Comprehensive Cradle to Grave Life Cycle Analysis of On-Road Vehicles in the United States based on GREET

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Abstract

To properly compare and contrast the environmental performance of one vehicle technology against another, it is necessary to consider their production, operation, and end-of-life fates. Since 1995, Argonne's GREET® life cycle analysis model (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) has been annually updated to model and refine the latest developments in fuels and materials production, as well as vehicle operational and composition characteristics. Updated cradle-to-grave life cycle analysis results from the model's latest release are described for a wide variety of fuel and powertrain options for U.S. light-duty and medium/heavy-duty vehicles. Light-duty vehicles include a passenger car, sports utility vehicle (SUV), and pick-up truck, while medium/heavy-duty vehicles include a Class 6 pickup-and-delivery truck, Class 8 day-cab (regional) truck, and Class 8 sleeper-cab (long-haul) truck. Powertrain coverage includes internal combustion (spark ignition and compression ignition) engines, hybrid electric, plug-in hybrid, full battery electric, and fuel cell vehicles powered by conventional and low carbon energy sources. The results offer insights into the current state of these technologies, as well as a projection of the likely environmental implications of future fuel and vehicle advancements through a time-series evaluation of life cycle greenhouse gas emissions.

Introduction

Energy security, climate change, and greenhouse gas (GHG) emissions are important challenges for both industry and governments. The U.S. transportation sector consumed 28 quadrillion Btu of primary energy sources in 2022, representing 29% of the nation's total energy consumption [1]. In 2022, petroleum supplied 89% of U.S. transportation energy consumption. This has led to 1.9 billion metric tons (tonnes) of CO_2 attributed to the U.S. transportation sector in 2022, or 37% of the total national GHG emissions [1].

Global climate change over the past 100 years has been largely attributed to increased GHG emissions in the Earth's atmosphere due to human activities [2]. The largest contributor to these GHG emissions is CO_2 resulting from fossil fuel combustion [2]. On-road vehicles, inclusive of light-duty vehicles (LDV) and medium- and heavy-duty vehicles (MHDV), contribute significantly to the emissions burden of the transportation sector.

To evaluate the GHG burdens associated with vehicle production and operation, this study utilizes an approach to life cycle analysis (LCA) often called cradle-to-grave (C2G) analysis. This method considers vehicle and fuel cycles starting from raw material extraction as well as fuel production and transport, vehicle manufacturing, vehicle use, and vehicle end-of-life (EOL), but not supporting infrastructure systems (e.g., refineries end-of-life or LCA of roads and bridges). A C2G analysis approach holistically frames the GHG performance of vehicle-fuel technologies.

Substantial research, development, and demonstration of vehicle and fuel technologies has been executed to improve energy efficiency and reduce GHG emissions in the transportation sector. Advanced vehicle technologies include more efficient internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), electric vehicles (EVs), and fuel cell vehicles (FCVs). Advanced fuel technologies include advanced biofuels, renewable electricity, and hydrogen.

Large reductions in transportation sector emissions will be needed to meet international, national, and state climate goals. The adoption of HEV, PHEV, FCV, and EV LDVs has increased dramatically in the past few years, highlighting the potential for a major emissions reduction in the next decade [3,4]. However, these remain a small share of U.S. LDV sales (~5% in 2021) and their deployment in the MHDV market is still nascent. Technological assessments of life cycle GHG emissions for different vehicle-fuel combinations, or vehicle-fuel pathways, are critical for informing near- and long-term actions and policy decisions.

Argonne National Laboratory has developed and maintained the GREET ® LCA model (Greenhouse gas, Regulated Emissions, and Energy use in Technologies) since 1995 with the support of the U.S. Department of Energy (DOE). Within that model, several baseline vehicle technologies are integrated and updated based on vehicle simulation results from Argonne's Autonomie model. That model provides detailed vehicle energy consumption data along with additional vehicle parameters, such as vehicle weight, battery power energy, etc. This article uses several baseline vehicles within GREET's latest release coupled with conventional and low-carbon fueling approaches to provide estimates of the GHG emissions associated with current and future (2035 and 2050) vehicles. The current study aimed to conduct an LCA across diverse vehicles, powertrain and fuel options using consistent assumptions, system boundaries, and impact factors, thus guaranteeing a fair comparison across the numerous technologies that are currently and will be available in the future.

Methods

This study uses Argonne's latest GREET model [5] to estimate the C2G GHG emissions associated with the vehicle types defined in the Appendix (**Table A1** [for LDVs] and **Table A2** [for MHDVs]). These include LDVs on the U.S. market for midsize sedans (Cars), small sport utility vehicles (SUV), and light-duty pickup trucks (PUT) along with MHDVs, namely a Class 6 Box truck used for pickup and delivery (PnD, or C6P), a Class 8 Regional haul truck (Day Cab, or C8S), and a Class 8 Long haul truck (Sleeper Cab, or C8L). Each of the LDV classes is modeled as a conventional gasoline (spark-ignition) ICEV, HEV, PHEV, EV, or FCV, while each of the MHDV classes can be modeled as a diesel ICEV, HEV, EV, and FCV. The vehicle miles traveled (VMT) defined for each class of the simulated vehicles are as follows: cars are 173,151 miles; SUV and PUT are 183,363; C6P are 300,000 miles; C8S and C8L are 1,000,000 miles.

Each of these vehicles have default specifications (vehicle weight, fuel energy consumption per traveled distance, battery and fuel cell power and energy) within GREET. These vehicle parameters are derived from detailed vehicle simulations conducted in the Autonomie model [6]. Note that while the fuel energy consumption modeling feature in GREET can be applied for all LDV and MHDV investigated, the temporal progression in-vehicle component sizing only currently exists for LDVs; as this feature is not yet implemented for MHDVs. Thus, the vehicle sizing for the Class 6 and Class 8 vehicles in this study is assumed to be constant over time. The gross vehicle weight values are used for the vehicle modeling in the Autonomie model for assessing their fuel energy consumption per traveled distance and for the vehicle cycle LCA. The sizing of batteries is based on Autonomie's power and energy specifications, but these are then integrated into Argonne's Battery Performance and Cost model (BatPaC) [7] to determine the material requirements for these batteries [8]. All details on vehicle systems material compositions are contained directly within GREET and are documented in technical reports [9,10].

For the LDV driving ranges, 50 miles and 300 miles range are assumed for PHEVs and EVs investigated in this study. For PHEVs, the share of driving mileage on charge depleting (CD) and charge sustaining (CS) modes is defined by the utility factor (UF) based on the UF curve in the SAE J2841 standard. The range of the FCV was assumed to be around 340 miles based on a previous technical report [6]. For MHDVs, the driving range is assumed to be 150, 250, and 500 miles for C6P, C8S, and C8L, respectively [6]. For the battery types used for the simulated HEVs, PHEVs, EVs, and FCVs, lithium-ion batteries with 80% Nickel, 10% Manganese, and 10% Cobalt cathode active material (NMC 811) are assumed for the current year simulation (year 2022) while 95% Nickel, 2.5% Manganese, and 2.5% Cobalt (NMC 95) is assumed for the two future year simulations (years 2035 and 2050). For the medium heavy duty FCVs simulated in this study, 350-bar hydrogen pressure is assumed for the C6P and C8S trucks while the 700-bar hydrogen pressure is assumed for the C8L trucks.

Figure 1 is presented to show the progression of fuel economy assumptions over time for each vehicle class and powertrain option investigated in this study. For all 6 types of vehicles investigated in this study, the EVs had the highest equivalent fuel economy [in miles per gasoline gallon equivalent (MPGGE) for LDVs or miles per diesel gallon equivalent (MPDGE) for MHDVs] across the powertrain options. The PHEVs and FCVs also had noticeably higher fuel economy compared to the ICEV baseline.

GREET contains life cycle inventory (LCI) data for both vehicle energy sources (fuel cycle) and materials for vehicle production (vehicle cycle), in GREET1 and GREET2 respectively. For each, there are detailed parameters that identify the embodied energy and emissions associated with all fuel and material inputs into the final product systems. GREET contains estimations of future conditions based on publicly available data, such as the Energy Information Administration's Annual Energy Outlook (AEO) [1]. In this LCA, default settings were used for energy and materials within GREET for the defined years (2022, 2035, and 2050) unless otherwise stated herein. The LCI serves as the backbone of the data used to evaluate the life cycle GHG performance. In this case, the stages related to the production of feedstocks, fuels (i.e., liquid fuels, electricity, and hydrogen), and the use of different fuel energy in the simulated vehicles are defined as the well-to-wheels stage (WTW) while the production and disposal of vehicle and its components [i.e., batteries, hydrogen storage system (HSS)] including their upstream material and energy inputs are defined as "vehicle cycle (VC)". From a process perspective in GREET, the correct simulation year is selected along with the correct vehicle and energy pathway to then collect the necessary WTW data, which is then combined with the associated VC data for each vehicle to result in the C2G life cycle results. For each of these simulated pathways, the WTW GHG emissions for each fuel pathway investigated here, on a unit energy basis, along with the VC GHG emissions from battery, HSS and other parts of the vehicle (vehicle less battery and hydrogen storage [B&H]) per vehicle lifetime are provided in Appendix **Tables A3-A10**.

In the C2G analysis, the impacts of infrastructure and facilities related to vehicle use (e.g., fuel stations, EV chargers), vehicle manufacturing (e.g., vehicle manufacturing plants), and vehicle energy resources production (e.g., fossil-fuel-based electric power plants, solar photovoltaic-based power plants, or battery storage facilities for electricity) are not included in the system boundary.

All simulated pathways in this study are presented in **Table 1** for LDVs and **Table 2** for MHDVs. For the present-day simulations (or 2022) fuel pathways were investigated that are considered conventional or relatively more available currently since they represent the majority of the market, while, for the future simulation years, we considered more pathways for decarbonized vehicle energy sources. For the electricity pathways, each simulation year considers the US average carbon intensity (CI) grid along with the highest and lowest CI grids for the corresponding simulation year, based on the North American Electric Reliability Corporation (NERC) regional grid mix using the AEO [1] data, as well as a State of California average grid mix. All of these are resident in GREET's electricity selection profile. This study uses an average electricity grid mix for the year of the vehicle's deployment throughout its lifetime. As the electrical grid is projected to reduce its CI over time, this is a conservative projection. Another approach is to utilize a marginal emissions CI, but that is not pursued in this research.

This study considers that hydrogen could be delivered in a gaseous or liquid form for FCVs. For the current year simulation, we assumed that hydrogen is produced via natural gas steam methane reforming (NGS H_2), while, for the two future

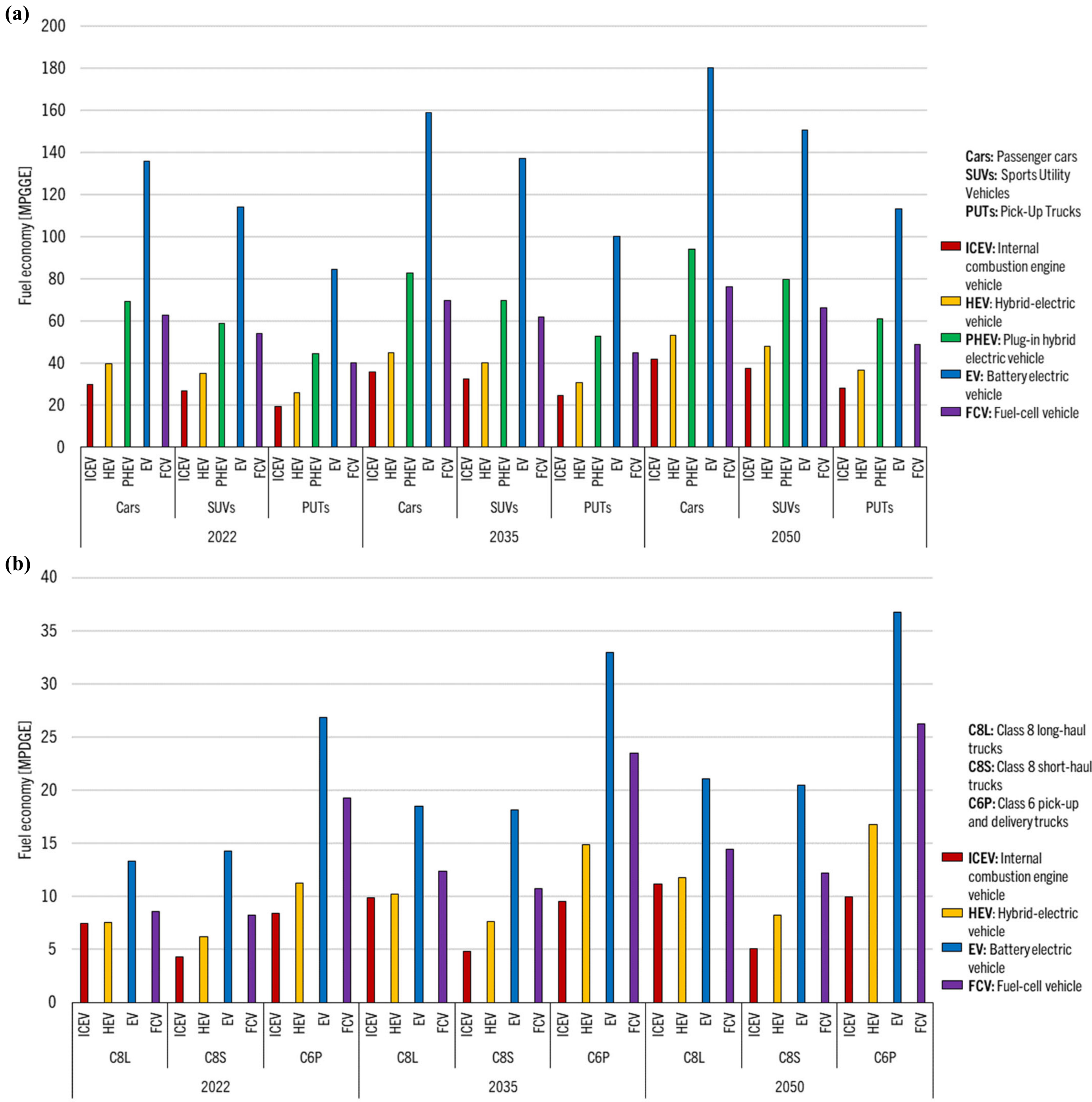

Figure 1: Fuel economy of the simulated (a) LDVs; and (b) MHDVs over simulation years (2022, 2035, and 2050).

simulation years, we added advanced H_2 production pathways such as natural gas auto-thermal reforming with carbon capture and storage (NGA H_2 w/CCS), low-temperature electrolysis in proton-exchange membrane (PEM) fuel cells using solar electricity (LTE), and high-temperature electrolysis in solid oxide electrolyzer cell (SOEC) using nuclear electricity (HTE). The LTE- or HTE-based H_2 production using US average grid electricity is not included in our analysis assuming that the energy-intensive characteristics of water electrolysis will require the use of low-carbon electricity to produce low-carbon H_2 in future projections. For example, our GREET model estimated that the CI of gaseous H_2 from LTE using US average grid will be 11.2 kgCO_2e/kg in 2035 while that of conventional NGS counterpart will be around 10.2 kgCO_2e/kg [5]. Therefore, for the purposes of simulating low-carbon H_2 produced via electrolysis in the future, a low-carbon electricity grid would be the right choice for its power grid option. While we recognize the potential of using low-carbon liquid fuels, such as biofuels and e-fuels, in LDVs, these options are not currently promoted or incentivized by state and federal governments as opposed to zero emissions vehicles (ZEVs). In this study we consider vehicle applications scope wider than just LDVs, so we limited the scope of decarbonization of LDVs to ZEV vehicles (i.e., EVs and FCVs). However, we refer the interested reader to our comprehensive cradle-to-grave study of LDVs [11], which evaluated low-carbon liquid fuels among the other decarbonization options.. However, the exclusion of alternative liquid fuel pathways for LDVs in this study must not be interpreted to say that these pathways cannot achieve comparable or more effective GHG emissions reduction than the options presented in this study. The GREET model contains such pathways for interested readers. For the MHDVs, conventional diesel fueling options and several alternative liquid fueling options are investigated in addition to the same electricity and hydrogen pathways noted for LDVs. These liquid fueling pathways are: conventional diesel, 20% soy-based bio-diesel blend in conventional diesel (B20), 100% renewable diesel derived from forest residue (RD100), and Fischer-Tropsch fuel produced from an electrocatalytic reduction of CO_2 (FT e-fuel, or FTE) pathway. For the FTE CO_2 capture and its electrocatalytic conversion to e-fuel, wind energy is assumed to be used.

This study calculates the GHG emissions by accounting for the weighted sum of CO_2, CH_4, and N_2O emissions using the 100-year time horizon global warming potential (GWP) defined by the most recent recommendations from the International Panel on Climate Change Sixth Assessment Report [2].

Table 1: LDV simulation parameters for the GREET model [5].

Year	Vehicle types	Powertrain	Fuel	Variations in electricity grid and/or H_2 path
2022	Cars, SUVs, PUT	ICEV	Gasoline (E10)	N/A
		HEV		
		PHEV	Gasoline (E10) + Electricity	US avg. grid
				MISO grid (highest CI)
				NPCC grid (lowest CI)
				CA grid
		EV	Electricity	US avg. grid
				MISO grid (highest CI)
				NPCC grid (lowest CI)
				CA grid
		FCV	Gaseous H_2	NGS H_2
			Liquid H_2	NGS H_2
2035 & 2050	Cars, SUVs, PUT	ICEV	Gasoline (E10)	N/A
		HEV		
		PHEV	Gasoline (E10) +Electricity	US avg. grid
				2035: FRCC 2050: PJM (highest CI)
				2035: NPCC 2050: WECC (lowest CI)
				CA grid
		EV	Electricity	US avg. grid
				2035: FRCC 2050: PJM (highest CI)
				2035: NPCC 2050: WECC (lowest CI)
				CA grid
		FCV	Gaseous H_2	NGS H_2
				NGA H_2 w/CCS
				LTE H_2 w/ 100% solar power
				HTE H_2 w/ 100% nuclear power
			Liquid H_2	NGS H_2
				LTE H_2 w/ 100% solar power
				HTE H_2 w/ 100% nuclear power

Table 2: MHDV simulation parameters for the GREET model [5].

Year	Vehicle types	Powertrain	Fuel	Variations in electricity grid and/or H_2 path
2022	C6P, C8S, C8L	ICEV	Gasoline (E10)	N/A
			B20	
			RD100	
		HEV	Gasoline (E10)	
			B20	
			RD100	
		EV	Electricity	US avg. grid
				MISO grid (highest CI)
				NPCC grid (lowest CI)
				CA grid
		FCV	Gaseous H_2	NGS H_2
			Liquid H_2	NGS H_2
2035 & 2050	C6P, C8S, C8L	ICEV	Gasoline (E10)	N/A
			B20	
			RD100	
			FT-E fuel	
		HEV	Gasoline (E10)	
			B20	
			RD100	
			FT-E fuel	
		EV	Electricity	US avg. grid
				2035: FRCC 2050: PJM (highest CI)
				2035: NPCC 2050: WECC (lowest CI)
				CA grid
		FCV	Gaseous H_2	NGS H_2
				NGA H_2 w/CCS
				LTE H_2 w/ 100% solar
				HTE H_2 w/ 100% nuclear
			Liquid H_2	NGS
				LTE H_2 w/ 100% solar
				HTE H_2 w/ 100% nuclear

Results and Discussions

Figure 2 shows the C2G GHG emissions of LDVs with different classes of vehicles (passenger cars, SUVs, and PUTs) with a set of powertrain types (ICEV, HEV, PHEV, EV, and FCVs). The breakdown of this result is presented in Appendix **Tables A7-A10**. For PHEVs, EVs, and FCVs, we have also presented some of the important variations in electricity grids [i.e., US avg. mix ("US"); regional grids with the highest and lowest CI for each simulation year; and State of California avg. mix ("CA")] and in H_2 production pathways [i.e., NGS; NGA with CCS; LTE using 100% solar power; and HTE using 100% nuclear power]. The C2G GHG emissions level of the 2022 ICEV was compared to the other simulation cases in the figure: equivalent to 2022 ICEV baseline (black dash line); 50% reduction from the 2022 baseline (orange dash line); and 75% reduction from the 2022 baseline (blue dash line). The emissions associated with the production, maintenance, and disposal for the battery, HSS and the rest of the vehicle production are presented with yellow, green, and blue bars, respectively.

The 2022 ICEV's C2G GHG emissions were estimated to be 394 gCO_2e/mi, 441 gCO_2e/mi, and 598 gCO_2e/mi for passenger cars, SUVs, and PUTs, respectively. These values are comparable to those values reported for ICEVs in 2020-2022 timeframe in our previous report (passenger cars: 382 gCO_2e/mi; SUVs; 429gCO_2e/mi) [11] and in other literature (passenger cars: about 410 gCO_2e/mi; SUVs: about 500 gCO_2e/mi) [12]. The differences in the current results and the results reported in Kelly et al. [11] are due to the annual GREET updates for the fuel and vehicle cycles. This annual update is focused on keeping the GREET model up to date with the latest available data for all components of the model. Such updates are very important, especially for rapidly improving technologies such as batteries and fuel cell systems for the EVs and FCVs.

When different current technology pathways (simulation year 2022) were compared, EVs achieved the highest GHG emissions reduction relative to the 2022 ICEV baseline out of all powertrain options currently available. When the US avg. electricity grid is used for the EVs, the C2G GHG emissions for passenger cars, SUVs, and PUTs were 186 gCO_2e/mi, 214 gCO_2e/mi, and 288 gCO_2e/mi, respectively, which was approximately a 50% reduction from each of their ICEV baselines. This significant C2G GHG reduction potential of EVs with currently available technology pathways is consistent with what was reported by the International Council on Cleaner Transportation (ICCT) [12] (60% - 68% reduction in C2G GHG emissions for EVs compared to their ICEV counterpart). Meanwhile, Ambrose et al. [13] reported the C2G GHG emissions of large electric SUVs in the 2020 timeframe, which was 324 gCO_2e/mi, and this corresponded to a 36% reduction from their study's ICEV baseline. Their EV GHG emissions were moderately higher than our value (214 gCO_2e/mi) for two main reasons: i) the higher CI of electricity assumed for the US avg. grid (~520 gCO_2e/kWh) in Ambrose's study compared to what is assumed here (i.e., ~440 gCO_2e/kWh); and ii) the larger vehicle weight and lower fuel economy assumed for the SUV defined in that study.

Challa et al. [14] reported GHG emissions from small electric SUVs on a WTW basis in the 2020 timeframe: 198 gCO_2e/mi. This is 33% higher than the WTW GHG emissions from our simulated EV counterpart (149 gCO_2e/mi). The main reason is the difference in the CI of electricity assumed for the US avg. grid in Challa et al. [14] (~600 gCO_2e/kWh), which was 36% higher than the CI of electricity assumed for the US avg. grid in our study. GREET has leveraged the EIA AEO report grid mix statistics [1], for its CI calculation for the US avg. grid. As we can see from the comparisons across different studies, the CI of electricity is one of the most critical factors affecting C2G GHG emissions of EVs. Thus, we investigated the impact of the CI of electricity grid in the US on our simulated plug-in electric vehicles. Variations in the CI of the electricity grid in different regions of the US are estimated to bring about ±10% differences in the EV's GHG reduction potential. With the CA electricity grid (the lowest CI grid in our simulation), the simulated EVs are expected to achieve up to a 65% GHG reduction from the ICEV baseline.

PHEVs showed about 45% reduction in GHG emissions compared to their ICEV counterpart in 2022. This is a moderately lower GHG reduction potential relative to EVs with the fixed electricity grid, which is consistent with what has been reported by other literature [12]. While FCVs using gaseous H_2 (FGs) showed similar GHG emissions reduction potential to PHEVs using the US avg. grid, the FCVs using liquid H_2 (FLs) had noticeably higher GHG emissions than the FGs or PHEVs. Compared to EVs, the current GHG emissions reduction potential of FCVs was not as significant due to the high CI of hydrogen from NGS. HEVs showed a similar level of GHG emissions compared to FGs, which was approximately a 20% reduction from the ICEV baseline.

For future projections, although the GHG emissions from ICEVs for all three LDV types (i.e., passenger cars, SUVs, and PUTs) are expected to decrease over time (i.e., approximately 20% and 30% reduction in 2035 and 2050, respectively, compared to the 2022 baseline), most of the other powertrain/fuel options are expected to achieve significantly higher GHG emissions reduction than future ICEVs operating on E10 gasoline. This is consistent with most of the literature presenting comparative LCA between ICEVs and advanced powertrain vehicles such as EVs and FCVs. As an example, Bieker [12] showed that while 10% - 12% of C2G GHG emissions reduction could be achieved with future ICEVs compared to the 2021 ICEV, over 65% GHG reduction could be achieved with future EVs with US avg. grid and even more with future FCVs with renewable H_2. In our study, EVs using the US avg. grid are expected to achieve approximately a 75% GHG reduction compared to the 2022 ICEV baseline in 2035 and even more in 2050. All FCVs using advanced H_2 technologies (i.e., NGA, LTE, and HTE) are expected to achieve more than 75% GHG emissions reduction relative to the 2022 ICEV baseline for all three vehicle types in 2035 and 2050. PHEVs relatively lower GHG reduction potential compared to the EVs and FCVs with the advanced H_2 production pathways, however, they are also expected to achieve significant GHG reduction (over 50%) relative to the 2022 ICEV baseline.

Challa et al. [14] is one of the few studies that forecasts much less GHG reduction potential for future EVs: almost no further reduction in GHG emissions using EVs as the simulation year proceeds from 2018 to 2030. This study assumed a nearly flat curve for their CI of electricity assumption for the US avg. mix between 2018 to 2030, which is much higher than what our GREET model (based on EIA's AEO [1]) would project for the CI of electricity of the US avg. mix between 2018 to 2030 (from 480 gCO_2e/kWh to 227 gCO_2e/kWh, about 53% reduction). Another important difference in the future EVs from the current EVs in this study is their battery composition: NMC95 is assumed for the future lithium-ion battery composition (for the 2022 simulation, NMC 811 is assumed), which resulted in some decrease in battery-associated GHG emissions. Similarly, the reductions in the HSS' power to weight ratio and CI of their upstream materials were accounted for in the future projection of the FCVs, thus resulting in some decrease in their vehicle cycle emissions.

Another important observation from **Figure 2** is that, for all current technology options, the GHG emissions from the vehicle cycle (inclusive of "batteries", "hydrogen storage system", and "vehicles less B&H" in the legend) are not the major sources of the C2G GHG emissions: most of the C2G GHG emissions originate from fuel production or vehicle operation during the fuel cycle. Thus, the C2G emissions trends are often different from the vehicle cycle GHG trends for the year 2022 simulation results. For example, although the GHG emissions associated with battery production are expected to make EVs' vehicle-cycle GHG emissions 60-70% higher than those of ICEVs, the EV's higher energy efficiency is expected to significantly reduce their WTW GHG emissions compared to their ICEV counterparts, thus resulting in more than 50% C2G emissions reduction compared to the ICEVs.

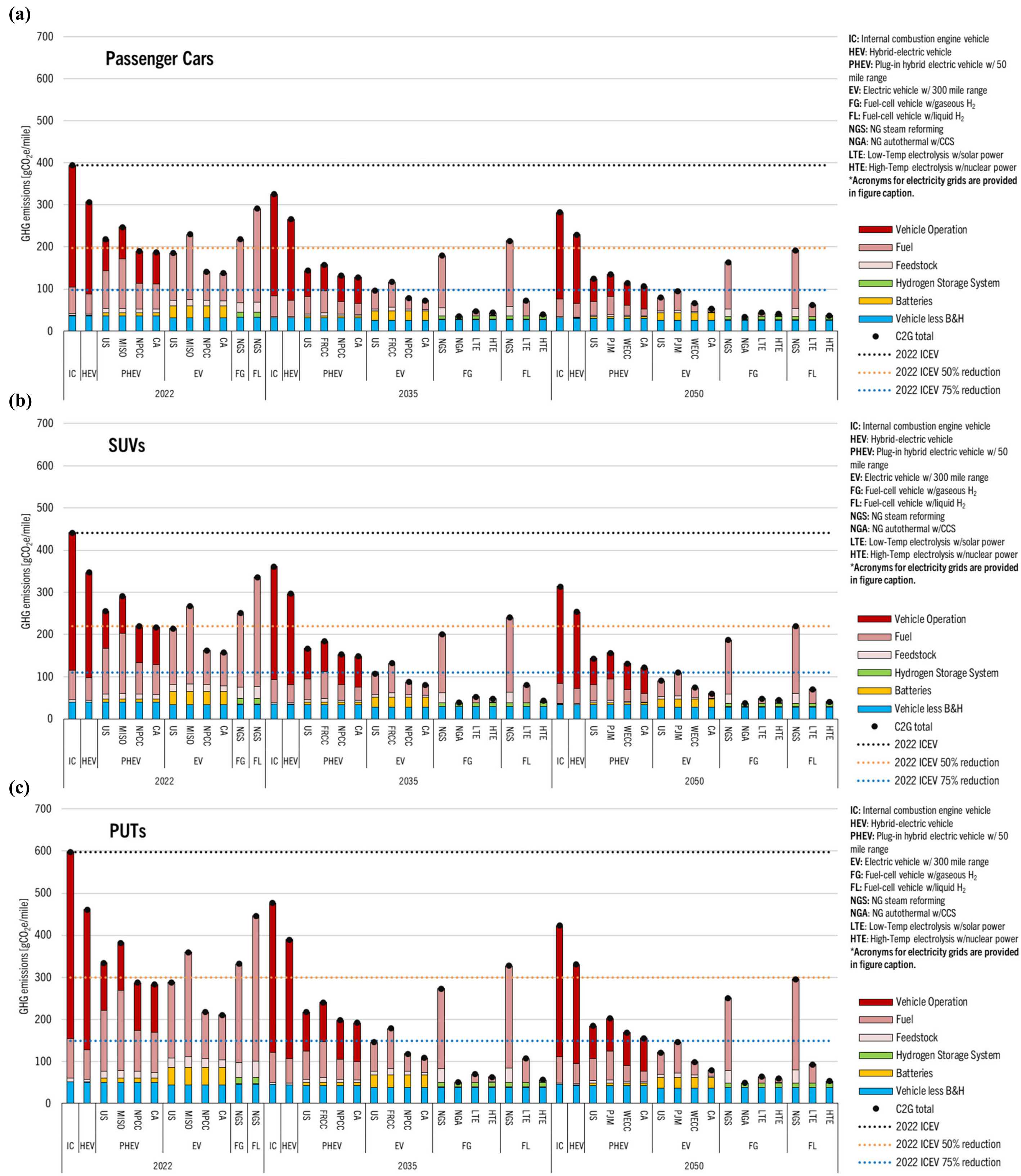

Figure 2: Cradle-to-grave GHG emissions for (a) passenger cars; (b) SUVs; and (c) PUTs. Results for PHEVs and EVs are presented with US average electricity grid, grids with the highest and lowest CI for each simulation year and the State of California average grid. The acronyms are as follows. US: US average; MISO: Midcontinent Independent System Operator; NPCC: Northeast Power Coordinating Council; CA: State of California average; FRCC: Florida Reliability Coordinating Council; PJM: Pennsylvania-New Jersey-Maryland Interconnection; WECC: Western Electricity Coordinating Council.

However, this should not be interpreted that the vehicle cycle GHG emissions are not important, especially when we are discussing future technologies. For future technologies, while the WTW GHG emissions are expected to be significantly reduced for most simulation cases relative to the simulation year 2022, their vehicle cycle GHG emissions are not expected to change much from the current year. As a result, in both future year projections, the majority of C2G emissions from EVs and FCVs (advanced H_2 technologies) are expected to originate from their vehicle cycle, thus making reductions in the vehicle cycle GHG emissions of increasing importance. Eventually, to achieve carbon-neutrality or -negativity in the transportation sector, these vehicle cycle GHG emissions associated with batteries, HSS, and steel and aluminum used for other vehicle components need to be reduced.

Figure 3 shows the C2G GHG emissions of MHDVs with different classes (i.e., C8L, C8S and C6P) of vehicles with a set of powertrain and fuel pathways (i.e., ICEV, HEV, EV, and FCVs). The breakdown of this result is also presented in Appendix **Tables A3-A6**. For this figure, a per mile functional unit is used, however, since the payload settings for all vehicles simulated in this figure is identical to 19 tons (US short tons), for per ton-mile basis, the presented values can be divided by that universal payload. For ICEVs and HEVs, we have taken B20, RD100 and FTE fuels into account as an alternative to the conventional ultra-low sulfur diesel fuel. Similarly, for EVs, and FCVs, we have considered variation in the electricity grids and in H_2 production pathways as in the case of LDVs. The C2G GHG emissions level of 2022 ICEV was compared to the other simulation cases in **Figure 3** for MHDVs, using the same format as used in **Figure 2** for LDVs.

It is observed that the ICEV baseline for C8S is significantly higher than that for C8L, mainly due to the differences in the representative drive-cycles for the two categories: C8L trucks operate mostly on highways while the C8S trucks include a heavy portion of intra-city driving. Typically, ICEVs have better engine efficiency during highway driving than city driving because the engine parameters can be optimized for a higher efficiency operating condition with fewer transient operation on highway [15]. This striking difference in C8S and C8L GHG emissions is consistently reported in Lee et al. [16] and Tong et al [17].

When we compare across the different current technology pathways (simulation year 2022), HEVs operating on the neat alternative liquid fuel (i.e., RD100) are expected to achieve the highest GHG emissions reduction relative to the 2022 ICEV baseline: depending on the vehicle classes, a 69% - 78% reduction could be achieved with the HEVs using RD100. EVs are expected to reduce more than 50% GHG emissions from their ICEV baseline for C8S and C6P trucks while the level of GHG reduction is estimated to be relatively lower for the C8L trucks (only 12% reduction for the EVs using US avg. grid compared to ICEV). For C8L trucks, if EVs use a higher CI electricity grid than the US avg., they could potentially be even more carbon-intensive than their ICEV counterpart. This is because the energy efficiency ratio of the EVs to ICEVs is not high enough to compensate for the CI of electricity production: for C8L trucks, the energy efficiency of EVs were only about two times higher than their ICEV counterpart, while the energy efficiency of EVs for C8S and C6P was about four times higher than their ICEV counterparts. This is consistent with what was reported in Liu et al. [18] that the application of EVs in C8L trucks does not result in noticeable reduction in WTW GHG emissions compared to their ICEV baseline. This low energy efficiency ratio between EVs and ICEVs for C8L trucks also exists for FCVs: while the energy efficiency of the C8S and C6P FCVs are twice that of their ICEV counterpart, C8L FCVs are only about 15% more efficient than their ICEV counterparts. This makes C8L FCVs' GHG reduction potential relatively lower than what could be achieved for FCVs in C8S or C6P trucks in 2022. However, for future simulation years, lower GHG levels can be obtained from the FCVs, primarily with the availability of low CI hydrogen produced from different pathways.

For future projections, the C2G GHG emissions of ICEVs operating on conventional diesel for all three MHDV types are expected to decrease over time to a moderate degree: compared to the 2022 ICEV baseline, i) for C8L, 24% and 32% reduction in 2035 and 2050, respectively; ii) for C8S, 12% and 16% reduction in 2035 and 2050, respectively; and iii) for C6P, 13% and 17% reduction in 2035 and 2050, respectively. This is mainly due to the consideration of future vehicle weight reduction and engine efficiency improvements, thus reducing the emissions from vehicle operation. The vehicle-cycle GHG emissions of the MHDVs constitute a very small portion of the C2G GHG emissions on a per-mile basis. Thus, reduction in the WTW GHG emissions is vital to achieve noticeable reductions in C2G GHG emissions: application of low CI fuel or electricity for the MHDVs will be important. ICEVs and HEVs powered by renewable liquid fuels such as RD100 and FTE or some of the alternative powertrain options such as EVs and FCVs are expected to achieve significantly higher GHG emissions reduction. In 2035 and 2050, all ICEVs and HEVs driving on RD100, or FTE are expected to achieve more than a 75% GHG emissions reduction relative to the 2022 ICEV baseline. Especially, those ICEVs and HEVs operating on FTE fuel are expected to achieve over 95% reduction in GHG emissions, nearing carbon neutrality. All FCVs using the advanced H_2 technologies (i.e., NGA, LTE, and HTE) are expected to achieve a 75% GHG reduction or more relative to the 2022 ICEV baseline for all three vehicle types in 2035 and 2050. EVs using the US avg. grid are also expected to achieve more than a 75% GHG reduction for C8S and C6P trucks compared to the 2022 ICEV baseline in future projections.

The contribution of the vehicle cycle GHG emissions to the C2G emissions on a per-mile basis was even smaller for MHDVs than observed for the LDVs. This is due to the high VMTs set for MHDVs (i.e., 300,000 miles for C6P and 1,000,000 miles for C8S and C8L) compared to those for LDVs (i.e., 173,151 miles for passenger cars and 183,363 miles for SUVs and PUTs), which, diluted the GHG emissions from the vehicle cycle on a per mile basis. Like LDVs, the WTW GHG emissions trend dominated the C2G results, thus emphasizing the GHG emissions reduction through low-carbon fuels (energy) and higher energy efficiency powertrain. However, eventually, to reach carbon-neutrality or -negativity in this sector of transportation, decarbonization of the vehicle cycle also needs to be addressed.

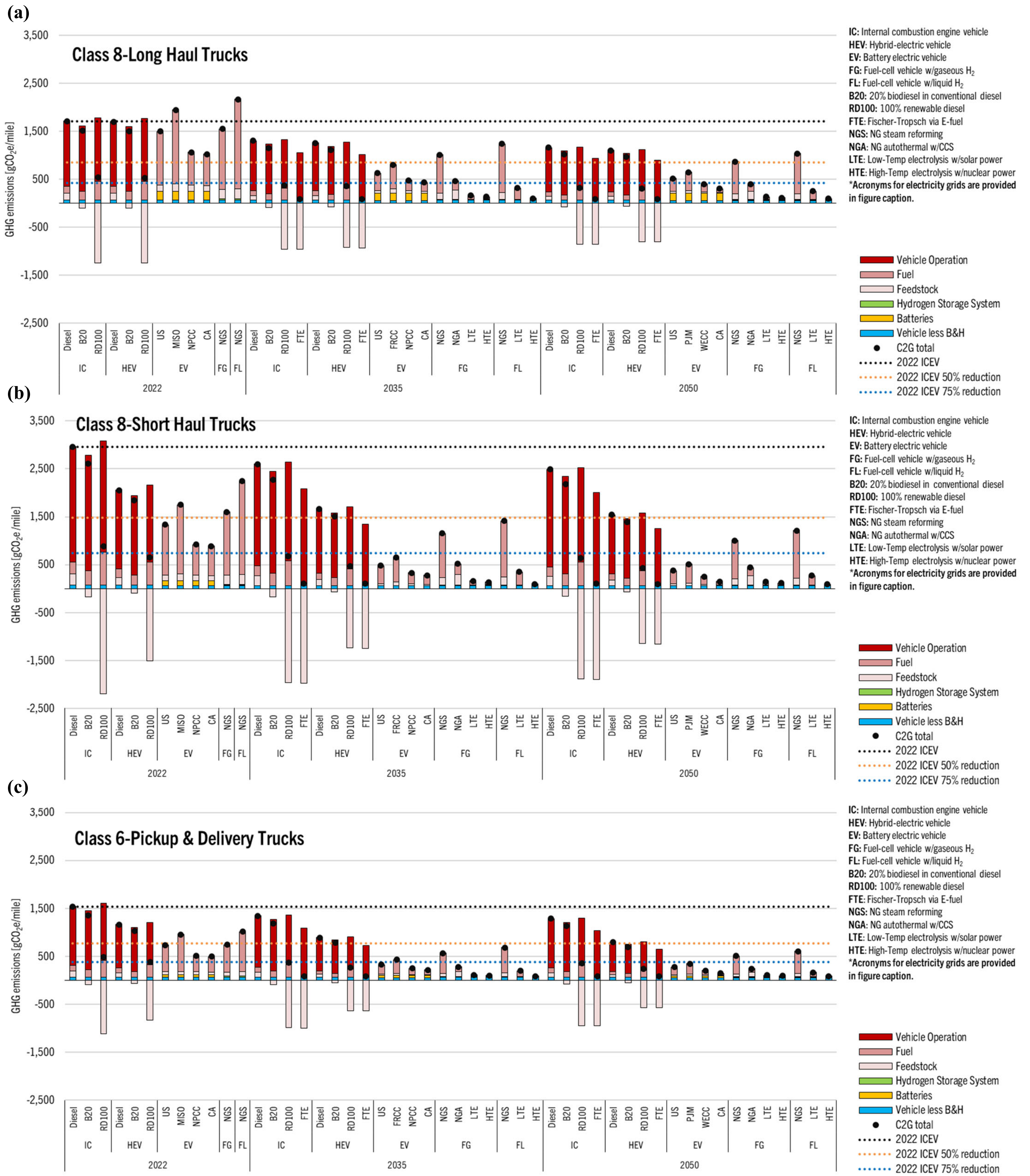

Figure 3: Cradle-to-grave GHG emissions for (a) Class 8 long-haul trucks; (b) Class 8 short-haul trucks; and (c) Class 6 PnD trucks. Results for EVs are presented with US average electricity grid, grids with the highest and lowest CI for each simulation year and the State of California average grid. The acronyms are as follows. US: US average; MISO: Midcontinent Independent System Operator; NPCC: Northeast Power Coordinating Council; CA: State of California average; FRCC: Florida Reliability Coordinating Council; PJM: Pennsylvania-New Jersey-Maryland Interconnection; WECC: Western Electricity Coordinating Council.

Summary/Conclusions

In this study, the C2G GHG emissions of different classes of vehicles (LDVs and MHDVs) with a suite of powertrain options (ICEVs, HEVs, PHEVs, EVs, and FCVs) and fuel/energy pathways are analyzed for the current technology year (2022) and for future technology years (2035 and 2050). For LDVs, EVs showed the greatest GHG emissions reduction potential (about 50% reduction from the 2022 E10 gasoline ICEV counterpart) for the current simulation year while both EVs and FCVs with the advanced H_2 pathways showed the most significant GHG emissions reduction potential for future projections (about 90% reduction from the 2022 E10 gasoline ICEV counterpart). For MHDVs, the FTE pathway in HEVs and FCVs with the advanced H_2 pathways using low- or high-temperature electrolysis showed the greatest GHG emissions reduction potential for both current and future years. Note that this study does not include a solar- or wind-only electricity pathway for the future grid available for EVs as some other studies do, but such a pathway would be indicated by a near-zero CI of electricity (gCO2e /kWh) and would thus yield very low GHG emissions rate for the vehicles. Here, NERC-based grids were used to indicate the broad-based charging typically seen in the market.

For the current year simulation, most of the C2G GHG emissions for both LDVs and MHDVs originate from the WTW GHG emissions for any type of vehicle, powertrain, and fuel/electricity grids, thus emphasizing the importance of decarbonizing the CI of the electricity grid and fuels using a suite of technologies currently available: expanding the low-CI electricity generation capacity to benefit EVs, PHEVs, and FCVs, and commercializing low-CI liquid fuels for ICEVs, HEVs, and PHEVs. However, for future projection years, while the WTW GHG emissions are expected to decrease over time, the vehicle-cycle emissions do not indicate the same level of reduction, thus leaving this piece of the C2G emissions as an important target opportunity moving forward. Decarbonization in material sourcing and improvements in material utilization efficiency will need to be achieved to continue to address vehicle-cycle emissions in the future.

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Definitions/Abbreviations

AEO	Energy Information Administration's Annual Energy Outlook
B&H	battery and hydrogen storage system
B20	20% soy-based bio-diesel blend in conventional diesel
BatPaC	Battery Performance and Cost model
C2G	cradle-to-grave
CA	State of California avg. mix
Cars	midsize sedans
CI	carbon intensity
Day Cab, or C8S	Class 8 Regional haul truck
DOE	U.S. Department of Energy
E10	gasoline with 10% ethanol
EOL	end-of-life
EVs	electric vehicles
FCEVs	fuel cell vehicles
FG	fuel cell vehicles using gaseous H_2
FL	fuel cell vehicles using liquid H_2
FT e-fuel, or FTE	Fischer-Tropsch fuel produced from an electrocatalytic reduction of CO_2
FRCC	Florida Reliability Coordinating Council
GHG	greenhouse gas
GREET	Greenhouse gas, Regulated Emissions, and Energy use in Technologies
GWP	global warming potential
HEVs	hybrid electric vehicles
HSS	hydrogen storage system
HTE	high-temperature electrolysis in solid oxide electrolyzer cell using nuclear electricity
ICCT	International Council on Cleaner Transportation
ICEVs	internal combustion engine vehicles
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
LCA	life cycle analysis
LCI	life cycle inventory
LDV	light-duty vehicles
LTE	low-temperature electrolysis in proton-exchange membrane fuel cell using solar electricity
MISO	Midcontinent Independent System Operator
MHDV	medium- and heavy-duty vehicles
MPDGE	miles per diesel gallon equivalent
MPGGE	miles per gasoline gallon equivalent
NERC	North American Electric Reliability Corporation
NGA H2 w/CCS	natural gas auto-thermal reforming with carbon capture and storage
NGS H2	natural gas steam methane reforming
NMC 811	lithium-ion batteries with 80% Nickel, 10% Manganese, and 10% Cobalt cathode active material
NMC 95	lithium-ion batteries with 95% Nickel, 2.5% Manganese, and 2.5% Cobalt cathode active material
NPCC	Northeast Power Coordinating Council
PEM	proton-exchange membrane
PHEVs	plug-in hybrid electric vehicles
PnD, or C6P	Class 6 Box truck used for pickup and delivery
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PUT	light-duty pickup trucks
RD100	100% renewable diesel derived from forest residue
Sleeper Cab, or C8L	Class 8 Long haul truck
SOEC	solid oxide electrolyzer cell
SUV	small sport utility vehicles
tonnes	metric tons
VC	vehicle cycle
VMT	vehicle miles traveled
WECC	Western Electricity Coordinating Council
WTW	well-to-wheels
ZEV	zero-emission vehicles

Appendix

Table A.1. Parameter settings used for the simulated light-duty vehicles and powertrain types in the GREET model [5].

Year	Vehicle types	Powertrain	Weight (kg)	Fuel Economy [MPGGE]	Battery Energy (kWh)	Battery Power (kW)	Fuel Cell Power (kW)
2022	Car	ICEV	1,480	29.8	-	-	-
		HEV	1,567	39.5	1.1	33.0	-
		PHEV	1,635	69.4	17.2	123.1	-
		EV	1,707	135.9	77.4	155.7	-
		FCV	1,495	62.8	1.7	52.7	98.3
	SUV	ICEV	1,554	26.5	-	-	-
		HEV	1,654	34.7	1.1	33.0	-
		PHEV	1,737	58.7	20.7	120.6	-
		EV	1,844	114.0	89.6	182.5	-
		FCV	1,583	53.9	1.3	39.6	106.4
	PUT	ICEV	2,099	19.5	-	-	-
		HEV	2,144	26.0	1.4	42.9	-
		PHEV	2,251	44.6	27.7	159.6	-
		EV	2,456	84.4	119.8	280.8	-
		FCV	2,095	40.3	1.7	52.7	159.4
2035	Car	ICEV	1,463	35.9	-	-	-
		HEV	1,543	44.9	1.1	31.5	-
		PHEV	1,593	82.8	14.0	116.8	-
		EV	1,628	159.0	66.3	143.1	-
		FCV	1,458	69.8	1.7	50.5	94.2
	SUV	ICEV	1,546	32.3	-	-	-
		HEV	1,629	40.3	1.2	34.7	-
		PHEV	1,690	69.8	16.8	110.3	-
		EV	1,747	136.9	75.5	157.6	-
		FCV	1,543	61.9	1.3	37.8	101.5
	PUT	ICEV	2,062	24.4	-	-	-
		HEV	2,110	30.5	1.4	48.1	-
		PHEV	2,186	53.0	22.4	143.4	-
		EV	2,337	100.2	102.3	252.5	-
		FCV	2,043	45.0	1.7	59.2	152.4
2050	Car	ICEV	1,465	42.0	-	-	-
		HEV	1,536	53.1	1.1	31.5	-
		PHEV	1,575	94.0	12.0	114.3	-
		EV	1,568	180.1	56.0	136.0	-
		FCV	1,446	76.4	1.8	53.6	92.3
	SUV	ICEV	1,542	37.7	-	-	-
		HEV	1,621	48.1	1.2	34.7	-
		PHEV	1,669	79.8	14.3	105.1	-
		EV	1,690	150.5	65.6	150.2	-
		FCV	1,528	66.2	1.3	37.8	99.3
	PUT	ICEV	2,094	27.8	-	-	-
		HEV	2,101	36.7	1.4	49.3	-
		PHEV	2,158	61.0	19.0	136.7	-
		EV	2,256	113.1	87.7	240.3	-
		FCV	2,022	48.9	1.7	60.6	148.9

Table A.2. Parameter settings used for the simulated medium heavy-duty vehicles and powertrain types in the GREET model [5].

Year	Vehicle option	Powertrain	Weight [kg]	Fuel economy [MPDGE]	Battery Energy (kWh)	Battery Power (kW)	Fuel Cell Power (kW)
2022	C8L	IC	4,821	7.5	-	-	-
		HEV	4,924	7.6	7.0	131.7	-
		EV	5,681	13.3	1359	15910	-
		FCV	5,012	8.6	18.0	339.5	382.0
	C8S	IC	7,570	4.3	-	-	-
		HEV	7,678	6.2	6.7	126.9	-
		EV	10,309	14.2	719.9	8431	-
		FCV	7,997	8.3	18.0	339.5	383.4
	C6P	IC	8,275	8.4	-	-	-
		HEV	8,397	11.3	4.3	80.8	-
		EV	14,569	26.8	212.3	2486	-
		FCV	9,301	19.3	4.5	84.4	154.3
2035	C8L	IC	4,821	9.9	-	-	-
		HEV	4,924	10.3	7.0	131.7	-
		EV	5,681	18.5	1359	15910	-
		FCV	5,012	12.4	18.0	339.5	382.0
	C8S	IC	7,570	4.8	-	-	-
		HEV	7,678	7.6	6.7	126.9	-
		EV	10,309	18.1	719.9	8431	-
		CV	7,997	10.7	18.0	339.5	383.4
	C6P	IC	8,275	9.6	-	-	-
		HEV	8,397	14.9	4.3	80.8	-
		EV	14,569	32.9	212.3	2486	-
		FCV	9,301	23.5	4.5	84.4	154.3
2050	C8L	IC	4,821	11.1	-	-	-
		HEV	4,924	11.8	7.0	131.7	-
		EV	5,681	21.1	1359	15910	-
		FCV	5,012	14.5	18.0	339.5	382.0
	C8S	IC	7,570	5.0	-	-	-
		HEV	7,678	8.3	6.7	126.9	-
		EV	10,309	20.5	719.9	8431	-
		FCV	7,997	12.2	18.0	339.5	383.4
	C6P	IC	8,275	10.0	-	-	-
		HEV	8,397	16.8	4.3	80.8	-
		EV	14,569	36.8	212.3	2486	-
		FCV	9,301	26.2	4.5	84.4	154.3

Table A.3. MHDV WTW GHG emissions breakdown in [gCO_2e/mi]

Year	Vehicle option	Powertrain	Fuel	Variations in electricity grid and/or H2 path	Feedstock GHG [gCO_2e/mi]	Fuel GHG [gCO_2e/mi]	Vehicle Operation GHG [gCO_2e/mi]	WTW Total [gCO_2e/mi]
2022	C8L	ICEV	Diesel	N/A	136	142	1,364	1,641
			B20		-101	174	1,364	1,438
			RD100		-1,247	390	1,321	464
		HEV	Diesel		135	141	1,354	1,630
			B20		-100	172	1,355	1,427
			RD100		-1,238	387	1,312	461
		EV	Electricity	US	133	1,118	0	1,252
				MISO	150	1,546	0	1,696
				NPCC	129	685	0	814
				CA	112	663	0	774
		FCV	Gaseous H_2	NG-SMR	193	1,266	0	1,459
			Liquid H_2		209	1,866	0	2,075
	C8S	ICEV	Diesel	N/A	240	250	2,403	2,893
			B20		-178	308	2,405	2,534
			RD100		-2,198	687	2,329	818
		HEV	Diesel		165	171	1,651	1,987
			B20		-90	217	1,652	1,779
			RD100		-1,508	490	1,599	581
		EV	Electricity	US	125	1,047	0	1,172
				MISO	141	1,447	0	1,588
				NPCC	121	641	0	762
				CA	104	620	0	725
		FCV	Gaseous H_2	NG-SMR	201	1,318	0	1,519
			Liquid H_2		217	1,943	0	2,160
	C6P	ICEV	Diesel	N/A	122	127	1,223	1,472
			B20		-90	156	1,224	1,290
			RD100		-1,117	349	1,185	418
		HEV	Diesel		91	94	910	1,095
			B20		-67	116	911	960
			RD100		-831	260	882	311
		EV	Electricity	US	66	556	0	622
				MISO	75	768	0	843
				NPCC	64	340	0	404
				CA	55	329	0	385
		FCV	Gaseous H_2	NG-SMR	86	566	0	653
			Liquid H_2		93	835	0	929
2035	C8L	ICEV	Diesel	N/A	98	104	1,037	1,238
			B20		-83	127	1,037	1,081
			RD100		-958	255	1,004	301
			FT-Efuel		-964	14	974	24
		HEV	Diesel		94	100	998	1,192
			B20		-78	122	998	1,042
			RD100		-922	246	967	291
			FT-Efuel		-928	14	938	24
		EV	Electricity	US	47	366	0	413
				FRCC	79	509	0	588
				NPCC	43	221	0	265
				CA	32	183	0	216
		FCV	H_2-gaseous	NG-SMR	133	800	0	933
				NG-ATR w/CCS	195	194	0	389

				LT-PEM electrolysis	0	80	0	80
				HT-SOEC electrolysis	9	45	0	54
			H_2-liquid	NG-SMR	144	1,016	0	1,160
				LT-PEM electrolysis	0	238	0	238
				HT-SOEC electrolysis	9	14	0	23
	C8S	ICEV	Diesel	N/A	201	212	2,125	2,537
			B20		-171	260	2,126	2,216
			RD100		-1,964	522	2,059	617
			FT-Efuel		-1,976	29	1,997	50
		HEV	Diesel		127	134	1,342	1,602
			B20		-74	170	1,343	1,439
			RD100		-1,239	346	1,300	408
			FT-Efuel		-1,247	19	1,266	38
		EV	Electricity	US	48	373	0	421
				FRCC	80	519	0	599
				NPCC	44	226	0	270
				CA	33	187	0	220
		FCV	H_2-gaseous	NG-SMR	154	926	0	1,080
				NG-ATR w/CCS	226	224	0	450
				LT-PEM electrolysis	0	93	0	93
				HT-SOEC electrolysis	10	52	0	62
			H_2-liquid	NG-SMR	166	1,175	0	1,342
				LT-PEM electrolysis	0	275	0	275
				HT-SOEC electrolysis	11	16	0	27
	C6P	ICEV	Diesel	N/A	101	107	1,074	1,282
			B20		-86	131	1,074	1,119
			RD100		-991	263	1,040	313
			FT-Efuel		-997	15	1,007	25
		HEV	Diesel		65	69	692	826
			B20		-55	85	692	722
			RD100		-638	169	671	202
			FT-Efuel		-641	10	651	20
		EV	Electricity	US	26	205	0	232
				FRCC	44	285	0	330
				NPCC	24	124	0	148
				CA	18	103	0	121
		FCV	H_2-gaseous	NG-SMR	70	422	0	493
				NG-ATR w/CCS	103	102	0	205
				LT-PEM electrolysis	0	42	0	42
				HT-SOEC electrolysis	5	24	0	28
			H_2-liquid	NG-SMR	76	536	0	612
				LT-PEM electrolysis	0	126	0	126
				HT-SOEC electrolysis	5	7	0	12
2050	C8L	ICEV	Diesel	N/A	85	91	920	1,096
			B20		-75	112	920	957
			RD100		-853	221	891	259
			FT-Efuel		-855	13	864	22

		HEV	Diesel		81	86	869	1,036
			B20		-69	106	870	907
			RD100		-806	210	842	246
			FT-Efuel		-809	12	817	21
		EV	Electricity	US	38	268	0	307
				PJM	54	385	0	439
				WECC	26	165	0	191
				CA	12	77	0	89
		FCV	H_2-gaseous	NG-SMR	114	675	0	789
				NG-ATR w/CCS	167	148	0	315
				LT-PEM electrolysis	0	59	0	59
				HT-SOEC electrolysis	7	34	0	41
			H_2-liquid	NG-SMR	123	839	0	962
				LT-PEM electrolysis	0	173	0	173
				HT-SOEC electrolysis	8	11	0	19
	C8S	ICEV	Diesel	N/A	189	202	2,034	2,425
			B20		-166	248	2,035	2,117
			RD100		-1,888	489	1,971	573
			FT-Efuel		-1,893	28	1,913	48
		HEV	Diesel		115	123	1,240	1,478
			B20		-67	157	1,241	1,331
			RD100		-1,149	315	1,201	367
			FT-Efuel		-1,152	17	1,172	37
		EV	Electricity	US	39	276	0	316
				PJM	56	397	0	453
				WECC	26	170	0	196
				CA	13	80	0	92
		FCV	H_2-gaseous	NG-SMR	135	799	0	934
				NG-ATR w/CCS	198	175	0	372
				LT-PEM electrolysis	0	70	0	70
				HT-SOEC electrolysis	9	40	0	48
			H_2-liquid	NG-SMR	146	993	0	1,139
				LT-PEM electrolysis	0	205	0	205
				HT-SOEC electrolysis	9	13	0	22
	C6P	ICEV	Diesel	N/A	95	102	1,026	1,223
			B20		-84	125	1,027	1,068
			RD100		-951	246	994	290
			FT-Efuel		-953	14	963	24
		HEV	Diesel		57	61	612	729
			B20		-50	74	613	637
			RD100		-566	147	593	174
			FT-Efuel		-567	8	577	18
		EV	Electricity	US	22	154	0	176
				PJM	31	221	0	252
				WECC	15	95	0	109
				CA	7	44	0	51
		FCV	H_2-gaseous	NG-SMR	63	373	0	436
				NG-ATR w/CCS	92	81	0	174
				LT-PEM electrolysis	0	32	0	32

				HT-SOEC electrolysis	4	19	0	23
			H_2-liquid	NG-SMR	68	463	0	531
				LT-PEM electrolysis	0	96	0	96
				HT-SOEC electrolysis	4	6	0	10

Table A.4. MHDV WTW GHG emissions breakdown in [gCO_2e/MJ]

Year	Vehicle option	Powertrain	Fuel	Variations in electricity grid and/or H2 path	Feedstock GHG [gCO_2e/MJ]	Fuel GHG [gCO_2e/MJ]	Vehicle Operation GHG [gCO_2e/MJ]	WTW Total [gCO_2e/MJ]
2022	C8L	ICEV	Diesel	N/A	7.5	7.8	75.0	90.3
			B20		-5.6	9.6	75.0	79.1
			RD100		-68.6	21.4	72.7	25.5
		HEV	Diesel		7.5	7.8	75.0	90.3
			B20		-5.5	9.6	75.0	79.1
			RD100		-68.6	21.5	72.7	25.5
		EV	Electricity	US	13.0	109.1	0.0	122.1
				MISO	14.7	150.8	0.0	165.4
				NPCC	12.6	66.8	0.0	79.4
				CA	10.9	64.6	0.0	75.5
		FCV	Gaseous H_2	NG-SMR	12.2	79.9	0.0	92.1
			Liquid H_2		13.2	117.8	0.0	131.0
	C8S	ICEV	Diesel	N/A	7.5	7.8	75.0	90.3
			B20		-5.6	9.6	75.0	79.1
			RD100		-68.6	21.4	72.7	25.5
		HEV	Diesel		7.5	7.8	75.0	90.3
			B20		-4.1	9.9	75.1	80.9
			RD100		-68.5	22.3	72.7	26.4
		EV	Electricity	US	13.0	109.1	0.0	122.1
				MISO	14.7	150.8	0.0	165.4
				NPCC	12.6	66.8	0.0	79.4
				CA	10.9	64.6	0.0	75.5
		FCV	Gaseous H_2	NG-SMR	12.2	79.9	0.0	92.1
			Liquid H_2		13.2	117.8	0.0	131.0
	C6P	ICEV	Diesel	N/A	7.5	7.8	75.1	90.4
			B20		-5.6	9.6	75.2	79.2
			RD100		-68.6	21.4	72.8	25.6
		HEV	Diesel		7.5	7.8	75.2	90.4
			B20		-5.6	9.6	75.2	79.2
			RD100		-68.6	21.4	72.8	25.7
		EV	Electricity	US	13.0	109.1	0.0	122.1
				MISO	14.7	150.8	0.0	165.4
				NPCC	12.6	66.8	0.0	79.4
				CA	10.9	64.6	0.0	75.5
		FCV	Gaseous H_2	NG-SMR	12.2	79.9	0.0	92.1
			Liquid H_2		13.2	117.8	0.0	131.0
2035	C8L	ICEV	Diesel	N/A	7.1	7.5	75.0	89.6
			B20		-6.0	9.2	75.1	78.2
			RD100		-69.3	18.4	72.7	21.8

			FT-Efuel		-69.8	1.0	70.5	1.8
		HEV	Diesel		7.1	7.5	75.0	89.6
			B20		-5.9	9.2	75.1	78.3
			RD100		-69.3	18.5	72.7	21.8
			FT-Efuel		-69.7	1.0	70.5	1.8
		EV	Electricity	US	6.4	49.5	0.0	55.9
				FRCC	10.7	68.8	0.0	79.5
				NPCC	5.8	29.9	0.0	35.8
				CA	4.4	24.8	0.0	29.2
		FCV	H_2-gaseous	NG-SMR	12.1	72.7	0.0	84.8
				NG-ATR w/CCS	17.7	17.6	0.0	35.3
				LT-PEM electrolysis	0.0	7.3	0.0	7.3
				HT-SOEC electrolysis	0.8	4.1	0.0	4.9
			H_2-liquid	NG-SMR	13.1	92.3	0.0	105.4
				LT-PEM electrolysis	0.0	21.6	0.0	21.6
				HT-SOEC electrolysis	0.8	1.3	0.0	2.1
	C8S	ICEV	Diesel	N/A	7.1	7.5	75.0	89.6
			B20		-6.0	9.2	75.0	78.2
			RD100		-69.3	18.4	72.7	21.8
			FT-Efuel		-69.8	1.0	70.5	1.8
		HEV	Diesel		7.1	7.5	75.0	89.6
			B20		-4.1	9.5	75.1	80.5
			RD100		-69.3	19.4	72.7	22.8
			FT-Efuel		-69.7	1.1	70.8	2.1
		EV	Electricity	US	6.4	49.5	0.0	55.9
				FRCC	10.7	68.8	0.0	79.5
				NPCC	5.8	29.9	0.0	35.8
				CA	4.4	24.8	0.0	29.2
		FCV	H_2-gaseous	NG-SMR	12.1	72.7	0.0	84.8
				NG-ATR w/CCS	17.7	17.6	0.0	35.3
				LT-PEM electrolysis	0.0	7.3	0.0	7.3
				HT-SOEC electrolysis	0.8	4.1	0.0	4.9
			H_2-liquid	NG-SMR	13.1	92.3	0.0	105.4
				LT-PEM electrolysis	0.0	21.6	0.0	21.6
				HT-SOEC electrolysis	0.8	1.3	0.0	2.1
	C6P	ICEV	Diesel	N/A	7.1	7.5	75.1	89.7
			B20		-6.0	9.2	75.2	78.3
			RD100		-69.3	18.4	72.8	21.9
			FT-Efuel		-69.8	1.0	70.5	1.8
		HEV	Diesel		7.1	7.5	75.2	89.8
			B20		-6.0	9.2	75.3	78.4
			RD100		-69.3	18.4	72.9	22.0
			FT-Efuel		-69.7	1.1	70.8	2.1
		EV	Electricity	US	6.4	49.5	0.0	55.9
				FRCC	10.7	68.8	0.0	79.5
				NPCC	5.8	29.9	0.0	35.8
				CA	4.4	24.8	0.0	29.2
		FCV	H_2-gaseous	NG-SMR	12.1	72.7	0.0	84.8
				NG-ATR w/CCS	17.7	17.6	0.0	35.3

				LT-PEM electrolysis	0.0	7.3	0.0	7.3
				HT-SOEC electrolysis	0.8	4.1	0.0	4.9
			H_2-liquid	NG-SMR	13.1	92.3	0.0	105.4
				LT-PEM electrolysis	0.0	21.6	0.0	21.6
				HT-SOEC electrolysis	0.8	1.3	0.0	2.1
2050	C8L	ICEV	Diesel	N/A	7.0	7.4	75.0	89.4
			B20		-6.1	9.1	75.1	78.1
			RD100		-69.6	18.0	72.7	21.1
			FT-Efuel		-69.8	1.0	70.5	1.8
		HEV	Diesel		7.0	7.4	75.0	89.4
			B20		-5.9	9.1	75.1	78.3
			RD100		-69.6	18.1	72.7	21.2
			FT-Efuel		-69.8	1.0	70.6	1.8
		EV	Electricity	US	5.9	41.4	0.0	47.4
				PJM	8.3	59.5	0.0	67.9
				WECC	4.0	25.5	0.0	29.5
				CA	1.9	11.9	0.0	13.8
		FCV	H_2-gaseous	NG-SMR	12.1	71.6	0.0	83.7
				NG-ATR w/CCS	17.7	15.7	0.0	33.4
				LT-PEM electrolysis	0.0	6.2	0.0	6.2
				HT-SOEC electrolysis	0.8	3.6	0.0	4.3
			H_2-liquid	NG-SMR	13.1	89.0	0.0	102.1
				LT-PEM electrolysis	0.0	18.4	0.0	18.4
				HT-SOEC electrolysis	0.8	1.1	0.0	2.0
	C8S	ICEV	Diesel	N/A	7.0	7.4	75.0	89.4
			B20		-6.1	9.1	75.0	78.0
			RD100		-69.6	18.0	72.7	21.1
			FT-Efuel		-69.8	1.0	70.5	1.8
		HEV	Diesel		7.0	7.4	75.0	89.4
			B20		-4.1	9.5	75.1	80.5
			RD100		-69.5	19.0	72.7	22.2
			FT-Efuel		-69.7	1.0	70.9	2.2
		EV	Electricity	US	5.9	41.4	0.0	47.4
				PJM	8.3	59.5	0.0	67.9
				WECC	4.0	25.5	0.0	29.5
				CA	1.9	11.9	0.0	13.8
		FCV	H_2-gaseous	NG-SMR	12.1	71.6	0.0	83.7
				NG-ATR w/CCS	17.7	15.7	0.0	33.4
				LT-PEM electrolysis	0.0	6.2	0.0	6.2
				HT-SOEC electrolysis	0.8	3.6	0.0	4.3
			H_2-liquid	NG-SMR	13.1	89.0	0.0	102.1
				LT-PEM electrolysis	0.0	18.4	0.0	18.4
				HT-SOEC electrolysis	0.8	1.1	0.0	2.0
	C6P	ICEV	Diesel	N/A	7.0	7.4	75.1	89.5
			B20		-6.1	9.1	75.2	78.2
			RD100		-69.6	18.0	72.8	21.2
			FT-Efuel		-69.8	1.0	70.5	1.8

		HEV	Diesel		7.0	7.4	75.2	89.7
			B20		-6.1	9.1	75.3	78.3
			RD100		-69.6	18.0	72.9	21.4
			FT-Efuel		-69.7	1.0	70.9	2.2
		EV	Electricity	US	5.9	41.4	0.0	47.4
				PJM	8.3	59.5	0.0	67.9
				WECC	4.0	25.5	0.0	29.5
				CA	1.9	11.9	0.0	13.8
		FCV	H_2-gaseous	NG-SMR	12.1	71.6	0.0	83.7
				NG-ATR w/CCS	17.7	15.7	0.0	33.4
				LT-PEM electrolysis	0.0	6.2	0.0	6.2
				HT-SOEC electrolysis	0.8	3.6	0.0	4.3
			H_2-liquid	NG-SMR	13.1	89.0	0.0	102.1
				LT-PEM electrolysis	0.0	18.4	0.0	18.4
				HT-SOEC electrolysis	0.8	1.1	0.0	2.0

Table A.5. MHDV vehicle cycle GHG emissions breakdown [gCO_2e/mi]

		Powertrain	Body	Powertrain System (including BOP)	Transmission System	Chassis (w/o battery)	Traction Motor	Generator	Electronic Controller	Van/Box	Hydrogen Storage System	Lift-gates	Vehicle assembly, disposal & recycling	Batteries	Trailers (only class 8)	Fluids	Vehicle cycle total
2022	C8L	ICEV	5.2	3.8	1.1	18.3	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.2	35.7	4.8	70.9
		HEV	5.2	3.8	1.1	18.3	0.4	0.0	0.0	0.0	0.0	0.0	1.8	1.2	35.7	4.8	72.3
		EV	5.2	0.0	0.5	18.3	1.9	0.0	0.2	0.0	0.0	0.0	1.8	183.4	35.7	2.0	249.0
		FCV	5.2	1.9	0.5	18.3	2.2	0.0	0.2	0.0	22.4	0.0	1.8	2.8	35.7	2.0	93.1
	C8S	ICEV	4.9	3.9	1.1	17.3	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.3	34.5	5.0	68.7
		HEV	4.9	3.9	1.1	17.3	0.4	0.0	0.0	0.0	0.0	0.0	1.7	1.2	34.5	5.0	70.0
		EV	4.9	0.0	0.5	17.3	1.9	0.0	0.2	0.0	0.0	0.0	1.7	96.9	34.5	2.2	160.1
		FCV	4.9	1.9	0.5	17.3	2.2	0.0	0.2	0.0	14.1	0.0	1.7	2.9	34.5	2.2	82.5
	C6P	ICEV	7.2	4.5	1.4	19.5	0.0	0.0	0.0	18.6	0.0	2.7	4.6	1.0	0.0	7.9	67.5
		HEV	7.2	4.6	1.4	19.5	0.7	0.0	0.1	18.6	0.0	2.7	4.6	2.2	0.0	7.7	69.3
		EV	7.2	0.0	0.7	19.5	2.7	0.0	0.3	18.6	0.0	2.7	4.6	49.3	0.0	5.8	111.4
		FCV	7.2	2.4	0.8	19.5	2.9	0.0	0.3	18.6	19.3	2.7	4.6	1.7	0.0	5.8	85.7
2035	C8L	ICEV	4.6	3.4	1.0	16.6	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.2	32.8	4.8	64.3
		HEV	4.6	3.4	1.0	16.6	0.3	0.0	0.0	0.0	0.0	0.0	1.1	1.0	32.8	4.7	65.5
		EV	4.6	0.0	0.4	16.6	1.7	0.0	0.2	0.0	0.0	0.0	1.1	155.9	32.8	1.9	215.2
		FCV	4.6	1.5	0.5	16.6	1.9	0.0	0.2	0.0	15.5	0.0	1.1	2.4	32.8	1.9	79.0
	C8S	ICEV	4.3	3.5	1.0	15.7	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.2	31.7	5.0	62.4
		HEV	4.3	3.5	1.0	15.7	0.3	0.0	0.0	0.0	0.0	0.0	1.0	1.1	31.7	4.9	63.5
		EV	4.3	0.0	0.4	15.7	1.7	0.0	0.2	0.0	0.0	0.0	1.0	0.1	31.7	2.1	57.3
		FCV	4.3	1.5	0.5	15.7	1.9	0.0	0.2	0.0	9.8	0.0	1.0	2.4	31.7	2.1	71.2
	C6P	ICEV	6.3	4.1	1.2	17.6	0.0	0.0	0.0	17.6	0.0	2.4	2.8	0.9	0.0	7.8	60.8
		HEV	6.3	4.2	1.2	17.6	0.7	0.0	0.1	17.6	0.0	2.4	2.8	1.9	0.0	7.6	62.3
		EV	6.3	0.0	0.7	17.6	2.4	0.0	0.2	17.6	0.0	2.4	2.8	41.9	0.0	5.8	97.7
		FCV	6.3	2.0	0.7	17.6	2.6	0.0	0.2	17.6	13.5	2.4	2.8	1.4	0.0	5.8	72.9
2050	C8L	ICEV	4.5	3.4	0.9	16.4	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.2	32.4	4.7	63.5
		HEV	4.5	3.4	0.9	16.4	0.3	0.0	0.0	0.0	0.0	0.0	0.9	1.0	32.4	4.7	64.6
		EV	4.5	0.0	0.4	16.4	1.7	0.0	0.2	0.0	0.0	0.0	0.9	152.8	32.4	1.9	211.2
		FCV	4.5	1.5	0.5	16.4	1.9	0.0	0.2	0.0	14.6	0.0	0.9	2.3	32.4	1.9	77.2
	C8S	ICEV	4.3	3.5	0.9	15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.2	31.3	4.9	61.6
		HEV	4.3	3.4	0.9	15.5	0.3	0.0	0.0	0.0	0.0	0.0	0.9	1.0	31.3	4.9	62.7
		EV	4.3	0.0	0.4	15.5	1.7	0.0	0.2	0.0	0.0	0.0	0.9	0.1	31.3	2.1	56.5

		FCV	4.3	1.5	0.5	15.5	1.9	0.0	0.2	0.0	9.2	0.0	0.9	2.4	31.3	2.1	69.8
	C6P	ICEV	6.2	4.0	1.2	17.3	0.0	0.0	0.0	17.5	0.0	2.3	2.6	0.9	0.0	7.8	59.9
		HEV	6.2	4.1	1.2	17.3	0.6	0.0	0.1	17.5	0.0	2.3	2.6	1.8	0.0	7.6	61.4
		EV	6.2	0.0	0.6	17.3	2.4	0.0	0.2	17.5	0.0	2.3	2.6	41.1	0.0	5.7	96.0
		FCV	6.2	1.9	0.7	17.3	2.6	0.0	0.2	17.5	12.7	2.3	2.6	1.4	0.0	5.7	71.2

Table A.6. MHDV Vehicle cycle GHG emissions breakdown [gCO_2e/vehicle lifetime]

		Powertrain	Body	Powertrain System (including BOP)	Transmission System	Chassis (w/o battery)	Traction Motor	Generator	Electronic Controller	Van/Box	Hydrogen Storage System	Lift-gates	Vehicle assembly, disposal & recycling	Batteries	Trailers (only class 8)	Fluids	Vehicle cycle total
2022	C8L	ICEV	5,169,038	3,821,392	1,084,568	18,301,159	0	0	0	0	0	0	1,833,008	179,606	35,714,215	4,814,285	70,917,271
		HEV	5,169,038	3,783,329	1,084,568	18,301,159	370,822	0	35,249	0	0	0	1,833,008	1,233,334	35,714,215	4,778,967	72,303,690
		EV	5,169,038	0	497,508	18,301,159	1,901,583	0	184,752	0	0	0	1,833,008	183,389,641	35,714,215	1,969,977	248,960,881
		FCV	5,169,038	1,924,401	542,837	18,301,159	2,161,986	0	209,878	0	22,447,651	0	1,833,008	2,827,652	35,714,215	1,969,977	93,101,802
	C8S	ICEV	4,893,601	3,920,268	1,085,674	17,343,683	0	0	0	0	0	0	1,738,871	269,409	34,464,165	5,021,582	68,737,253
		HEV	4,893,601	3,852,614	1,085,674	17,343,683	370,517	0	35,256	0	0	0	1,738,871	1,245,218	34,464,165	4,986,264	70,015,863
		EV	4,893,601	0	497,508	17,343,683	1,901,583	0	184,752	0	0	0	1,738,871	96,947,615	34,464,165	2,177,274	160,149,052
		FCV	4,893,601	1,930,985	545,048	17,343,683	2,170,023	0	211,356	0	14,117,704	0	1,738,871	2,872,553	34,464,165	2,177,274	82,465,263
	C6P	ICEV	2,159,396	1,354,987	417,182	5,853,217	0	0	0	5,573,157	0	813,554	1,372,012	314,311	0	2,380,054	20,237,869
		HEV	2,159,396	1,381,485	417,182	5,853,217	223,692	0	21,741	5,573,157	0	813,554	1,372,012	663,390	0	2,310,702	20,789,529
		EV	2,159,396	0	223,144	5,853,217	811,749	0	78,335	5,573,157	0	813,554	1,372,012	14,791,176	0	1,749,929	33,425,669
		FCV	2,159,396	716,156	232,846	5,853,217	872,831	0	85,725	5,573,157	5,786,733	813,554	1,372,012	506,939	0	1,749,929	25,722,495
2035	C8L	ICEV	4,583,415	3,434,091	957,043	16,587,825	0	0	0	0	0	0	1,050,179	156,289	32,817,718	4,756,054	64,342,614
		HEV	4,583,415	3,399,821	957,043	16,587,825	329,859	0	29,563	0	0	0	1,050,179	1,039,442	32,817,718	4,721,118	65,515,983
		EV	4,583,415	0	439,011	16,587,825	1,693,793	0	154,682	0	0	0	1,050,179	155,919,247	32,817,718	1,944,025	215,189,894
		FCV	4,583,415	1,533,779	479,010	16,587,825	1,925,741	0	175,718	0	15,519,434	0	1,050,179	2,367,574	32,817,718	1,944,025	78,984,418
	C8S	ICEV	4,341,762	3,531,643	958,019	15,743,755	0	0	0	0	0	0	1,007,105	234,434	31,670,457	4,959,810	62,446,985
		HEV	4,341,762	3,470,464	958,019	15,743,755	329,592	0	29,569	0	0	0	1,007,105	1,050,607	31,670,457	4,924,874	63,526,204
		EV	4,341,762	0	439,011	15,743,755	1,693,793	0	154,682	0	0	0	1,007,105	78,145	31,670,457	2,147,781	57,276,491
		FCV	4,341,762	1,538,966	480,961	15,743,755	1,932,900	0	176,956	0	9,782,978	0	1,007,105	2,406,646	31,670,457	2,147,781	71,230,268
	C6P	ICEV	1,900,930	1,230,134	370,031	5,275,990	0	0	0	5,277,263	0	715,493	839,243	273,506	0	2,347,878	18,230,469
		HEV	1,900,930	1,255,380	370,031	5,275,990	197,981	0	18,339	5,277,263	0	715,493	839,243	564,985	0	2,279,277	18,694,913
		EV	1,900,930	0	197,924	5,275,990	723,048	0	65,585	5,277,263	0	715,493	839,243	12,576,237	0	1,725,239	29,296,952
		FCV	1,900,930	591,819	206,529	5,275,990	777,455	0	71,772	5,277,263	4,045,861	715,493	839,243	428,443	0	1,725,239	21,856,038
2050	C8L	ICEV	4,507,395	3,383,990	940,605	16,365,683	0	0	0	0	0	0	949,633	153,257	32,440,463	4,744,927	63,485,953
		HEV	4,507,395	3,350,210	940,605	16,365,683	324,526	0	28,826	0	0	0	949,633	1,017,044	32,440,463	4,710,068	64,634,453
		EV	4,507,395	0	431,470	16,365,683	1,666,743	0	150,785	0	0	0	949,633	152,774,780	32,440,463	1,939,289	211,226,241
		FCV	4,507,395	1,483,137	470,782	16,365,683	1,894,986	0	171,292	0	14,623,487	0	949,633	2,314,952	32,440,463	1,939,289	77,161,099
	C8S	ICEV	4,270,175	3,481,364	941,564	15,536,195	0	0	0	0	0	0	913,117	229,886	31,306,517	4,948,200	61,627,017
		HEV	4,270,175	3,421,022	941,564	15,536,195	324,265	0	28,831	0	0	0	913,117	1,028,018	31,306,517	4,913,341	62,683,045
		EV	4,270,175	0	431,470	15,536,195	1,666,743	0	150,785	0	0	0	913,117	76,629	31,306,517	2,142,562	56,494,192
		FCV	4,270,175	1,488,143	472,700	15,536,195	1,902,031	0	172,498	0	9,222,413	0	913,117	2,353,266	31,306,517	2,142,562	69,779,616
	C6P	ICEV	1,867,411	1,213,950	363,962	5,201,301	0	0	0	5,238,664	0	702,892	770,815	268,200	0	2,342,319	17,969,514
		HEV	1,867,411	1,239,029	363,962	5,201,301	194,636	0	17,897	5,238,664	0	702,892	770,815	553,063	0	2,273,869	18,423,540
		EV	1,867,411	0	194,677	5,201,301	711,500	0	63,933	5,238,664	0	702,892	770,815	12,320,408	0	1,721,138	28,792,740
		FCV	1,867,411	575,674	203,141	5,201,301	765,039	0	69,964	5,238,664	3,820,723	702,892	770,815	419,140	0	1,721,138	21,355,904

Table A.7. LDV WTW GHG emissions breakdown in [gCO_2e/mi]

Year	Vehicle types	Powertrains	Fuel selected	Variations in electricity grid and/or H2 path	Feedstock	Fuel	Vehicle Operation	WTW Total

2022	Cars	ICEV	Gasoline (E10)	N/A	5	62	290	357
		HEV			4	47	219	270
		PHEV	Gasoline (E10) + Electricity	US avg.	10	89	75	175
				MISO	11	118	75	204
				NPCC	10	61	75	146
				CA	9	60	75	144
		EV	Electricity	US avg.	13	112	0	125
				MISO	15	154	0	170
				NPCC	13	68	0	81
				CA	11	66	0	77
		FCV	H_2-gaseous	NG-SMR	23	151	0	174
			H_2-liquid		25	222	0	247
	SUVs	ICEV	Gasoline (E10)	N/A	6	70	326	401
		HEV			4	53	249	307
		PHEV	Gasoline (E10) + Electricity	US avg.	12	108	88	208
				MISO	14	142	88	243
				NPCC	12	73	88	173
				CA	10	72	88	170
		EV	Electricity	US avg.	16	133	0	149
				MISO	18	184	0	202
				NPCC	15	82	0	97
				CA	13	79	0	92
		FCV	H_2-gaseous	NG-SMR	27	175	0	202
			H_2-liquid		29	259	0	288
	PUTs	ICEV	Gasoline (E10)	N/A	8	95	444	547
		HEV			6	71	333	410
		PHEV	Gasoline (E10) + Electricity	US avg.	16	145	113	274
				MISO	18	191	113	322
				NPCC	16	98	113	227
				CA	14	95	113	223
		EV	Electricity	US avg.	21	180	0	202
				MISO	24	249	0	273
				NPCC	21	110	0	131
				CA	18	107	0	125
		FCV	H_2-gaseous	NG-SMR	36	234	0	270
			H_2-liquid		39	346	0	384
2035	Cars	ICEV	Gasoline (E10)	N/A	3	49	241	293
		HEV			3	39	193	234
		PHEV	Gasoline (E10) + Electricity	US avg.	5	41	62	108
				FRCC	7	53	62	122
				NPCC	4	30	62	96
				CA	3	27	62	92
		EV	Electricity	US avg.	6	43	0	49
				FRCC	9	60	0	70
				NPCC	5	26	0	31
				CA	4	22	0	26
		FCV	H_2-gaseous	NG-SMR	21	123	0	144
				NG-ATR w/CCS	0	0	0	0
				LT PEM Electrolysis	0	12	0	12
				HT-SOEC-Electrolysis	1	7	0	8
			H_2-liquid	NG-SMR	22	157	0	179
				LT PEM Electrolysis	0	37	0	37

				HT-SOEC-Electrolysis	1	2	0	4
	SUVs	ICEV	Gasoline (E10)	N/A	4	54	268	326
		HEV			3	44	215	262
		PHEV	Gasoline (E10) + Electricity	US avg.	5	50	72	127
				FRCC	9	64	72	144
				NPCC	5	36	72	113
				CA	4	32	72	108
		EV	Electricity	US avg.	6	50	0	57
				FRCC	11	70	0	81
				NPCC	6	30	0	36
				CA	4	25	0	30
		FCV	H_2-gaseous	NG-SMR	23	139	0	162
				NG-ATR w/CCS	0	0	0	0
				LT PEM Electrolysis	0	14	0	14
				HT-SOEC-Electrolysis	1	8	0	9
			H_2-liquid	NG-SMR	25	177	0	202
				LT PEM Electrolysis	0	41	0	41
				HT-SOEC-Electrolysis	2	2	0	4
	PUTs	ICEV	Gasoline (E10)	N/A	5	72	355	432
		HEV			4	58	284	345
		PHEV	Gasoline (E10) + Electricity	US avg.	7	66	94	167
				FRCC	11	85	94	190
				NPCC	7	48	94	148
				CA	5	43	94	142
		EV	Electricity	US avg.	9	69	0	78
				FRCC	15	96	0	110
				NPCC	8	42	0	50
				CA	6	34	0	41
		FCV	H_2-gaseous	NG-SMR	32	191	0	223
				NG-ATR w/CCS	0	0	0	0
				LT PEM Electrolysis	0	19	0	19
				HT-SOEC-Electrolysis	2	11	0	13
			H_2-liquid	NG-SMR	34	243	0	277
				LT PEM Electrolysis	0	57	0	57
				HT-SOEC-Electrolysis	2	3	0	6
2050	Cars	ICEV	Gasoline (E10)	N/A	2	42	206	250
		HEV			2	33	163	198
		PHEV	Gasoline (E10) + Electricity	US avg.	4	33	53	90
				FRCC	5	42	53	101
				NPCC	3	24	53	80
				CA	2	17	53	72
		EV	Electricity	US avg.	5	32	0	37
				FRCC	6	46	0	52
				NPCC	3	20	0	23
				CA	1	9	0	11
		FCV	H_2-gaseous	NG-SMR	19	111	0	130
				NG-ATR w/CCS	0	0	0	0
				LT PEM Electrolysis	0	10	0	10

				HT-SOEC-Electrolysis	1	6	0	7
			H_2-liquid	NG-SMR	20	138	0	158
				LT PEM Electrolysis	0	28	0	28
				HT-SOEC-Electrolysis	1	2	0	3
	SUVs	ICEV	Gasoline (E10)	N/A	3	46	230	279
		HEV			2	36	180	219
		PHEV	Gasoline (E10) + Electricity	US avg.	5	39	61	105
				FRCC	6	51	61	118
				NPCC	3	29	61	93
				CA	2	20	61	83
		EV	Electricity	US avg.	5	38	0	44
				FRCC	8	55	0	63
				NPCC	4	24	0	27
				CA	2	11	0	13
		FCV	H_2-gaseous	NG-SMR	22	128	0	150
				NG-ATR w/CCS	0	0	0	0
				LT PEM Electrolysis	0	11	0	11
				HT-SOEC-Electrolysis	1	6	0	8
			H_2-liquid	NG-SMR	23	159	0	182
				LT PEM Electrolysis	0	33	0	33
				HT-SOEC-Electrolysis	1	2	0	4
	PUTs	ICEV	Gasoline (E10)	N/A	4	63	311	378
		HEV			3	48	236	287
		PHEV	Gasoline (E10) + Electricity	US avg.	6	52	78	136
				FRCC	8	68	78	154
				NPCC	4	38	78	121
				CA	3	26	78	107
		EV	Electricity	US avg.	7	51	0	58
				FRCC	10	73	0	84
				NPCC	5	31	0	36
				CA	2	15	0	17
		FCV	H_2-gaseous	NG-SMR	29	173	0	203
				NG-ATR w/CCS	0	0	0	0
				LT PEM Electrolysis	0	15	0	15
				HT-SOEC-Electrolysis	2	9	0	10
			H_2-liquid	NG-SMR	32	215	0	247
				LT PEM Electrolysis	0	44	0	44
				HT-SOEC-Electrolysis	2	3	0	5

Table A.8. LDV WTW GHG emissions breakdown in [gCO_2e/MJ]

Year	Vehicle types	Powertrains	Fuel selected	Variations in electricity grid and/or H2 path	Feedstock	Fuel	Vehicle Operation	WTW Total

2022	Cars	ICEV	Gasoline (E10)	N/A	1.3	15.6	73.0	89.9
		HEV			1.3	15.6	73.1	90.0
		PHEV	Gasoline (E10) + Electricity	US avg.	5.9	52.5	44.3	102.7
				MISO	6.6	68.9	44.3	119.8
				NPCC	5.8	35.8	44.3	85.8
				CA	5.1	34.9	44.3	84.3
		EV	Electricity	US avg.	15.3	128.3	0.0	143.6
				MISO	17.3	177.4	0.0	194.6
				NPCC	14.8	78.6	0.0	93.4
				CA	12.8	76.0	0.0	88.8
		FCV	H_2-gaseous	NG-SMR	12.2	79.9	0.0	92.1
			H_2-liquid		13.2	117.8	0.0	131.0
	SUVs	ICEV	Gasoline (E10)	N/A	1.3	15.6	73.1	90.0
		HEV			1.3	15.6	73.1	90.0
		PHEV	Gasoline (E10) + Electricity	US avg.	6.0	53.5	43.5	103.0
				MISO	6.7	70.4	43.5	120.6
				NPCC	5.9	36.4	43.5	85.7
				CA	5.2	35.5	43.5	84.2
		EV	Electricity	US avg.	15.3	128.3	0.0	143.6
				MISO	17.3	177.4	0.0	194.6
				NPCC	14.8	78.6	0.0	93.4
				CA	12.8	76.0	0.0	88.8
		FCV	H_2-gaseous	NG-SMR	12.2	79.9	0.0	92.1
			H_2-liquid		13.2	117.8	0.0	131.0
	PUTs	ICEV	Gasoline (E10)	N/A	1.3	15.6	73.0	89.9
		HEV			1.3	15.6	73.1	90.0
		PHEV	Gasoline (E10) + Electricity	US avg.	6.2	54.4	42.7	103.3
				MISO	6.8	71.8	42.7	121.3
				NPCC	6.0	36.9	42.7	85.6
				CA	5.3	36.0	42.7	84.0
		EV	Electricity	US avg.	15.3	128.3	0.0	143.6
				MISO	17.3	177.4	0.0	194.6
				NPCC	14.8	78.6	0.0	93.4
				CA	12.8	76.0	0.0	88.8
		FCV	H_2-gaseous	NG-SMR	12.2	79.9	0.0	92.1
			H_2-liquid		13.2	117.8	0.0	131.0
2035	Cars	ICEV	Gasoline (E10)	N/A	1.0	14.9	73.1	88.9
		HEV			1.0	14.9	73.1	88.9
		PHEV	Gasoline (E10) + Electricity	US avg.	3.2	29.0	43.3	75.5
				FRCC	4.9	36.9	43.3	85.1
				NPCC	3.0	21.0	43.3	67.2
				CA	2.4	18.9	43.3	64.6
		EV	Electricity	US avg.	7.5	58.2	0.0	65.7
				FRCC	12.5	80.9	0.0	93.5
				NPCC	6.9	35.2	0.0	42.1
				CA	5.2	29.1	0.0	34.3
		FCV	H_2-gaseous	NG-SMR	12.1	72.7	0.0	84.8
				NG-ATR w/CCS	0.0	0.0	0.0	0.0
				LT PEM Electrolysis	0.0	7.3	0.0	7.3
				HT-SOEC-Electrolysis	0.8	4.1	0.0	4.9
			H_2-liquid	NG-SMR	13.1	92.3	0.0	105.4
				LT PEM Electrolysis	0.0	21.6	0.0	21.6
				HT-SOEC-Electrolysis	0.8	1.3	0.0	2.1
	SUVs	ICEV	Gasoline (E10)	N/A	1.0	14.9	73.1	88.9

		HEV			1.0	14.9	73.2	89.0
		PHEV	Gasoline (E10) + Electricity	US avg.	3.2	29.4	42.5	75.1
				FRCC	5.0	37.5	42.5	85.0
				NPCC	3.0	21.2	42.5	66.7
				CA	2.4	19.0	42.5	63.9
		EV	Electricity	US avg.	7.5	58.2	0.0	65.7
				FRCC	12.5	80.9	0.0	93.5
				NPCC	6.9	35.2	0.0	42.1
				CA	5.2	29.1	0.0	34.3
		FCV	H_2-gaseous	NG-SMR	12.1	72.7	0.0	84.8
				NG-ATR w/CCS	0.0	0.0	0.0	0.0
				LT PEM Electrolysis	0.0	7.3	0.0	7.3
				HT-SOEC-Electrolysis	0.8	4.1	0.0	4.9
			H_2-liquid	NG-SMR	13.1	92.3	0.0	105.4
				LT PEM Electrolysis	0.0	21.6	0.0	21.6
				HT-SOEC-Electrolysis	0.8	1.3	0.0	2.1
	PUTs	ICEV	Gasoline (E10)	N/A	1.0	14.9	73.0	88.9
		HEV			1.0	14.9	73.1	88.9
		PHEV	Gasoline (E10) + Electricity	US avg.	3.3	29.7	41.8	74.8
				FRCC	5.1	38.0	41.8	84.9
				NPCC	3.0	21.3	41.8	66.2
				CA	2.4	19.1	41.8	63.4
		EV	Electricity	US avg.	7.5	58.2	0.0	65.7
				FRCC	12.5	80.9	0.0	93.5
				NPCC	6.9	35.2	0.0	42.1
				CA	5.2	29.1	0.0	34.3
		FCV	H_2-gaseous	NG-SMR	12.1	72.7	0.0	84.8
				NG-ATR w/CCS	0.0	0.0	0.0	0.0
				LT PEM Electrolysis	0.0	7.3	0.0	7.3
				HT-SOEC-Electrolysis	0.8	4.1	0.0	4.9
			H_2-liquid	NG-SMR	13.1	92.3	0.0	105.4
				LT PEM Electrolysis	0.0	21.6	0.0	21.6
				HT-SOEC-Electrolysis	0.8	1.3	0.0	2.1
2050	Cars	ICEV	Gasoline (E10)	N/A	0.9	14.8	73.1	88.8
		HEV			0.9	14.8	73.2	88.8
		PHEV	Gasoline (E10) + Electricity	US avg.	3.0	26.1	42.2	71.3
				FRCC	4.0	33.7	42.2	80.0
				NPCC	2.2	19.3	42.2	63.7
				CA	1.3	13.6	42.2	57.1
		EV	Electricity	US avg.	7.0	48.7	0.0	55.7
				FRCC	9.8	70.0	0.0	79.9
				NPCC	4.7	30.0	0.0	34.7
				CA	2.2	14.0	0.0	16.3
		FCV	H_2-gaseous	NG-SMR	12.1	71.6	0.0	83.7
				NG-ATR w/CCS	0.0	0.0	0.0	0.0
				LT PEM Electrolysis	0.0	6.2	0.0	6.2
				HT-SOEC-Electrolysis	0.8	3.6	0.0	4.3
			H_2-liquid	NG-SMR	13.1	89.0	0.0	102.1
				LT PEM Electrolysis	0.0	18.4	0.0	18.4
				HT-SOEC-Electrolysis	0.8	1.1	0.0	2.0
	SUVs	ICEV	Gasoline (E10)	N/A	0.9	14.8	73.2	88.8

		HEV			0.9	14.8	73.3	88.9
		PHEV	Gasoline (E10) + Electricity	US avg.	3.1	26.4	41.3	70.8
				FRCC	4.1	34.3	41.3	79.8
				NPCC	2.2	19.4	41.3	63.0
				CA	1.3	13.5	41.3	56.2
		EV	Electricity	US avg.	7.0	48.7	0.0	55.7
				FRCC	9.8	70.0	0.0	79.9
				NPCC	4.7	30.0	0.0	34.7
				CA	2.2	14.0	0.0	16.3
		FCV	H_2-gaseous	NG-SMR	12.1	71.6	0.0	83.7
				NG-ATR w/CCS	0.0	0.0	0.0	0.0
				LT PEM Electrolysis	0.0	6.2	0.0	6.2
				HT-SOEC-Electrolysis	0.8	3.6	0.0	4.3
			H_2-liquid	NG-SMR	13.1	89.0	0.0	102.1
				LT PEM Electrolysis	0.0	18.4	0.0	18.4
				HT-SOEC-Electrolysis	0.8	1.1	0.0	2.0
	PUTs	ICEV	Gasoline (E10)	N/A	0.9	14.8	73.1	88.7
		HEV			0.9	14.8	73.2	88.8
		PHEV	Gasoline (E10) + Electricity	US avg.	3.1	26.8	40.3	70.2
				FRCC	4.2	34.9	40.3	79.4
				NPCC	2.3	19.6	40.3	62.1
				CA	1.3	13.5	40.3	55.1
		EV	Electricity	US avg.	7.0	48.7	0.0	55.7
				FRCC	9.8	70.0	0.0	79.9
				NPCC	4.7	30.0	0.0	34.7
				CA	2.2	14.0	0.0	16.3
		FCV	H_2-gaseous	NG-SMR	12.1	71.6	0.0	83.7
				NG-ATR w/CCS	0.0	0.0	0.0	0.0
				LT PEM Electrolysis	0.0	6.2	0.0	6.2
				HT-SOEC-Electrolysis	0.8	3.6	0.0	4.3
			H_2-liquid	NG-SMR	13.1	89.0	0.0	102.1
				LT PEM Electrolysis	0.0	18.4	0.0	18.4
				HT-SOEC-Electrolysis	0.8	1.1	0.0	2.0

Table A.9. LDV vehicle cycle GHG emissions breakdown in [gCO_2e/mi]

		Powertrain	Body	Powertrain System (including BOP)	Transmission System	Chassis (w/o battery)	Traction Motor	Generator	Electronic Controller	Hydrogen Storage System	Vehicle assembly, disposal & recycling	Batteries	Fluids	Vehicle cycle total
2022	Passenger car	ICEV	13	4	2	8	0	0	0	0	5	0	4	37
		HEV	11	5	2	8	1	1	0	0	5	1	4	37
		PHEV	11	5	2	7	1	1	1	0	5	7	4	43
		EV	11	1	2	7	2	0	1	0	5	29	1	60
		FCV	11	4	1	8	1	0	1	11	5	1	1	44
	SUV	ICEV	12	4	2	10	0	0	0	0	5	0	6	40
		HEV	11	4	1	10	1	1	0	0	5	1	6	41
		PHEV	11	4	1	10	1	1	0	0	5	8	6	47

		EV	11	1	1	10	3	0	1	0	5	32	2	65
		FCV	9	4	1	11	1	0	1	13	5	1	2	48
	PUT	ICEV	17	5	3	15	0	0	0	0	6	0	6	52
		HEV	15	5	2	14	1	1	1	0	6	1	6	51
		PHEV	14	5	2	14	1	1	1	0	6	10	6	60
		EV	15	0	2	14	4	0	2	0	6	42	2	86
		FCV	15	6	1	13	2	0	1	15	6	1	2	62
2035	Passenger car	ICEV	11	4	2	7	0	0	0	0	4	0	4	32
		HEV	10	4	2	7	1	0	0	0	4	1	4	32
		PHEV	9	4	1	6	1	1	0	0	4	5	4	36
		EV	9	1	1	6	2	0	1	0	4	21	1	47
		FCV	10	3	1	7	1	0	1	8	4	1	1	36
	SUV	ICEV	11	3	2	9	0	0	0	0	3	0	6	35
		HEV	10	4	1	9	1	1	0	0	3	1	6	35
		PHEV	9	4	1	9	1	1	0	0	3	5	6	40
		EV	9	1	1	9	2	0	1	0	3	23	2	51
		FCV	8	3	1	10	1	0	1	9	3	1	2	39
	PUT	ICEV	15	5	2	13	0	0	0	0	4	0	6	45
		HEV	14	4	1	13	1	1	1	0	4	1	6	44
		PHEV	13	5	1	12	1	1	1	0	4	7	6	50
		EV	13	0	1	12	3	0	2	0	4	31	2	68
		FCV	13	4	1	12	1	0	1	11	4	1	2	50
2050	Passenger car	ICEV	11	4	2	7	0	0	0	0	3	0	4	31
		HEV	10	4	2	7	1	0	0	0	3	1	4	31
		PHEV	9	4	1	6	1	1	0	0	3	4	4	34
		EV	9	1	1	6	2	0	1	0	3	18	1	43
		FCV	10	3	1	7	1	0	1	7	3	1	1	34
	SUV	ICEV	11	3	2	9	0	0	0	0	3	0	6	35
		HEV	10	4	1	9	1	0	0	0	3	1	6	34
		PHEV	9	4	1	9	1	1	0	0	3	5	6	38
		EV	9	1	1	9	2	0	1	0	3	20	2	47
		FCV	8	3	1	10	1	0	1	9	3	1	2	37
	PUT	ICEV	15	5	2	13	0	0	0	0	3	0	6	45
		HEV	13	4	1	12	1	1	1	0	3	1	6	43
		PHEV	12	5	1	12	1	1	1	0	3	6	6	48
		EV	13	0	1	12	3	0	2	0	3	26	2	62
		FCV	13	4	1	12	1	0	1	10	3	1	2	48

Table A.10. LDV vehicle cycle GHG emissions breakdown in [gCO_2e/vehicle lifetime]

		Powertrain	Body	Powertrain System (including BOP)	Transmission System	Chassis (w/o battery)	Traction Motor	Generator	Electronic Controller	Hydrogen Storage System	Vehicle assembly, disposal & recycling	Batteries	Fluids	Vehicle cycle total
2022	Passenger car	ICEV	2,177,981	726,454	371,281	1,407,154					926,130	35,140	759,267	6,403,409
		HEV	1,964,656	796,258	307,384	1,305,389	113,342	100,944	84,760		926,130	154,109	693,396	6,446,370
		PHEV	1,852,749	844,061	289,657	1,252,005	173,109	153,024	86,970		926,130	1,220,132	693,396	7,491,234
		EV	1,865,321	178,940	291,067	1,258,002	423,395	0	242,590		926,130	5,103,817	180,865	10,470,128
		FCV	1,989,988	630,909	165,306	1,340,976	216,262		170,160	1,844,528	926,130	210,092	180,865	7,675,218
	SUV	ICEV	2,258,164	719,337	358,191	1,910,318					935,999	52,222	1,137,718	7,371,949
		HEV	2,094,859	758,142	264,414	1,825,418	128,374	114,166	89,352		935,999	168,221	1,051,337	7,430,281
		PHEV	1,977,496	805,096	249,600	1,764,402	191,388	169,353	90,459		935,999	1,458,796	1,051,337	8,693,925
		EV	1,967,571	118,170	248,347	1,759,243	481,823	0	254,717		935,999	5,906,439	310,902	11,983,210
		FCV	1,698,501	682,628	180,534	2,080,033	242,334		191,736	2,319,051	935,999	186,759	310,902	8,828,475
	PUT	ICEV	3,065,149	962,679	462,242	2,765,402					1,008,737	52,222	1,137,718	9,454,149

		HEV	2,818,874	927,638	299,068	2,602,373	171,860	152,188	117,158		1,008,737	195,194	1,051,337	9,344,425
		PHEV	2,634,533	995,672	279,511	2,480,342	269,306	238,496	119,292		1,008,737	1,912,257	1,051,337	10,989,482
		EV	2,718,524	90,018	288,422	2,535,943	688,807	0	348,919		1,008,737	7,787,313	310,902	15,777,584
		FCV	2,783,912	1,023,243	236,956	2,438,732	313,053		252,149	2,725,144	1,008,737	224,107	310,902	11,316,933
2035	Passenger car	ICEV	1,904,805	634,142	342,554	1,260,451					634,186	30,578	743,599	5,550,316
		HEV	1,711,423	693,680	267,903	1,167,237	98,360	83,281	71,603		634,186	122,277	678,441	5,528,391
		PHEV	1,612,675	733,863	252,255	1,119,638	150,980	126,149	72,121		634,186	832,071	678,441	6,212,379
		EV	1,621,386	148,153	253,135	1,123,837	368,998	0	200,238		634,186	3,700,180	172,025	8,222,138
		FCV	1,713,438	497,172	142,708	1,190,440	186,970		139,598	1,309,597	634,186	167,497	172,025	6,153,631
	SUV	ICEV	1,985,704	631,373	332,661	1,732,632					639,251	45,443	1,114,607	6,481,671
		HEV	1,822,868	660,704	230,467	1,646,689	111,480	94,196	75,442		639,251	144,937	1,029,161	6,455,194
		PHEV	1,718,322	699,708	217,249	1,591,511	166,824	139,533	74,913		639,251	995,874	1,029,161	7,272,343
		EV	1,708,389	97,637	215,993	1,586,268	420,342	0	210,001		639,251	4,209,614	297,632	9,385,128
		FCV	1,458,056	535,607	155,729	1,859,337	209,509		157,032	1,646,504	639,251	149,832	297,632	7,108,489
	PUT	ICEV	2,714,876	835,361	423,727	2,456,773					670,762	45,443	1,114,607	8,261,550
		HEV	2,499,105	807,064	260,252	2,315,925	149,323	125,364	98,459		670,762	178,191	1,029,161	8,133,607
		PHEV	2,334,090	864,365	243,068	2,208,209	235,304	196,327	98,267		670,762	1,305,113	1,029,161	9,184,666
		EV	2,408,246	74,194	250,790	2,256,616	602,391	0	286,852		670,762	5,631,317	297,632	12,478,800
		FCV	2,437,423	803,846	204,164	2,158,168	271,208		205,466	1,934,826	670,762	205,997	297,632	9,189,493
2050	Passenger car	ICEV	1,875,449	624,189	339,877	1,244,336					597,084	29,985	741,078	5,451,998
		HEV	1,674,733	678,842	262,191	1,147,434	96,190	80,826	69,742		597,084	119,057	676,064	5,402,162
		PHEV	1,578,047	718,013	246,868	1,100,755	147,771	122,425	70,050		597,084	695,302	676,064	5,952,378
		EV	1,585,235	143,774	247,521	1,104,225	360,885	0	194,225		597,084	3,064,213	170,835	7,467,997
		FCV	1,667,893	473,423	138,948	1,165,905	182,062		134,855	1,240,380	597,084	172,358	170,835	5,943,743
	SUV	ICEV	1,946,658	618,772	328,692	1,707,548					601,067	44,561	1,110,906	6,358,205
		HEV	1,782,701	646,315	225,454	1,620,818	108,983	91,378	73,442		601,067	141,191	1,025,648	6,316,997
		PHEV	1,680,385	684,310	212,515	1,566,695	163,204	135,353	72,720		601,067	833,202	1,025,648	6,975,099
		EV	1,670,426	94,743	211,255	1,561,426	411,261	0	203,706		601,067	3,589,961	295,845	8,639,690
		FCV	1,417,797	508,965	151,537	1,823,165	203,914		151,586	1,559,480	601,067	146,049	295,845	6,859,404
	PUT	ICEV	2,719,922	834,409	426,597	2,449,814					629,644	44,561	1,110,906	8,215,854
		HEV	2,451,843	789,662	254,649	2,275,162	146,057	121,642	95,826		629,644	177,156	1,025,648	7,967,289
		PHEV	2,288,681	845,074	237,703	2,168,863	230,244	190,391	95,297		629,644	1,088,178	1,025,648	8,799,724
		EV	2,362,398	71,989	245,359	2,216,889	589,778	0	278,219		629,644	4,735,040	295,845	11,425,162
		FCV	2,378,526	763,219	198,622	2,112,405	264,027		198,173	1,832,563	629,644	205,024	295,845	8,878,048

Table A.11. Summary of CI and grid mixes of electricity grids used for simulation

Year	Grid name	CI [gCO_2e/kWh]	Grid mix	Share [%]	Year	Grid name	CI [gCO_2e/kWh]	Grid mix	Share [%]	Year	Grid name	CI [gCO_2e/kWh]	Grid mix	Share [%]
2022	US avg.	440	Residual oil	0.3%	2035	US avg.	201	Residual oil	0.2%	2050	US avg.	170	Residual oil	0.1%
			Natural gas	38.5%				Natural gas	20.6%				Natural gas	21.0%
			Coal	20.6%				Coal	7.9%				Coal	5.0%
			Nuclear	18.9%				Nuclear	15.9%				Nuclear	12.6%
			Biomass	0.3%				Biomass	0.2%				Biomass	0.2%
			Hydro	6.8%				Hydro	6.3%				Hydro	4.9%
			Geothermal	0.4%				Geothermal	0.5%				Geothermal	0.7%
			Wind	10.7%				Wind	23.8%				Wind	22.7%
			Solar PV	3.3%				Solar PV	22.1%				Solar PV	30.0%
			Others	0.4%				Others	2.4%				Others	2.7%
	MISO	596	Residual oil	0.2%		FRCC	286	Residual oil	0.1%		PJM	244	Residual oil	0.0%
			Natural gas	30.9%				Natural gas	42.2%				Natural gas	28.9%
			Coal	36.6%				Coal	6.2%				Coal	7.9%
			Nuclear	14.2%				Nuclear	11.4%				Nuclear	24.6%
			Biomass	0.2%				Biomass	0.2%				Biomass	0.0%
			Hydro	1.4%				Hydro	0.3%				Hydro	0.9%
			Geothermal	0.0%				Geothermal	0.0%				Geothermal	0.0%
			Wind	15.3%				Wind	0.0%				Wind	14.2%
			Solar PV	0.9%				Solar PV	38.9%				Solar PV	18.2%
			Others	0.3%				Others	0.8%				Others	5.2%
	NPCC	286	Residual oil	0.2%		NPCC	129	Residual oil	0.0%		WECC	106	Residual oil	0.1%
			Natural gas	50.5%				Natural gas	23.4%				Natural gas	15.1%
			Coal	0.7%				Coal	0.0%				Coal	1.7%
			Nuclear	23.6%				Nuclear	21.8%				Nuclear	3.2%
			Biomass	1.1%				Biomass	1.1%				Biomass	0.4%
			Hydro	16.0%				Hydro	15.7%				Hydro	17.3%
			Geothermal	0.0%				Geothermal	0.0%				Geothermal	3.8%
			Wind	4.0%				Wind	18.9%				Wind	26.0%
			Solar PV	2.0%				Solar PV	4.7%				Solar PV	30.9%
			Others	1.9%				Others	14.4%				Others	1.6%
	CA grid	272	Residual oil	0.0%		CA grid	105	Residual oil	0.0%		CA grid	50	Residual oil	0.0%
			Natural gas	42.8%				Natural gas	18.3%				Natural gas	7.8%
			Coal	3.4%				Coal	0.0%				Coal	0.0%
			Nuclear	8.3%				Nuclear	0.0%				Nuclear	0.0%
			Biomass	0.9%				Biomass	1.0%				Biomass	0.8%
			Hydro	12.5%				Hydro	10.7%				Hydro	6.5%

			Geothermal	3.8%				Geothermal	6.8%				Geothermal	8.1%
			Wind	7.4%				Wind	5.8%				Wind	5.9%
			Solar PV	20.3%				Solar PV	56.3%				Solar PV	69.5%
			Others	0.7%				Others	1.1%				Others	1.4%

Table A.12. Summary of CI for different hydrogen pathways

Year	Hydrogen phase	Production pathway	CI [kgCO_2e/kg-H_2]	Year	Hydrogen phase	Production pathway	CI [kgCO_2e/kg-H_2]	Year	Hydrogen phase	Production pathway	CI [kgCO_2e/kg-H_2]
2022	H_2-gaseous	NG-SMR	11.1	2035	H_2-gaseous	NG-SMR	10.2	2050	H_2-gaseous	NG-SMR	10.1
						NG-ATR w/CCS	3.6			NG-ATR w/CCS	3.4
						LT-PEM electrolysis	0.9			LT-PEM electrolysis	0.8
	H_2-liquid	NG-SMR	15.7			HT-SOEC electrolysis	0.6			HT-SOEC electrolysis	0.5
					H_2-liquid	NG-SMR	12.6		H_2-liquid	NG-SMR	12.3
						LT-PEM electrolysis	2.6			LT-PEM electrolysis	2.2
						HT-SOEC electrolysis	0.3			HT-SOEC electrolysis	0.2