCEV at 5% of the 2030 fleet. In addition, Dashboard 3 can modify the fuel and electric charging costs.

For this study, Dashboard 3 was first used to evaluate a Baseline fleet. The fleet was defined using vehicle, technology, and fuel option market penetration levels that were derived from IHS Markit data on 2019 US vehicles sold. AVL assumed that the 2019 fleet would be representative of older vehicles for 2030, since the average age of the VIO in 2030 is assumed to be about 12 years.

The composition of the Baseline fleet, shown in Figure 3.12, is based on the market share of each vehicle and powertrain type in 2019. Each of the fuels in the figure, such as electricity or E10, was assigned to a fuel that is available for use in GREET. The fleet was set up and evaluated in Dashboard 3 using the 2030 US Average GHG electrical grid. The per-vehicle fleet average, lifecycle CO_2 emissions is 51.15 U.S. ton and TCO is \$37,300, as weighted by market share in the Baseline fleet. This fleet average is a composite primarily of the SUV HEV, Sedan ICEV, SUV ICEV, and Pickup HEV performance, based on the minimum market shares shown in Figure 3.12, but it does not map to a specific type of vehicle in the Baseline fleet. The total emissions of the fleet can be calculated by multiplying the number of vehicles in the fleet by the per-vehicle lifecycle CO_2 emissions.

Once the Baseline fleet was evaluated, AVL used Dashboard 3 to understand the range of 2030 fleets that are possible using the corresponding Conventional and Highly Electrified vehicle options. For these analyses, the fuel prices were held constant in real terms as discussed in Section 2.4. Most vehicle and powertrain market shares were allowed to have a broad range, with the exception of the FCEV market share that was limited to 5% of the 2030 Low GHG Emissions fleet.

One fleet scenario, shown in Figure 3.13, uses the Low GHG Emissions vehicles listed in Table 3.1 that were drawn from the Conventional and Highly Electrified options shown in Figure 3.10 and Figure 3.11. Here, the point clouds represent different market shares for each of the available vehicles. For example, the market share of the Sedan ICEV using E85 is shown in the breakout plot on Figure 3.13 marked “Example content”. In this point cloud of conventional vehicles with the 2030 California (CA) grid, all the Low GHG Emissions vehicle fleet options will robustly support an overall reduction of fleet GHG emissions. However, for the 2030 US Average grid, some of the Highly Electrified fleet options generate too much lifecycle CO_2 to offset the lifecycle CO_2 of the legacy Baseline fleet.

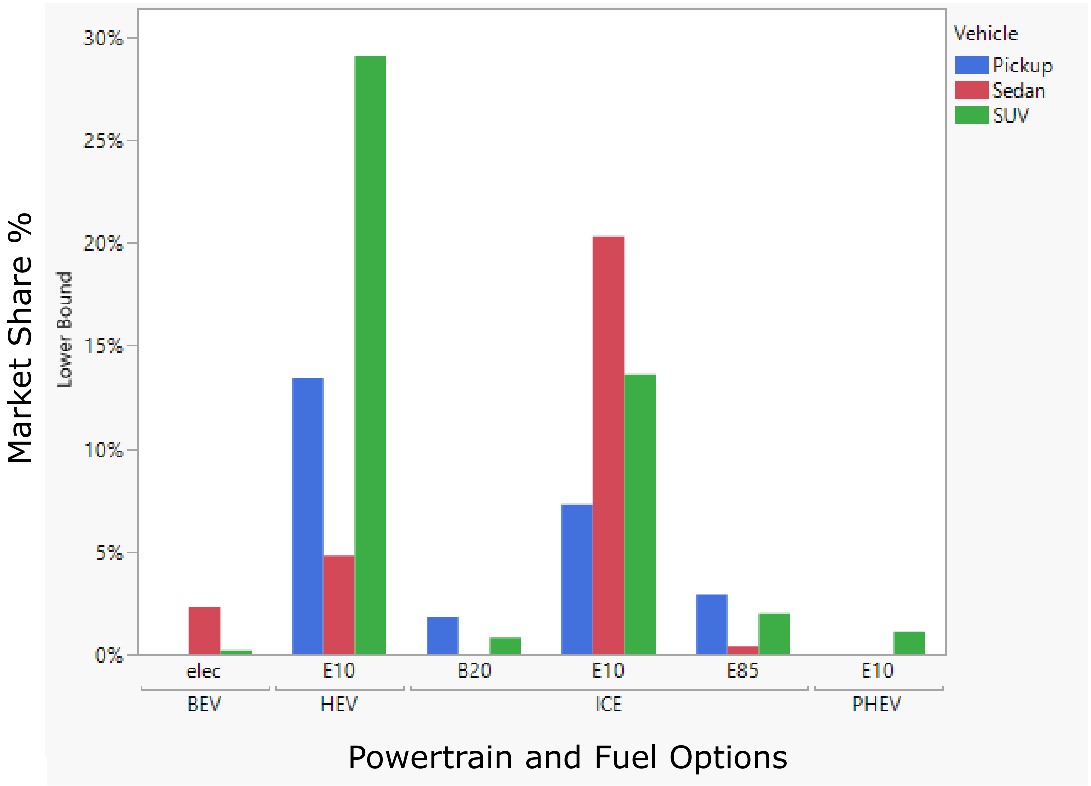


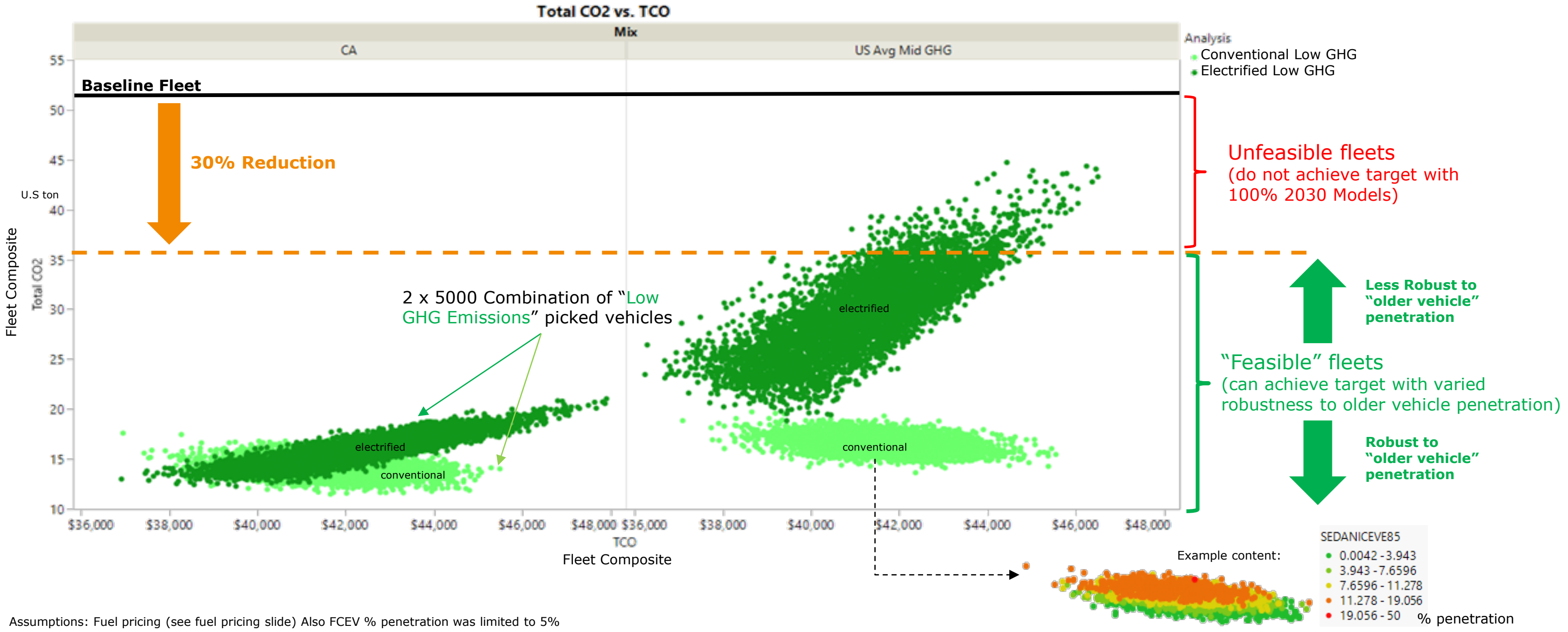
Figure 3.12 – Market share for each of several powertrain and fuel options for Baseline fleet that is derived from 2019 fleet data.

Note that market shares of the various vehicles in the fleet also affect the fleet averaged TCO. This is demonstrated more clearly in Figure 3.14, where 40% of the fleet is effectively at the Baseline fleet lifecycle CO_2 emissions and thus 60% of the fleet is at the 2030 new vehicle level. In this example, the new vehicles must be better than the target line to offset the GHG emissions of the legacy Baseline fleet vehicles. A follow-on study could estimate the contributions to the fleet CO_2 emissions by year and then average in the 2030 vehicles, but the assumptions were that the fleet would continue to improve its emissions in a steady fashion and that a simple two-point average would suffice to demonstrate the concept.

Similarly, the three MECA Scenario fleets documented in Table 3.2 were evaluated and the fleet results are shown in Figure 3.15 for all three fleets. For each Scenario, AVL evaluated 5,000 combinations of market shares for each of the vehicles within the Scenario. Each combination is represented with a point in the “clouds” of points shown on Figure 3.15. As with the Low GHG Emissions fleet, the FCEV in MECA Scenario 3 had a maximum market share of 5%. Because the technology mixes are less aggressive than in the Low GHG Emissions fleet, fewer fleet market share combinations in the three MECA Scenarios shown in Figure 3.15 are likely to lead to an overall VIO that meets a future blanket reduction in lifecycle CO_2 emissions. The example in Figure 3.16 assumes a 40% share of Baseline (2019) vehicles combined with the 2030 vehicle mix options in the point clouds. Only the MECA Scenario 2 and Scenario 3 fleets will lead to an overall 30% reduction in this case. On the other hand, the MECA Scenario vehicles combinations have TCO values that are roughly $2,000 to $4,000 lower than those for the Low GHG Emissions vehicle combinations.

The effect of electric grid GHG emissions is also pronounced, with a significantly higher fleet composite CO_2 for fleet combinations using the US Average grid than the California (CA) grid. The grid CO_2 emissions not only affect the emissions associated with driving BEVs and PHEVs, but they also affect the CO_2 emissions associated with vehicle manufacture and fuel transport.

The results from the three MECA Scenarios and the two AVL Low GHG Emissions Scenarios are combined together on Figure 3.17. Here, the MECA Scenario 3 overlaps strongly with the AVL electrified Low GHG Emissions fleet options, both on lifecycle CO_2 emissions and TCO. The AVL conventional vehicles, which include HEV and FCEV, seem to have the best lifecycle CO_2 emissions, but they have a marginally higher TCO than the other options.



Assumptions: Fuel pricing (see fuel pricing slide) Also FCEV % penetration was limited to 5%

Figure 3.13 – 2030 Fleets using the Conventional and Highly Electrified Low GHG Emissions vehicles. Point clouds represent new 2030 vehicles only. Assumed target for fleetwide GHG emissions is a 30% reduction from 2019 baseline.

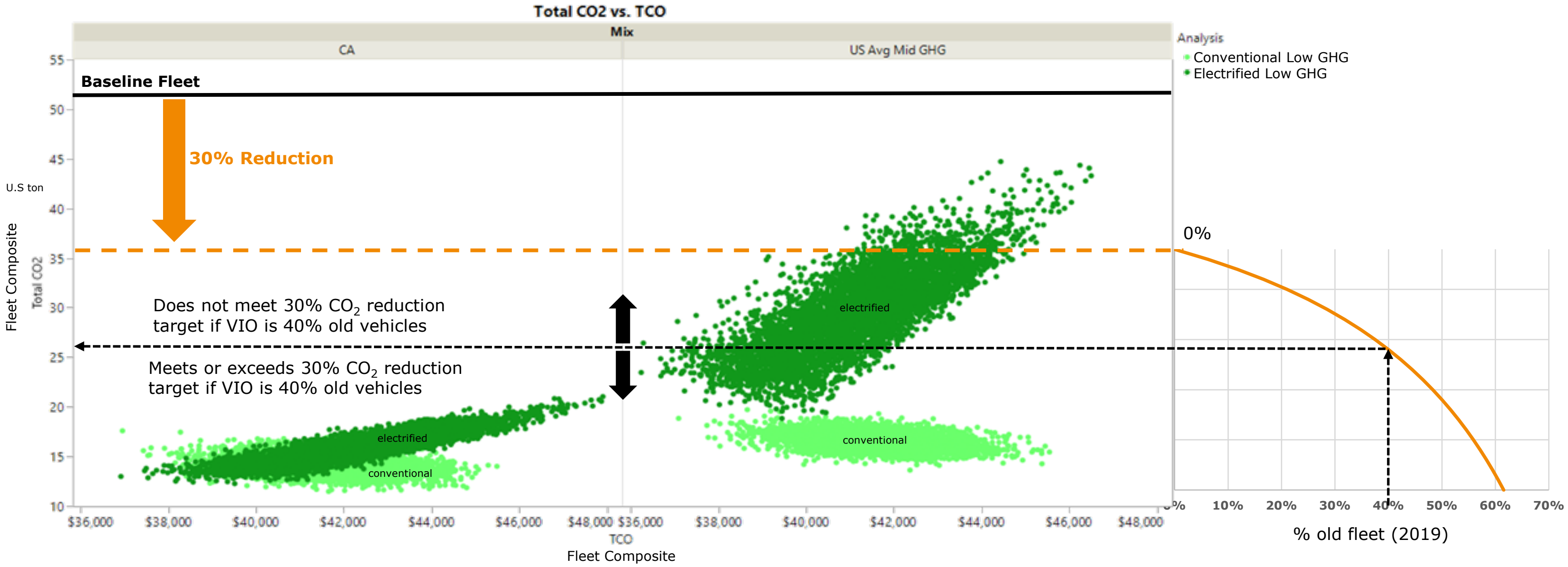


Figure 3.14 – Example showing fleet options meeting a 30% CO_2 emissions reduction. The example marked here assumes the Baseline fleet results represent 40% of the VIO emissions and the 2030 fleet results, 60% of the VIO.

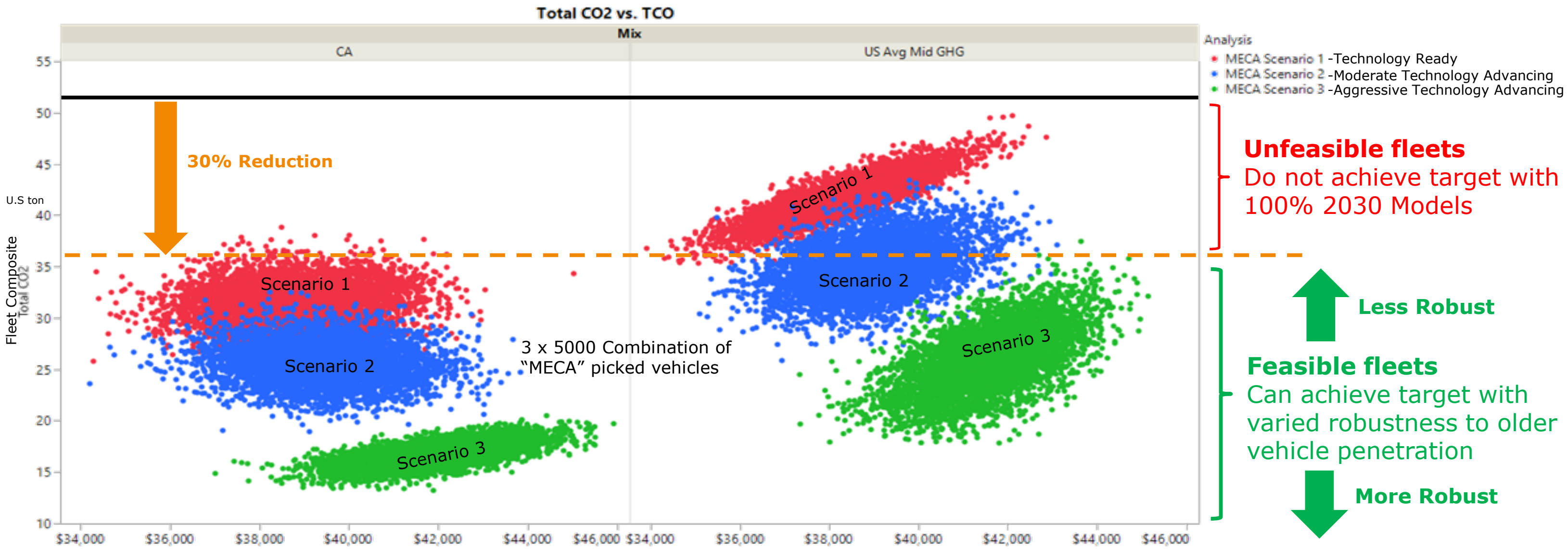


Figure 3.15 – 2030 Fleets using the MECA Scenario vehicles as shown in Table 3.2. Point clouds represent new 2030 vehicles only. Assumed target for fleetwide GHG emissions is a 30% reduction from 2019 baseline.

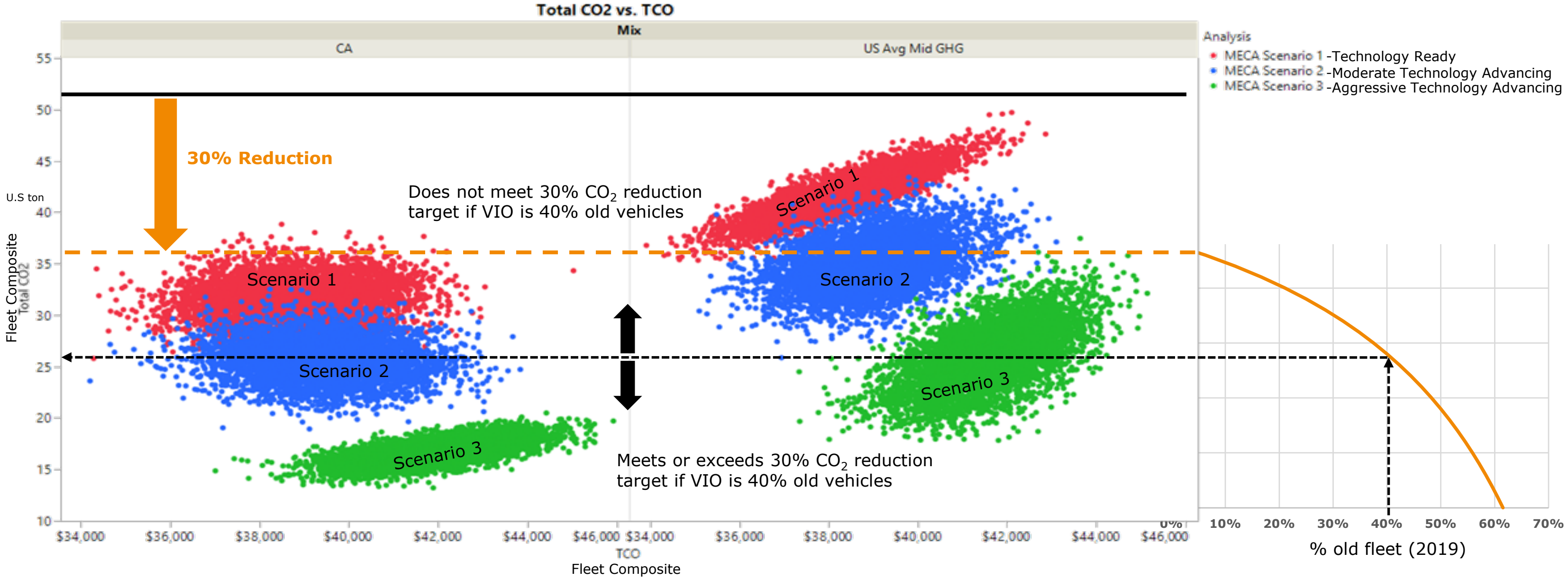


Figure 3.16 – Example showing fleet options meeting a 30% CO_2 emissions reduction. The example marked here assumes the Baseline fleet results represent 40% of the VIO emissions and the 2030 MECA Scenario fleet results, 60% of the VIO.

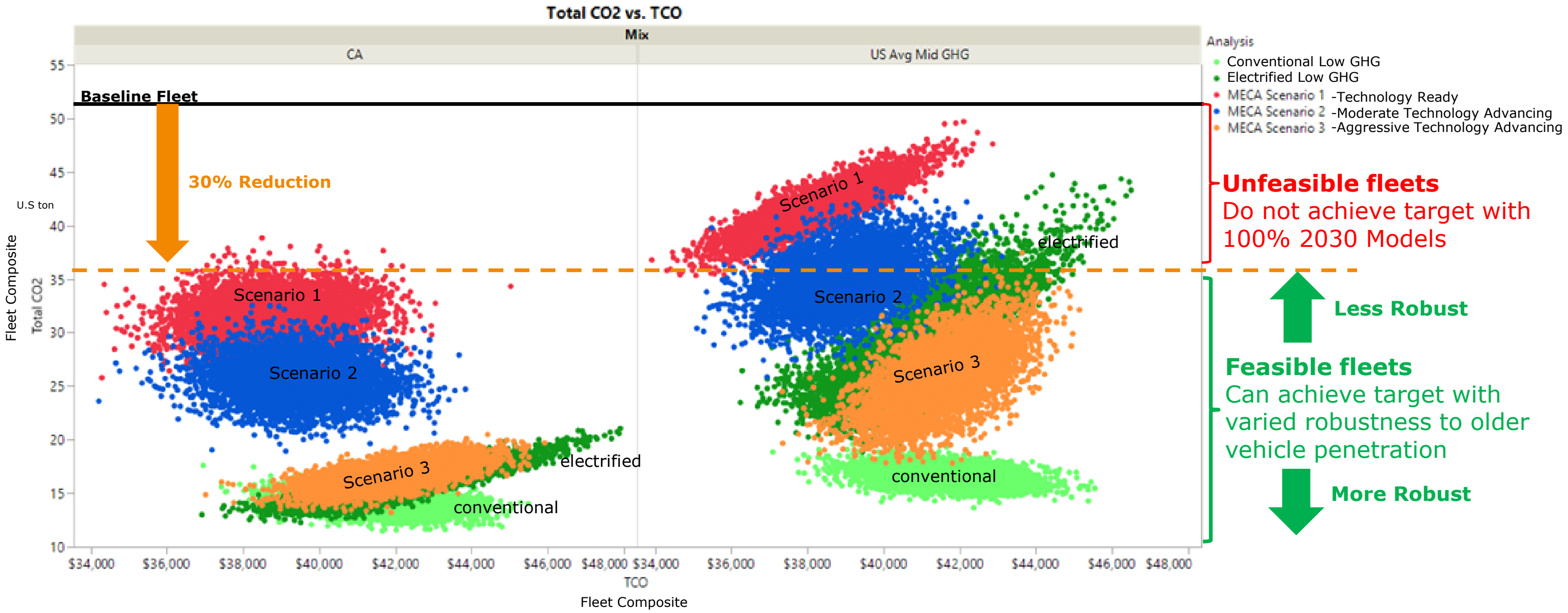


Figure 3.17 – 2030 Fleets comparing the results from the Low GHG Emissions and MECA Scenario vehicle options. Point clouds represent new 2030 vehicles only.

4. Conclusions

AVL has completed a study looking at lifecycle emissions and TCO from a 2019 Baseline fleet and the following five vehicle fleet scenarios for 2030:

1. Low GHG Emissions Conventional
2. Low GHG Emissions Highly Electrified
3. MECA Scenario 1 (Technology ready options)
4. MECA Scenario 2 (Moderate technology advancing)
5. MECA Scenario 3 (Aggressive technology advancing)

To conduct the analyses, AVL used GREET to populate the overall design space of interest. AVL also developed new tools for vehicle-level studies—Dashboards 1 and 2—and for fleet-level studies—Dashboard 3. Dashboard 1 is a stand-alone tool to evaluate a specific vehicle, powertrain, and fuel combination, whereas Dashboard 2 is used to populate the fleet analyzed in Dashboard 3.

For the Baseline fleet, the market shares used for the various vehicle types were based on market data available for 2019. For each of the 2030 fleet scenarios, the market shares of the vehicles in each fleet were varied to create different combinations. These combinations were then evaluated to calculate a fleet composite lifecycle CO_2 emissions value and a TCO on a per-vehicle basis. The various vehicle combinations within each fleet scenario show differing levels of robustness to the market share of older vehicles.

The TCO follows the expected trend that increased technology content in the vehicle will increase the first cost of the vehicle, albeit with some offset in lower operating costs over the vehicle lifetime.

Given the assumptions, the simulation results found that the electricity source mix and associated GHG emissions strongly influence the lifecycle CO_2 emissions from all vehicles, especially PHEV and BEV. Even though the 2030 US Average grid represents some level of improvement in GHG emissions from a 2019 baseline, the study results suggest that further improvements may be needed from this moderate GHG emissions level to meet the 2030 GHG emissions targets for VIO.

In addition to the CO_2 emissions, AVL also calculated lifecycle NOx and CH_4 values for each fleet option within a given Scenario. The trends in the lifecycle results are aligned with expectations, in that the electricity mix and the fuel used on the vehicle both affect the NOx and CH_4 emissions.

The CO_2 target for new vehicles is strongly influenced by the composition of the VIO. A larger fraction of older vehicles in the VIO means that newer vehicles must be that much better to meet overall CO_2 targets. While the approach used in this study does simplify the mix of older and newer vehicles by using only two categories, it does demonstrate the methodology. More granularity by model year could be introduced in a follow-on study.

In addition, a follow-on study could look at the effect of fuels with lower WTP CO_2 emissions on the Baseline fleet emissions performance. This study assumed that the

Baseline fleet did not improve at all from its 2019 performance. If, however, fuels with lower WTP CO_2 become more readily available, the Baseline fleet performance would naturally improve because the WTP contribution to overall lifecycle CO_2 emissions would decrease.

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Appendix A. Definition of Abbreviations and Acronyms

ANL	Argonne National Laboratory
BEV	Battery electric vehicle
CA	California
CI	Carbon intensity
DOE	United States Department of Energy
EV	Electrified vehicle or Electric vehicle
FCEV	Fuel cell–electric vehicle
FT	Fischer–Tropsch
GGE	Gallon of gasoline equivalent
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
LCA	Lifecycle carbon analysis
LDV	Light-duty vehicle
MECA	Manufacturers of Emission Controls Association
NG	Natural gas
PHEV	Plug-in hybrid electric vehicle
TTW	Tank to wheels
US	United States of America
VIO	Vehicles in operation, the vehicle parc
VM	Vehicle manufacture
VO	Vehicle operation
VMT	Vehicle miles traveled
WTP	Well to pump

Appendix B. Side Study: Electricity Scenarios and Generation Mix

As has been discussed in the main report, AVL considered 19 electricity scenarios that encompassed several mixes of generating sources and thereby represented a broad span of grid-level GHG emissions. The overall set of 19 scenarios and their respective generation mixes are shown in Figure B.1. The electrical generation sources for 2030 include natural gas, coal, nuclear, residual oil, biomass, and other sources. Here, “other sources” includes a combination of hydroelectric, geothermal, wind, and other renewable power sources.

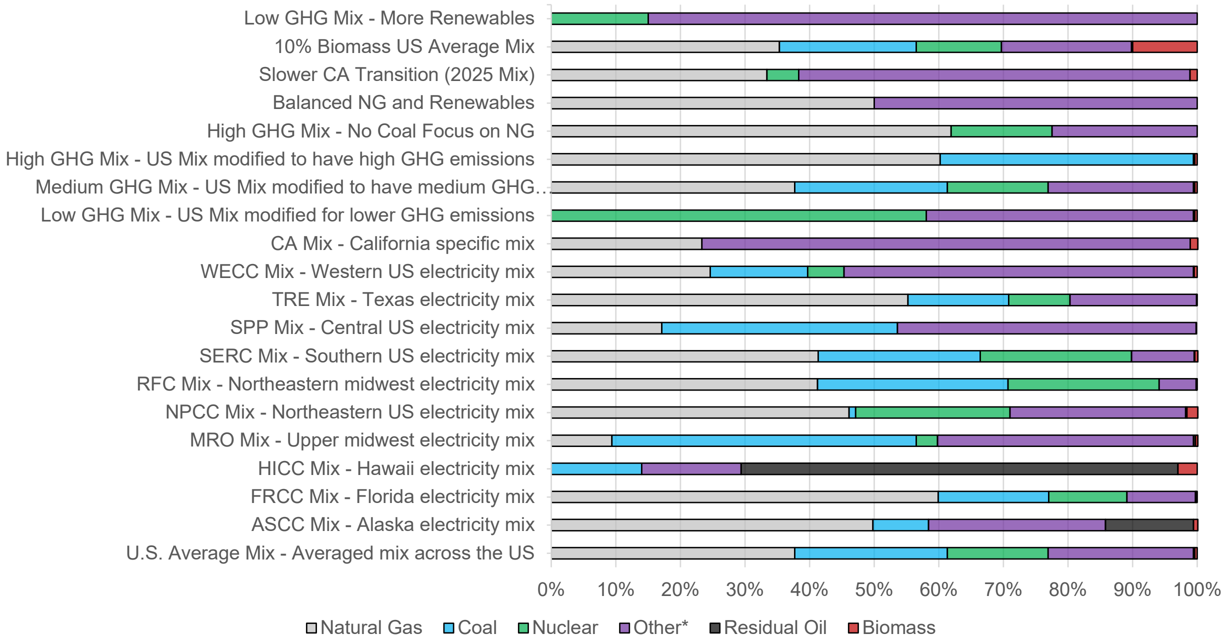


Figure B.1 – Electricity scenarios showing various mixes of electricity sources, where “Other” includes hydroelectric, geothermal, wind, and other low-GHG sources.

Ten of these scenarios are based on the electricity generation mixes found in various regions of the US. These regions are identified in Figure B.2 .

AVL had originally proposed 15 electricity scenarios, and four more were added during the course of the study. The two following added scenarios were requested by MECA.

- Slower California (CA) transition (2025 mix)
- Balanced natural gas (NG) and renewables

The other two added scenarios were added for comparison purposes, as follows:

- 10% Biomass – Adjust the US Average mix to include 10% power from biomass
- Low GHG Renewables — 85% renewables and 15% nuclear power, which reduces the reliance on nuclear power for a low GHG electrical grid

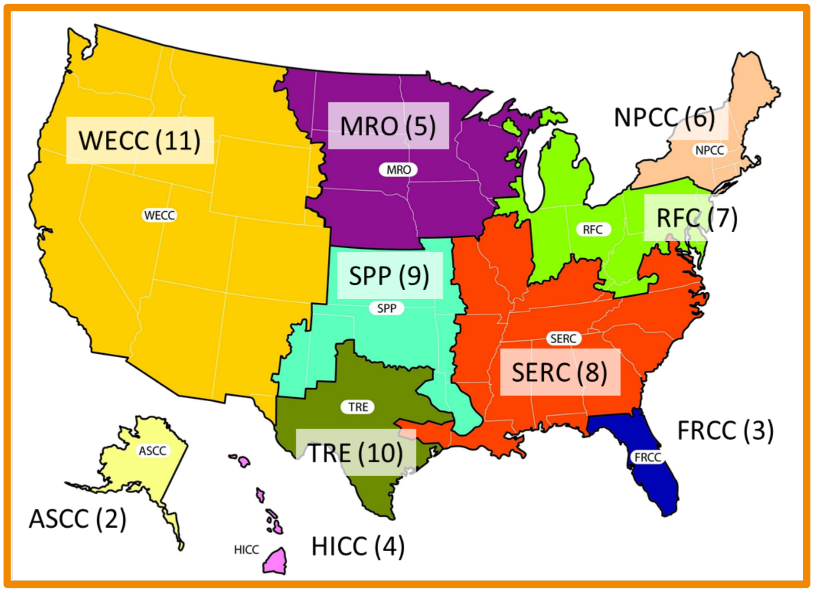


Figure B.2 – Regional electrical sub-grids that are used to generate ten of the electricity scenarios.

All of the 19 scenarios were evaluated using a Sedan BEV. This allows the comparison to eliminate CO_2 emissions from vehicle operation, leaving only the WTP and vehicle manufacture contributions. And the fuel—here, electricity—is almost completely dependent on the CO_2 emissions of the electricity scenario. The results from the electricity scenario evaluation using the Sedan BEV are shown in Figure B.3. The Hawaiian (HICC) mix has the highest CO_2 emissions, which is a consequence of 67% of the electricity in that scenario coming from residual oil-fueled power plants.

The lifecycle CO_2 emissions from the Sedan BEV are shown in Figure B.4 for six electricity scenarios, including the two scenarios added at MECA's request and the two added for comparison purposes. The two low-GHG mixes yield only small differences in lifecycle CO_2 emissions. The higher nuclear power contribution to the original Low GHG mix increases the WTP CO_2 emissions by a tiny amount. The increase to 10% biomass in the US Average mix leads to a 6.1% reduction in lifecycle CO_2 emissions. Lastly, the Slower CA Transition and Balanced NG and Renewables mixes both significantly decrease lifecycle CO_2 emissions compared to the US Average mix.

The lifecycle NOx emissions were also evaluated for the Sedan BEV and the 19 electricity scenarios, and these results are shown in Figure B.5. Again, since the vehicle is a BEV, there are no NOx emissions from vehicle operation, and the main contribution to NOx emissions comes from the electricity generation for the WTP emissions. Unsurprisingly, the Hawaiian (HICC) mix emits the most NOx by a wide margin.

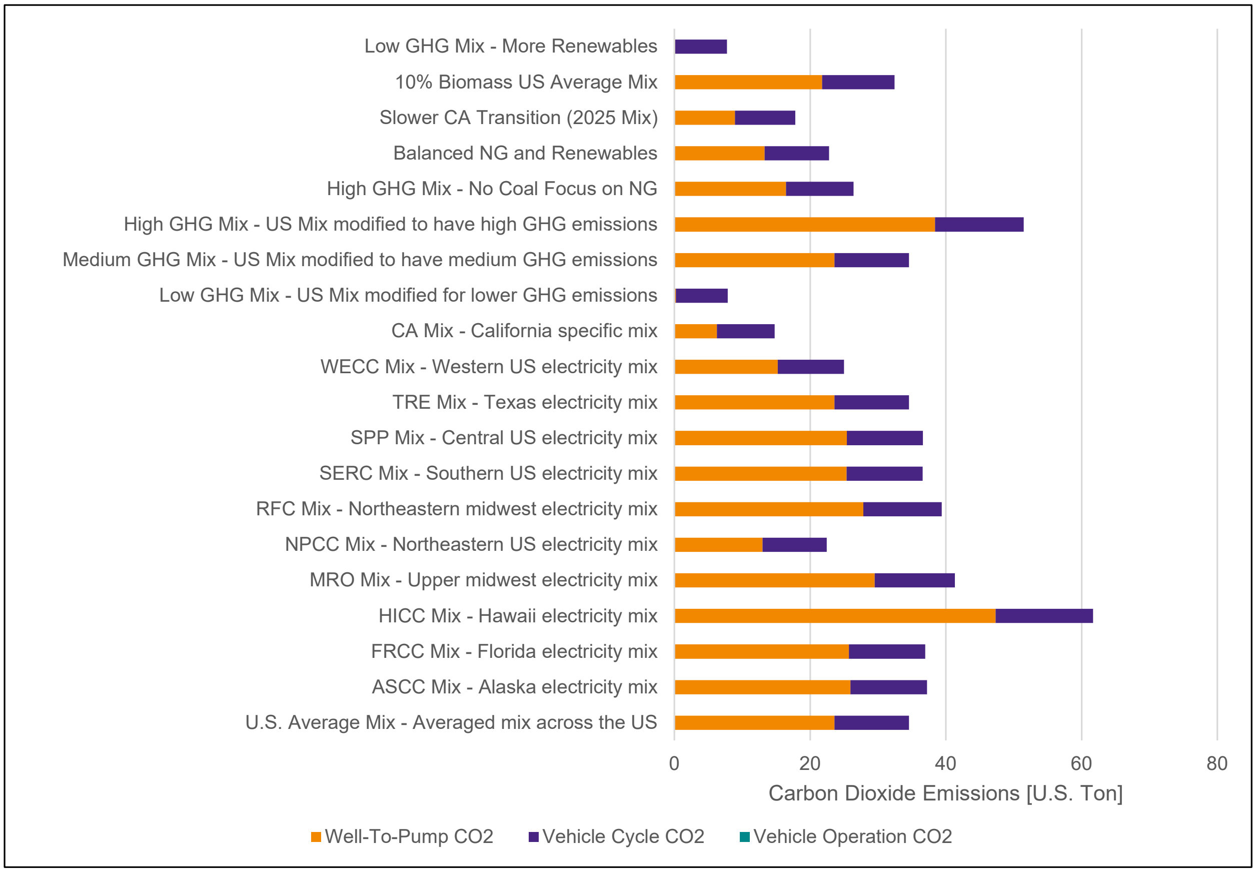


Figure B.3 – Lifecycle CO_2 emissions from Sedan BEV for all electricity scenarios.

For reference, a SULEV30 sedan operating over a similar lifetime would generate about 0.0032 tons of NOx during vehicle operation (VO). Assuming that the WTP NOx emissions from refineries and fuel transport is about the same again, the lifecycle NOx emissions for a modern SULEV30 sedan would be approximately 0.006 tons. This result is comparable to the lowest lifecycle NOx emissions shown in Figure B.5. In this case, however, the NOx emissions are primarily from distributed sources—the vehicles—whereas in the BEV scenarios the NOx emissions are primarily from point sources.

The trends with lifecycle methane emissions are more like those of the lifecycle CO_2 emissions, as shown in Figure B.6. The High GHG mix generates the most methane emissions, although the Medium GHG mixes and most of the regional mixes are clustered together. As with the CO_2 emissions, the higher nuclear power contribution in the Low GHG mix increases the WTP methane emissions slightly.

AVL also estimated the lifetime energy usage of the Sedan BEV over the 19 electricity scenarios, as shown in Figure B.7. Again, since the vehicle is a BEV, the electricity generation and corresponding WTP energy are the main constituents that depend on the electricity scenario. The vehicle manufacture energy also varies with electricity scenario, if less dramatically. The vehicle operation energy, however, is constant across all 19 electricity scenarios.

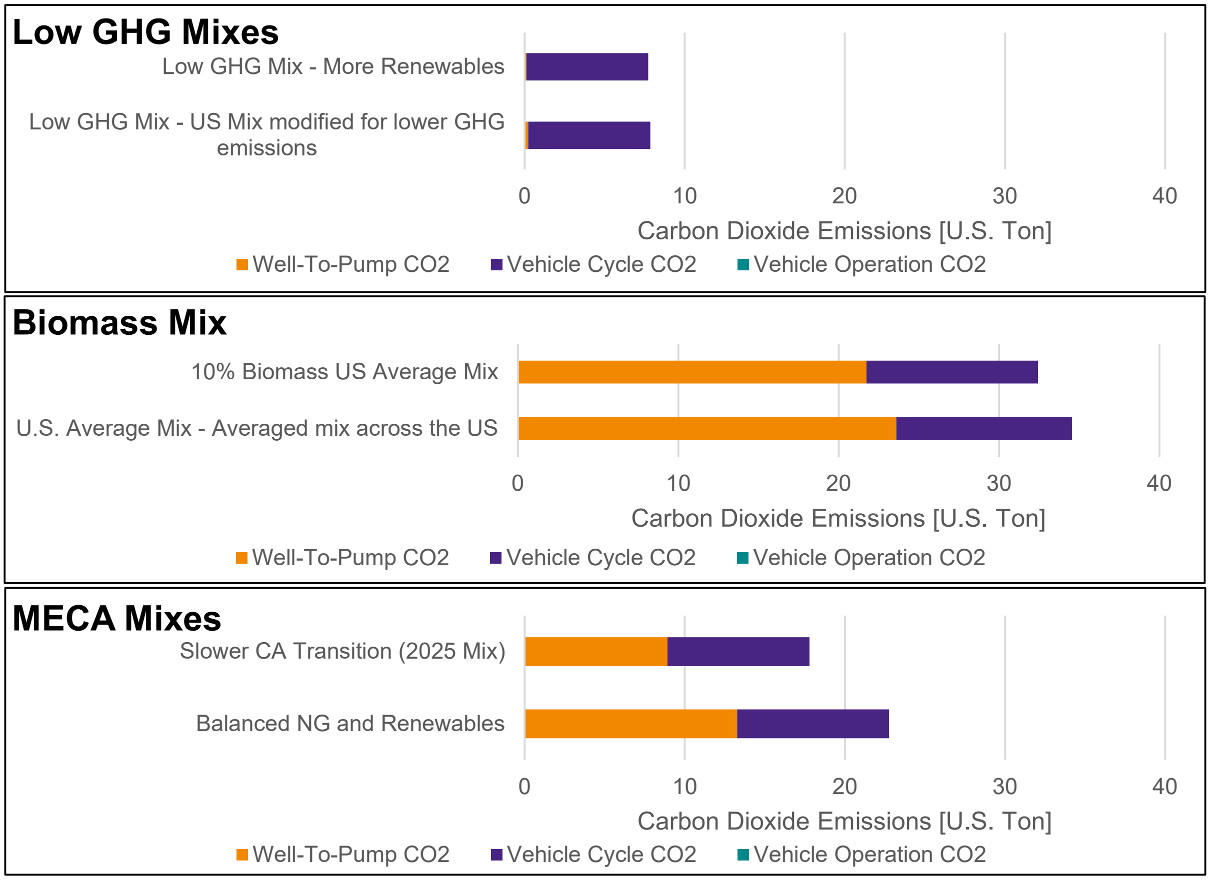


Figure B.4 – Lifecycle CO_2 emissions from Sedan BEV six focus scenarios.

The lifetime carbon intensity of the various electricity scenarios was also estimated using the Sedan BEV, and those results are shown in Figure B.8. The main variation comes once again from the WTP carbon intensity (CI), although there is some slight variation in the vehicle manufacture CI. It is interesting that the HICC Mix does not have the highest value for this metric; instead, it is in a group of higher CI scenarios.

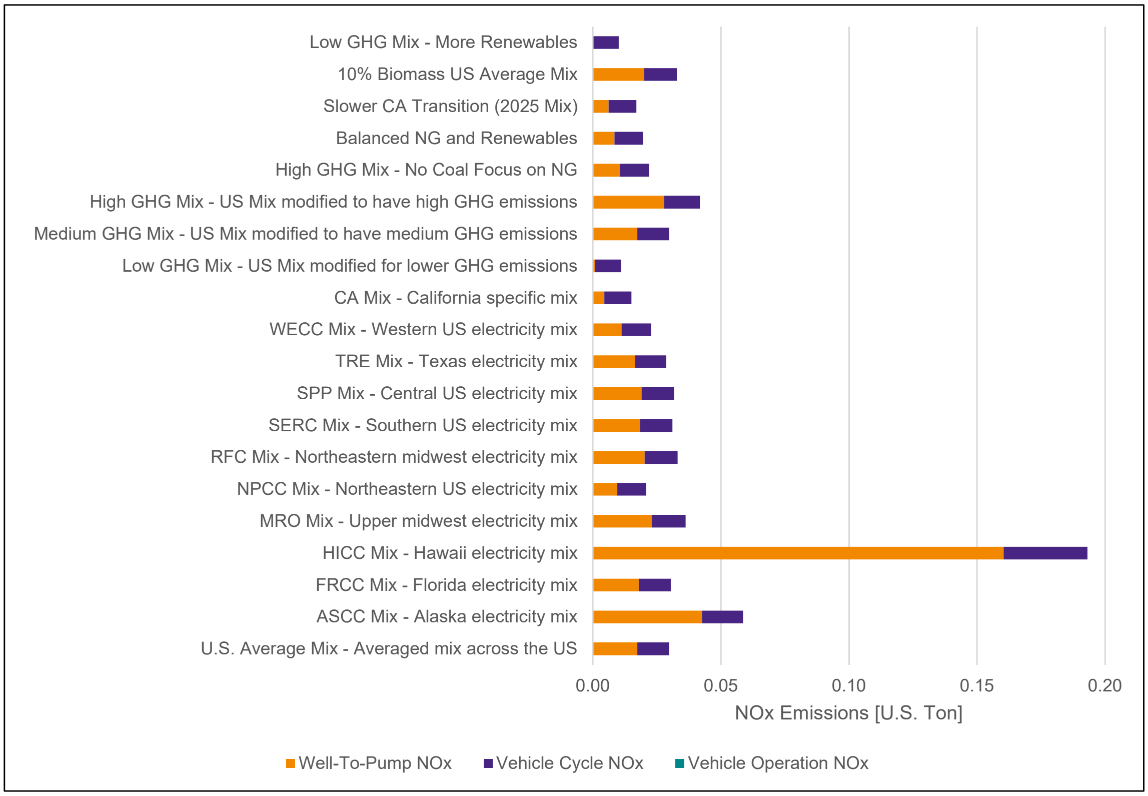


Figure B.5 – Lifecycle NOx emissions from Sedan BEV for all electricity scenarios.

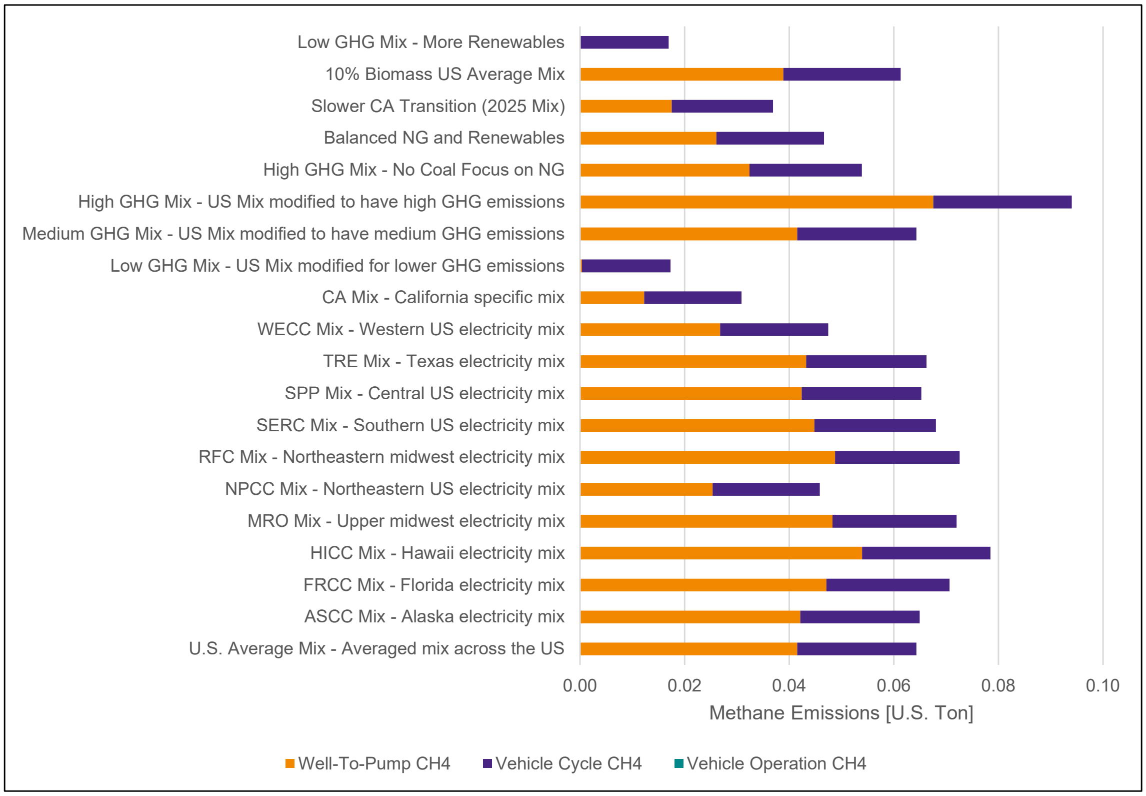


Figure B.6 – Lifecycle CH_4 emissions from Sedan BEV for all electricity scenarios.

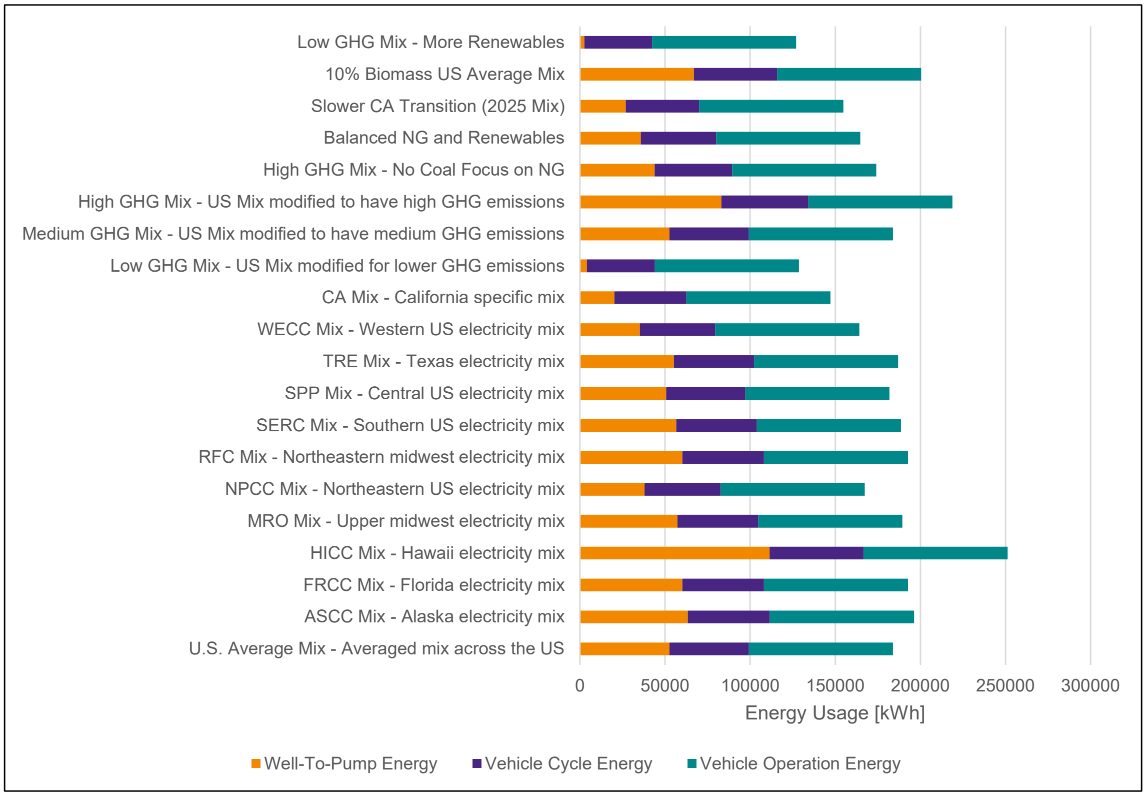


Figure B.7 – Lifecycle energy usage for Sedan BEV for all electricity scenarios.

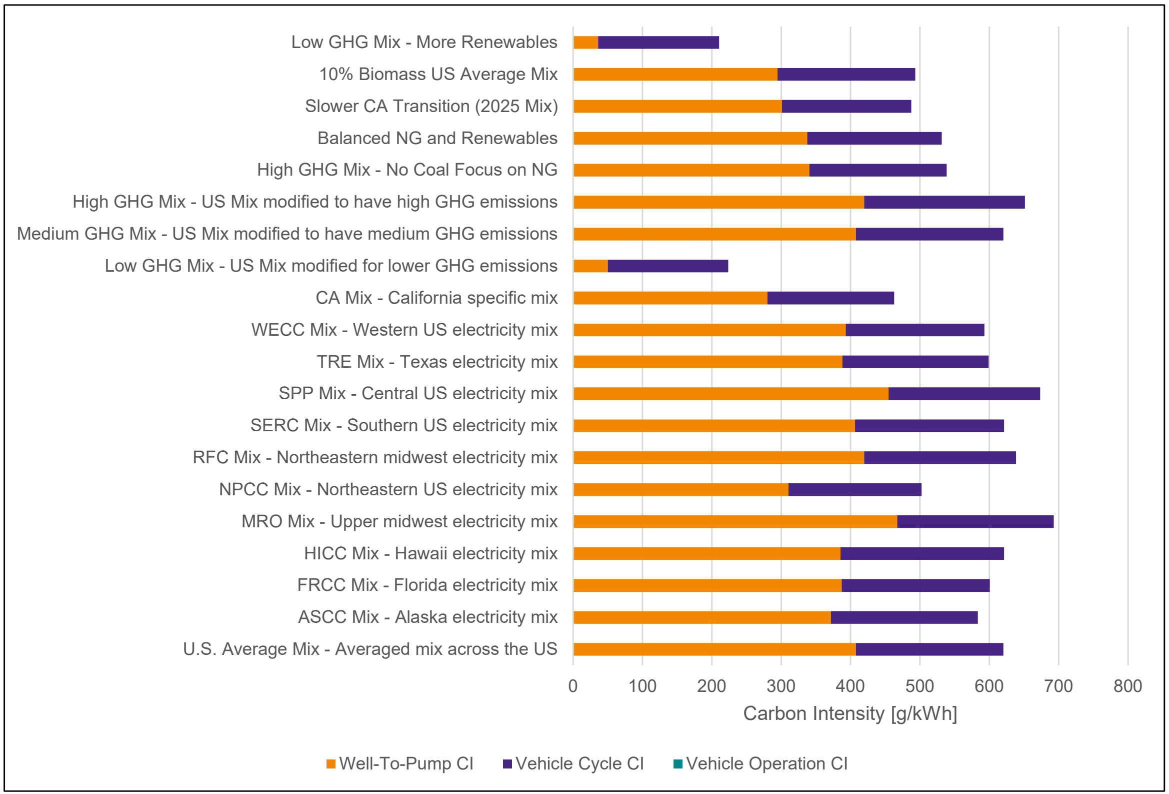


Figure B.8 – Lifecycle carbon intensity for Sedan BEV for all electricity scenarios.

Appendix C. Side Study: Electro-Fuels

One of the fuel options considered for the study was electro-fuels, also called e-fuels, since they represent a zero or negative net carbon fuel option for light-duty vehicles.

For this study, AVL assumed that the following steps are used to make electro-fuels:

1. Produce hydrogen gas (H_2) from electrolysis of water using renewable electricity.
   $2\ H_2O \rightarrow 2\ H_2 + O_2$
2. React hydrogen with carbon dioxide (CO_2) to form water and carbon monoxide (CO) through the water gas shift (WGS) reaction,
   $H_2 + CO_2 = H_2O_{(g)} + CO$.
3. Separate the CO from the water and add more hydrogen to form synthesis gas.

The synthesis gas, a mixture of H_2 and CO, can be used to form diesel and kerosene (jet fuel) through the Fischer–Tropsch process, where the net desired reaction is

$$(2n+1)\ H_2 + n\ CO = C_nH_{(2n+2)} + n\ H_2O,$$

where n is between 10 and 20 for kerosene and diesel components. The resulting Fischer–Tropsch fuel is paraffinic (*i.e.*, has straight-chain alkanes) and has no sulfur or aromatic compounds. A typical yield is about 50% Fischer–Tropsch fuels, with 70% of that fuel yield being useful for diesel engines.

Given that the synthesis gas is generated from water, renewable electricity, and captured CO_2, the resulting Fischer–Tropsch diesel fuel will have a net negative carbon content at generation. AVL assumed that some GHG is generated in transporting the Fischer–Tropsch diesel fuel to the pump, offsetting some of the benefits of the fuel.

The main side product of the Fischer–Tropsch process is methane (CH_4). Normally this is a problem since the Fischer–Tropsch process typically uses methane as the input reactant. In the electro-fuels process, though, the resulting methane is also a net negative carbon fuel because captured CO_2 is used as the input. It is possible, then, that the methane side product could also be sold as a carbon-free natural gas constituent in parallel with the liquid fuel sales.

Alternatively, the synthesis gas can be used to form methanol (CH_3OH) by

$$2\ H_2 + CO = CH_3OH,$$

which is then supplied to the Mobil methanol to gasoline (MTG) reaction sequence to form gasoline. The MTG process is not as efficient as the Fischer–Tropsch process, and AVL therefore assumed a smaller carbon offset for electro-gasoline than for electro-diesel.

For electro-fuels to be a competitive option in the future, the hydrogen gas used to make the fuels should be produced at or adjacent to the facility where the electro-fuel is being produced to minimize the CO_2 emissions associated with the transport of the hydrogen from where it is produced to where it is used.

For e-gasoline, AVL assumed that the fuel provides a CO_2 credit to the feedstock equal to 75% of the TTW CO_2 emissions estimate. Similarly, for e-diesel, AVL assumed that the CO_2 credit to the feedstock equaled 90% of the TTW CO_2. The difference in the two CO_2

credit levels reflects that the MTG process is has a lower yield of liquid fuel per unit synthesis gas input than the Fischer–Tropsch process used to make e-diesel does. AVL recognizes that these assumed CO_2 credit levels are conservative estimates, and that the actual benefit could be closer to 100% of the TTW CO_2 emissions for both fuels depending on the energy sources for the fuel production and distribution to fueling stations.

Appendix D. Detailed Simulation Results

This appendix expands on the discussion of the simulation results provided in Section 0. The large design space considered in this study meant that the results are correspondingly large, especially when all 19 electricity scenarios are being considered.

To fully sample the design space, a total of 12,900 runs were executed in GREET. The distribution of runs executed for each vehicle, powertrain, and fuel type is shown in Figure D.1. These results allowed over 500 regression models to be created by the AVL team, and these models were then populated into the Dashboards developed for the study. The results from each run included the CO_2, NOx, and CH_4 emissions estimates as calculated by GREET.

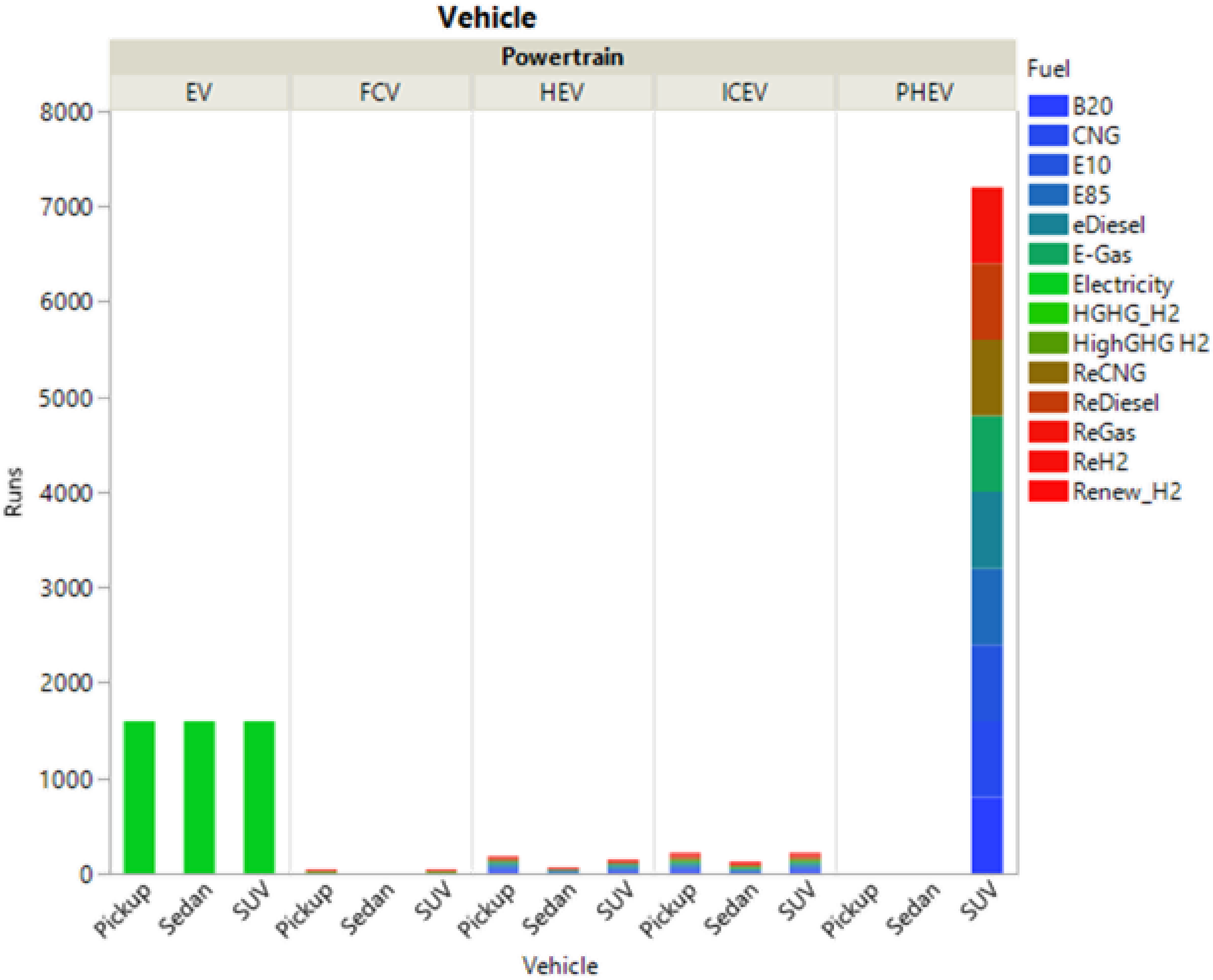


Figure D.1 – Number of GREET runs executed for each vehicle, powertrain, and fuel combination.

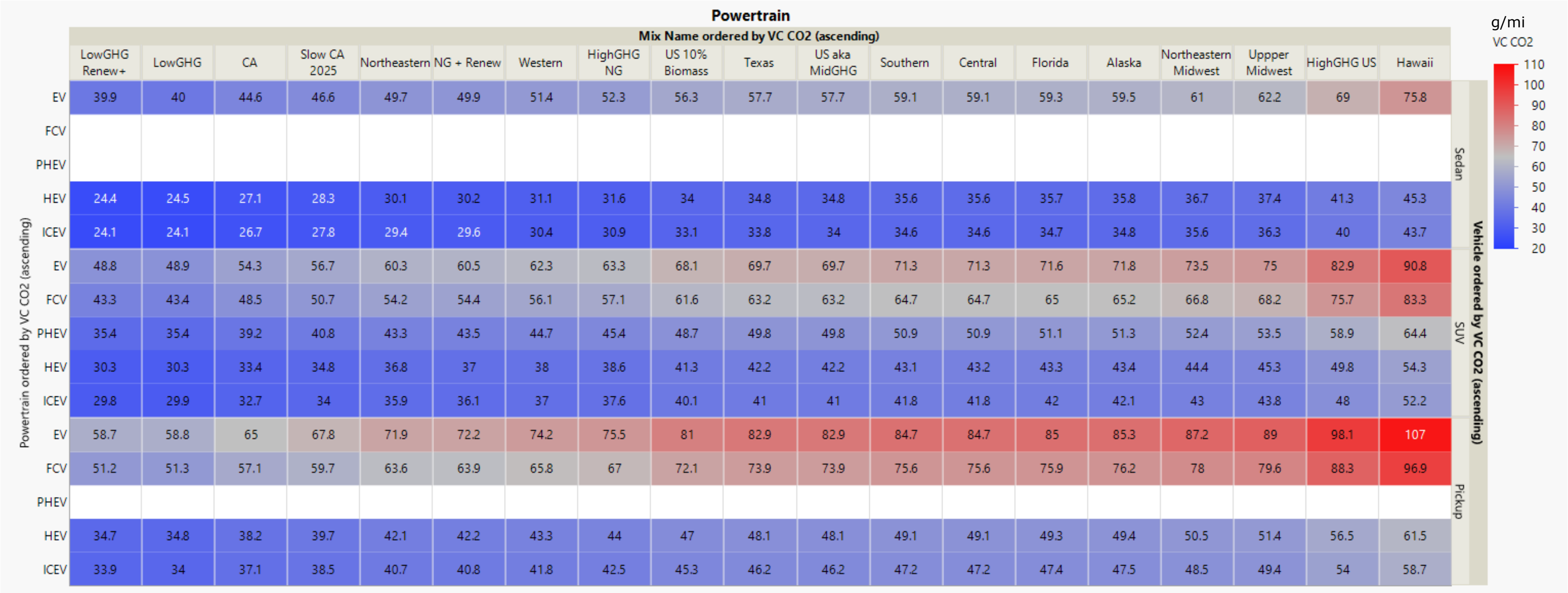
The CO_2 emissions from the electricity scenarios can be used to calculate the emissions associated with vehicle manufacture, as shown in Table D.1. Similarly, the GREET results were also used to calculate the CO_2 emissions from vehicle operation for each of the vehicle, powertrain, and fuel combinations considered.

AVL also calculated emissions coverage matrices across all 19 electricity scenarios with variations in the four key parameters for this study: BEV range, battery charging efficiency, battery replacement during vehicle life, and battery recycling at end of life. Figure D.2 and Figure D.3 show the emissions coverage for all 19 scenarios and for the California grid only, respectively.

The upper parts of Figure D.2 and Figure D.3 show the fuel options analyzed in GREET, and the color indicates how many cases were evaluated for each combination. The whisker plots on the lower parts of these two figures show the distribution of total lifecycle CO_2 emissions estimates, where the mean is marked by the white line; the middle 50%, by the box; and the middle 90%, by the whiskers. In Figure D.2 these whisker plots include the effects of the grid scenarios. As there is only one grid considered for Figure D.3, the whisker plots show the effects of the GREET parameter variations only.

AVL also looked at the effects of the fuel and electricity grid scenarios on the WTP contribution to lifecycle NOx and methane emissions. These results are shown on Figure D.4 and Figure D.5 , respectively. Combinations that are contained in a black box have equivalent lifecycle emissions, such as the NOx emissions from the SUV ICEV and the SUV PHEV using E10 with the Florida grid scenario that is shown in Figure D.4 . For most of the electricity scenarios in Figure D.4 , the WTP NOx emissions are higher for the SUV ICEV than for the SUV PHEV.

Table D.1 – Mean vehicle manufacturing CO_2 emissions for various combinations of vehicle, powertrain, and electricity scenario.



Powertrain

Mix Name ordered by VC CO2 (ascending)

Vehicle ordered by VC CO2 (ascending)	Powertrain ordered by VC CO2 (ascending)	LowGHG Renew+	LowGHG	CA	Slow CA 2025	Northeastern	NG + Renew	Western	HighGHG NG	US 10% Biomass	Texas	US aka MidGHG	Southern	Central	Florida	Alaska	Northeastern Midwest	Uppper Midwest	HighGHG US	Hawaii
Sedan	EV	39.9	40	44.6	46.6	49.7	49.9	51.4	52.3	56.3	57.7	57.7	59.1	59.1	59.3	59.5	61	62.2	69	75.8
	FCV																			
	PHEV																			
	HEV	24.4	24.5	27.1	28.3	30.1	30.2	31.1	31.6	34	34.8	34.8	35.6	35.6	35.7	35.8	36.7	37.4	41.3	45.3
	ICEV	24.1	24.1	26.7	27.8	29.4	29.6	30.4	30.9	33.1	33.8	34	34.6	34.6	34.7	34.8	35.6	36.3	40	43.7
SUV	EV	48.8	48.9	54.3	56.7	60.3	60.5	62.3	63.3	68.1	69.7	69.7	71.3	71.3	71.6	71.8	73.5	75	82.9	90.8
	FCV	43.3	43.4	48.5	50.7	54.2	54.4	56.1	57.1	61.6	63.2	63.2	64.7	64.7	65	65.2	66.8	68.2	75.7	83.3
	PHEV	35.4	35.4	39.2	40.8	43.3	43.5	44.7	45.4	48.7	49.8	49.8	50.9	50.9	51.1	51.3	52.4	53.5	58.9	64.4
	HEV	30.3	30.3	33.4	34.8	36.8	37	38	38.6	41.3	42.2	42.2	43.1	43.2	43.3	43.4	44.4	45.3	49.8	54.3
	ICEV	29.8	29.9	32.7	34	35.9	36.1	37	37.6	40.1	41	41	41.8	41.8	42	42.1	43	43.8	48	52.2
Pickup	EV	58.7	58.8	65	67.8	71.9	72.2	74.2	75.5	81	82.9	82.9	84.7	84.7	85	85.3	87.2	89	98.1	107
	FCV	51.2	51.3	57.1	59.7	63.6	63.9	65.8	67	72.1	73.9	73.9	75.6	75.6	75.9	76.2	78	79.6	88.3	96.9
	PHEV																			
	HEV	34.7	34.8	38.2	39.7	42.1	42.2	43.3	44	47	48.1	48.1	49.1	49.1	49.3	49.4	50.5	51.4	56.5	61.5
	ICEV	33.9	34	37.1	38.5	40.7	40.8	41.8	42.5	45.3	46.2	46.2	47.2	47.2	47.4	47.5	48.5	49.4	54	58.7

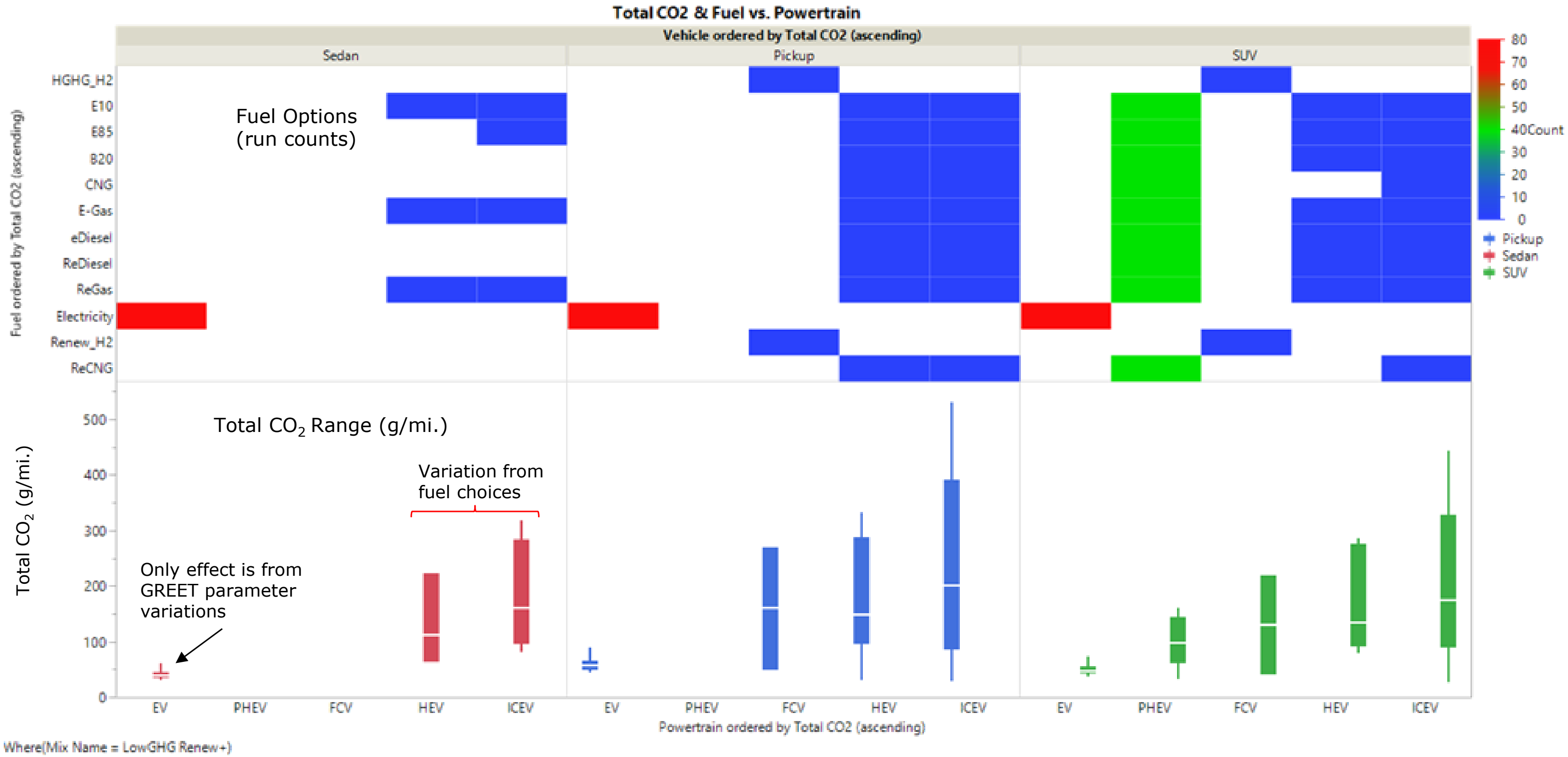


Figure D.2 – Emissions coverage matrix across 19 electricity scenarios and vehicle variations.

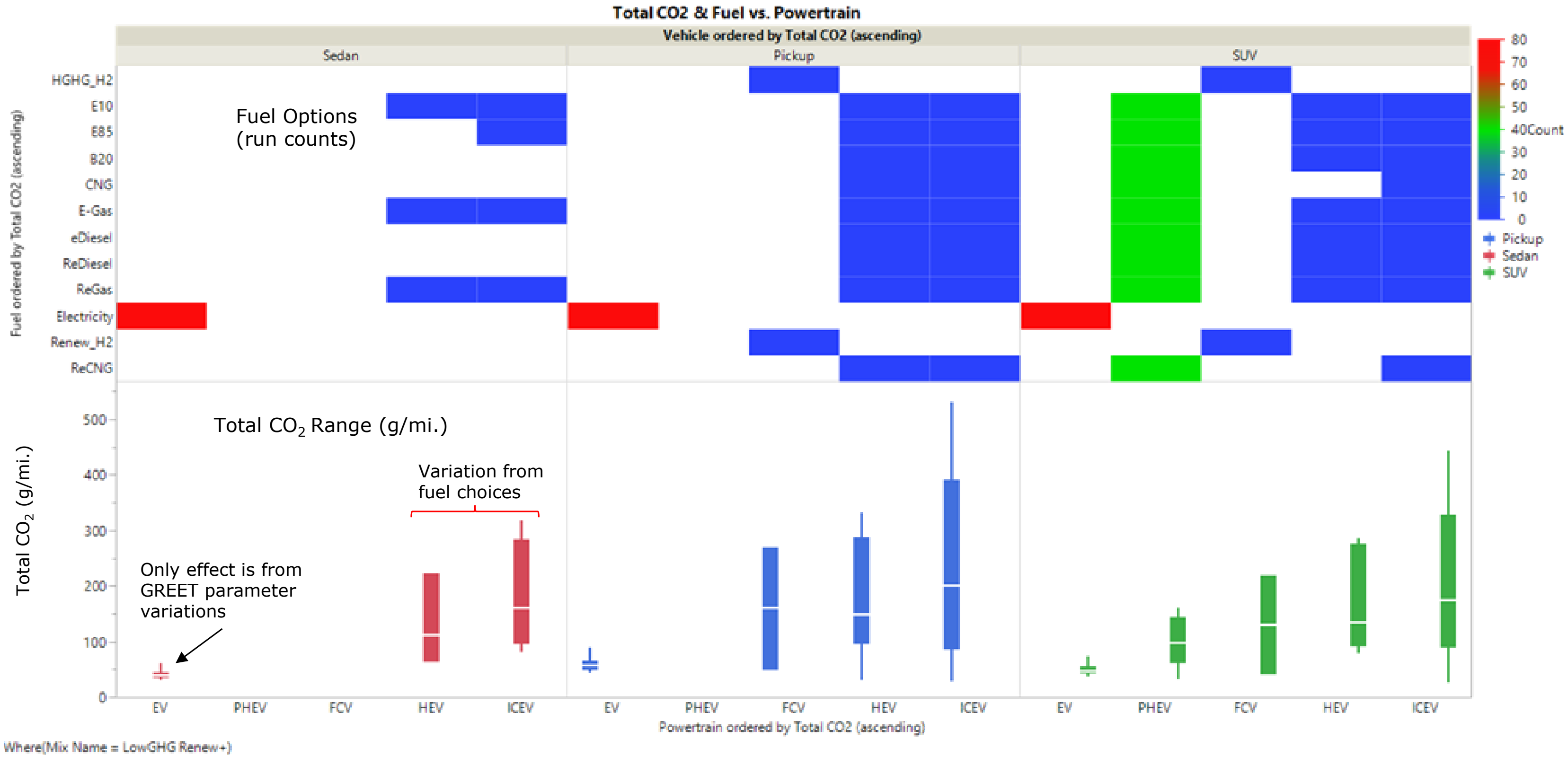


Figure D.3 – Emissions coverage matrix using the California grid scenarios and vehicle variations.

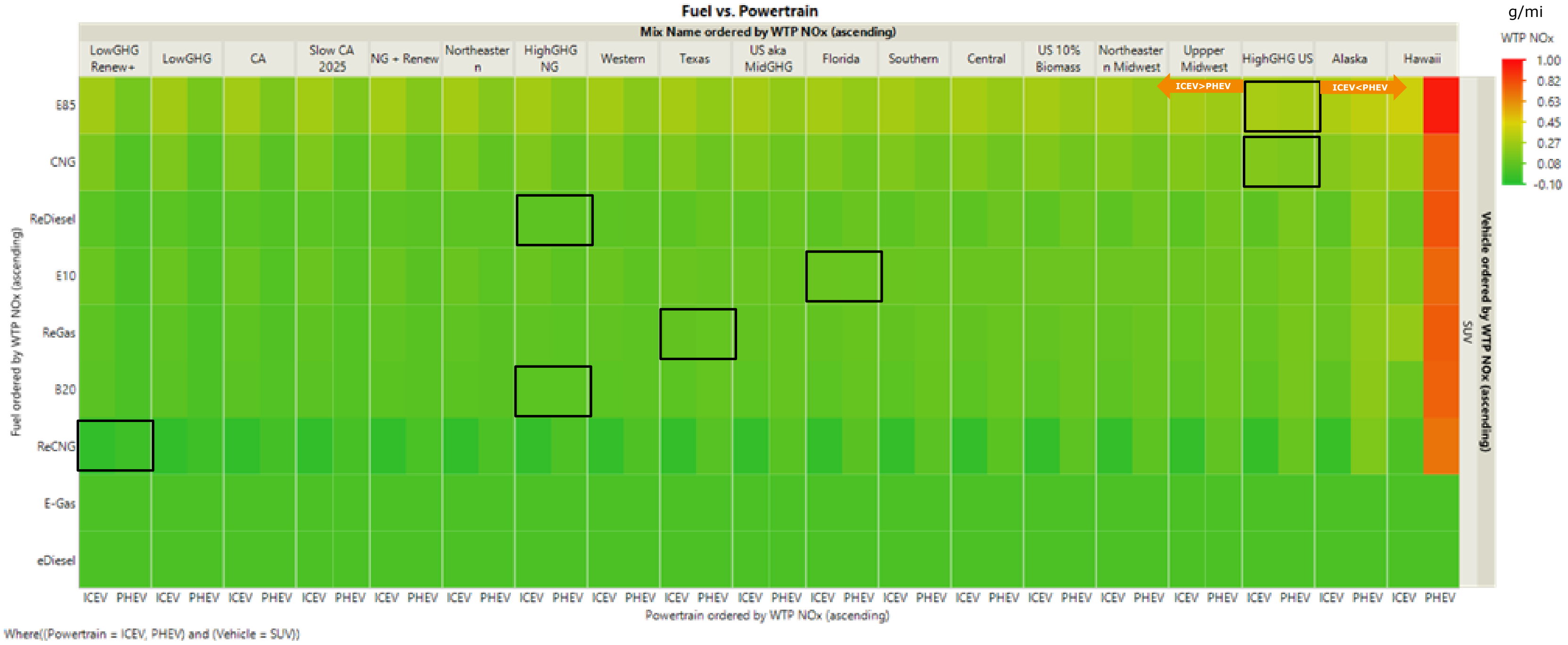


Figure D.4 – Summary comparison of WTP NOx emissions for the SUV ICEV and PHEV by fuel and by electricity scenario. Boxes mark combinations where the emissions are equivalent.

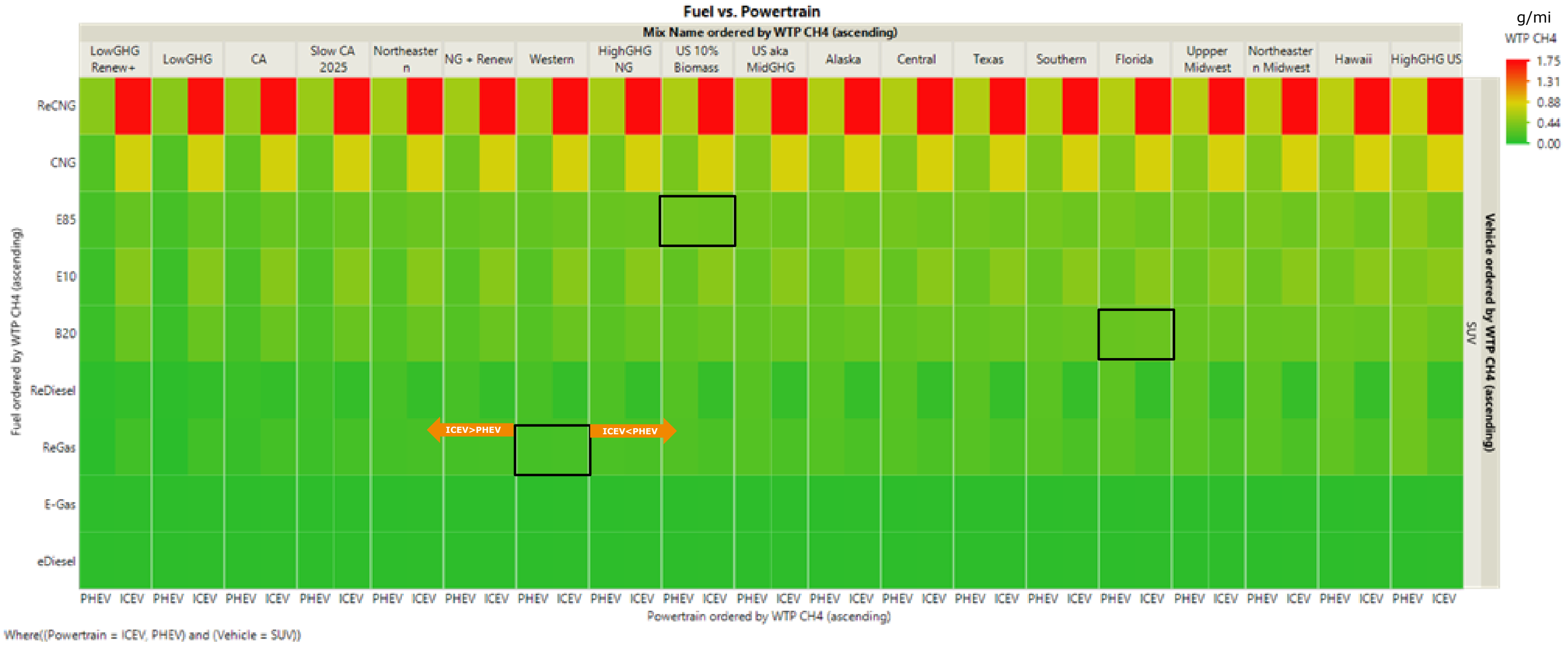


Figure D.5 – Summary comparison of WTP CH_4 emissions for the SUV ICEV and PHEV by fuel and by electricity scenario. Boxes mark combinations where the emissions are equivalent.

Appendix E. Side Study: Cathode Material

One of the side studies conducted during the overall project was to understand the effect of the cathode material on the GHG emissions from BEVs. The default cathode in GREET is NMC111, which has the associated vehicle manufacture CO_2 emissions shown in Table E.1. Four other non-default chemistries were also considered, although their associated CO_2 emissions are all between 192 and 194 g/mi., as shown in Table E.1.

Table E.1 – Cathode chemistry options and associated CO_2 emissions on gram per mile basis.

Chemistry	NMC111	NMC622	NMC811	NMC532	NCA
CO_2 (g/mi.)	209.63	192.53	192.03	193.69	192.72

AVL chose NMC622 for this project because it is the most commonly used Li-ion battery chemistry for vehicles. Note that the use of NMC622 provides an 8.15% lower CO_2 emissions benefit for the batteries compared to the default choice of NMC111.

The CO_2 emissions contribution of the battery packs to the lifecycle emissions is about 11.1% for HEV and 17.2% for PHEV. Note that lead acid batteries also contribute to the overall vehicle lifecycle CO_2 emissions.

At the complete vehicle level, though, simulations on cathode production location and battery assembly location have a negligible effect on the net results, as shown in Table E.2. Currently, changing the cathode production location is only possible for NMC111 and not NMC622. Therefore, this approach was only used for HEV and PHEV and only with the default GREET battery chemistry.

Table E.2 – Effect of cathode production and battery assembly locations on CO_2 emissions on gram per mile basis.

Parameter	HEV	PHEV
CO_2 (g/mi.)	314.659	246.763
CO2 (g/mi.) 100% cathode production in China	314.721	247.237
CO2 (g/mi.) 100% cathode production and battery assembly in China	314.768	247.455