Cradle-to-Grave (C2G) Analysis of U.S. Light Duty Vehicle-Fuel Options

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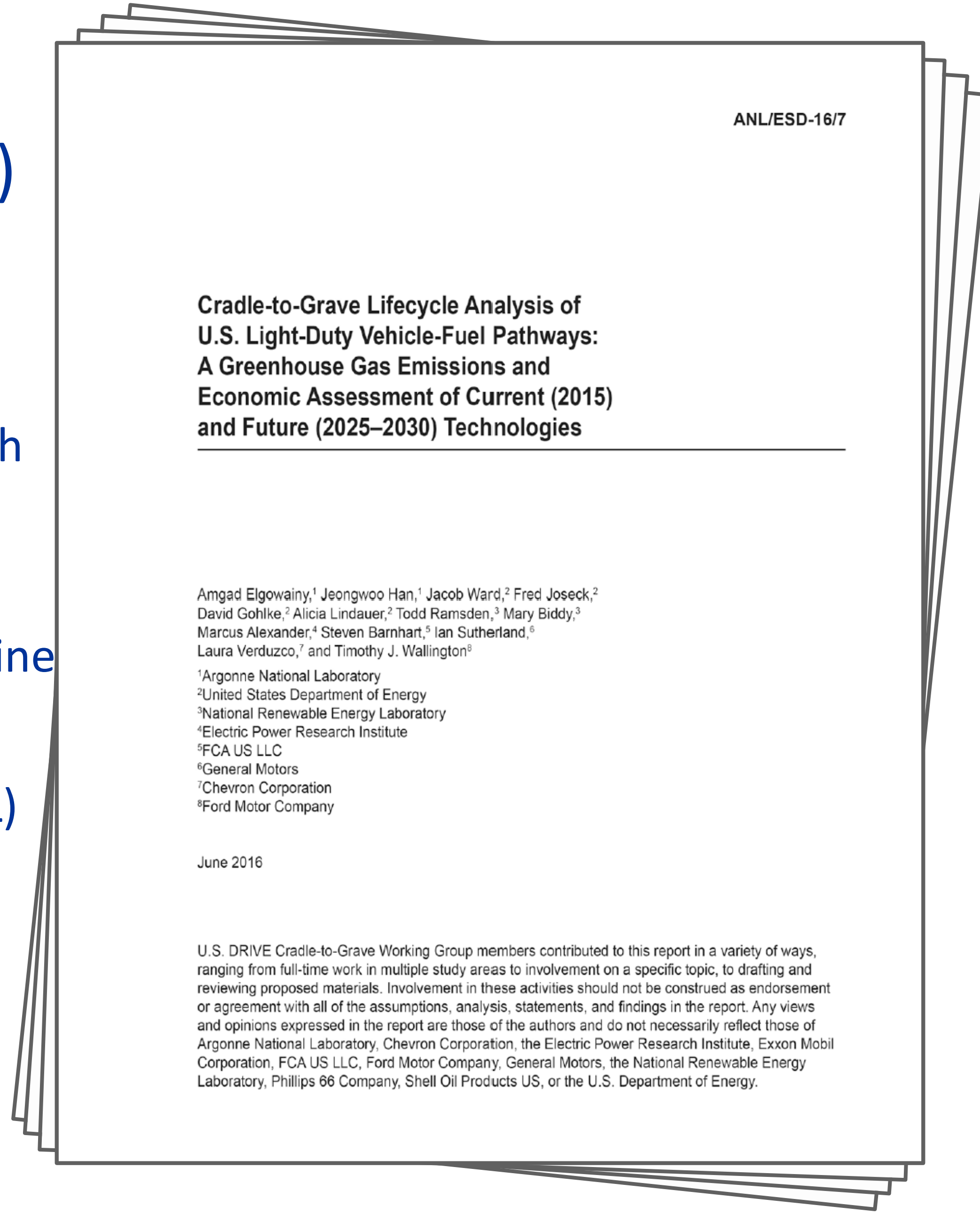
Scope of C2G Analysis

- Current and future (2030) vehicle-fuel pathways
  - GHG emissions
  - Levelized cost of driving for each pathway (at volume)
  - Cost of avoided GHG emissions relative to a conventional gasoline vehicle
  - Technology readiness level (TRL) assessment
- Fuel cycle and vehicle cycle
- Report published June 2016; revised September 2016



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Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025–2030) Technologies

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U.S. DRIVE Cradle-to-Grave Working Group members contributed to this report in a variety of ways, ranging from full-time work in multiple study areas to involvement on a specific topic, to drafting and reviewing proposed materials. Involvement in these activities should not be construed as endorsement or agreement with all of the assumptions, analysis, statements, and findings in the report. Any views and opinions expressed in the report are those of the authors and do not necessarily reflect those of Argonne National Laboratory, Chevron Corporation, the Electric Power Research Institute, Exxon Mobil Corporation, FCA US LLC, Ford Motor Company, General Motors, the National Renewable Energy Laboratory, Phillips 66 Company, Shell Oil Products US, or the U.S. Department of Energy.

https://greet.es.anl.gov/publication-c2g-2016-report

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Vehicle-Fuel Pathways

Vehicle Technology	Gasoline*	Diesel	CNG	LPG	E85	H_2	Electricity
ICEV	X	X	X	X	X		
HEV	X						
H_2 FCEV						X	
BEV90							X
BEV210							X
PHEV10 ¥	75%						25%
PHEV35 ¥	42%						58%

Notes: each X (or fractional X) designates a vehicle-fuel combination in an analyzed pathway; each vehicle is presumed to be optimized for the fuel on which it operates.

** Gasoline (E10) is assumed to contain 10% corn ethanol by volume.*

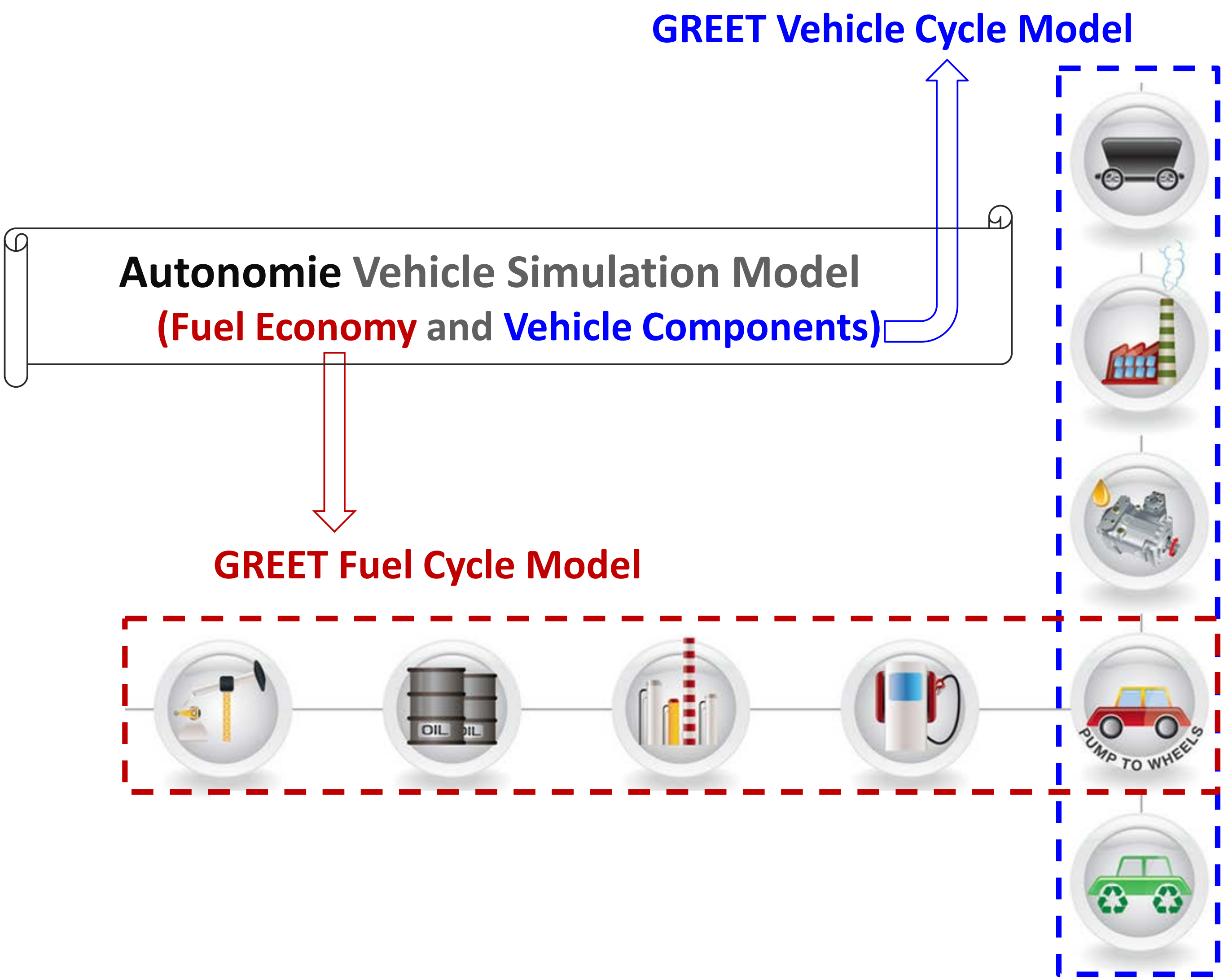
¥ PHEV10 is modeled as a power-split PHEV and PHEV35 is modeled as an Extended Range Electric vehicle (EREV). The PHEV gasoline and electricity energy usage mix is assumed per SAE J2841 - Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data.

Fuel Pathway Assumptions

	CURRENT TECHNOLOGY cases	FUTURE TECHNOLOGY Cases
Gasoline (E10)	U.S. average crude mix (blended with 10% corn ethanol)	Pyrolysis of forest residue (no ethanol blending)
Diesel	U.S. average crude mix	Pyrolysis of forest residue
		Hydroprocessed renewable diesel (HRD) from soybeans
		20% Fatty Acid Methyl Ester (FAME) drop-in bio-based diesel (B20) from soybeans
		Gas-to-liquid Fischer-Tropsch Diesel (GTL FTD w/CCS)
CNG	U.S. average of conventional and shale gas mix	---
LPG	75% from U.S. conventional and shale gas mix, and 25% from U.S. average crude mix	---
Ethanol (E85)	85% corn ethanol (blended with 15% petroleum gasoline blendstock)	85% Cellulosic from corn stover (blended with 15% petroleum gasoline blendstock)
Hydrogen	Centralized production from Steam Methane Reforming (SMR)	Electrolysis from wind
		Biomass (poplar) gasification
		Natural gas SMR with Carbon Capture and Storage (CCS)
Electricity	EIA-AEO U.S. average electricity generation mix in 2014	Natural gas Advanced Combined Cycle (ACC)
		Natural gas ACC with CCS
		Wind
		Solar photovoltaic (PV)

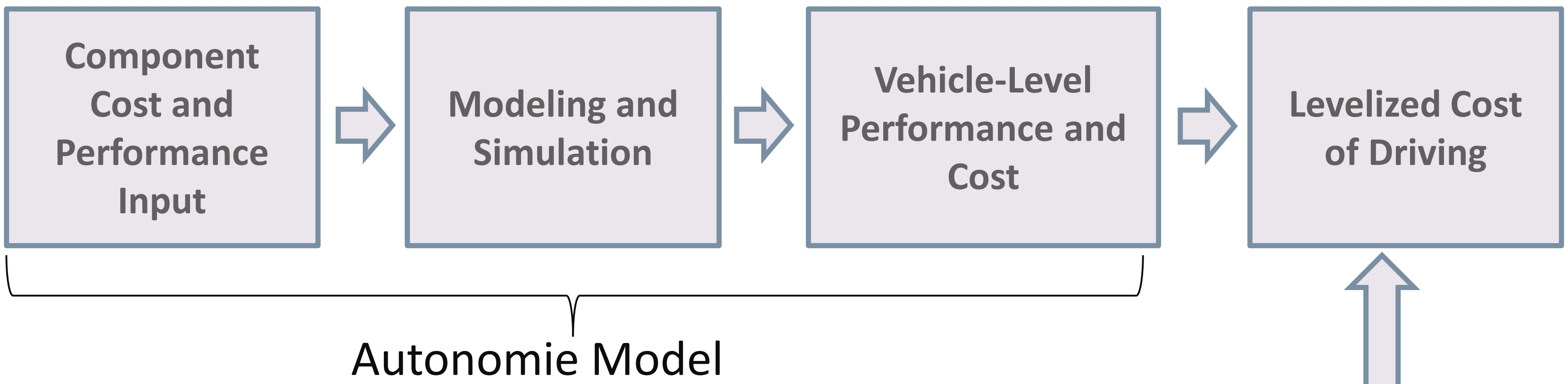
Assumptions:
- **Fuel pathways constrained to those to be scalable for both fuel and vehicles, unless otherwise specified**
- **Default electricity mix used for future cases unless otherwise specified: 2030 generation mix projected by AEO 2015**

C2G GHG Emissions Modeling Approach



GREET® = Greenhouse gases, Regulated Emissions, and Energy use in Transportation

Cost Analysis Approach: Methodologies and Models



Models used for cost analysis

<table>
<tr><th rowspan="2"></th><th rowspan="2">Vehicle</th><th colspan="7">Fuel</th></tr>
<tr><th>Gasoline</th><th>Diesel</th><th>CNG</th><th>LPG</th><th>E85</th><th>H2</th><th>Electricity</th></tr>
<tr><td>ICEV</td><td rowspan="5">DOE vehicle costing analysis (Autonomie)</td><td colspan="4" rowspan="3">EIA's Annual Energy Outlook (AEO) (and TEA models for FUTURE TECHNOLOGY pathways)</td><td rowspan="3">TEA models</td><td rowspan="4"></td><td rowspan="2"></td></tr>
<tr><td>HEV</td></tr>
<tr><td>PHEV</td><td rowspan="3">EIA's AEO</td></tr>
<tr><td>BEV</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>FCEV</td><td>H2A, HDSAM models</td></tr>
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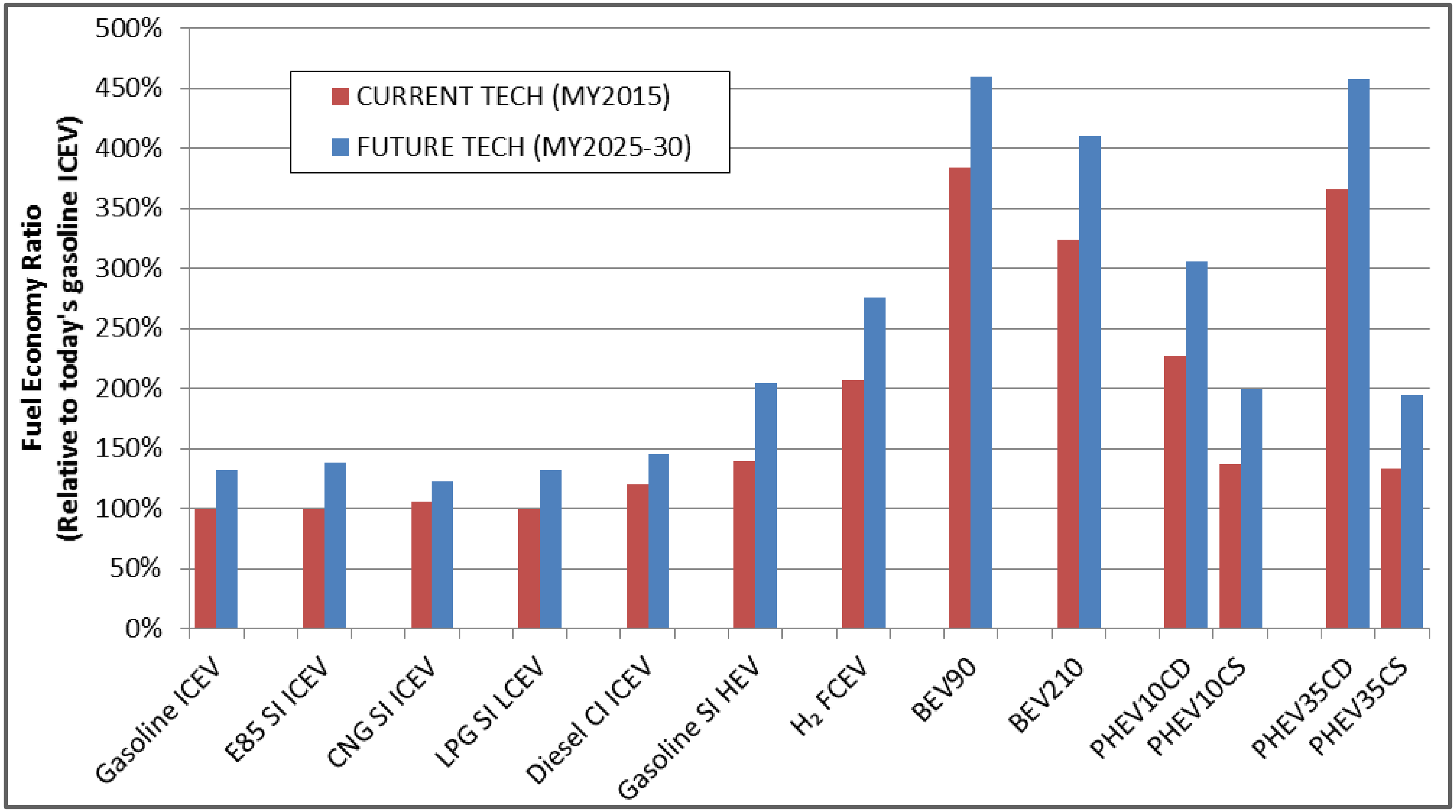
Vehicle Fuel Economy (mpgge)



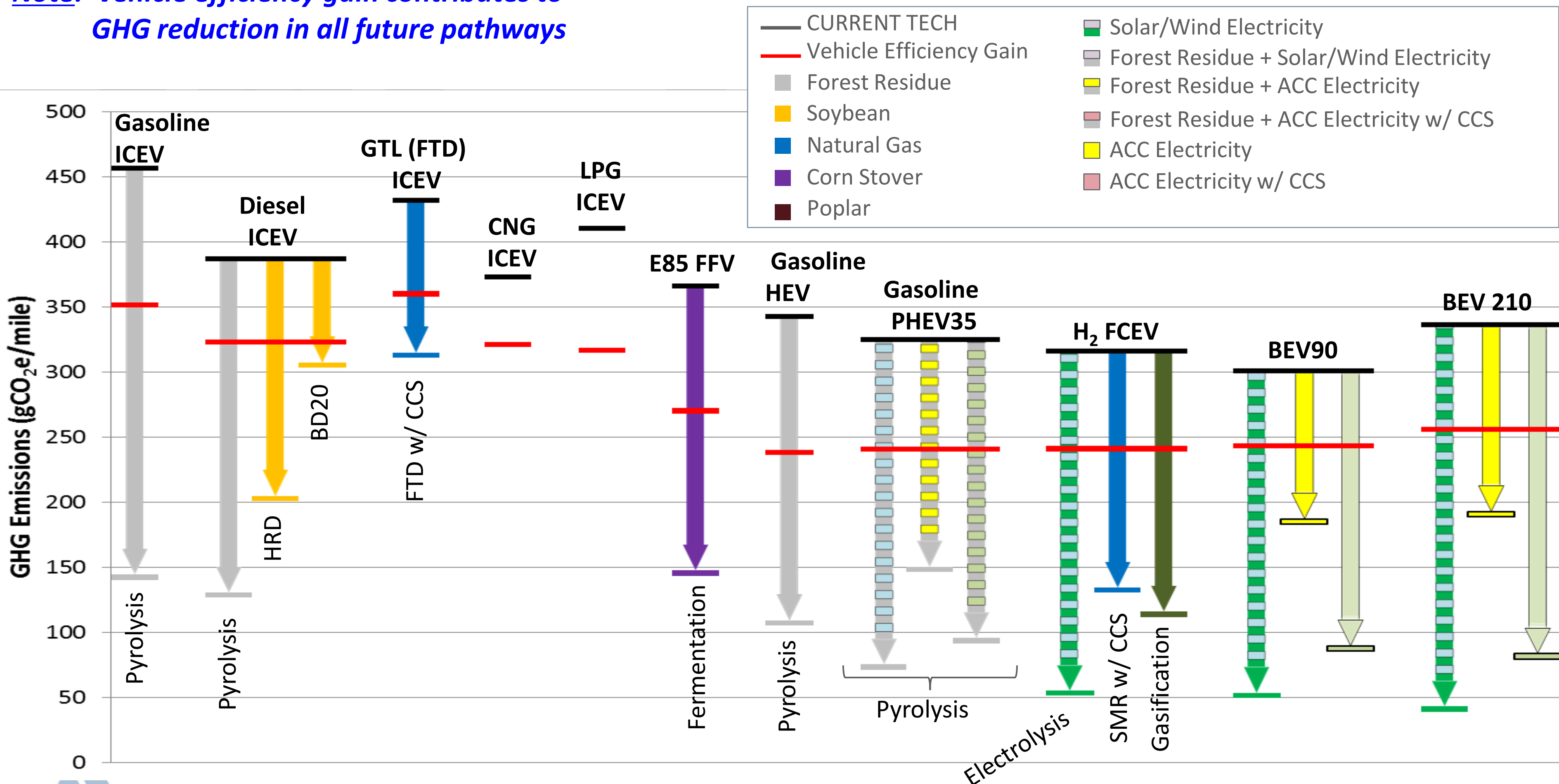
- Data from DOE/GPRA process and *Autonomie* modeling (*Moawad et al., 2016*)
- Fuel economies measured in miles per gallon of gasoline energy equivalent relative to a baseline gasoline ICEV:
  - Today*: 26.2 mpg adjusted
  - Future*: 34.5 mpg adjusted

** Combined two-cycle fuel economy*
For PHEV, CD = Charge Depleting, CS = Charge Sustaining

C2G GHG Emissions for current and future vehicle-fuel pathways

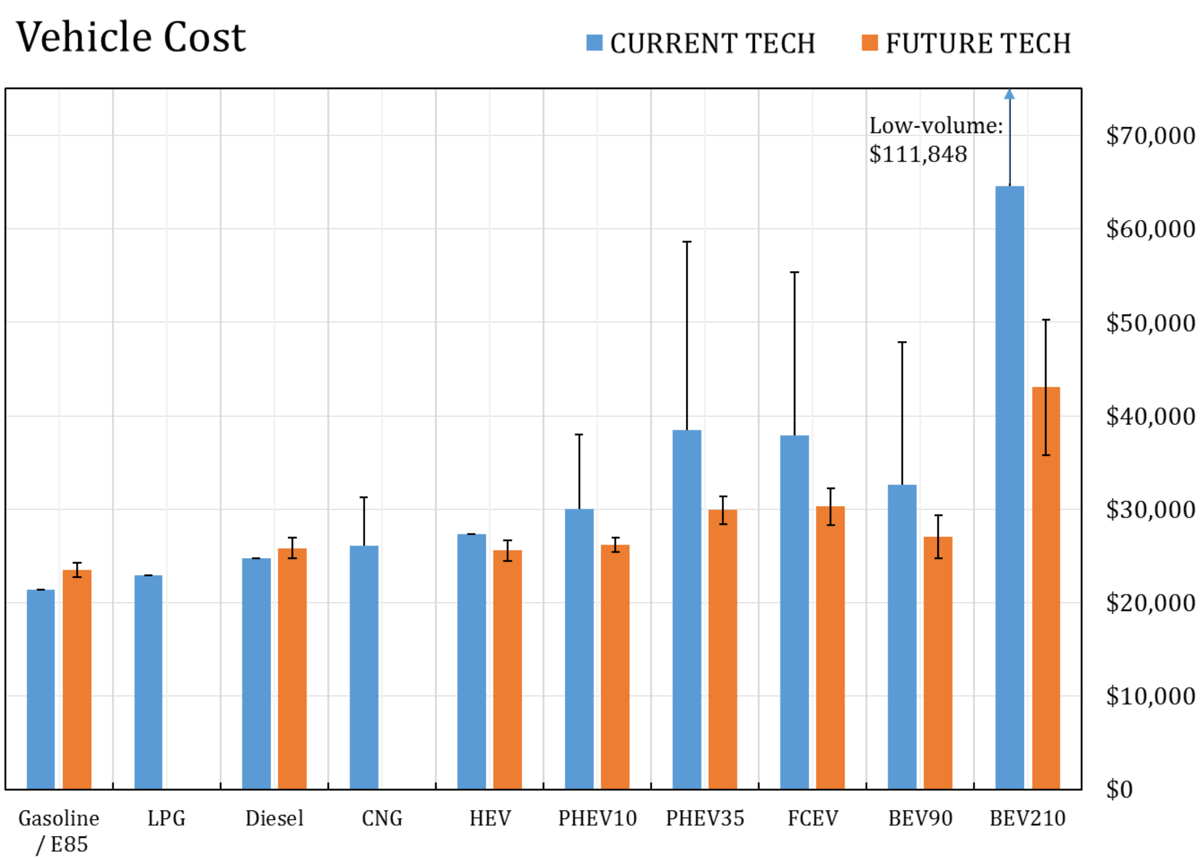
Large GHG reductions for light-duty vehicles are challenging and require consideration of the entire lifecycle, including vehicle manufacture, fuel production, and vehicle operation.

***Note*: Vehicle efficiency gain contributes to GHG reduction in all future pathways**



Vehicle Cost Assumptions (2013$)

High-volume production is critical to the viability of advanced technologies. Incremental costs of advanced technologies in FUTURE TECHNOLOGY, HIGH VOLUME cases are significantly reduced, reflecting estimated R&D outcomes.

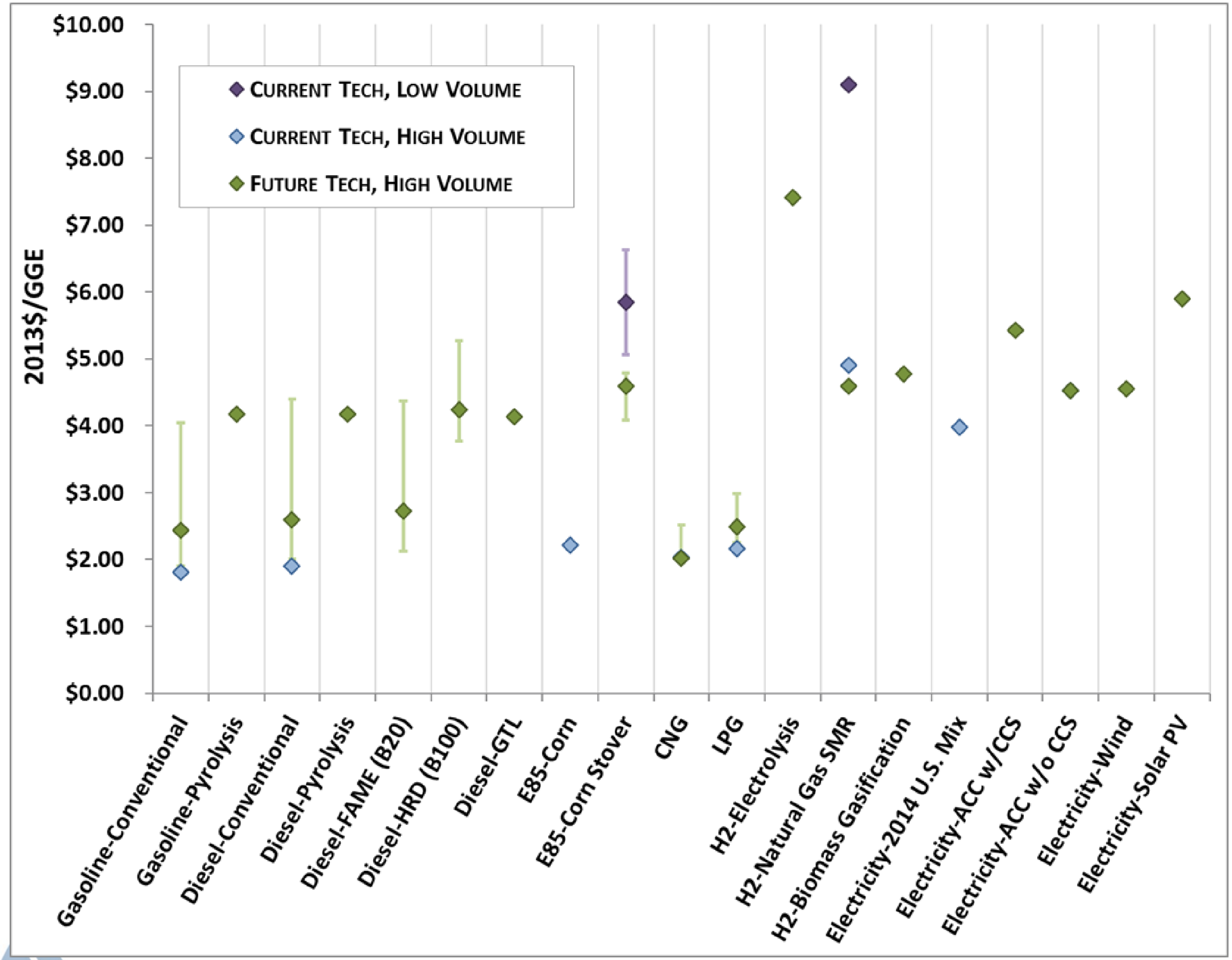


Important notes:

- ***Costs are modeled cost-to-manufacture, at volume, plus 50% retail markup using Autonomie.***
- ***FUTURE TECH costs reflect a range of estimated, uncertain R&D outcomes, the optimistic end of which aligns with DOE cost targets.***
- ***Vehicle technology cost assumptions are similar to those in previous studies (NRC [2013], NPC [2012], and MIT [2008]).***
- ***Uncertainty bars for FUTURE TECH cases represent high and low manufacturing costs assuming a medium degree of technical progress, for CURRENT TECH case represent low-volume production costs.***

Fuel Cost (2013$/gge)

Low-carbon fuels can have significantly higher costs than conventional fuels.



Average Oil Price (2013$/barrel) in AEO 2015		
	2015	2025
High Oil		158
Reference	50	82
Low Oil		57

Levelized Cost of Driving (LCD) Framework

Vehicle-fuel costs are compared on the same axis via LCD:

Total Levelized Cost of Driving (LCD) ($/mi driven) = **LCD Vehicle Cost Component ($/mi driven)** + **LCD Fuel Cost Component ($/mi driven)**

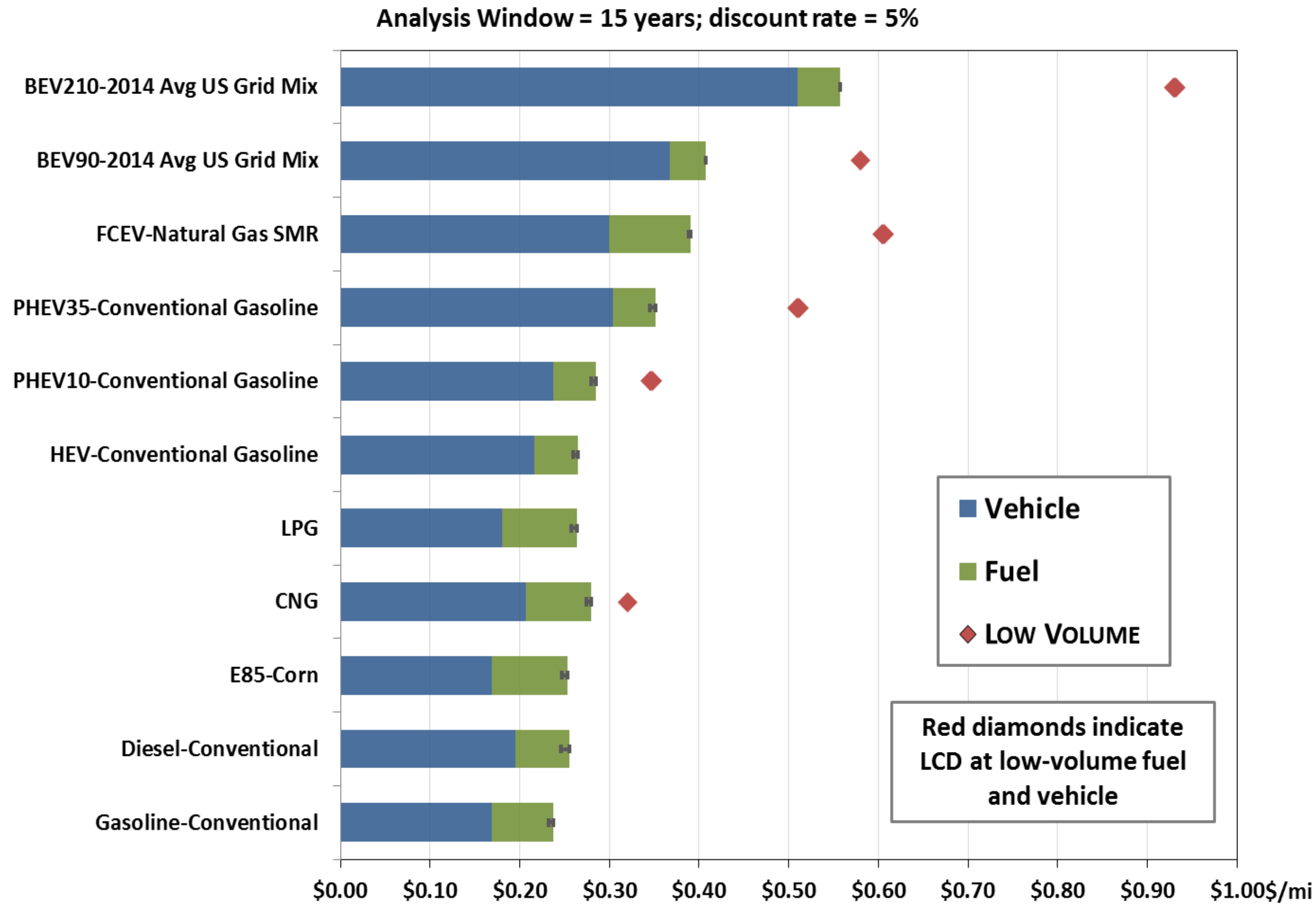
Based on the following overarching assumptions:

Parameters	Values	Notes
Analysis Period (years)	3, 5, and 15	3–5 is typically used as payback period, 15 is societal perspective
Annual VMT	14,231 (first year), decreasing to 9,249 (at assumed 15-year end-of-life) Total lifetime miles of 178,102	NHTSA passenger car travel mileage schedule (http://www-nrd.nhtsa.dot.gov/Pubs/809952.pdf) BEV90 travel 70% of the annual VMT (approximated from INL *EV Project* data)
Discount Rate (%)	3, 5, and 7	Real Discount Rate, consumer cash flow
Depreciation Rate	17.5% annual depreciation	Used to calculate residual value (assumed zero at end of 15-year life)

LCD excludes variable costs other than fuel (maintenance, insurance, etc.)

Levelized Cost of Driving - Current Tech

Vehicle cost is the major (60-90%) and fuel cost the minor (10-40%) component of the levelized cost of driving when projected at volume. Treatment of residual vehicle cost is an important consideration. Many alternative vehicles and/or fuels cost significantly more than conventional gasoline vehicles for the CURRENT TECHNOLOGY case, even when costs are projected for high-volume production.

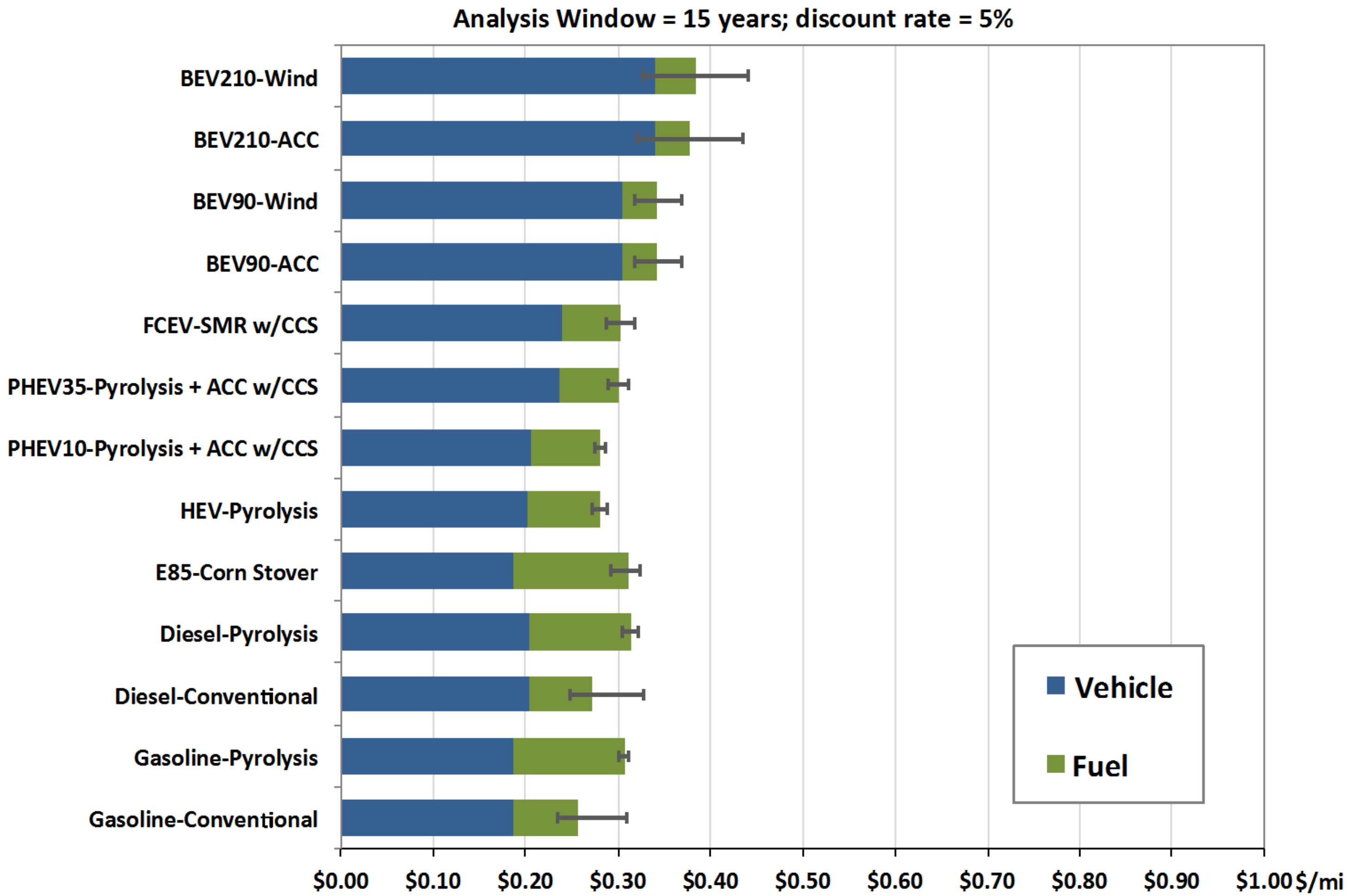


- Cost estimates are **based on <u>volume production (“at/above optimal scale”).</u>**
- Cost in this analysis is defined as **<u>policy-neutral final transaction price</u>**.

Example above is one of nine combinations of analysis window and discount rate analyzed

Levelized Cost of Driving - Future Tech

Incremental cost of advanced technologies in the FUTURE TECHNOLOGY, HIGH VOLUME cases are significantly reduced reflecting estimated R&D outcomes.



- Cost estimates are **based on volume production (“at/above optimal scale”).**
- Cost in this analysis is defined as **policy-neutral final transaction price**.

Example above is one of nine combinations of analysis window and discount rate analyzed

Cost of Avoided GHGs – Analysis Framework

Cost of avoided GHG emissions (\$/tonne CO_2e) calculated from the difference in the cost of driving an alternative vehicle-fuel platform compared to a gasoline ICE divided by the difference in the GHG emissions of the alternative vehicle compared to a gasoline ICE:

$$\text{Cost of Avoided GHG Emissions } (\$/\text{tonne } CO_2e) = \frac{\text{Levelized Cost of Driving for Alternative Vehicle } (\$/\text{mi driven}) - \text{Levelized Cost of Driving for Gasoline ICE } (\$/\text{mi driven})}{\text{C2G GHG Emissions for Gasoline ICE } (\text{tonne } CO_2e/\text{mi driven}) - \text{C2G GHG Emissions for Alternative Vehicle } (\text{tonne } CO_2e/\text{mi driven})}$$

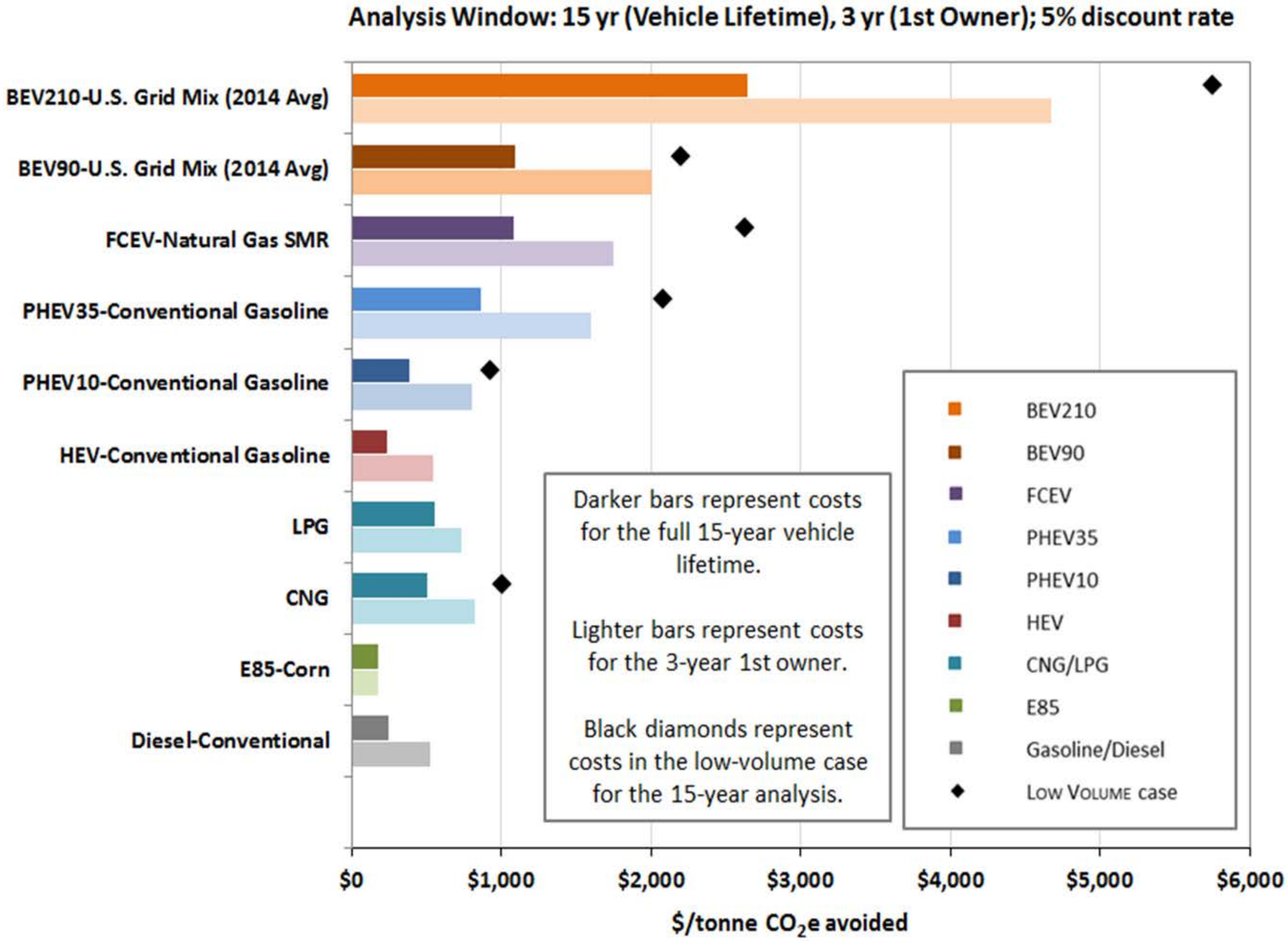
Note: LCD excludes variable costs other than fuel (maintenance, insurance, etc.). GHG emissions on a tonne CO_2e basis derived from C2G GHG emissions analysis (g/mi basis)

Based on the following overarching assumptions:

Parameter	Assumption	Notes
Baseline Comparison Vehicle	Comparable gasoline ICE (2015 vehicle for current year, 2025 vehicle for future)	Future alternative vehicles compared to future gasoline vehicles (vehicle glider efficiency improvements separated out)
Analysis Period (years)	15 years for base analysis; sensitivity at 3 yrs.	15 years represents societal perspective; 3 years represents 1st owner costs

Cost of Avoided GHG Emissions – Current Tech

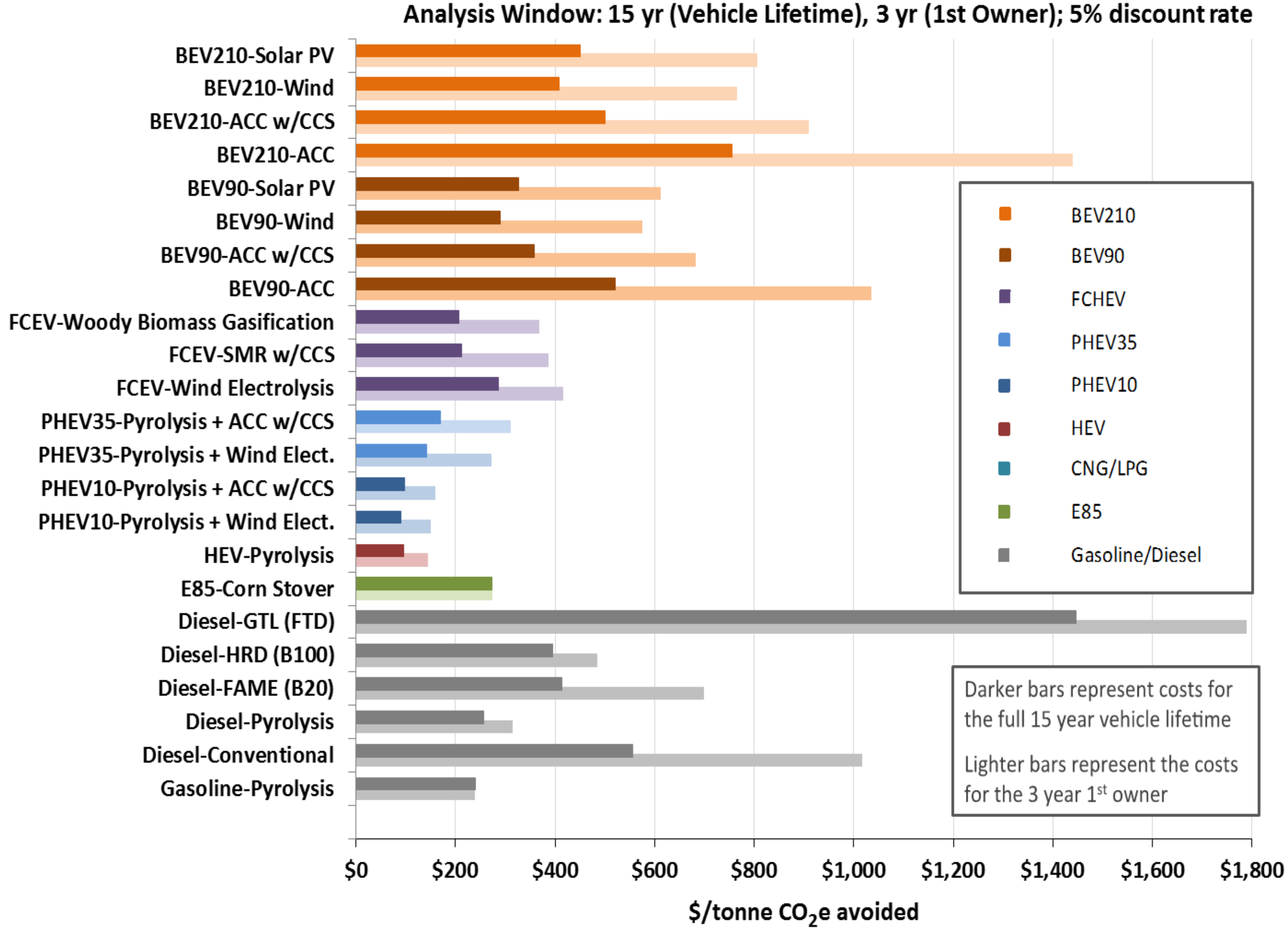
For the Current Technology, High Volume case, carbon abatement costs are generally on the order of \$100s per tonne CO_{2e} to \$1,000s per tonne CO_{2e} for alternative vehicle-fuel pathways compared to a conventional gasoline vehicle baseline.



Note: Other cobenefits of alternative vehicle-fuel pathways such as improved air quality are not captured in this study

Cost of Avoided GHG Emissions – Future Tech

Future Technology, High Volume carbon abatement costs are generally expected to be in the range $100-$1,000/tonne CO_{2e}



Informing TRLs: Barriers Analysis

Significant technical barriers still exist for the introduction of some alternative fuels. Further, market transition barriers - such as low-volume costs, fuel or make/model availability, and vehicle/fuel/infrastructure compatibility - may play a role as well.

	Gasoline	Diesel					Ethanol	Pyrolysis-based Gasoline /Electricity (PHEV)				Electricity (BEV)				Hydrogen				
	Pyrolysis – forest residue	Pyrolysis – forest residue	GTL FTD w/o CCS	GTL FTD w/ CCS	HRD – soybeans	FAME – soybeans	Fermentation – corn stover	ACC w/o CCS	ACC w/ CCS	Wind	Solar	ACC w/o CCS	ACC w/ CCS	Wind	Solar	Electrolysis – Wind	Electrolysis – Solar	SMR (w/o CCS)	SMR (w/ CCS)	Woody biomass gasification
Vehicle																				
Feedstock																				
Production																				
Distribution																				
Dispensing																				
Fuel Spec																				
Consumer Acceptance																				
TRL	6–7	6–7	9	7	9	9	8	6–7	6–7	6–7	6–7	9	7	9	9	8–9	8–9	8–9	7	7

No major barriers   Some significant barriers   Considerable barriers

Conclusions

Emissions

- Large GHG reductions for light-duty vehicles are challenging, and require consideration of the entire lifecycle, including vehicle manufacture, fuel production, and vehicle operation.

Cost

- High-volume production is critical to the viability of advanced technologies.
- Incremental costs of advanced technologies in FUTURE TECHNOLOGY, HIGH VOLUME cases are significantly reduced, reflecting estimated R&D outcomes.
- Low-carbon fuels can have significantly higher costs than conventional fuels.
- Vehicle cost is the major (60–90%) and fuel cost the minor (10–40%) component of the levelized cost of driving when projected at volume. Treatment of residual vehicle cost is an important consideration. Many alternative vehicles and/or fuels cost significantly more than conventional gasoline vehicles for the CURRENT TECHNOLOGY case, even when costs are projected for high-volume production.

Cost of Carbon Abatement

- For the CURRENT TECHNOLOGY, HIGH VOLUME case, carbon abatement costs are generally on the order of \$100s per tonne CO_{2e} to \$1,000s per tonne CO_{2e} for alternative vehicle-fuel pathways compared to a conventional gasoline vehicle baseline.
- FUTURE TECHNOLOGY, HIGH VOLUME carbon abatement costs are generally expected to be in the range \$100–\$1,000/tonne CO_{2e}

Technology Feasibility

- Significant technical barriers still exist for the introduction of some alternative fuels. Further, market transition barriers – such as low-volume cost, fuel or make/model availability, and vehicle/fuel/infrastructure compatibility – may play a role as well.

Acronyms

- ACC: Advanced Combined Cycle
- AEO: Annual Energy Outlook
- ANL: Argonne National Laboratory
- B20: 20% biodiesel, 80% petroleum diesel (by volume)
- B100: 100% FAME biodiesel
- BEV: Battery Electric Vehicle
- BEV90: BEV with 90 miles (actual on-road) driving range
- BEV210: BEV with 210 miles (actual on-road) driving range
- C2G: Cradle-To-Grave
- CCS: Carbon Capture and Storage
- CD: Charge Depleting (battery operation mode of PHEV)
- CI: Compression Ignition
- CNG: Compressed Natural Gas
- CO_2: Carbon dioxide
- CO_2e: Carbon dioxide equivalent greenhouse gas quantity
- CS: Charge Sustaining (hybrid operation mode of PHEV)
- DOE: Department of Energy
- E10: Blend of 10% ethanol and 90% gasoline (by volume)
- E85: Blend of 85% ethanol and 15% gasoline (by volume)
- EIA: Energy Information Administration
- EREV: Extended Range Electric Vehicle
- FAME: Fatty Acid Methyl Esters
- FCEV: Fuel Cell Electric Vehicle
- FTD: Fischer-Tropsch Diesel
- GGE: Gasoline Gallon Equivalent
- GHG: Greenhouse Gases
- GPRA: Government Performance and Results Act
- GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation
- GTL: Gas-To-Liquid
- H_2: Hydrogen
- H2A: Hydrogen Analysis Models
- HDSAM: Hydrogen Delivery Scenario Analysis Model
- HEV: Hybrid Electric Vehicle
- HRD: Hydroprocessed Renewable Diesel
- ICEV: Internal Combustion Engine Vehicle
- INL: Idaho National Laboratory
- LCA: Life Cycle Analysis
- LCD: Levelized Cost of Driving
- LDV: Light Duty Vehicle
- LPG: Liquefied Petroleum Gas
- mi: mile
- mpgge: miles per gasoline gallon equivalent
- MY: Model Year
- NG: Natural gas
- NHTSA: National Highway Traffic Safety Administration
- PEV: Plug-in Electric Vehicle
- PHEV: Plug-in Hybrid Electric Vehicle
- PHEV10: PHEV with 10 miles (actual on-road) driving range
- PHEV35: PHEV with 35 miles (actual on-road) driving range
- PV: Photovoltaic
- R&D: Research and Development
- SAE: Society of Automotive Engineers
- SI: Spark Ignition
- SMR: Steam Methane Reforming
- TEA: Techno-Economic Analysis
- TRL: Technology Readiness Level
- VMT: Vehicle Miles Travelled
- w/: with
- w/o: without

Thank you!

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C2G report is accessible at

https://greet.es.anl.gov/publication-c2g-2016-report

Backup

Definitions

"Pathway" vs. "Scenario"

- **Pathway:** A fuel or energy production pathway is defined as a distinct, technically feasible, route or a sequence of processes **starting with one or more feedstocks and ending with an intermediate or a final product**. (A pathway is not necessarily constrained by feedstock, economic, policy, and market considerations.)
- **(vs. Scenario:** A scenario is defined as a postulated fuel/energy production **pathway or a mix of pathways that factor in real or hypothetical feedstock, economic, policy, and market considerations**.)

Cost

- **Cost** in this analysis **is defined as policy-neutral final transaction cost**. Explained in more detail, costs conveyed here are intended to be the final cost/price to the consumer, excluding tax (i.e. fuel sales tax) and/or credits (i.e. PEV subsidies) on the final product. This framework intentionally excludes policy interventions to focus on technology/market challenges/opportunities.

Volume Production

- Cost estimates are **based on volume production ("at/above optimal scale")**, which is intentionally not standardized across vehicle-fuel pathways, since scale is recognized as inherently a function of the technology/production pathway. *Costs during the transition to volume production are not considered.*
  - **"Current Technology, High Volume" case** = MY2015 vehicles and fuels projected at high volume characterized using technology in 2015.
  - **"Current Technology, Low Volume" case** = vehicles projected at low volume (10k – 100k units) and low-volume fuel production (hydrogen).
  - **"Future Technology, High Volume" case** = MY2025–2030 vehicles and fuels projected at high volume.