RESEARCH BRIEF

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Life-cycle greenhouse gas emissions of U.S. sedans and SUVs with different powertrains and fuel sources

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The ability of battery electric vehicles (BEVs) to greatly reduce energy consumption and emissions is among the factors driving widespread government interest in them in the United States and globally. While these vehicles emit no pollution during operation, a detailed assessment of their life-cycle emissions is critical for understanding their net greenhouse gas (GHG) advantages relative to other technologies. This brief updates a 2021 analysis by the International Council on Clean Transportation (ICCT) that estimated the life-cycle emissions of passenger vehicles, including sedans and sport utility vehicles (SUVs), in major global vehicle markets.[1] In this brief, we focus on the United States and expand the analysis to include "strong" hybrid electric vehicles that can temporarily power a vehicle without the engine; these have increased to more than 5% of new light-duty vehicle sales in the United States since 2021.[2] This work considers model year 2024 vehicles and projected model year 2030 vehicles.

The earlier ICCT study found that the life-cycle GHG emissions of average battery electric mid-size cars sold in the United States in 2021 were 57%–68% lower than

1 Georg Bieker, *A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars* (International Council on Clean Transportation, 2021), https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/.

2 U.S. Environmental Protection Agency, *The 2023 EPA Automotive Trends Report* (December 2023), https://www.epa.gov/automotive-trends

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internal combustion engine (ICE) vehicles, depending on the average carbon intensity of the electricity grid. These findings align with estimates of model year 2020 electric and gasoline cars done by Argonne National Laboratory (ANL). ANL found that a BEV with a 300-mile electric drive range reduces life-cycle emissions by nearly 60% compared with a gasoline vehicle (this included emissions from battery and vehicle manufacturing, feedstock and fuel production, vehicle use, and end-of-life disposal).[3] Our updated analysis estimates that the life-cycle GHG emissions of model year 2024 BEV sedans in the United States are 66%–70% lower than conventional gasoline vehicles, depending on the average carbon intensity of the electricity grid. For SUVs, we estimate that the life-cycle GHG emissions for model year 2024 BEVs is 71%–74% lower than conventional gasoline vehicles, depending on the same conditions.

POLICY CONTEXT

In March 2024, the U.S. Environmental Protection Agency (EPA) finalized its multi-pollutant emissions standards, which set new emissions limits on GHGs and criteria air pollutants from vehicle tailpipes.[4] These standards apply to all new light- and medium-duty vehicles from model years 2027 through 2032. Tailpipe emissions from vehicle models sold in the United States are certified according to the amount of pollution emitted during laboratory tests. Since zero-emission vehicles, including battery electric and fuel cell electric vehicles, emit no pollution, they are assigned a certification value of 0 g/mi.

EPA's new standards are expected to rapidly reduce emissions from light-duty vehicles, which were the largest source of GHG emissions from all transport modes in the United States in 2022.[5] Vehicle manufacturers may pursue various strategies to comply with these standards, including electrification, improved engine efficiency (e.g., regenerative braking), and use of idle-reduction technologies. To estimate how industry might comply with the new standards, EPA conducted a technology cost assessment that considered a wide range of combustion, hybrid, and electric vehicle technologies. It found that selling more BEVs would be the most cost-effective way to comply. Therefore, EPA predicts that 68% of new light-duty vehicles sold in 2032 will be plug-in electric—56% BEVs and 13% plug-in hybrid electric vehicles (PHEVs).[6] This comes amid other developments in the United States, including President Biden's Executive Order setting a target of a 50% sales share for electric vehicles by 2030 and the adoption of California's Advanced Clean Cars II regulation (100% zero-emission

3 U.S. Environmental Protection Agency (EPA), "Electric Vehicle Myths," Other Policies and Guidance, May 14, 2021, https://www.epa.gov/greenvehicles/electric-vehicle-myths.

4 EPA, "Multi-Pollutant Emissions Standards for Mode Years 2027 and Later Light-Duty and Medium-Duty Vehicles," Pub. L. No. 40 CFR Parts 85, 86, 600, 1036, 1037, 1066, and 1068, EPA-HQ-OAR-2022-0829; FRL-8953-04-OAR (2024), https://www.govinfo.gov/content/pkg/FR-2024-04-18/pdf/2024-06214.pdf.

5 EPA, "Fast Facts on Transportation Greenhouse Gas Emissions," Overviews and Factsheets, accessed June 6, 2024, https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions.

6 International Council on Clean Transportation, "The EPA Final Multi-Pollutant Rule for Light and Medium-Duty Vehicles Sends a Resounding Message about the Accelerating Transition to Electric Vehicles in the U.S.," press release, March 20, 2024, https://theicct.org/pr-epa-final-multi-pollutant-rule-for-light-and-medium-duty-vehicles-sends-a-resounding-message-about-the-accelerating-transition-to-ev-in-the-us-mar24/.

vehicle sales by 2035) by 13 states plus the District of Columbia, which together represent 34% of the U.S. light-duty vehicle market.[7]

METHODOLOGY

This study assesses the life-cycle GHG emissions of four common vehicle powertrains: ICE vehicles, hybrid electric vehicles (HEVs), PHEVs, and BEVs. We consider average medium-size model year 2024 vehicles and projected model year 2030 vehicles based on industry average data. For 2030 vehicles, we account for future manufacturing efficiency gains and decarbonization of the power grid. The specifications of the representative vehicle models are based on EPA data. We assume that the liquid fuel combusted by conventional gasoline ICE vehicles, HEVs, and PHEVs is gasoline blended with 10% ethanol (E10) and that the electricity used by PHEVs and BEVs is grid-average electricity. We also separately assess the life-cycle GHG emissions of BEVs powered by 100% renewable electricity. Our life-cycle emissions estimates are organized into four stages: fuel consumption, fuel production, vehicle manufacture, and battery manufacture. Results are in units of grams of carbon dioxide equivalent per mile traveled (gCO_2e/mi).

FUEL CONSUMPTION

Technical specifications for fuel economy (mi/gal) and electricity consumption (kWh/mi) are based on EPA modeling (summarized in Table 1). Specifications for new vehicles of each powertrain and segment are based on EPA's Optimization Model for reducing Emissions of Greenhouse Gases from Automobiles (OMEGA) modeling output files in the agency's "Light-duty central case" compliance analysis supporting the 2024 Final Rulemaking.[8] For each powertrain and segment, 2024 specifications are based on EPA data of the industry average model year 2023 values for the baseline fleet; 2030 specifications are based on EPA analysis of how industry is expected to comply with the final multi-pollutant standards in 2030. For electric vehicles, electricity consumption values correspond to BEVs with 300 mi range and PHEVs with 40 mi electric range.

7 The White House, "Fact Sheet: President Biden Announces Steps to Drive American Leadership Forward on Clean Cars and Trucks," August 5, 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/fact-sheet-president-biden-announces-steps-to-drive-american-leadership-forward-on-clean-cars-and-trucks/; Anh Bui and Peter Slowik, *Electric Vehicle Market and Policy Developments in U.S. States*, 2023 (International Council on Clean Transportation, 2024), https://theicct.org/publication/ev-ldv-us-major-markets-monitor-2023-june24/.

8 EPA, "Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA)," accessed June 6, 2024, https://www.epa.gov/regulations-emissions-vehicles-and-engines/optimization-model-reducing-emissions-greenhouse-gases#omega-2.5.0.

Table 1
Fuel and electricity consumption in 2024 and 2030 by powertrain and vehicle type

Year	Powertrain	Vehicle segment	Fuel economy (mi/gal)	Electricity consumption (kWh/mi)
2024	ICE	Sedan	35	—
	HEV	Sedan	50	—
	PHEV	Sedan	43	0.36
	BEV	Sedan	—	0.27
	ICE	SUV	26	—
	HEV	SUV	37	—
	PHEV	SUV	33	0.43
	BEV	SUV	—	0.31
2030	ICE	Sedan	36	—
	HEV	Sedan	48	—
	PHEV	Sedan	43	0.38
	BEV	Sedan	—	0.25
	ICE	SUV	27	—
	HEV	SUV	39	—
	PHEV	SUV	35	0.39
	BEV	SUV	—	0.31

To estimate total fuel consumption, we applied an average lifetime mileage of approximately 195,000 mi for sedans and 209,000 mi for SUVs, as Bieker did for the 2021 ICCT study. For PHEVs, we applied an electric drive share of 39.5% based on real-world utility factors for PHEVs with a 40 mi electric drive range in California.[9]

We sourced combustion or tank-to-wheel (TTW) emission factors for corn ethanol and gasoline from the EPA 2010 Renewable Fuel Standard (RFS) rulemaking, a landmark fuels regulation built on a comprehensive life-cycle analysis of eligible fuel pathways.[10] Per the RFS, fossil gasoline has TTW emissions of 79 kgCO_2e/MMBTU and corn ethanol has nominal TTW emissions of 0.8 kg CO_2e/MMBTU. Corn ethanol's emissions are very low because most of the CO_2 released during biogenic fuel combustion is offset by the CO_2 assumed to have been sequestered during plant growth. While BEVs and PHEVs in electric drive produce no tailpipe emissions, the operation of these vehicles is associated with emissions from the fuel production stage.

FUEL PRODUCTION

Emissions from fuel production, sometimes referred to as well-to-tank (WTT) emissions, are linked to extracting and refining gasoline blendstock, processing fuel, and producing electricity used to power electric vehicles. We sourced gasoline and corn ethanol emission factors that occur upstream of fuel combustion from the RFS rulemaking. These include production, transportation, and land-use change emissions

9 Aaron Isenstadt et al., *Real World Usage of Plug-in Hybrid Vehicles in the United States* (International Council on Clean Transportation, 2022), https://theicct.org/publication/real-world-phev-us-dec22/.

10 EPA, "40 CFR Part 80. Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program," 2010, https://www.govinfo.gov/content/pkg/FR-2010-03-26/pdf/2010-3851.pdf; EPA, "Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis," February 2010, https://nepis.epa.gov/Exe/ZyPDF.cgi/P1006DXP.PDF?Dockey=P1006DXP.PDF.

from corn cultivation. According to the RFS, fossil gasoline has WTT emissions of 19 $kgCO_2e$/MMBTU and WTT emissions for corn ethanol are 77.2 $kgCO_2e$/MMBTU.

For electricity, we sourced emission factors for each power generation source from the Intergovernmental Panel on Climate Change (IPCC), reported in gCO_2e per kWh.[11] These estimates account for the embodied emissions associated with the production of infrastructure for electricity generation; adopting these results in our analysis is a conservative approach, given that the ongoing decarbonization of the economy will lead to future reductions in power plant construction emissions.[12]

We multiplied these emission factors by the annual share of electricity sourced from each power generation type over a given vehicle lifetime. Electricity shares are drawn from the International Energy Agency's (IEA) World Energy Outlook.[13] For the future development of the electricity grid, we consider both the IEA's Announced Pledges Scenario (APS) and the more conservative Stated Policies Scenario (STEPS). The latter scenario only accounts for the effect of current policies and assumes no further policies to accelerate the decarbonization of the U.S. power grid. In particular, the projections of the STEPS in earlier versions of the IEA report underestimated the growth trajectories later realized for wind and solar power in the United States. We calculated an average electricity carbon intensity of 231 gCO_2e/kWh over the operating lifetime for vehicles sold in model year 2024 using the STEPS and an average electricity carbon intensity of 189 gCO_2e/kWh for the APS. Over the lifetime of new vehicles projected to be sold in 2030, we calculated an average electricity carbon intensity of 161 gCO_2e/kWh and 116 gCO_2e/kWh for the STEPS and APS, respectively.

VEHICLE MANUFACTURE

Across all powertrains, the vehicle manufacturing stage utilizes similar materials and processes to produce the chassis, body, and other components including tires and steering systems. Life-cycle emissions from this stage are closely linked to vehicle weight. The vehicle curb weights applied in this analysis are summarized in Table 2; as above, the specifications are based directly on the output files from EPA's OMEGA modeling supporting the 2024 Final Rulemaking.[14] We assumed that emissions from the vehicle manufacturing stage drop 15% between 2024 and 2030, consistent with Bieker's 2021 analysis. Emission reductions are expected due to increases in process efficiency and a growing share of renewables fueling the electricity grid. We use the GREET vehicle cycle model to obtain the life-cycle emissions from vehicle components, fluids, and assembly, disposal, and recycling (ADR).

11 William Moomaw et al., "Annex II: Methodology," in *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, eds. O. Edenhofer et al. (Cambridge University Press, 2011) https://www.ipcc.ch/site/assets/uploads/2018/03/Annex-II-Methodology-1.pdf.

12 Michaja Pehl et al., "Understanding Future Emissions from Low-Carbon Power Systems by Integration of Life-Cycle Assessment and Integrated Energy Modelling," *Nature Energy* 2, no. 12 (December 2017): 939–45, https://doi.org/10.1038/s41560-017-0032-9.

13 International Energy Agency, "World Energy Outlook 2023," October 2023, https://www.iea.org/reports/world-energy-outlook-2023.

14 EPA, "Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA)."

Table 2
Vehicle curb weight assumptions across model year, powertrain, and vehicle type

Year	Powertrain	Segment	Weight (kg)	Weight (lb)
2024	ICE	Sedan	1,457	3,211
	HEV	Sedan	1,442	3,179
	PHEV	Sedan	1,552	3,422
	BEV	Sedan	1,974	4,352
	ICE	SUV	1,797	3,962
	HEV	SUV	1,835	4,045
	PHEV	SUV	2,095	4,618
	BEV	SUV	2,336	5,150
2030	ICE	Sedan	1,447	3,191
	HEV	Sedan	1,448	3,191
	PHEV	Sedan	1,445	3,185
	BEV	Sedan	1,848	4,074
	ICE	SUV	1,813	3,997
	HEV	SUV	1,646	3,630
	PHEV	SUV	1,818	4,007
	BEV	SUV	2,199	4,849

BATTERY MANUFACTURE

We assumed that BEVs and PHEVs sold in 2024 have lithium-ion batteries comprised of a nickel manganese cobalt oxide (NMC)-622 battery pack and that the small battery used in hybrid vehicles is also lithium ion. Although other battery packs will be sold in later years, for simplicity, we assumed all vehicles projected to be sold in 2030 have NMC-955 batteries.

Consistent with our approach for electricity consumption and curb weight, the technical specifications for battery capacity (kWh) are based directly on EPA modeling. The battery capacity for new BEVs and PHEVs for each segment in 2024 are based on the industry-average model year 2023 values from EPA's OMEGA modeling output files for the baseline fleet.[15] The battery capacities of new vehicles projected to be sold in 2030 are based on EPA's technical modeling of how industry will comply with the new multi-pollutant standards in 2030. Battery capacities correspond to a real-world electric range of 300 mi for BEVs and 40 mi for PHEVs.

Table 3
BEV and PHEV battery capacities by vehicle type and model year

Year	BEV (300 mi range)		PHEV (40 mi range)	
	Sedan (kWh)	SUV (kWh)	Sedan (kWh)	SUV (kWh)
2024	85	98	19	23
2030	80	97	20	21

15 EPA, "Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA)."

Like the vehicle manufacturing stage, our estimates for emissions from the battery production stage are drawn from GREET. We updated GREET's default capacity assumptions with the assumed battery capacities and assumed that the per-kilowatt-hour battery manufacturing emissions decrease 15% between 2024 and 2030 due to improved process efficiency and grid decarbonization.

RESULTS

MODEL YEAR 2024

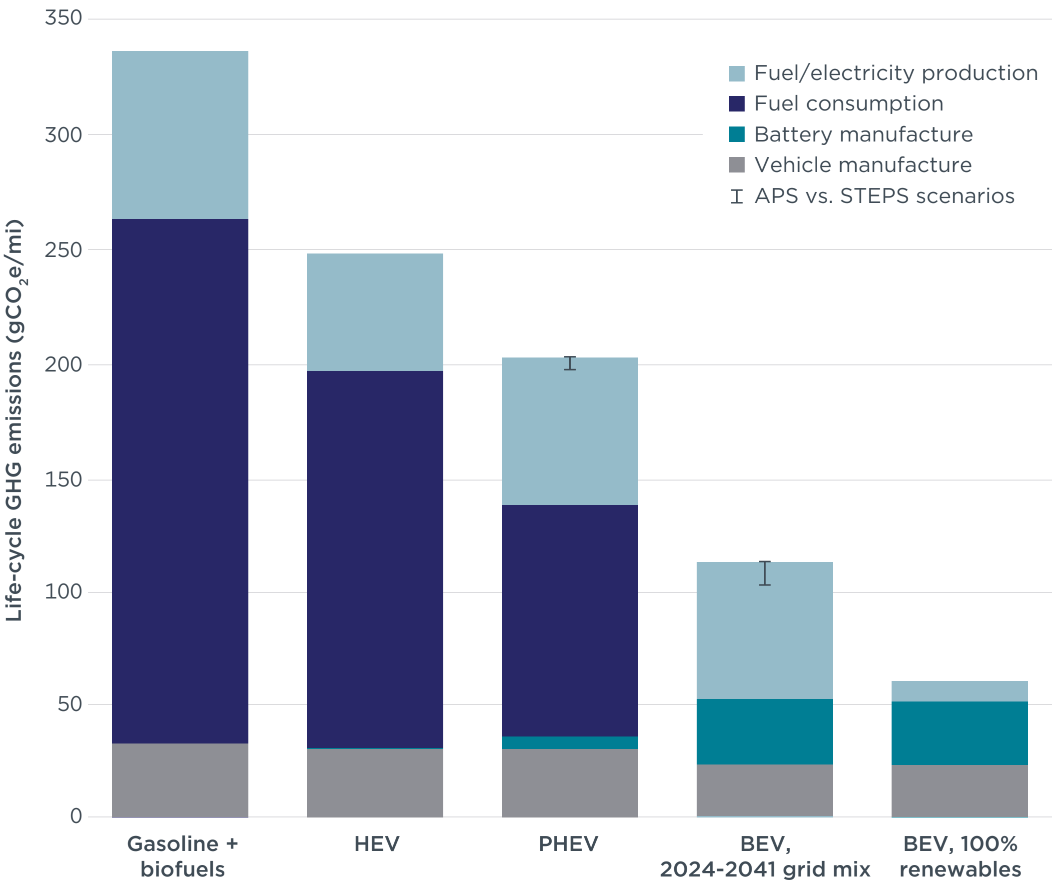
For both sedans and SUVs, conventional gasoline vehicles have the highest life-cycle GHG emissions. These are followed by HEVs, PHEVs, BEVs powered by grid-average electricity, and finally BEVs powered by 100% renewable electricity. Fuel consumption (TTW emissions) is the largest share of emissions for conventional ICE vehicles, HEVs, and PHEVs. BEVs have no emissions from fuel consumption, and BEVs powered by 100% renewable electricity have low emissions from the fuel production (WTT) stage.

Most emissions associated with BEV sedans are from the manufacturing stage; these are higher than for PHEVs, HEVs, and conventional gasoline ICE vehicles. However, the emissions benefits of BEV technology are quickly apparent once they enter operation. The higher manufacturing emissions for model year 2024 BEV sedans are "paid off" after approximately 15,200 mi of driving compared with an average conventional ICE and 25,600 mi of driving compared with an average HEV.

Figure 1 shows the emissions (standardized in gCO_2e/mi) from each production stage for the model year 2024 sedans we assessed. We estimate that BEVs reduce emissions between 66% (when powered by the average grid under the STEPS) and 83% (when powered by 100% renewable electricity) across their entire vehicle lifetime compared with gasoline vehicles and PHEVs reduce emissions by 40%. The error bars in the figure indicate the difference between the STEPS and APS.

Figure 1

Estimated life-cycle GHG emissions for model year 2024 sedans



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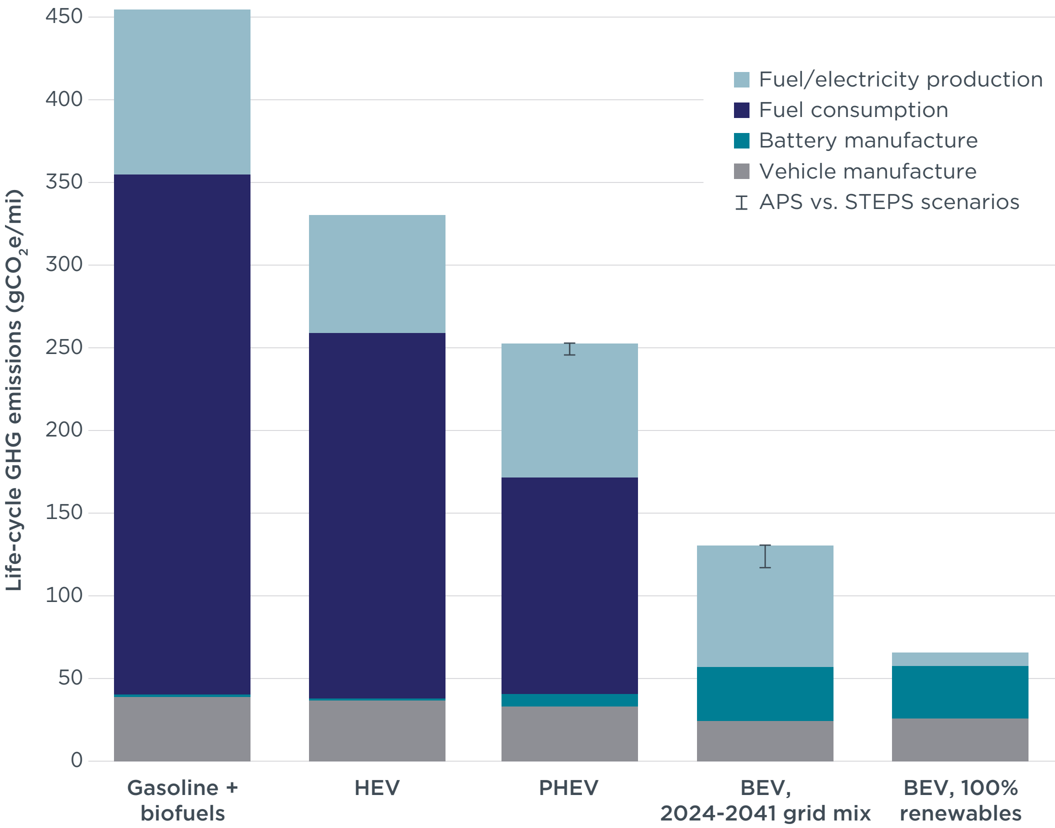
For SUVs, relative emission reductions are slightly higher than sedans across all powertrains. SUVs are associated with higher life-cycle GHG emissions than sedans because they weigh more and are less fuel efficient (Figure 2). Across the vehicle life cycle, higher weights have a lesser effect on emissions from vehicle manufacturing and a greater effect on emissions from fuel consumption and production. For this vehicle segment and model year, BEVs reduce emissions between 71% (when powered by the average grid under the STEPS scenario) and 85% (when powered by 100% renewable electricity) relative to a conventional gasoline vehicle. PHEVs reduce emissions by 44% and HEVs reduce emissions by 27%. Here, higher BEV manufacturing emissions are "paid off" after approximately 11,800 mi and 19,800 mi of driving compared with conventional ICE vehicles and HEVs, respectively.

Figure 2

Estimated life-cycle GHG emissions for model year 2024 SUVs



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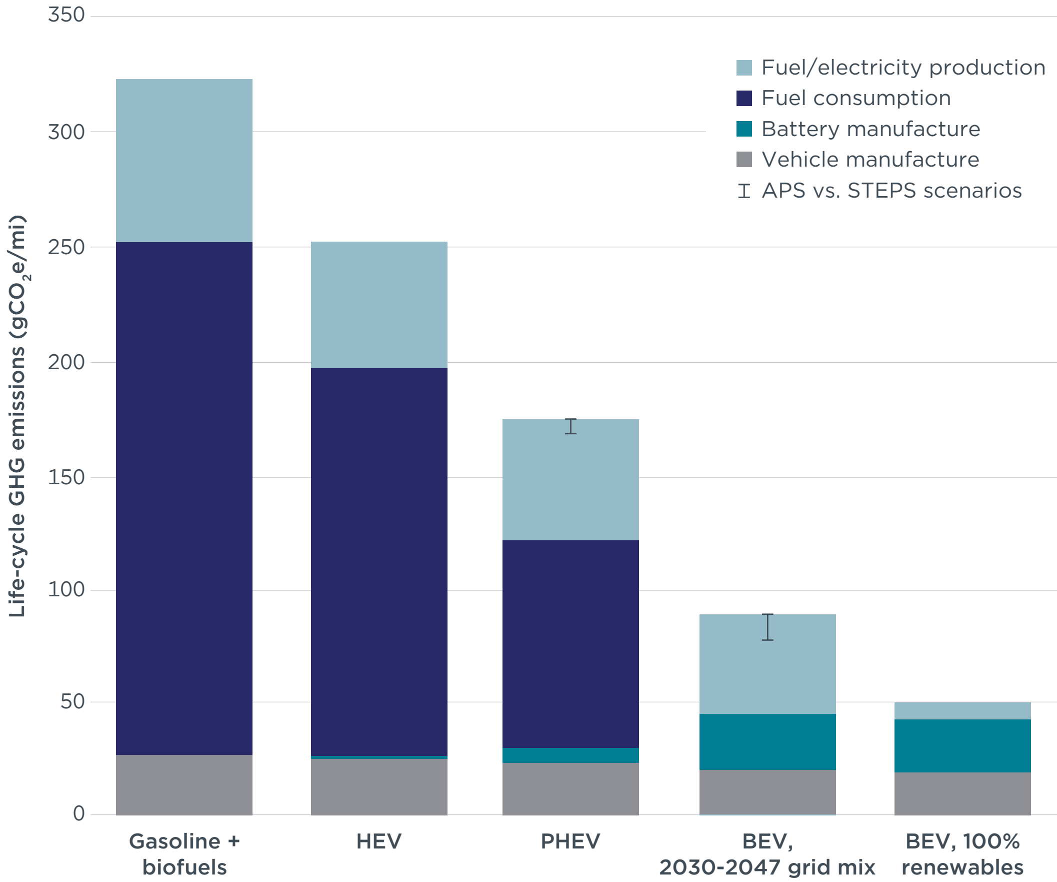
MODEL YEAR 2030

For vehicles projected to be sold in model year 2030, the biggest changes result from power grid decarbonization, improved battery efficiency, and process improvements during vehicle and battery manufacturing. The IEA STEPS predicts that GHG emissions from grid-sourced electricity decline from 231 gCO_2e/MJ to 161 gCO_2e/MJ—30%—across the vehicle lifetime. EPA predicts that BEV and ICE sedan fuel efficiency will improve slightly between 2024 and 2030 and that it will decrease for HEVs. There are currently no policies in place to prevent performance “backsliding.” Vehicle manufacturers are thus likely to pursue less-costly compliance modes with the multi-pollutant standards than modifying ICE engines.

For sedans, we estimate that BEVs powered by a grid-average electricity mix reduce life-cycle emissions by 75% relative to conventional gasoline vehicles. BEVs powered by 100% renewable electricity reduce life-cycle emissions by 85% (Figure 3). Higher BEV manufacturing emissions are “paid off” after approximately 11,100 mi and 16,600 mi of driving compared with conventional ICE vehicles and HEVs, respectively.

Figure 3

Estimated life-cycle GHG emissions for projected model year 2030 sedans



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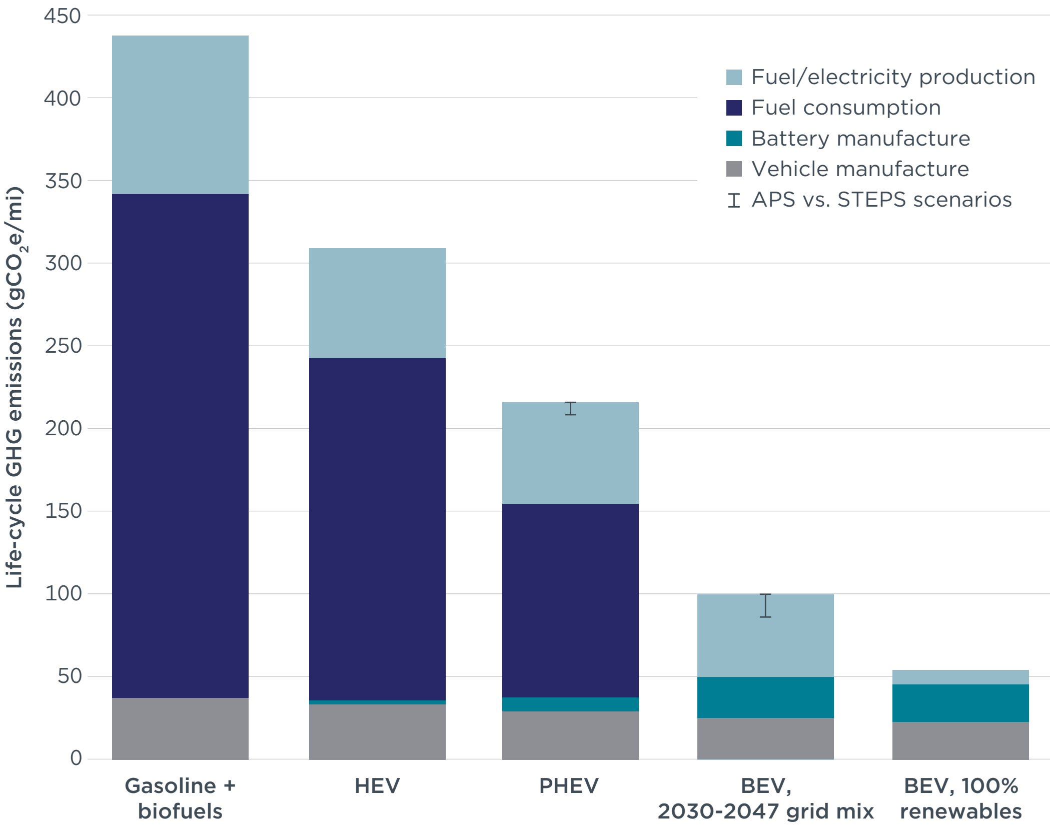
Similar results hold for SUVs projected to be sold in 2030. Across all vehicle production stages, emissions decrease due to improved process efficiencies and ongoing power grid decarbonization. BEVs powered by grid-average electricity reduce emissions by 77% relative to conventional gasoline ICE vehicles and by 87% when powered with 100% renewable electricity (Figure 4). Higher BEV manufacturing emissions are "paid off" after approximately 9,500 miles and 14,600 miles of driving compared with conventional ICE vehicles and HEVs, respectively.

Figure 4

Estimated life-cycle GHG emissions for projected model year 2030 SUVs



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KEY INSIGHTS

These results show that BEV sedans and SUVs have the lowest life-cycle GHG emissions across all powertrains. The GHG emissions of model year 2024 PHEVs (both sedans and SUVs) are roughly 2 times higher over their lifetime compared with BEVs powered by the average grid mix. Model year 2024 HEVs emit 2.2 times (sedans) and 2.5 times (SUVs) more than BEVs powered by the average grid, and conventional ICE vehicles emit up to 3.5 times (SUVs) more. Notably, compared with BEVs powered by 100% renewable electricity, this difference increases to 4.9 times more GHG emissions for HEV SUVs and 6.7 times more for conventional ICE SUVs.

For new vehicles projected to be sold in 2030, the relative benefits of BEVs are even larger. Conventional ICE SUVs were estimated to have 7.5 times higher life-cycle GHG emissions than BEVs powered by 100% renewable electricity. This is due to the ongoing decarbonization of the electricity grid and improved efficiency of BEVs. Projected new PHEVs in 2030 emit 2.1 times (sedans) and 2.2 times (SUVs) more life-cycle GHGs than new BEVs powered by grid-average electricity.

While PHEVs and HEVs have a lower GHG footprint than ICE vehicles, their emissions reduction potential is more limited than for BEVs. BEVs not only deliver emissions reduction at the tailpipe, but across the entire vehicle lifetime for representative sedans and SUVs sold in the United States.

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