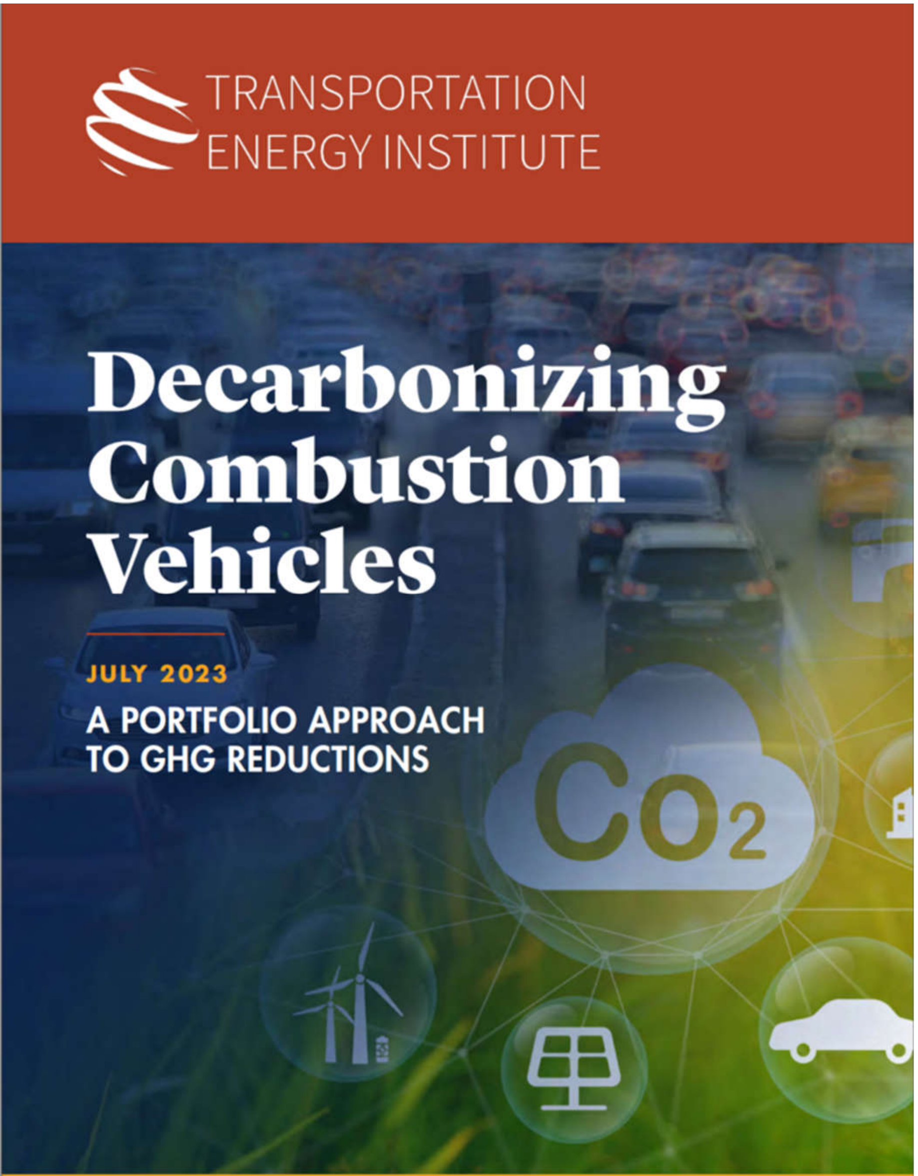

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Summary of Findings

Overview:

Leaders throughout the world, both political and financial, have determined that reducing carbon emissions, especially from transportation, is a top priority. Many have implemented policies to support the transition of the market away from internal combustion engine vehicles (ICEVs) and towards zero-tailpipe emissions vehicles (ZEVs), like battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs). Yet there are nearly 300 million internal combustion engine vehicles (ICEVs) in the United States and 1.5 billion in the world. In light of these facts and the efforts of the decarbonization movement, the Transportation Energy Institute Board of Advisors commissioned Stillwater Associates to evaluate the current and future opportunities to reduce carbon emissions from ICEVs, both those currently in the market and those yet to be sold.

Report structure

Study is presented in four primary sections, which address key issues as follows:

Part 1 – Prelude

- Establishes the importance of early GHG emissions reductions
- Examines the current vehicle fleet, associated emissions and pace of turnover

Part 2 – Lifecycle Analysis of Options

- Evaluates and compares the lifecycle emissions of ICEV fuel options
- Examines pending developments that could affect the lifecycle emissions of ICEV fuels
- Reviews trends related to criteria pollutant emissions

Part 3 – Biofuels

- Reviews biofuels utilization and projected consumption
- Examines feedstock production and diversification, including opportunities for cellulosic feedstocks
- Reviews regulatory issues affecting biofuels

Part 4 – Market Transition Requirements

- Reviews feasibility of various low-carbon ICEV fuels, opportunities and challenges to deliver each to market
- Reviews ICE vehicle options for lower carbon operations
- Compares and contrasts ICEV fuels based upon emissions reduction potential, compatibility, cost and market/regulatory hurdles

The value of early carbon mitigation

Greenhouse gases can remain in the atmosphere for more than 100 years. Given the compounding effect of emissions over time, reducing GHG emissions today will have a more profound effect on the environment than waiting to reduce emissions in the future.

TABLE 2. TRANSPORTATION-RELATED GREENHOUSE GAS CONCENTRATIONS AND GLOBAL WARMING POTENTIAL

GREENHOUSE GAS	CONCENTRATION IN ATMOSPHERE*	ATMOSPHERIC LIFETIME	GLOBAL WARMING POTENTIAL
Carbon Dioxide (CO_2)	416 ppm	Varies	1
Methane (CH_4)	1.895 ppm	100 years	29.8
Nitrous Oxide (N_2O)	0.334 ppm	114 years	273

Sources: Argonne GREET Model (anl.gov) using the IPCC Sixth Assessment Report values and the Global Monitoring Laboratory

** As of November 2022*

(Table 2, Page 16)

ICEVs dominate the market

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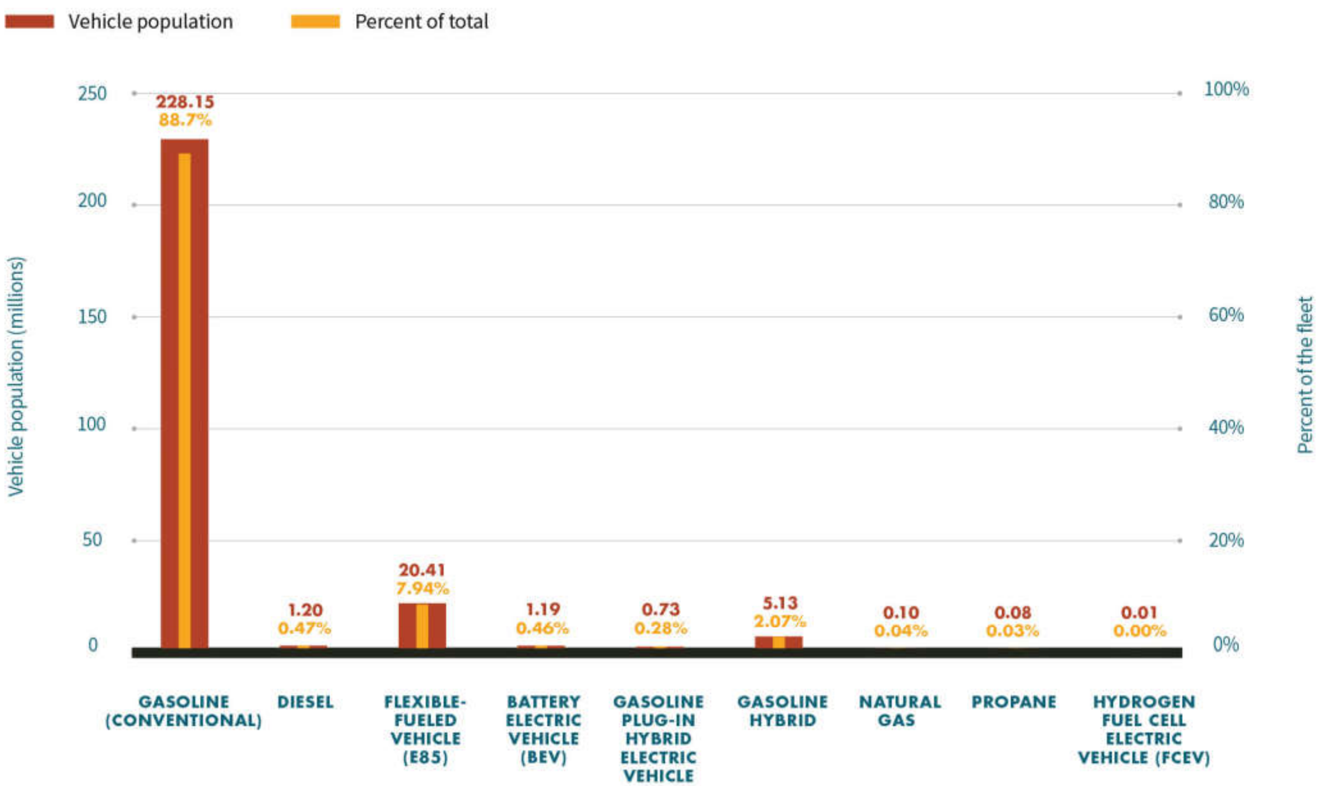
Vehicles equipped with an ICE represented more than 99% of light duty vehicles in operation in the U.S. in 2022.

Given the atmospheric longevity of GHGs, and considering the size of the current ICEV fleet, finding a way to reduce CO_{2e} emissions from these vehicles is of great importance.

FIGURE 2. LIGHT DUTY VEHICLE POPULATION AND PERCENT OF TOTAL FOR FUEL TYPES AND TECHNOLOGIES



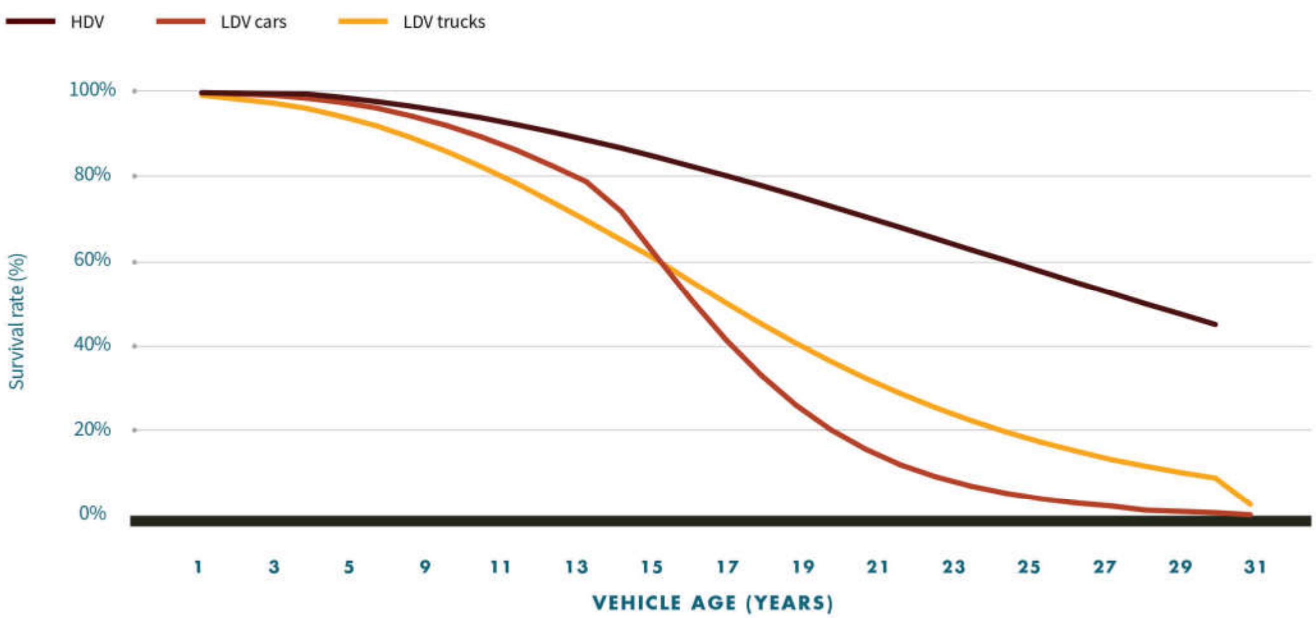
Source: EIA AEO 2022 Vehicle Stock Table 39

(Figure 2, Page 19)

Vehicles stay on the road a very long time

Data from Oak Ridge National Laboratory shows that half of light duty vehicles sold today will still be on the road in 16 years and some will remain in operation for up to 30 years. Heavy duty vehicles have an even longer expected lifespan. Consequently, the transition to new technology vehicles will take a very long time, amplifying the value of reducing emissions from ICEVs.

FIGURE 5. VEHICLE SURVIVAL RATE FOR CARS, TRUCKS, AND HEAVY-DUTY TRUCKS



Source: Oak Ridge National Laboratory Transportation Energy Data Book Edition 40, *Tables 3.14, 3.15, 3.16.*

(Figure 5, page 23)

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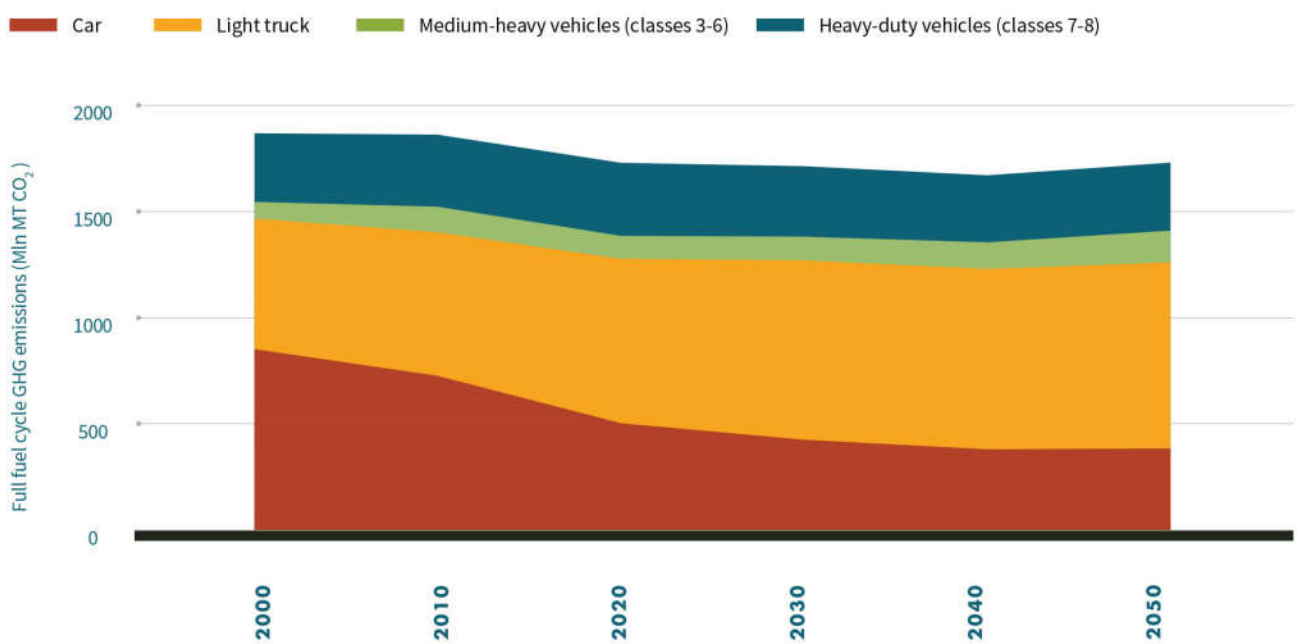
Reducing GHG emissions from fleet is critical

The current fleet emits nearly 2 billion MT CO_{2e} per year. To seriously address carbon emissions, we must solve for the ICEV fleet.

FIGURE 11. ON-ROAD VEHICLES GHG EMISSIONS



Source: Argonne National Labs VISION 2021 Base Case

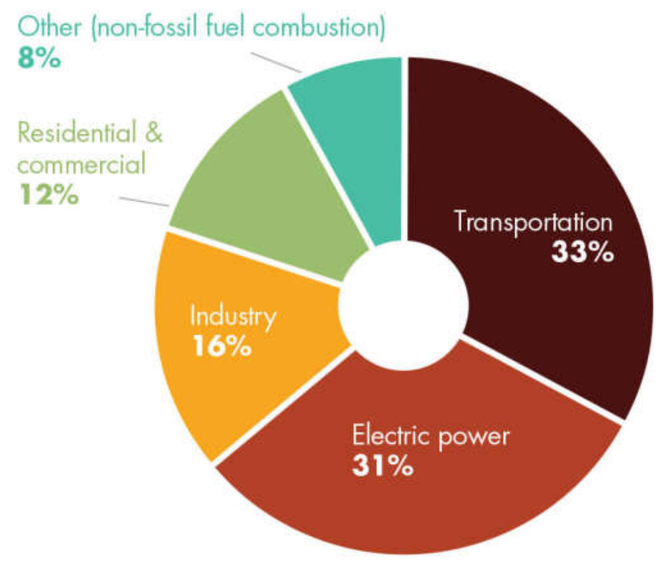
(Figure 11, page 30)

Transportation is the leading source of U.S. GHG emissions

According to the IPCC, anthropogenic (human-caused) CO_2 makes up 5% of the CO_2 inflow into the atmosphere (with natural CO_2 making up the remaining 95%), and U.S. energy use accounts for 13.9% of worldwide anthropogenic CO_2 emissions.

In the U.S., transportation represents 33% and electric power generation represents 31% of national CO_2 emissions.

FIGURE 17. U.S. ANTHROPOGENIC CO_2 EMISSIONS BY SOURCE (1990-2020)



Total U.S. emissions in 2020 = 5,981 million metric tons of CO_2 equivalent (excludes land sector). Percentages may not add up to 100% due to independent rounding.

Source: Overview of Greenhouse Gases | EPA

(Figure 17, page 36)

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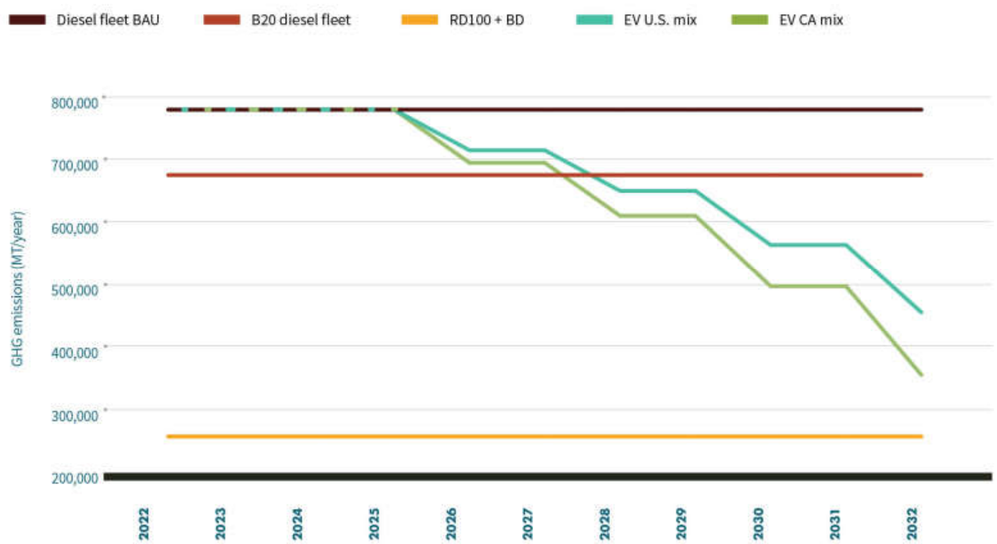
Fuel blends contribute to GHG reductions

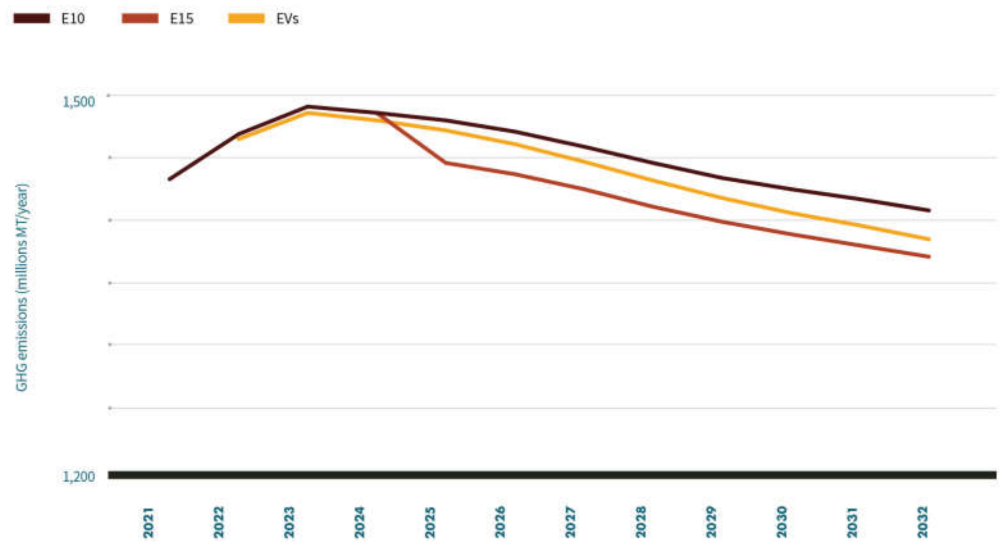
Leveraging existing biofuels options can reduce GHG emissions today and into the future.

FIGURE 20. MEDIUM- AND HEAVY-DUTY VEHICLE ANNUAL GHG EMISSION SCENARIO (2022-2032)



Source: Stillwater assessment using 2021 GREET and EPA MOVES3 assumptions

FIGURE 21. LIGHT- AND MEDIUM DUTY VEHICLE ANNUAL GHG EMISSIONS REDUCTION SCENARIO (2022-2032)



Source: Stillwater assessment using 2022 GREET and EIA AEO 2022 Reference Case

(Figure 20, page 39; Figure 21, page 40)

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Lowering carbon intensity of fuels is key

Retrofitting the existing fleet is not feasible, so to reduce GHG emissions we must reduce the life cycle carbon intensity (the amount of GHG emitted per unit of energy) for the fuel consumed by ICEVs. This table shows the current carbon intensity of existing fuels – but there are opportunities to reduce the CI of these base products.

TABLE 5. FUEL CARBON INTENSITY ASSUMPTIONS

FUEL TYPE	CARBON INTENSITY (gCO_2e/MJ)	EER-ADJUSTED CARBON INTENSITY (gCO_2e/MJ)
Gasoline (E0, E10, E15)	93, 91, 89	
Diesel	91	
Natural Gas (CNG / LNG)	75 / 77	
Ethanol (100%)	57	
Ethanol (E85)	64	
Biodiesel (B20)	80	
Biodiesel (100%)	36	
Renewable Diesel (100%)	34	
Electricity (U.S. mix)	130	Light Duty, 33; Heavy Duty, 33
Hydrogen (gas / liquid)	93 / 134	Light Duty, 48 / 69; Heavy Duty, 44 / 64
Propane	79	

Note: Uses a 2021 sales-weight average technology share to GREET fuel economy estimates, to determine LD EV EER of 3.9 and 1.9 FCV. The simple average of GREET 2022 LM&H duty vehicle EERs is 3.9 and 2.1 for EVs and FCEVs, respectively.

Source: 2022 GREET model

(Table 5, page 45)

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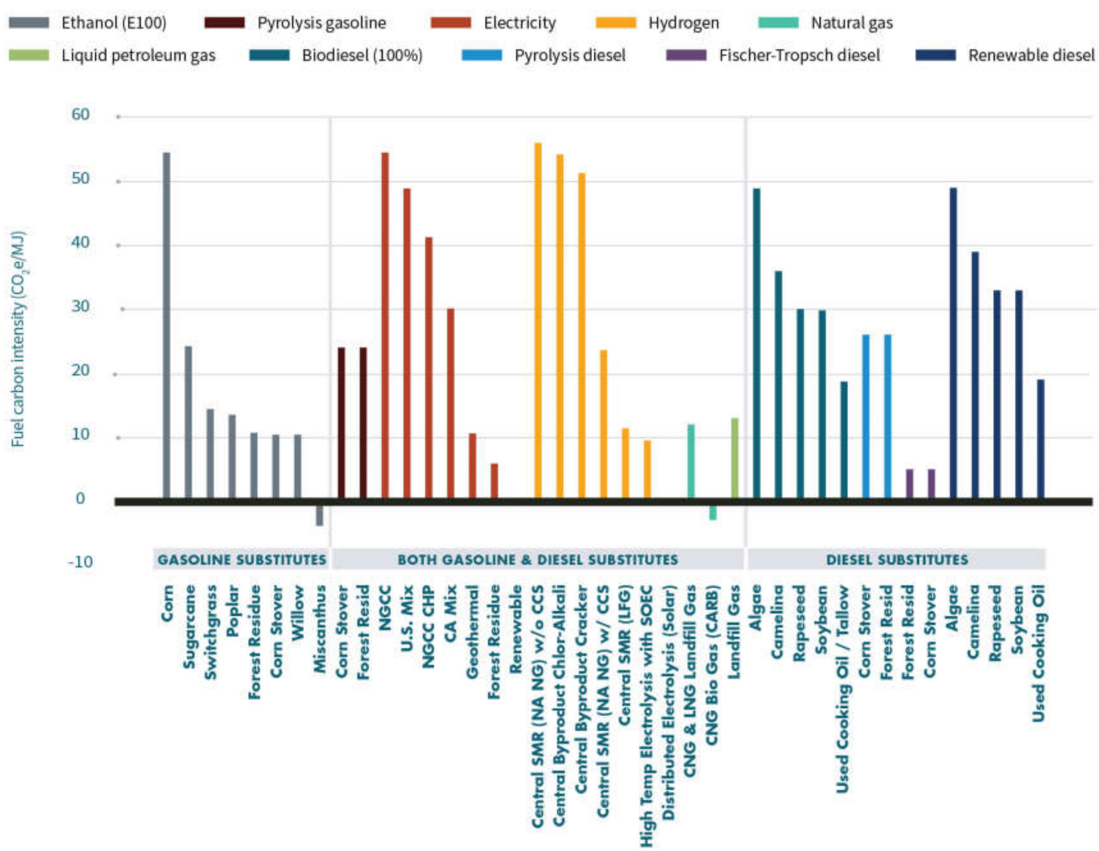
Fuel options with a low life cycle CI are available

Figure 22 shows the GHG reduction potential from 41 existing transportation fuel options relative to gasoline at 90 gCO_{2e}/MJ. The list was restricted to those that provide GHG reductions similar to or greater than EVs fueled with U.S. mix electricity (excluding coal).

There are at least 24 biofuel sources that can be supplied and consumed by existing infrastructure and vehicles today that deliver a carbon intensity at or below that achieved with EVs.

Note: The fuels listed in Figure 22 are unblended; blend restrictions exist for BD and ethanol.

FIGURE 22. LOW-CARBON FUEL OPTIONS AVAILABLE FOR TRANSPORTATION FUELS



Source: GREET 2021 & 2022. Assumes EV EER of 2.4 and FCEV 1.7.

(Figure 22, page 43)

Options for lower carbon petroleum

There are a variety of opportunities to reduce the life cycle CI of petroleum products, many of which yield economic benefits as well

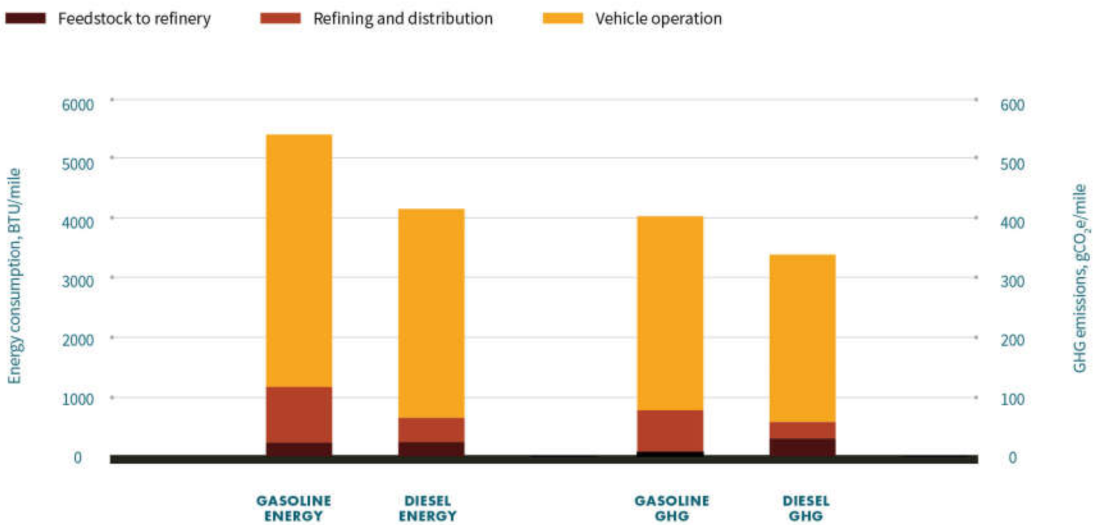
Crude Oil Production:

- Leverage renewable energy for power needs, in place of fossil natural gas
- Reduce flaring and fugitive emissions

Refining and distribution:

- Increase energy efficiency through process optimization, thermal integration, increased insulation and elimination of steam leaks
- Leverage renewable electricity and renewable natural gas to supply necessary power for operations
- Use carbon capture and storage where possible, most easily implemented on the fluid catalytic cracker and hydrogen production systems, which could reduce GHG emissions by 15% for gasoline production and 30% for diesel production
- Convert steam turbine drivers with electric motors
- Use renewable natural gas to produce hydrogen

FIGURE 24. ENERGY CONSUMPTION AND GHG EMISSIONS FROM PRODUCTION AND USE OF GASOLINE AND DIESEL



Source: GREET model, Stillwater analysis

(Figure 24, page 48)

Options for lower carbon biofuels

Feedstock Production –

Most GHG emissions come from diesel used in equipment and the application of nitrogen-based fertilizers.

- Fuel equipment with biodiesel or renewable diesel
- Use low fertilizer-dependent seeds to reduce nitrogen application
- Implement sustainable agronomic practices
- Use corn kernel fiber to produce ethanol (EPA pathway approval pending)

Plant Operations –

Most GHG emissions come from use of natural gas and electricity to power operations.

- Ethanol plants located near livestock feedlots can distribute wet distillers grains and solubles (WDGS), reducing energy needed to produce dry DGS
- Leverage renewable natural gas and electricity
- Invest in more efficient technologies, such as membrane dryers
- Implement carbon capture and storage, most effectively on the fermenter effluent at a dry mill plant, which could reduce CO_{2e} emissions by about 40%

(Pages 51-54)

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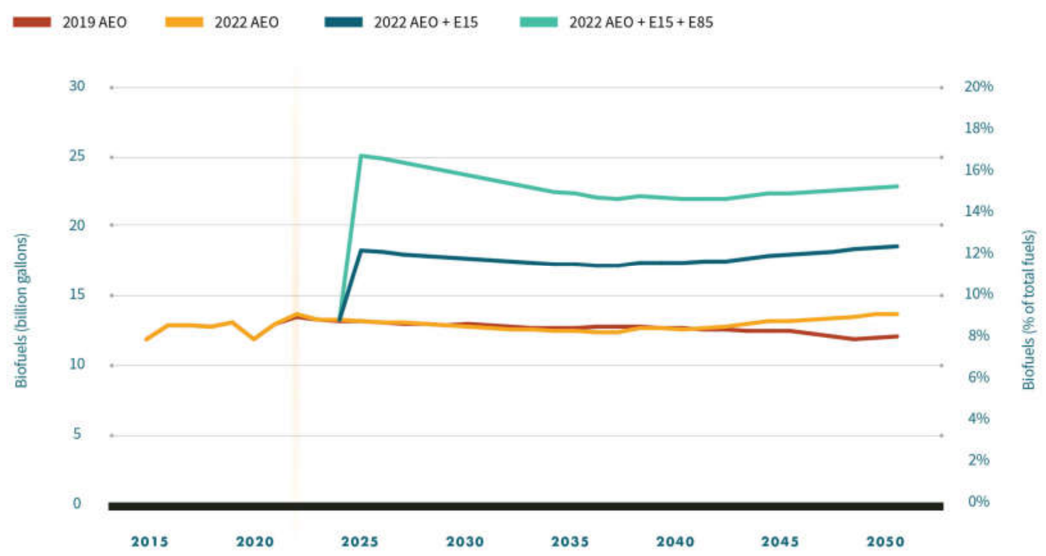
Increasing use of low carbon fuels in vehicles

There are low CI fuels currently available in the market that could be used more broadly.

- **E15:** The vast majority of vehicles in operation are legally permitted to operate on E15, which has a lower CI than E10. If all U.S. gasoline demand were converted from E10 to E15, the transportation system would reduce GHG emissions by 22,000 metric tons per year. (Page 54)
- **E85:** Expand the use of E85 and mid-level ethanol blends in flexible fuel vehicles
- **B20:** Most infrastructure and vehicles are approved to operate on biodiesel blends up to 20%, which would reduce the fuel's carbon intensity 13% below diesel fuel
- **RD:** All diesel-powered vehicles can operate on renewable diesel, which has a carbon intensity that is 63% lower than diesel.
- **RNG:** All natural gas vehicles can run on renewable natural gas, which can have a negative CI score. RNG currently accounts for about 84% of CNG and LNG used in transportation in the U.S.

FIGURE 34. BASELINE TOTAL BIOFUEL DEMAND PROJECTIONS

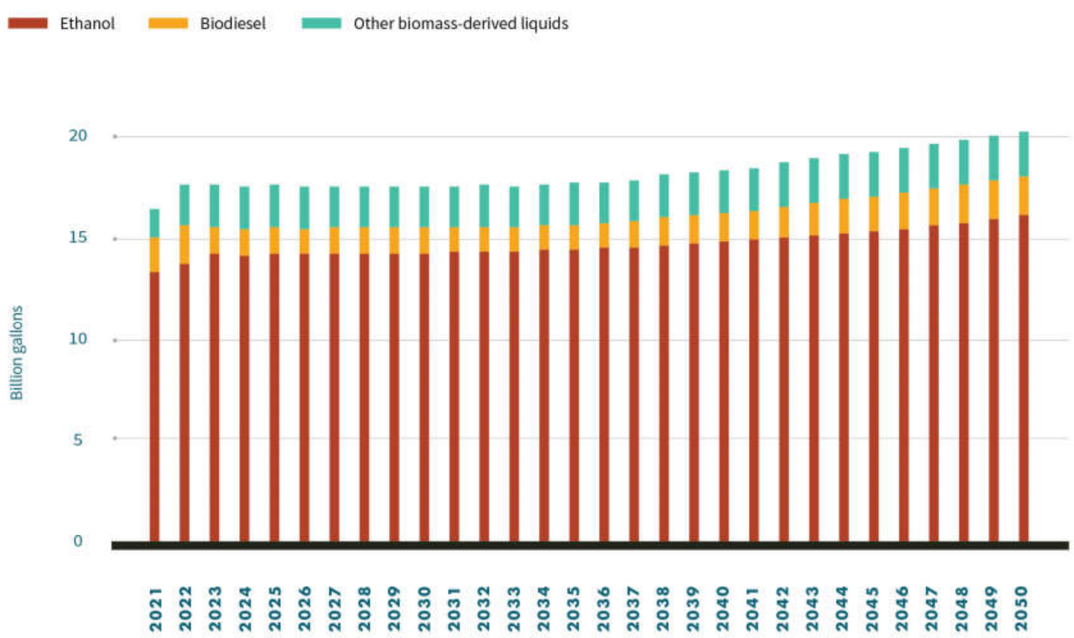


Source: EIA AEO 2019 and 2022 Reference Case projections

(Figure 34, page 73)

Feedstock availability for additional biofuels

FIGURE 47. PROJECTED BIOFUEL PRODUCTION IN THE U.S. IN THE AEO REFERENCE CASE



Source: AEO 2022

Feedstocks Supply:

- Studies show US has potential to produce over a billion tons of biomass
- Agriculture has achieved steady improvements in per-acre yields for corn and soybeans
- Market has been increasing use of inedible tallow, used cooking oil and distillers corn oil for biofuel production
- There is growing potential for nonfood feedstocks, such as oilseeds from cover crops like pennycress, carinata and camelina
- Half of the cellulosic biofuel target of the RFS could be met by harvesting agricultural residues
- The other half could be met by producing energy crops, like miscanthus, on marginal land without diverting productive cropland. (Certain economic and regulatory conditions would be required for such energy crops to be viable)

(Figure 47, page 99)

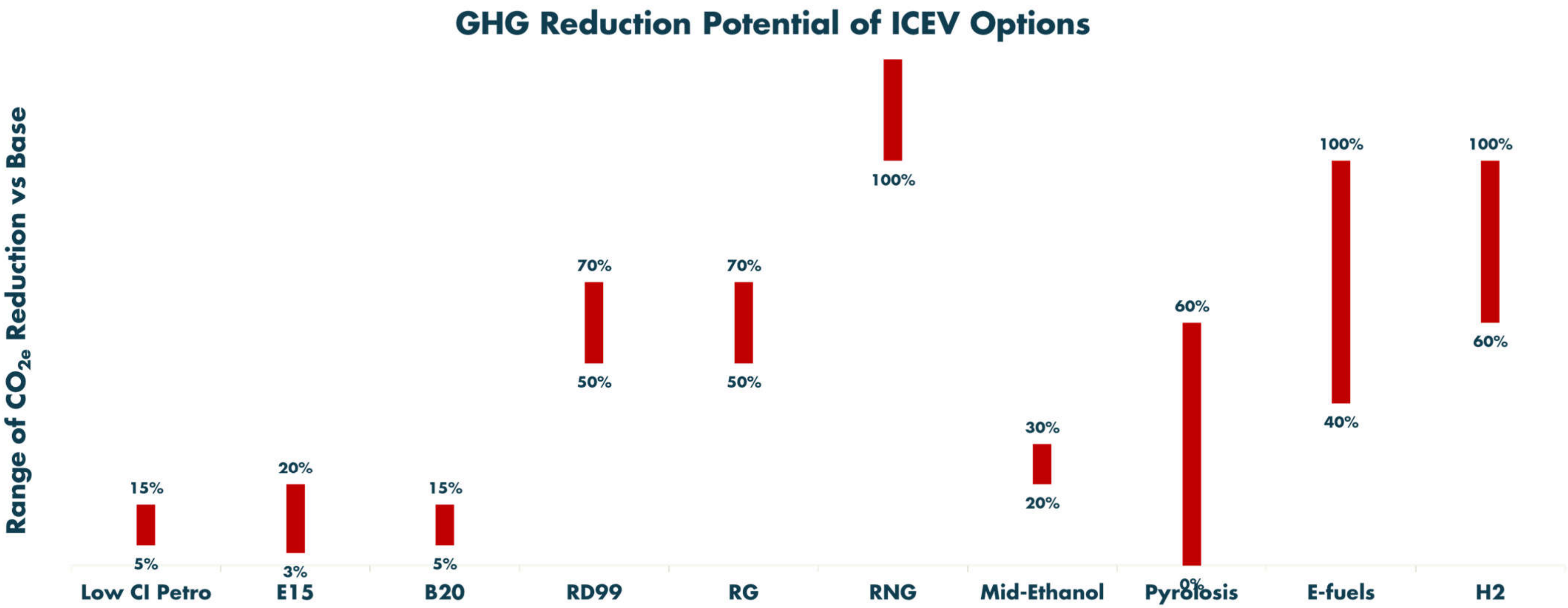
Portfolio of low-carbon ICEV fuels

Each option faces challenges and no option is a silver bullet solution for all applications. However, with key adjustments to regulations or market developments, each may have an opportunity to contribute to a lower carbon transportation sector.

Currently Available for ICEVs	Currently Available for AFVs	Potential Fuels
Ethanol	Renewable Natural Gas	Pyrolysis Fuels
Biodiesel	Renewable Propane	Biomass to Liquids
Renewable Diesel	E85	E-fuels
Renewable Gasoline		Hydrogen
Fischer-Tropsch Diesel		

Range of GHG reduction potential

The final tables in the report show the potential GHG reduction of various options. Below is a graphical representation of those ranges, demonstrating that meaningful reductions are available from ICEVs in the near- and mid-term.



(Data drawn from Table 16, page 176)

Feasibility of low-carbon fuel options

Tables 16 and 17 (next two slides) show the time, costs and regulatory/marketplace developments required to bring these fuel options to market. This table summarizes some of those analyses.

Feasibility	Low Carbon Options	Benefits	Barriers
Available Today	E10/E15/E85 B20 RD100 RNG	Drop-in solutions for existing vehicles	Declining FFV population E15/E85 fueling infrastructure BD/RD feedstocks Limited NGV population
Near-Term Potential	Higher ethanol blends Non-food feedstocks Carbon capture and storage Advanced ICEV technologies	Deeper decarbonization with near-to-market technologies	New vehicles and fuel infrastructure required Support for growers of non-food feedstocks Regulatory certainty
Longer-Term Potential	Cellulosic ethanol FT diesel E-Fuels	Increased volume potential Deeper decarbonization Greater variability in the liquid fuel mix	Technological development to make economic Surplus low-carbon power

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Each low CI option was evaluated

TABLE 16. COMPARISON OF ALTERNATIVES TO DECARBONIZE ICEVs

OPTION	PAIRED VEHICLE TECH-NOLOGY	STATUS/ POTENTIAL OF FUEL PRODUCTION	COMPATIBLE WITH CURRENT FUEL DELIVERY LOGISTICS?	COMPATIBLE WITH CURRENT FUEL DISPENSING SYSTEM?	CONSUMER ACCEPTANCE	SHORTEST TIME TO FULL MATURITY	RELATIVE UNSUBSIDIZED COST OF TRANSITION	CARBON EMISSIONS REDUCTION VS. CURRENT FLEET & FUELS
Current ULSD & E10 Gasoline	Current Gas ICEV	Current	Yes	Yes	Yes	Current	None	base
Reduced CI Gasoline & Diesel	Current Gas ICEVs	Current	Yes	Yes	Yes	Mid-Term	Low-Med	5-15%
Ethanol (E15)	Current Gas ICEV	50% ethanol increase	Yes, mostly	Yes	Yes	Near-Term	Low	3%
Ethanol (E15)	Plug-in Hybrids (PHEVs)	50% ethanol increase	Yes	Yes	Yes	Mid-Term	Low-Med	20%
Biodiesel (B5)	Current Diesel ICEV	Requires ~100% increase over current production	Yes	Yes	Yes	Near-Term	Low-Med	<5%
Biodiesel (B20)	Current Diesel ICEV	Requires ~700% increase over current production	Yes, mostly	Yes	Except in colder regions	Mid-Term	Med	5-15%
Renewable Diesel (R99)	Current Diesel ICEV	Requires 20x increase over current production	Yes	Yes	Yes	Mid-Term	Low-Med	50-70%
Renewable Diesel (R99)	Plug-in Hybrids (PHEVs)	Requires 20x increase over current production	Yes	Yes	Yes	Mid-Term	Med	55-85%
Renewable Gasoline (RG)	Current Gas ICEV	Niche fuel, scaling challenges w/o cellulosic, pyrolysis, BTL, or e-fuels breakthrough	Yes	Yes	Yes	Mid-Term	Med	50-70%
Renewable Natural Gas (RNG)	NGV	Small	No	No	Risks	Near-Term	Med	100+%
Renewable Propane (RP)	LPG ICEV	Small	No	No	Likely	Near-Term	Low-Med	60-70%
Ethanol (Intermediate Blends	Dedicated Vehicle	3-4x increase over current production	Yes	No	Likely	Long-Term	Med	20-30%
Ethanol (E85)	FFV	500% ethanol increase	No	Yes	Maybe	Long-Term	Med	25%
Biodiesel (B20+)	Current Diesel ICEV	400-2000% increase	No	No	Maybe	Long-Term	Med-High	40-60%
Cellulosic Ethanol	Current Gas ICEVs	Tiny with high potential	Yes	Yes	Yes	Long-Term	Very High	5-10%
Cellulosic Diesel	Current Diesel ICEVs	Tiny with high potential	Yes	Yes	Yes	Long-Term	Very High	60-90%
Pyrolysis Fuels	Current Gas & Diesel ICEVs	technology not yet commercialized; sizeable potential	Yes	Yes	Likely	Long-Term	Very High	0-60%
FT Diesel (BTL)	Current Diesel ICEVs	Tiny with high potential	Yes	Yes	Likely	Long-Term	Very High	20-100+%
E-Fuels	Current Gas & Diesel ICEVs	High potential technology not yet commercialized	Yes	Yes	Yes	Long-Term	Very High?	40-100%
Hydrogen (H_2)	H_2 ICEV	FT of RNG	No	No	Challenged	Long-Term	Very High	60-100%+
ICEV Improvements	NA	NA	Yes	Yes	Yes	Contin-uous	Low	20-50%

(Table 16, page 176)

Each low CI option was grouped into tiers

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TABLE 17. TIERED ICEV CARBON-REDUCTION POTENTIAL OF ALTERNATIVE OPTIONS (Table ES-1 in Executive Summary)

TIER	OPTION	PAIRED VEHICLE TECHNOLOGY	CARBON REDUCTION VS. CURRENT FLEET & FUELS	POTENTIAL IMPACT	REGULATORY	MARKETPLACE
0	Current ULSD & E10 Gasoline	Current Gas ICEV	base	N/A	N/A	N/A
1	Biodiesel (B5)	Current Diesel ICEV	<5%	small	N/A	Increased feedstock generation
1	Ethanol (E15)	Current Gas ICEV	3%	small	Wider EPA approval	Infrastructure build-out
1	Renewable Gasoline (RG)	Current Gas ICEV	50-70%	small	Continuation/expansion of existing regulatory incentives	Scalability of production
1	Renewable Natural Gas (RNG)	NGV	100+%	small	Continuation/expansion of existing regulatory incentives	Conversion of vehicles and fueling infrastructure
1	Renewable Propane (RP)	LPG ICEV	60-70%	small	Continuation/expansion of existing regulatory incentives	Conversion of vehicles and fueling infrastructure
1	Reduced CI Gasoline & Diesel	Current ICEVs	5-15%	small to medium	Strengthened regulations on upstream flaring and methane emissions; continued move to renewable marine fuels; continued regulatory incentives for CCUS and use of renewable energy at refineries	Refinery investment in CCUS and usage of renewable energy
1	Ethanol (E15)	Hybrids (HEV & PHEV)	20%	small to medium	E15 approval and increased incentives for hybrid expanded vehicle purchases	Conversion to hybrid vehicle fleet and expansion of E15 infrastructure
1	Biodiesel (B20)	Current Diesel ICEV	5-15%	small to medium	N/A	Increased feedstock generation
1	Ethanol (E85)	FFV	15-25%	small to medium	Increased incentives for FFV production and purchase (adjustments to CAFE) and potential aftermarket equipment certification program for FFV conversions	Fueling infrastructure expansion and increased vehicle and fuel availability
1	Renewable Diesel (R99)[3]	Current Diesel ICEV	50-70%	medium	Continuation/expansion of existing regulatory incentives	Increased feedstock generation
1	Renewable Diesel (R99)	Hybrids (HEV & PHEV)	55-85%	medium	Increased incentives for hybrid vehicles	Conversion to hybrid vehicle fleet and increased feedstock generation
2	Ethanol (Intermediate Blends)	Dedicated Vehicle	5-15%	small	New incentives for development of dedicated intermediate-ethanol-blend vehicle production	Expanded compatible fuel infrastructure
2	Biodiesel (B20+)	Current Diesel ICEV	40-60%	small	Establish ASTM standards	OEM warranty, expanded fueling infrastructure, and increased feedstock generation
2	ICEV Improvements	NA (current fuels)	20-50%	medium	Technology-neutral testing and CAFE standards	Broad OEM roll-out
2/3	Hydrogen (H_2)	H_2 ICEV	60-100%+	small	Substantial financial incentives	Build-out of hydrogen production hubs, expansion of dedicated fueling infrastructure, conversion of vehicle fleet to H_2
3	Cellulosic Ethanol (E10)	Current Gas ICEVs	5-10%	small	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	Cellulosic Diesel	Current Diesel ICEVs	60-90%	medium	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	FT Diesel (BTL)	Current Diesel ICEVs	20-100+%	medium	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	Pyrolysis Fuels	Current Gas & Diesel ICEVs	0-60%	large	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	E-Fuels	Current Gas & Diesel ICEVs	40-100%	large	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost

(Table 17, page 177)

Summary and Conclusions

- There is no single solution for decarbonizing the on-road transportation sector
- ICEVs will comprise a significant portion of the fleet well into the future, despite policy efforts to accelerate a transition to new vehicles
- GHG emissions accumulate and remain in the atmosphere for more than 100 years –
  - Early emissions reductions is critical to achieving environmental objectives
  - This necessitates lowering the carbon emissions from ICEVs and not waiting for the market to transition to new vehicles
- Carbon emissions from the current and future fleet of ICEVs can be reduced through a variety of ways, most notably renewable fuels and ICEV technologies. Combining low carbon fuels with higher efficiency ICEVs and hybrids increases the GHG reduction potential
  - There are at least 24 biofuels that can reduce emissions equal to or more than today's EVs charging from the U.S. electricity grid, even when excluding coal power plants from the mix
  - Reducing emissions by up to 15% with existing fuels would remove up to 300 million MT of CO_{2e} emissions each year
- New fuel options being explored and developed today (e.g., pyrolysis, e-fuels, H2-ICE) show tremendous promise in reducing carbon emissions of ICEVs, but need support to overcome technological, cost and market hurdles.
  - Reducing emissions by at least 40% with innovative fuels would remove 800 million MT of CO_{2e} emissions each year
- Given the varying degrees of viability and timing uncertainties, a portfolio approach to ICEV decarbonization is advisable.
  - A portfolio approach for ICE fuels and future vehicle technologies will result in both ICEVs' (near-term) and ZEVs' (longer term) roles in minimizing transportation carbon emissions being realized.