Program Record (Vehicle Technologies Office)		
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Title: Details for the Light Duty Vehicle Greenhouse Gas Life Cycle Assessment Fact Sheet: R&D GREET 2023		
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Item

This program record documents the technical details of the "R&D GREET 2023 Annual Update" fact sheet (henceforth referred to as "fact sheet") [1]. It describes the life cycle inventory (LCI), system boundaries, and other important assumptions used for the life cycle analysis (LCA) shown as three use examples of the R&D GREET 2023 in the fact sheet.

Introduction

This program record provides the technical details of the analyses results presented in the R&D GREET 2023 Annual Update fact sheet (henceforth referred to as "fact sheet") [1]. In the fact sheet, three examples are presented using the R&D GREET 2023 [2] to quantify and compare the greenhouse gas (GHG) emissions from different light-duty transportation systems on a system-to-system and year-to-year basis. Those examples include comparisons between the life cycle GHG emissions of 1) a gasoline-based internal combustion engine vehicle (ICEV) and a full electric vehicle (EV) using the United States (US) average grid mix on a per vehicle mile traveled (i.e., gCO_2e/mile) basis; 2) gasoline and US average grid electricity for current (2024) and future (2050) years on a per MJ delivered basis; and 3) a gasoline-based ICEV and an EV using the US average grid mix over time (2024-2050) on a per vehicle mile traveled (i.e., gCO_2e/mile) basis. This program record provides more technical details of the fact sheet including the 1) simulation parameter settings and background; 2) definitions of terms, assumptions, and system boundaries used for the LCA; and 3) results and discussion for those exemplary analyses.

In addition to the R&D GREET 2023 examples, the R&D GREET web page that accompanies the fact sheet [3] also provides a summary and articulates the value of LCA in general. LCA has been used for governmental policy development, incentive designs, and research and development decisions for transportation fuels and vehicle technologies in different pieces of legislation, regulations, and governmental agencies in the US. The LCA framework has also been widely

[1] R&D GREET 2023 Annual Update- Light Duty Vehicles; DOE/EE-2856; US Department of Energy: Washington, D.C.; July 2024. https://www.energy.gov/sites/default/files/2024-07/eere-greet-fact-sheet_july-2024.pdf

[2] GREET: Greenhouse Gases, Regulated Emissions, and Energy use in Technologies Model ® (2023 Excel), 2023. Argonne National Laboratory. doi:10.11578/GREET-Excel-2023/dc.20230907.1. http://greet.anl.gov (accessed on 6/21/2024).

[3] The United States Department of Energy website, https://www.energy.gov/eere/rd-greet-model (accessed on 7/30/2024).

leveraged by energy suppliers, automakers, and other stakeholders in the light-duty on-road transportation space to rigorously identify steps that they can take towards more sustainable production, use, and disposal of vehicle and fuel systems. The use cases of LCA in the private sector include corporate GHG emissions accounting (e.g., GHG Protocol [4], please see Appendix B for more details of R&D GREET's capability on corporate GHG accounting) and reporting to global and regional regulatory bodies [e.g., Climate Disclosure Project (CDP) [5], Corporate Sustainability Reporting Directive (CSRD) [6], Securities and Exchange Commission (SEC) [7], etc.], corporate climate goal settings [i.e., Science Based Target Initiative (SBTi) net-zero target setting and voluntary compliance] [8], and carbon credit project developments. The fact sheet [1] provides a general overview of the value of LCA while providing several technical use cases of the R&D GREET 2023 tool [2].

1 R&D GREET simulation parameters used for the fact sheet

For all three examples shown in the fact sheet, the model year (MY) of the model vehicle is set to be the same as the simulation year (SY) that determined the temporal context of the fuel production technology – meaning the simulation reflects a vehicle produced in a given year using a fuel produced in that same year. Thus, for current year simulations, both SY and MY are set as 2024. There were two different future year simulations: i) near-term future year where both SY and MY are set as 2035; and ii) long-term future year where both SY and MY are set as 2050. A sport utility vehicle (SUV) is selected as the model vehicle type representing light-duty vehicles (LDVs) in this context. The selection of SUV as the model LDV is based on the vehicle type market share published by the Environmental Protection Agency (EPA) Automotive Trends Report [9]: SUVs currently account for the greatest market share (58%, sum of car and truck SUVs) out of all LDV categories, including sedan/wagon, SUVs, minivan/van and pickup trucks.

For important vehicle parameters such as life-time vehicle miles traveled (VMT), fuel economy, vehicle weights, and battery capacity, the default settings implemented in R&D GREET 2023 [2] are used (see **Table 1**). R&D GREET 2023 [2] sources the time-dependent vehicle parameters mentioned above from Argonne National Laboratory's (ANL) Autonomie model [10]. The fuel economy assumptions are: 26.5, 32.3, and 37.7 miles per gasoline gallon equivalent (MPGGE), respectively, for MY 2024, 2035, and 2050 gasoline-based ICEVs and 114, 137, and 151 MPGGE,

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[4] Bhatia, P.; Cummis, C.; Brown, A.; Draucker, L.; Rich, D.; Lahd, H. *Product Life Cycle Accounting and Reporting Standard*; Greenhouse Gas Protocol, 2011.

[5] Climate Disclosure Project (CDP) website, https://www.cdp.net/en (accessed on 6/21/2024).

[6] EU Commission website on CSRD, https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en (accessed on 6/21/2024).

[7] SEC website, https://www.sec.gov/news/press-release/2024-31 (accessed on 6/21/2024).

[8] *SBTi Corporate Net-Zero Standard*; Science Based Target Initiative (SBTi): London, UK; March 2024.

[9] *The 2022 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975*; EPA-420-S-22-001; United States Environmental Protection Agency (EPA): Washington, D.C.; December 2022.

[10] Islam, E.S.; Prada, D.N.; Vijayagopal, R.; Mansour, C.; Phillips, P.; Kim, N.; Alhajjar, M.; Rousseau, A. *Detailed Simulation Study to Evaluate Future Transportation Decarbonization Potential*; ANL/TAPS-23/3; Argonne National Laboratory: Lemont, IL; October 2023.

respectively, for MY 2024, 2035, and 2050 EVs [2]. It is assumed that all SUVs, regardless of their powertrain and fuel pathway options, drive 183,363 miles throughout their lifetime. **Table 1** summarizes the LDV powertrain and fuel options presented in the fact sheet.

Table 1. Summary of the light-duty on-road vehicle and fuel pathways presented in the fact sheet

Model vehicle type	SY/MY	Powertrain	Fuel economy [MPGGE]	Fuel type	Fuel production pathway	Vehicle weight [kg]	Battery Energy [kWh]
Small SUVs	2024	ICEV	26.5	Gasoline (E10)	Petroleum gasoline with 10% corn ethanol	1,554	-
		EV300	114	Electricity	US average grid mix (2022) using R&D GREET2023 baseline	1,844	90
	2035	ICEV	32.3	Gasoline (E10)	Petroleum gasoline with 10% corn ethanol	1,546	-
		EV300	137	Electricity	US average grid mix (2035) using NREL MidCase from 2023 Standard Scenario	1,733	75
	2050	ICEV	37.7	Gasoline (E10)	Petroleum gasoline with 10% corn ethanol	1,542	-
		EV300	151	Electricity	US average grid mix (2050) using NREL MidCase from 2023 Standard Scenario	1678	66

For EVs, the default R&D GREET 2023 setting for all-electric range (AER) of 300 miles is used for vehicle parameter settings [2]. This 300-mile AER is the average AER for EVs based on simulations conducted using Autonomie [10]. The battery chemistry of MY 2024 EVs is assumed to be lithium-ion (Li-ion) nickel-manganese-cobalt (NMC) 811 (80% nickel, 10% manganese, and 10% cobalt) while NMC 95 (95% nickel, 2.5% manganese, and 2.5% cobalt) is assumed for the EVs in MY 2035 and MY 2050. For all simulation parameters not mentioned herein, the default settings in the R&D GREET 2023 model [2] are used.

ICEVs are assumed to use the blend of 10 vol. % corn-ethanol with petroleum gasoline blendstock (i.e., E10), while EVs are assumed to be charged by the US average grid. The current year US average grid generation mix is based on the Energy Information Administration (EIA)'s Annual

Energy Outlook (AEO) 2023 report [11], and the 2035 and 2050 US average grid generation mixes are based on the National Renewable Energy Laboratory (NREL) MidCase scenario in the 2023 Standard Scenario [12].

2 Terms, assumptions, and system boundary definitions used for the fact sheet

Figure 1 shows the system boundary for the life cycle (also known as the “cradle to grave” or C2G) presented in the fact sheet [1]. The life cycle includes the following processes:

i) Fuel production (also known as the “well-to-pump”) including the primary energy or feedstock production and transportation, conversion of the primary energy or feedstock to fuel, and the transportation and distribution of fuels to end users;

ii) Fuel use (also known as the “pump-to-wheels”) in vehicles;

iii) Facility construction for fuel production (also known as the “facility-cycle”) including the acquisition of raw materials, production of components and its assemblies required for fuel production facilities such as power generation plants, solar panels, wind turbines, battery storage facilities, etc.; and

iv) Vehicle production and disposal (also known as the “vehicle-cycle") including the acquisition of raw materials, manufacturing and assembly of vehicle components and the end-of-life treatment for vehicle disposal.

Each of these processes is clearly labeled in Figure 4 to Figure 5 as: i) “Construction: fuel production facility” for facility-cycle impacts; ii) “Production: Vehicle” for vehicle manufacturing impact less battery production; iii) “Production: Battery” for battery manufacturing impact; iv) “Production: Fuel” for well-to-pump impact; v) Use: Vehicle Operation” for pump-to-wheels or use-stage of fuel impact; and vi) “End-of-life: Vehicle & Battery Disposal” for disposal impact of vehicle.

The impacts of infrastructure and facilities required for vehicle use (e.g., fuel stations, EV chargers) and manufacturing (e.g., vehicle manufacturing plants) are not included in the system boundary. This is because their impact is likely even smaller than infrastructure for fuel production facilities, which already only represent <5% of full life cycle GHG emissions per VMT.

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[11] *Annual Energy Outlook: AEO 2023*; US Energy Information Administration (EIA): Washington, D.C.; March 2023.

[12] Gagnon, P.; Pham, A.; Cole, W. *2023 Standard Scenarios Report: A US Electricity Sector Outlook*; NREL/TP-6A40-87724; National Renewable Energy Laboratory: Golden, CO; January 2024.

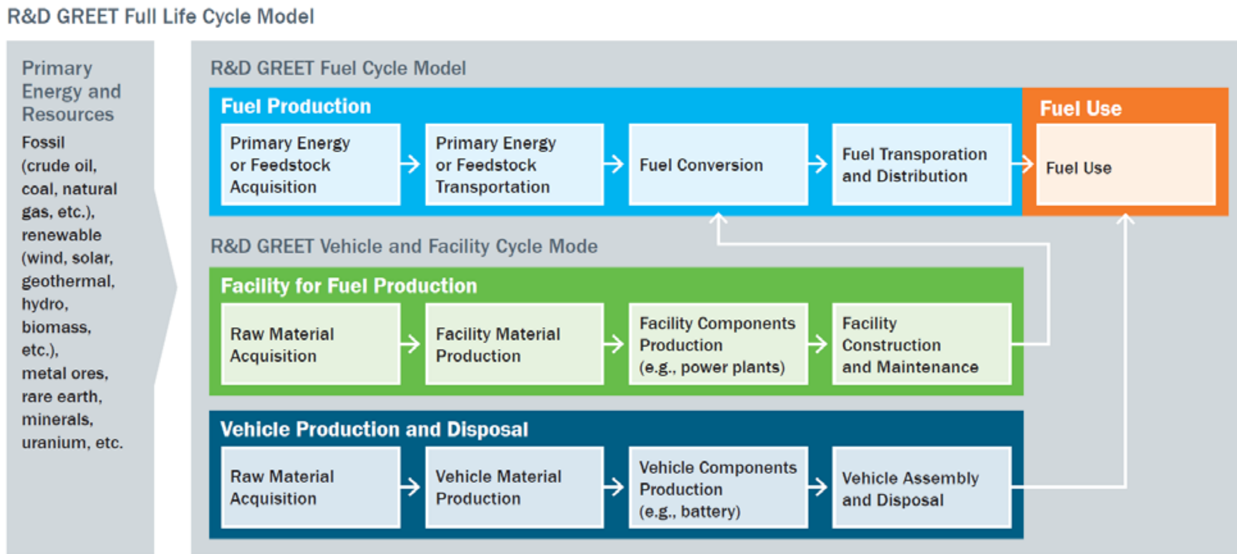

Figure 1. System boundary and the processes covered in full life cycle, or C2G LCA.

Figure 2 depicts the system boundary and its included processes for the R&D GREET fuel cycle model (see Figure 1). The fuel cycle includes both fuel production (i.e., well-to-pump) and fuel use in vehicle (i.e., pump-to-wheels) processes, but does not include the impacts from vehicle production and disposal or facility construction for fuel production. A fuel-cycle analysis (also known as well-to-wheels) can help assess GHG emissions for different vehicles and fuel options when the datasets required to address the embodied impacts of vehicles and facilities are not available.

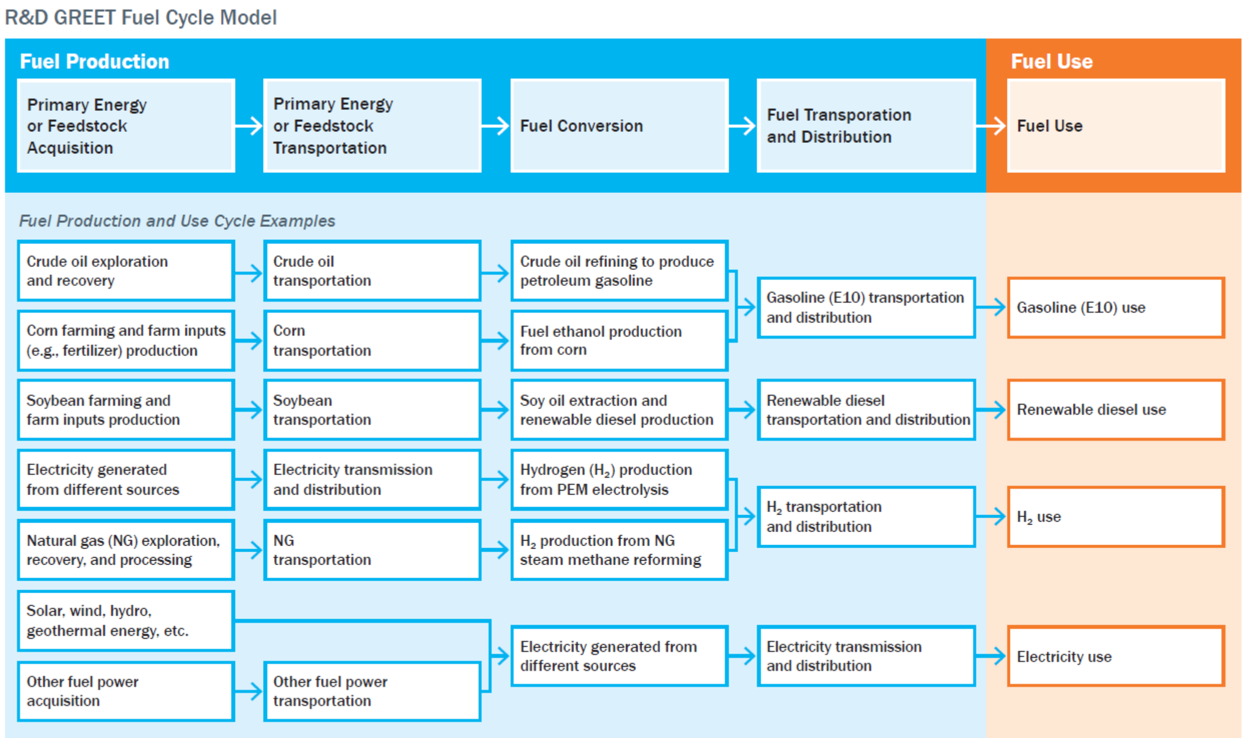

Figure 2. System boundary and included processes for fuel production and fuel use. Examples are shown indicating how the same system boundaries apply to different fuels.

The vehicle production and disposal and facility construction for fuel are simulated in the R&D GREET vehicle and facility cycle model (see Figure 1). It calculates the energy and environmental impacts associated with producing and disposing vehicles and constructing and maintaining facilities that produce transportation fuels. As shown in Figure 3, both vehicle production and facility construction include raw material acquisition, material production, components production, and related transportation logistics. The vehicle production and disposal further involve vehicle assembly from components, as well as vehicle end-of-life disposal and related materials' recycling processes. For the facility for fuel production, it further includes the facility construction and the maintenance of related facilities.

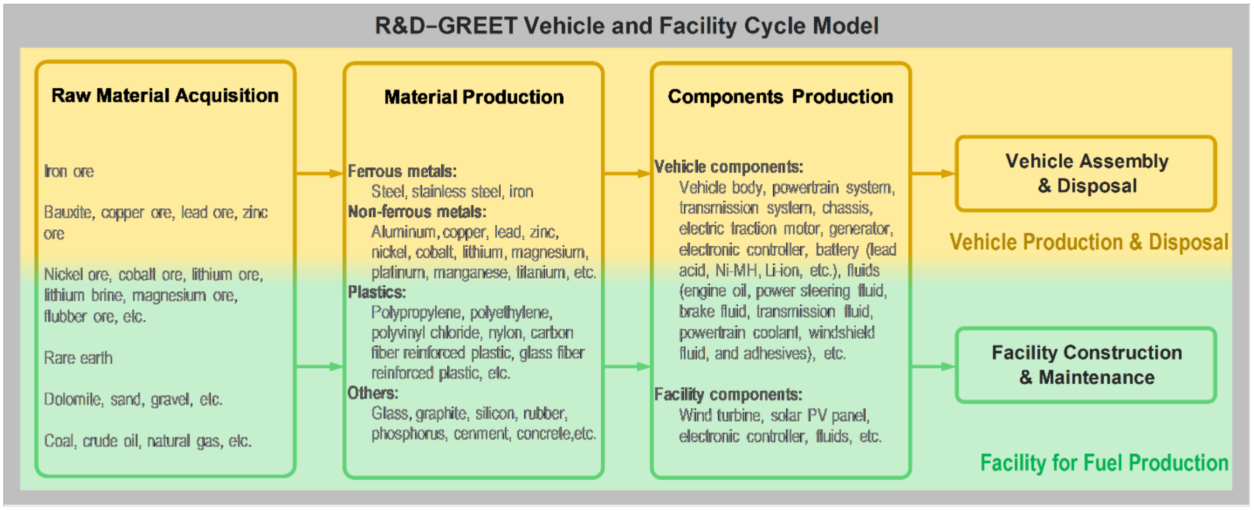

Figure 3. **System boundary and included processes for vehicle production & disposal and facility for fuel production. Details of the materials and processes constituting the vehicle production & disposal and facility cycle are shown to provide the list of covered materials and processes.**

3 Results and discussion for the examples presented in the fact sheet

In this section, a summary of the LCA results presented in the fact sheet [1] is provided. Figure 4 presents the life cycle GHG emissions reduction potential of an SUV EV compared to an SUV ICEV for MY 2024. An average SUV EV is expected to reduce life cycle GHG emissions by 52% compared to an average SUV ICEV in the current year (2024). The major contributor of GHG emissions from the ICEV is from fuel use (i.e., the combustion of gasoline during vehicle operation), which accounts for 73% of its life cycle GHG emissions. In contrast, EVs have zero GHG emissions from their use stage. Although the GHG emissions from fuel and battery production are greater for EVs than ICEVs, this is more than offset by the GHG emissions reduction during the EVs' use. The result mentioned above is consistent with our recent C2G analysis on LDV's GHG emissions [13].

[13] Kelly, J.C.; Kim, T.; Kolodziej, C.P.; Iyer, R.K.; Tripathi, S.; Elgowainy, A.; Wang, M. Comprehensive Cradle-to-Grave Life Cycle Analysis of On-Road Vehicles in the United States Based on GREET; *SAE 2024-01-2830*.

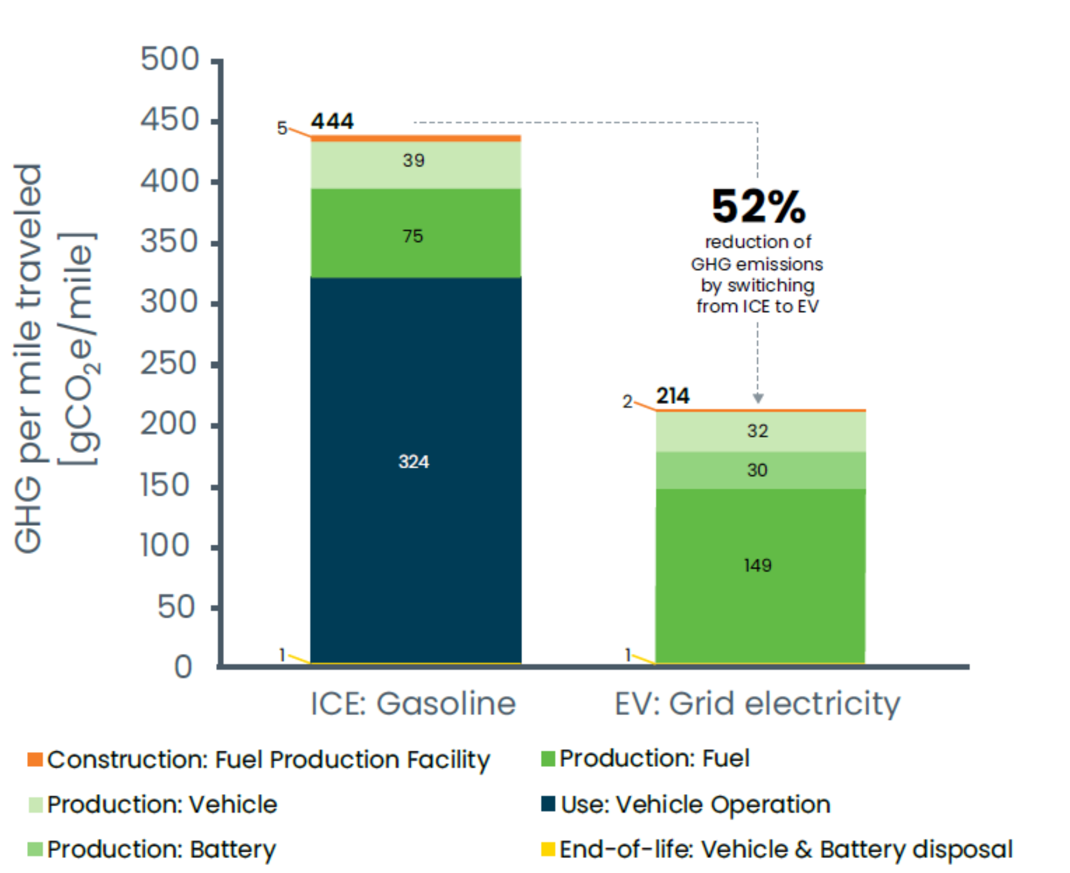

Figure 4. Comparison of the life cycle GHG emissions from ICEV (gasoline) and from EV (US average grid electricity) for MY 2024 SUV.

It is important to note, however, that the presented results for the EV can depend significantly on simulation parameter selection (e.g., the choice of electricity grid, AER, and battery chemistry). For example, the fuel production stage GHG emissions can depend greatly on the region where the EV is charged since there are significant differences in the carbon intensity (CI) of grid electricity across the US. It is recommended to internalize the results shown in Figure 4 as a comparison between EVs and ICEVs in the US *on average*, not as definitive values that are true for all regions and models of EVs on the road. For the current year simulation, the life cycle GHG emissions of an SUV EV in the US can increase or decrease by 25% depending on the North American Electricity Reliability Corporation (NERC) region selected [13].

Between 2024 and 2050 the life cycle GHG emissions of gasoline are calculated to only be reduced by 1%, while those of grid electricity are expected to decrease by 77% on a per MJ basis [14]. The primary reason for this dramatic decrease for grid electricity is the increased deployment of low-carbon (renewable and nuclear) power generation in the US. Using this data, we can expand on Figure 4 by projecting the life cycle GHG emissions for ICEVs and EVs into the future.

[14] Please refer to Appendix A for more details on grid generation mix projections used in this analysis.

Figure 5 presents the life cycle GHG emissions reduction potential between 2024 and 2050 for ICEV and EV using gasoline and grid electricity, respectively. Although the ICEV is expected to reduce its life cycle emissions by a moderate degree over time (28.4% reduction between 2024 and 2050, mainly due to improvements in fuel economy), the EV's GHG emissions reduction potential is expected to be significantly greater (66% reduction from 2024 to 2050, due to renewable electricity deployment). This result is consistent with a previous analysis [13]. Figure 5 also provides the projected electricity grid generation mix between 2024 and 2050, which shows about 85% of US power generation will be renewable or nuclear.

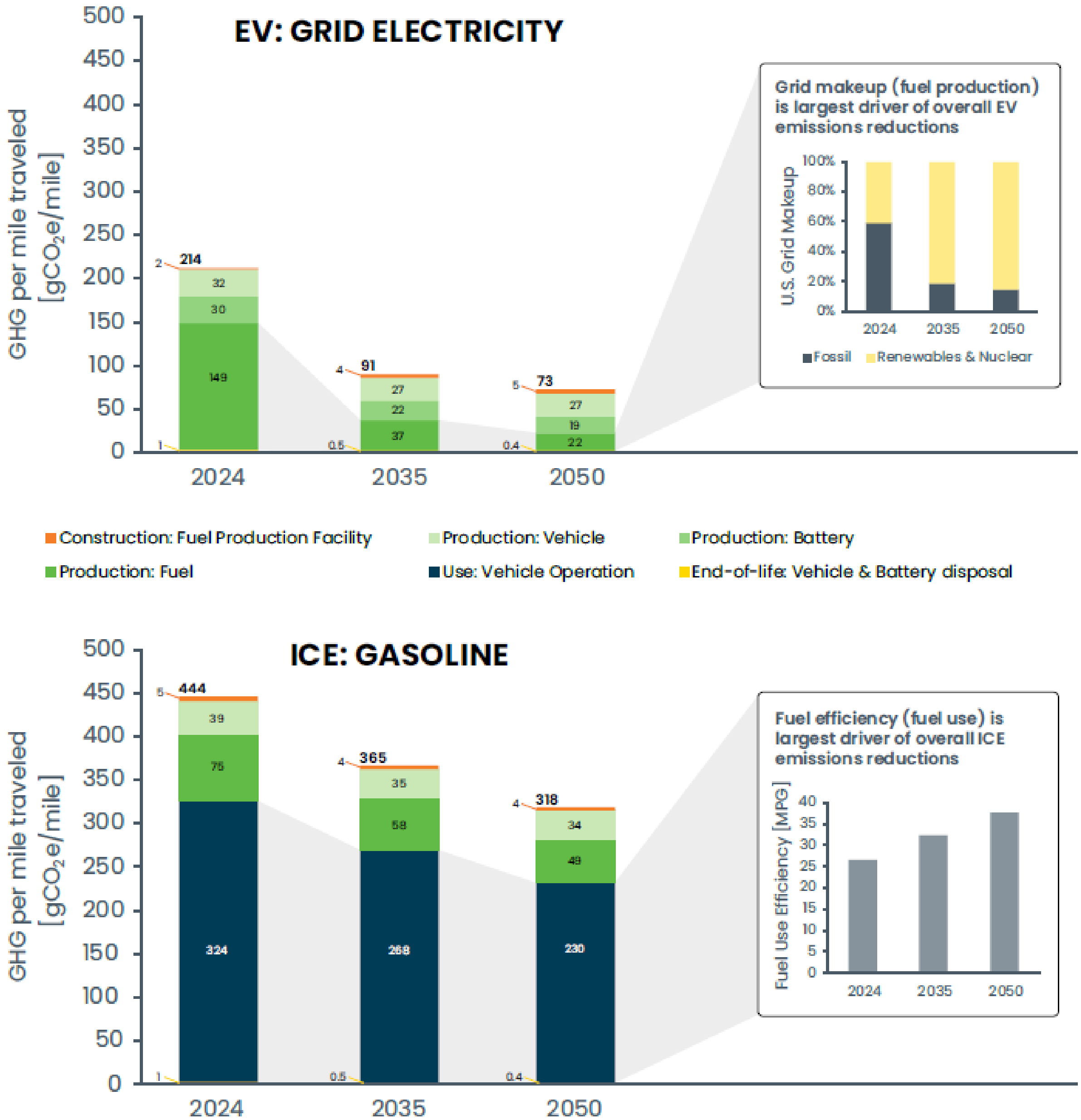

Figure 5. Projections of life cycle GHG emissions per mile from 2024 to 2050 for ICEV (gasoline) and EV (US average grid electricity)

Appendix A. Key assumptions for the electricity generation mixes

For the LCA conducted for the fact sheet [1] and for this program record, different electricity generation mixes are assumed for different timelines. For the US average grid mix representing the 2024 SY, the default settings in the R&D GREET 2023 model [2] based on EIA's AEO [11] are used. For the US average grid mix representing 2035 and 2050, the generation mix projections published in NREL's 2023 Standard Scenario [12] for MidCase are used. **Table 3** shows the assumed generation mixes for each scenario.

Table 2. Electricity grid mixes used for the LCA presented in the fact sheet

	US average grid mix in 2022 [2,11]	US average grid mix in 2035 [12]	US average grid mix in 2050 [12]
Fuel cycle (excluding facility impact) CI [gCO_2e/kWh]	440	130	86
Full life cycle (including facility impact) [gCO_2e/kWh]	443	143	102
Oil	0.3%	0.5%	0.1%
NG	38.5%	14.0%	14.1%
Coal	20.6%	4.3%	0.8%
Nuclear	18.9%	13.0%	7.7%
Biomass	0.3%	0.3%	0.2%
Hydro	6.8%	6.4%	4.7%
Geothermal	0.4%	0.9%	0.8%
Wind	10.7%	38.5%	36.5%
Solar	3.3%	19.5%	27.7%
Others	0.4%	2.6%	7.3%

Appendix B. R&D GREET coverages for enterprise scope GHG emissions

Enterprise scope emissions, often referred to as Scope 1, Scope 2, and Scope 3 emissions, are designed in the context of corporate and organizational GHG emissions accounting. Developed by the World Resource Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), these scope emission categories are defined by the Greenhouse Gas Protocol and are intended to help individual organizations measure and report their total emissions along their supply and value chains. Figure 7 illustrates the definitions and coverages of individual scope emissions. Scope 1 emissions represent all direct emissions from sources that are within the operational control of the reporting organization. They typically include emissions from on-site fuel combustion in stationary and mobile sources, industrial and manufacturing processes, and fugitive emissions. Scope 2 emissions are indirect emissions associated with the consumption of purchased or acquired energy from energy suppliers. These emissions result from the generation of electricity, heat, steam, and cooling purchased by the reporting organization. Scope 3 emissions are a broader category that includes all other indirect emissions that occur in the supply and value chains of the reporting organization. These emissions can be quite extensive and diverse, encompassing emissions related to the upstream activities such as production of raw materials, transportation, employee commuting, business travel, etc., and downstream activities such as the transportation, processing, use, and end-of-life treatment of products sold by the organization, etc.

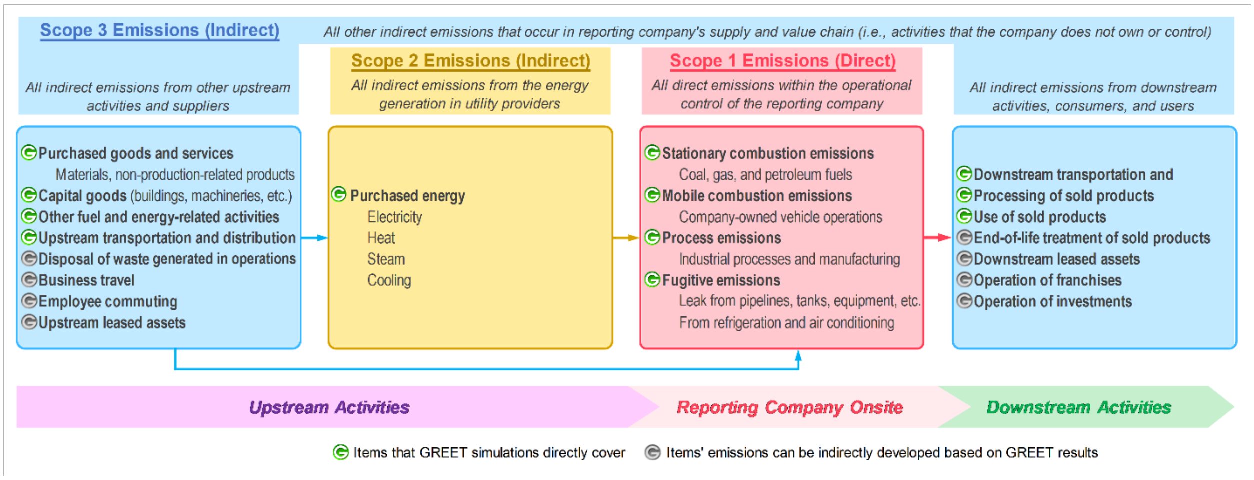

Figure 5. The definitions and R&D GREET coverages of enterprise Scope 1, Scope 2, and Scope 3 emissions.

Different from enterprise scope emissions that are designed for individual organizations in their GHG emission reporting, the R&D GREET model is designed to address life cycle energy use and environmental impacts of individual products, vehicle technologies, and fuel/energy production pathways. Figure 7 also briefly illustrates the R&D GREET coverage in the context of the enterprise scope emissions. In summary, R&D GREET directly includes simulations of all Scope 1 and Scope 2 emissions, and a portion of Scope 3 emissions. For Scope 3 emissions that are not directly simulated by R&D GREET, such as business travel, employee commuting, leased assets, etc., R&D GREET's results can be used indirectly to develop them to some extent. For example, R&D GREET includes LCA emission results of different transportation modes and they can be used to develop emissions of business travel and employee commuting; R&D GREET's buildings LCA module can be used to develop emissions embodied in buildings to address emissions of enterprises' leased assets.