Decarbonizing ICEVs – A Key Step in the Energy Transition

SwRI LCA for Transport Symposium

November 16, 2023

Disclaimer

Stillwater Associates LLC prepared this report for the sole benefit of Southwest Research Institute Life-Cycle Analysis for Transport Symposium attendees.

Stillwater Associates LLC conducted the analysis and prepared this report using reasonable care and skill in applying methods of analysis consistent with normal industry practice. All results are based on information available at the time of preparation. Changes in factors upon which the report is based could affect the results. Forecasts are inherently uncertain because of events that cannot be foreseen, including the actions of governments, individuals, third parties, and competitors. Nothing contained in this report is intended as a recommendation in favor of or against any particular action or conclusion. Any particular action or conclusion based on this report shall be solely that of Southwest Research Institute Life-Cycle Analysis for Transport Symposium attendees.

NO IMPLIED WARRANTY OF MERCHANTABILITY SHALL APPLY. NOR SHALL ANY IMPLIED WARRANTY OF FITNESS FOR ANY PARTICULAR PURPOSE.

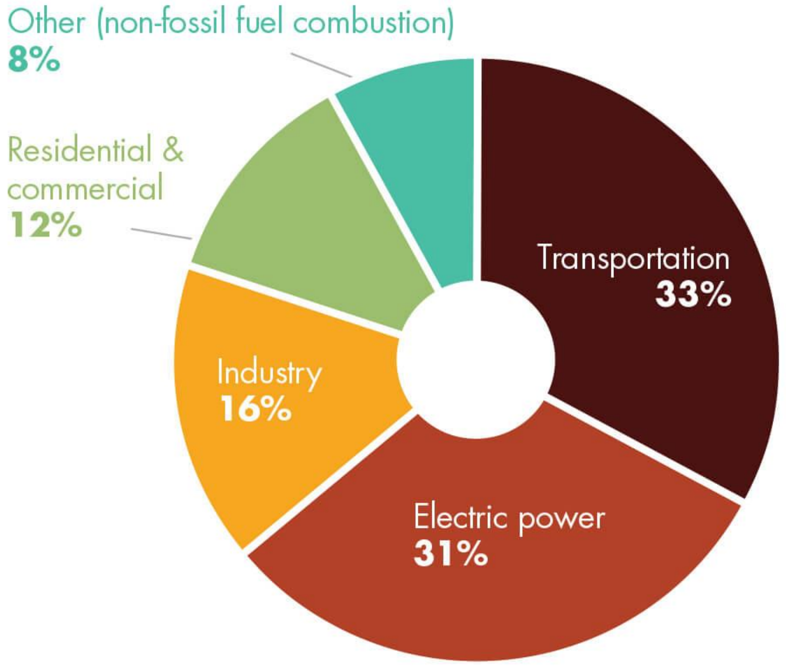
Fueling the future of transportation energy with trusted industry experience

1. Stillwater Associates leverage decades of experience to help clients navigate transportation fuels market challenges. **We see things others miss.**
2. Our clients: government agencies, oil and renewable fuels companies, trade associations, technology developers, private equity firms, and law firms.
3. Leading experts on low carbon fuel (LCF) programs, the federal Renewable Fuel Standard (RFS), and the Inflation Reduction Act of 2022 (IRA).
4. **Stillwater's LCFS and C&T Newsletters and suite of Credit Price Outlooks** offer producers, importers, traders, and investors the right information to make smart credit market decisions.
5. **Questions?** Our team of experts is available to provide specific analysis and tailored strategy for your needs.

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

The value of early carbon mitigation

1. Greenhouse gases can remain in the atmosphere for more than 100 years.
2. 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

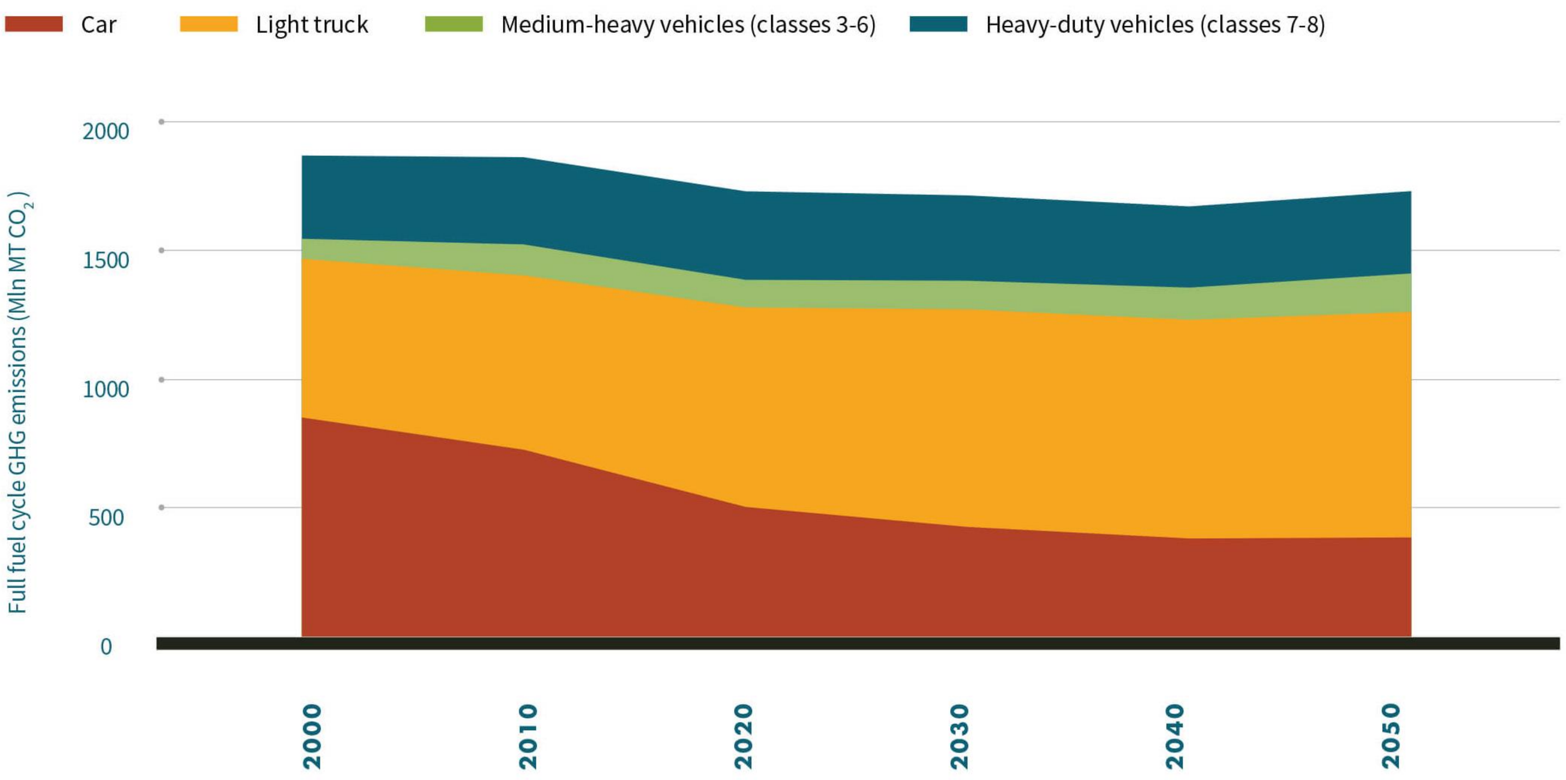
** As of November 2022*

(Table 2, Page 16)

Reducing GHG emissions from fleet is critical

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

FIGURE 11. ON-ROAD VEHICLES GHG EMISSIONS



Source: Argonne National Labs VISION 2021 Base Case

(Figure 11, page 30)

Maximizing GHG Reductions

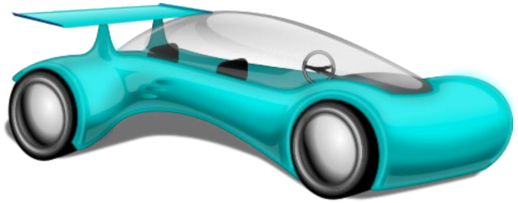
ZEVs

Decarbonize the power grid as fleet penetration grows

Existing ICEVs

Decarbonize the fuel mix which they already use

Future ICEVs

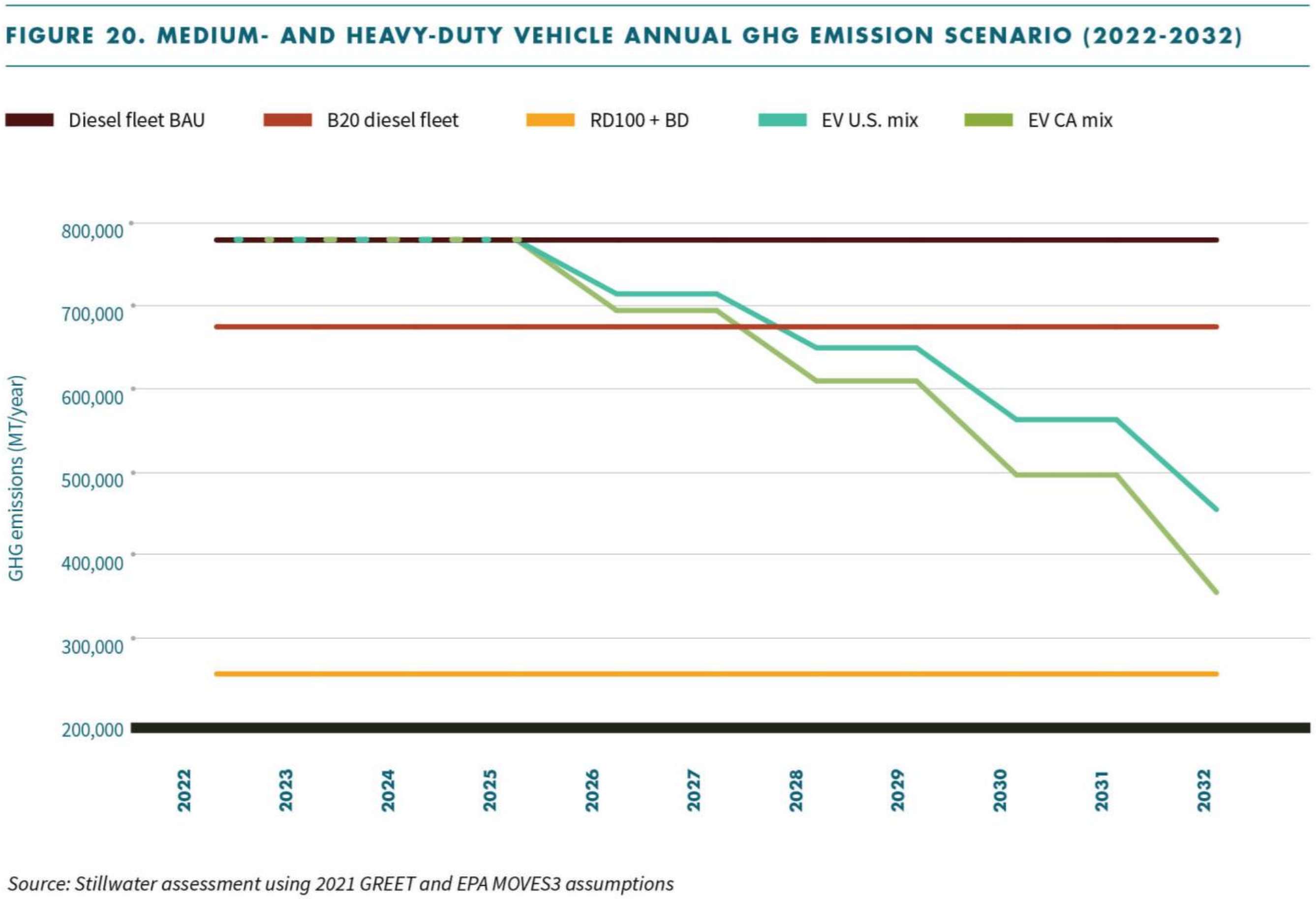


Continued progress in ICEV technology **plus** decarbonization of fuel supply

Most options require significant investment in production and infrastructure.

Scenarios – Decarbonization of Diesel Fleet

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



Hypothetical fleet of 10,000 Medium- and Heavy-Duty trucks

Cases

1. Base Case – 100% petroleum diesel
2. Immediate transition of all fuel to B20
3. Immediate transition to renewable diesel + biodiesel
4. 20% of fleet replaced each year with EVs (starting in 2026, U.S. and California power grid mix)

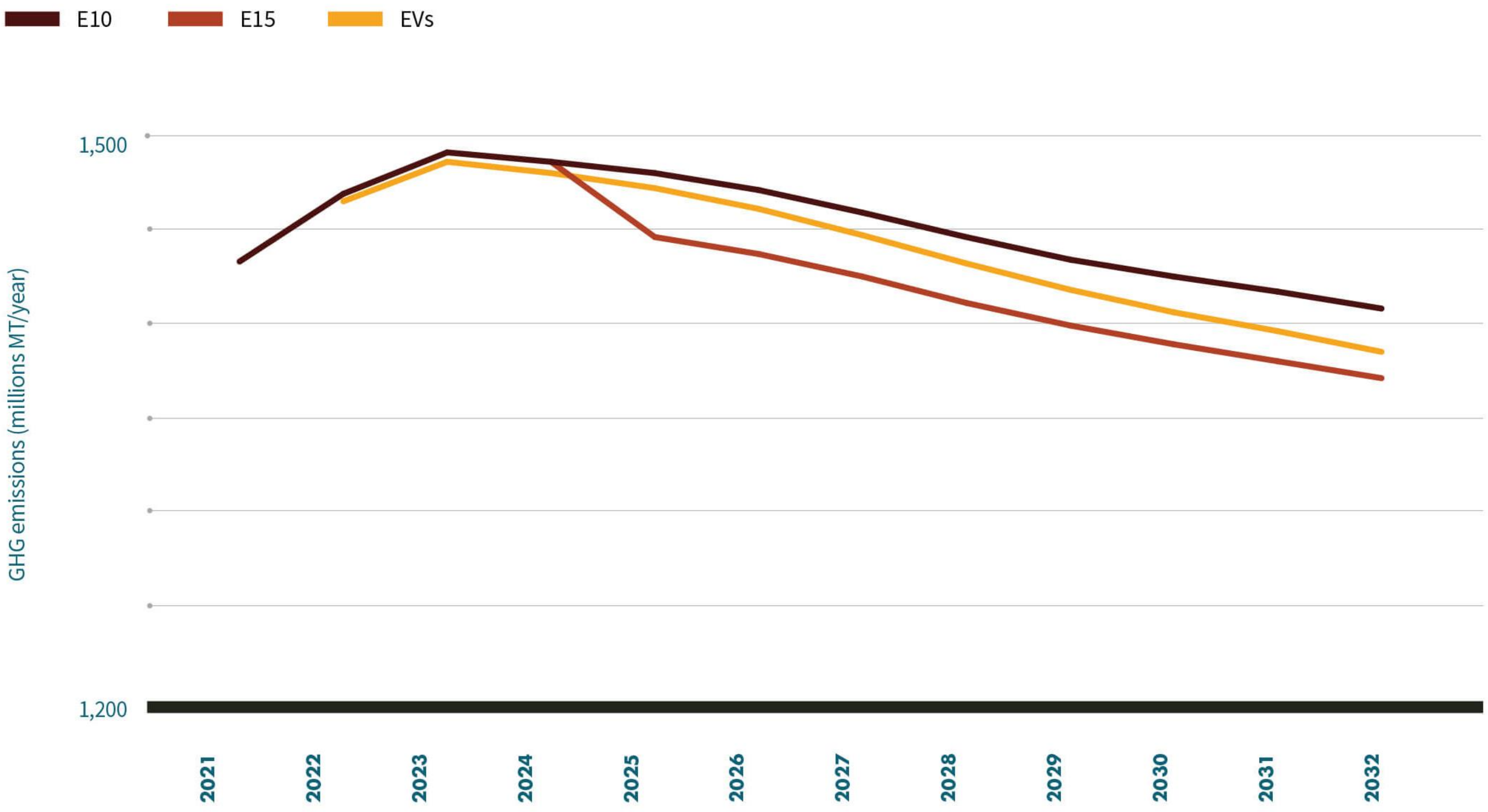
- In 2Q2023, the California diesel pool was 54% renewable diesel and 7% biodiesel.
- Displacement of petroleum diesel is expected to continue increasing.

(Figure 20, page 39)

Scenarios – Pace of LD Transition

1. Gasoline demand increased 2021-23 with Covid recovery
2. Black line shows pace of emissions decline with E10 and no additional electrification
3. Red line shows the impact of replacing all E10 with E15 starting in 2025
4. Yellow line shows anticipated reductions due to electrification (EIA 2022 AEO)

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

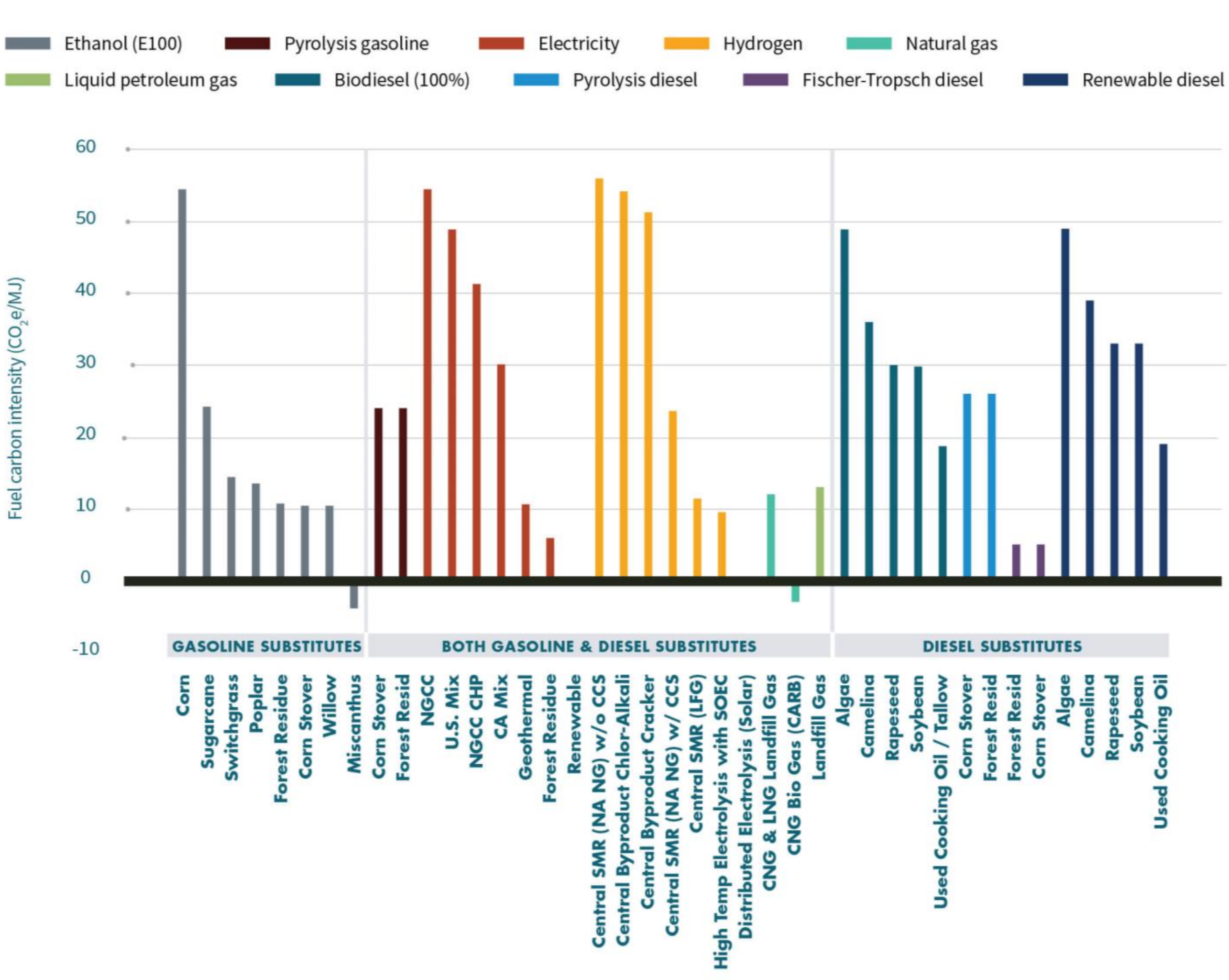
(Figure 21, page 40)

Fuel options with a low life cycle CI are available

1. GREET Model evaluates 41 existing transportation fuel options relative to gasoline at 90 gCO_2e/MJ.
2. Illustrated options all offer GHG reductions similar to or greater than EVs fueled with U.S. mix electricity
3. 24 biofuel options are compatible with existing infrastructure and vehicles and deliver GHG emissions at or below that achieved with EVs charged with the U.S. grid mix.
4. Low-carbon fuels such as E15, E85, B20, RD, and RNG are currently available in the market and could be used more broadly with existing vehicles.

Note: The fuels listed here 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.

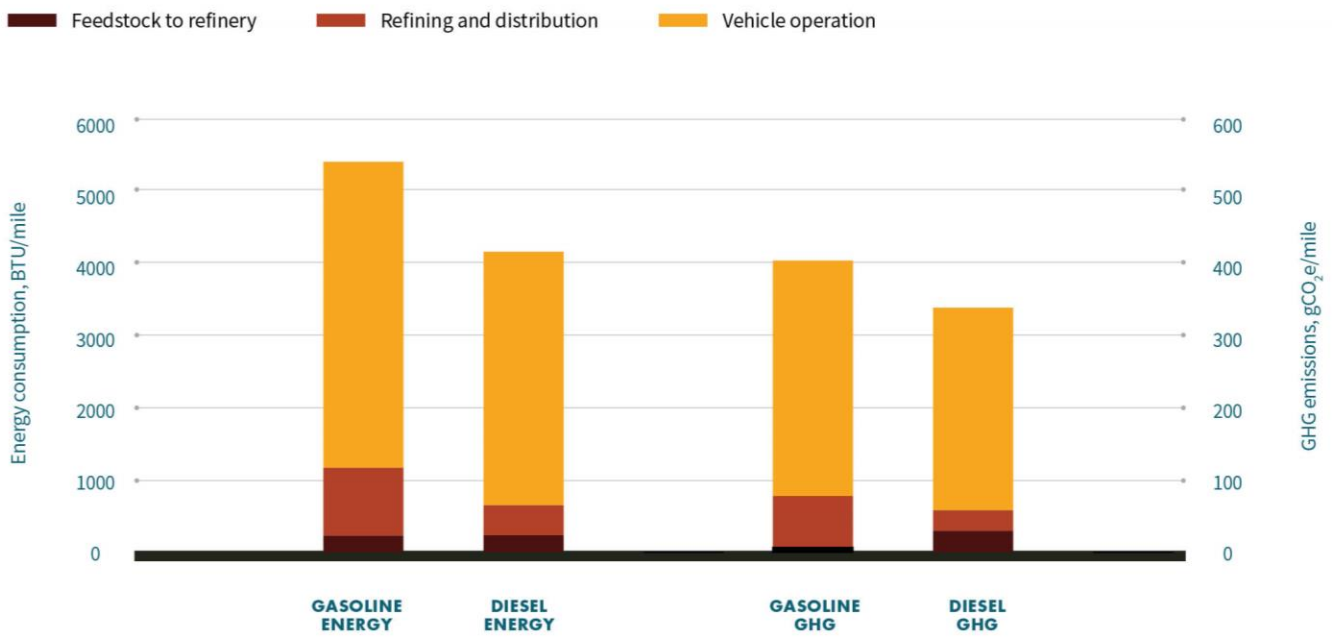
(Figure 22, page 43)

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.

1. **Crude Oil Production:**
   a. Renewable energy for power needs
   b. Reduce flaring and fugitive emissions
2. **Refining and distribution:**
   a. Increase energy efficiency
   b. Use renewable electricity and renewable natural gas
   c. Use carbon capture and storage at optimal locations; could reduce GHG emissions by 15% for gasoline production and 30% for diesel production
   d. Increase electrification
   e. 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 currently come from diesel used in equipment and nitrogen-based fertilizers.

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

Options for lower carbon biofuels – Plant Operations

Most GHG emissions currently come from natural gas and electricity usage.

image source: Reuters

1. Maximize production of Wet Distillers Grains with Solubles (WDGS) vs Dry Distillers Grains with Solubles (DDGS) – location dependent
2. Use renewable natural gas and electricity
3. Invest in more efficient technologies such as membrane dryers
4. 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%

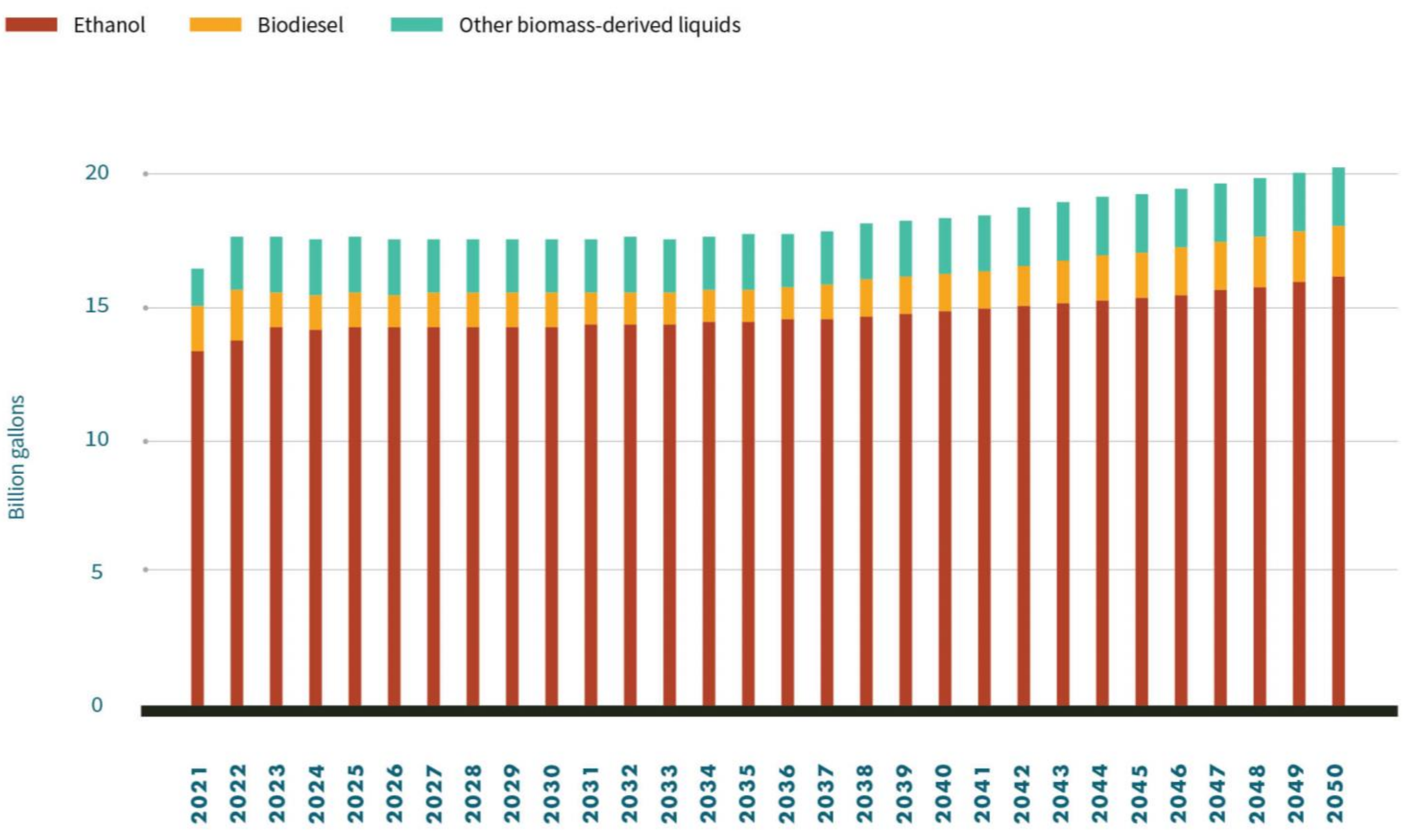
(Pages 51-54)

Feedstock availability for additional biofuels

The U.S. has potential to produce over a billion tons of biomass annually.

1. Steady **improvements in per-acre yields** for corn and soybeans
2. Use of inedible tallow, used cooking oil and distillers corn oil for biofuel production
3. **Nonfood feedstocks** such as oilseeds from cover crops like pennycress, carinata and camelina
4. Half of the cellulosic biofuel target of the RFS could be met by harvesting **agricultural residues**
5. 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. PROJECTED BIOFUEL PRODUCTION IN THE U.S. IN THE AEO REFERENCE CASE



Source: AEO 2022

(Figure 47, page 99)

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%

** Excerpt from full table **

(Table 16, page 176)

High-Level Conclusions from Fuels Evaluation

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

Summary

1. Decarbonizing ICEVs is required to address climate change
   a. Transportation is largest source of U.S. GHG emissions
   b. GHGs have long atmospheric lifetimes – prompt action is prudent
   c. ICEVs will comprise the bulk of the U.S. fleet for many years even with policies promoting EV adoption
2. Many options exist to decarbonize ICEVs
   a. Biofuels are and will continue to be the lowest-hanging fruit
   b. Expanding beyond current options requires a policy environment which supports investment in growing existing and near-commercial options
3. For more details see our recent study – "Decarbonizing Combustion Vehicles: A Portfolio Approach to GHG Reductions" available at https://www.transportationenergy.org/research/reports/