REPORT

Transforming the Transportation Fuels Marketplace:

The Consumer Reports Low-Carbon Fuel Standard Initiative

MOHAMMAD TAYARANI, PHD

QUINTA WARREN, PHD

NOVEMBER 2022

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Acknowledgement

The authors of the report would like to take this opportunity to thank their colleagues at Consumer Reports for their valuable contribution to the report: Debra Kalensky, Scott Medintz, Tracy Anderman, David Friedman, Chris Harto, Dylan Jaff, Sierra Wilbar and Jake Fisher.

1 Executive Summary

Low-carbon fuels offer enormous potential benefits, but also face great challenges. This report describes the benefits of and barriers to low-carbon fuels (LCFs), examines the state of public opinion toward them, and explores potential policy principles that would promote their use.

Context

The U.S. transportation sector is responsible for 27% of greenhouse gas (GHG) emissions, and compared with other sectors, has the highest increase in its GHG emissions since 1990.[1] The vast majority of those emissions, about 83%,[2] come from cars, trucks, and buses. Beyond its effects on climate change, transportation has proven economic and health impacts on consumers. It's the second-largest expenditure category for American families, and it greatly contributes to air pollution in urban areas, posing a threat to public health, particularly among racial and ethnic minorities and low-income communities.

Two large-scale shifts, however, have the potential to dramatically reduce both toxic and GHG emissions: electrification of the transportation sector and the proliferation of other low-carbon fuels (LCFs).

Benefits and Barriers

Environmental impact is among the primary benefits of low-carbon fuels, so we look closely at factors that contribute to or minimize the carbon intensity—i.e., the amount of carbon dioxide produced while generating a unit of energy—of various LCFs. They range from 65 grams to 345 grams of CO_2 equivalent (gr CO_2e) per mile, compared with 410 gr CO_2e for traditional gasoline.

Cost is another significant consideration. Consumer support for LCFs relies to a great extent on whether they lower the overall cost of vehicle ownership, or at least do not increase it. The outlook for LCFs is generally positive in this respect: Electric vehicles (EVs) can cost 10% to 40% more to purchase than an internal combustion engine counterpart, but generally have lower total lifetime ownership costs when you consider their lower fuel and maintenance costs. Meanwhile, some (but not all) biofuels offer cost savings over traditional fossil fuels.

Accessibility is another important factor. Light-duty vehicle models that run on low-carbon fuels, primarily electric vehicles, have recently proliferated. The number of all-electric models on the market has increased threefold since 2015. Biofuel-based models have not kept pace, however.

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1 U.S. Environmental Protection Agency, "Greenhouse Gas Inventory Data Explorer," 2020, https://cfpub.epa.gov/ghgdata/inventoryexplorer.

2 U.S. Environmental Protection Agency, "Fast Facts on Transportation Greenhouse Gas Emissions," 2020, https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions.

Another aspect of accessibility is the ease (or difficulty) of charging and refueling, and here the current status is less encouraging. Among LCFs, electric vehicles have the largest public charging infrastructure network. But DC fast chargers, which enable drivers to charge EVs to 80% capacity in 20 to 30 minutes, are still not readily available in many areas.

Distribution of other low-cost fuels is an even greater challenge. Ethanol has the second-largest distribution network with 4,230 stations, but they are mostly located in the Midwest. There are about 827 biodiesel stations nationwide, but 18 states lack even a single station. Only 53 stations, located mostly in California and Texas, offer liquefied natural gas; and only 54 stations, all in California, offer hydrogen to the public.

Public Support and Awareness

Public awareness and support are vital to the success of any policy, LCF-related policies included. Even if such policies were implemented without public support and awareness, their chance of success would be very low because the market is largely driven by public demand.

A 2022 nationally representative survey of 8,027 U.S. adults conducted by CR from January 27 to February 18, 2022, on consumer awareness of and attitudes toward battery-electric vehicles and LCFs revealed that 25% of Americans had previously heard about drop-in low-carbon fuels, which are chemically similar to petroleum and diesel fuels and can therefore be used directly within existing internal combustion engines. And 67% of them said they would be very likely or somewhat likely to use these fuels in their personal vehicle if they were priced the same as traditional fuel.

Policy Principles

Implementation of Low-Carbon Fuel Standards (LCFSs) can benefit from the following recommendations:

- Transportation accounts for 27% of greenhouse gas (GHG) emissions in the U.S. To address this, there should be a strategy to decarbonize transportation fuels by increasing consumers' options for affordable low-GHG-emitting transportation fuels. This will be most effectively accomplished by steadily growing market opportunities for low-carbon fuels with transparency, scale, and fair competition. Any such markets or programs must include safeguards to protect and enhance consumer benefits, and ensure equitable distribution of these benefits.

- In 2020, emissions from light-duty vehicles represented the highest emissions from the transportation sector, at 57%. In order to achieve emissions reductions at the scale needed to mitigate the impacts of climate change, LCF policies should be used as a tool to rapidly scale down emissions in the light-duty vehicle market.

- In 2020, heavy-duty vehicles comprise 26% of total transportation GHG emissions while comprising only 11% of total vehicle miles traveled. LCF policies should therefore identify opportunities to ensure emissions reductions in these highest-emitting vehicle classes and fleets to maximize emissions benefits. LCF policies should also identify opportunities to reduce emissions in sectors that are hardest to electrify, such as aviation and maritime transportation.

- It is critical that regulators take a transparent, uniform, and traceable approach to measuring the life cycle emission performance of low-carbon fuels. But this approach alone is not sufficient to get significant reductions in carbon intensity. There must be stringent standards contained in any LCF policy to achieve emissions reductions in the transportation sector. These standards must ensure the best possible technology is being used to support carbon intensity reduction, including with respect to life cycle analysis and standardization of applicable verification and reporting.

- In addition to individual state efforts, the federal government and the states can and should make a sustained effort to expand the research, development, and deployment of low- and zero-carbon fuels technologies and practices, including demonstration projects and technical assistance.

- Any LCF policy must prioritize justice and equity by recognizing that those communities impacted most by transportation GHG emissions are low-income and communities of color. To do so, policies should identify opportunities to invest a significant portion of credit revenues into overburdened communities to fund infrastructure projects to support the emergence of more LCFs.

2 Glossary

Battery electric vehicle (BEV): A vehicle that operates only on electric power.

Hybrid electric vehicle (HEV): A vehicle with both an internal combustion engine and an electric motor that runs on battery power.

Hydrogen fuel cell vehicle (HFCV): A vehicle with an electric powertrain that runs on hydrogen.

Internal combustion engine (ICE) vehicle: A conventional vehicle fueled only by gasoline.

Low-carbon fuels (LCFs): Fuels with lower carbon intensity compared with fossil fuel-based gasoline or diesel.

Low-Carbon Fuel Standard (LCFS): A regulatory program to reduce carbon intensity of transportation fuels.

Plug-in hybrid electric vehicle (PHEV): A vehicle that can operate on either electricity or gasoline, and on which the battery is charged with an external electricity source.

Sustainable aviation fuel (SAF): A low-carbon fuel that can replace regular diesel jet fuel.

3 Introduction

The transportation sector is responsible for 27% of greenhouse gas (GHG) emissions and is a main contributor to climate change in the U.S.[3] To address GHG emissions and toxic air pollutants from the transportation sector, efforts have been made to increase the efficiency of vehicle technology, and encourage the production and use of fuels with lower carbon content in transportation. Low-carbon fuels (LCFs), ranging from liquid biofuels to renewable gas, have been introduced to the market with the goals of reducing the GHG emissions of the transportation sector and providing readily available alternative choices for consumers. Non-electric LCFs are likely to play more of a complementary role to electrification in the passenger sector,[4] but they can play a vital role in achieving deep GHG emissions reductions in the freight sector and in other transportation modes. It is therefore important to provide a clear picture of benefits and barriers of LCFs from consumers' perspectives.

Definition of Low-Carbon Fuels

LCFs are transportation fuels that have lower carbon intensity (CI) compared with regular gasoline or diesel. CI is defined as the life cycle GHG emissions of a fuel and is calculated either as grams of carbon dioxide (CO_2) equivalent per unit of energy of a fuel (gCO_2e/MJ) or as grams of carbon dioxide equivalent per unit of distance that the vehicle can travel on the fuel ($gCO_2e/mile$). Low-carbon fuels for the transportation sector include:

- Biofuels:
    - Bio-CNG (compressed natural gas), bio-LNG (liquified natural gas), and bio-L-CNG (liquified compressed natural gas)
    - Gasoline mixed with 10% or higher ethanol, and 100% ethanol ("E100")
    - A diesel blend containing biomass-based diesel, 100% biomass-based diesel ("B100"), and renewable diesel
    - Sustainable aviation fuel (SAF) (alternative jet fuel)
- Other LCFs:
    - Natural gas
    - Propane

[3] U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020," 2022, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020.
[4] Lepitzki, J., Axsen, J., "The role of a low carbon fuel standard in achieving long-term GHG reduction targets," *Energy Policy* 119, (2018): 423-440, https://doi.org/10.1016/j.enpol.2018.03.067.

- Electricity
- Hydrogen
- Any other liquid or non-liquid fuel with a CI lower than regular gasoline

While so-called "drop-in" low-carbon fuels are chemically similar to petroleum-based fuels and can therefore be used directly within existing internal combustion engines, others such as ethanol and biodiesel have different chemical characteristics than petroleum-based fuels and therefore have to be blended with fossil fuels. For instance, E-15 is gasoline blended with 15% ethanol, and B20 is diesel blended with 20% biodiesel.

With the emerging technologies for generating renewable electricity, including solar and wind, clean electricity can be converted to other forms of energy. Electro-fuels (E-fuels) are the next generation of low-carbon fuels still in the development stage, and are produced using renewable electricity.

3.1.1 Low-Carbon Fuels in Aviation, Rail, and Maritime Sectors

The aviation sector accounts for 7% of U.S. GHG emissions. The sector has aimed to achieve net-zero emissions by 2050.[5] Sustainable aviation fuels (SAF) are drop-in biofuels that are chemically identical to conventional fossil-based jet fuel. SAF is one of the main tools to achieve the net-zero target because, unlike for surface transportation, hydrogen- and electricity-based powertrains have not been fully commercialized for the aviation sector. Currently, more than 50 airports across the world are distributing about 100 million liters of SAF each year and more than 450,000 flights have used it.[6] Several airlines across the world and the U.S. are either using SAF or have announced plans to utilize it in the near future.[7] The high investment costs of production facilities, however, call into question both the economic feasibility of non-fossil fuel-based jet fuels and whether the volumetric demand can be met.[8, 9]

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[5] IATA, "Net-Zero Carbon Emissions by 2050," press release no. 66, October 2021, https://www.iata.org/en/pressroom/2021-releases/2021-10-04-03.
[6] IATA, "Developing Sustainable Aviation Fuel (SAF)," https://www.iata.org/en/programs/environment/sustainable-aviation-fuels.
[7] White House Briefing Room, 2021a, "FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation," The White House, September 9, 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation.
[8] Ng, K.S., Farooq, D., Yang, A., "Global biorenewable development strategies for sustainable aviation fuel production," *Renewable and Sustainable Energy Reviews* 150, (October 2021) 111502, https://doi.org/10.1016/j.rser.2021.111502.
[9] Dyk, S. van, Saddler, J., "Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF): Technologies, Potential and Challenges," IEA Bioenergy, December 2021.

Rail transportation accounts for 2% of U.S. GHG emissions and is set to meet the net-zero GHG emissions by 2050.[10] If electric rail systems are sourced with clean electricity, they have the potential to help achieve climate change goals in transportation systems. However, while some other countries are moving to electrify their rail systems, the U.S. railway system is mainly diesel-based. In that context, blending biodiesel into diesel has shown the potential to reduce carbon intensity by 5% for a soybean-based blend of B20 compared with ultra-low sulfur diesel (ULSD).[11, 12]

Maritime transportation, which accounts for 2% of U.S. GHG emissions, could also benefit from low-carbon fuels to meet the zero-emission target by 2050.[13] Long trip durations and limited refueling options are the main factors to be considered in preparing the sector for low-carbon fuels. It may require tremendous investment to make LCFs available for refueling around the globe, including in developing countries. While advanced biofuels are the most feasible solution for the near future, green ammonia and green hydrogen can be the next-generation low-carbon fuels to reduce carbon intensity from this sector.[14]

The benefits and challenges in expanding LCFs are still uncertain and could affect further success of increasing LCFs market share at regional, national, and global levels.

[10] U.S. Department of Transportation, Federal Railroad Administration, "Federal Railroad Administration Announces Climate Challenge to Meet Net-Zero Greenhouse Gas Emissions by 2050," April 2022, https://railroads.dot.gov/newsroom/press-releases/federal-railroad-administration-announces-climate-challenge-meet-net-zero-0.

[11] Frey, H.C., Graver, B.M., Hu, J., "Locomotive Biofuel Study – Rail Yard and Over the Road Measurements Using Portable Emissions Measurement System," U.S. Department of Transportation Office of Research, Development, and Technology, 2015.

[12] Stead, C., Wadud, Z., Nash, C., Li, H., "Introduction of Biodiesel to Rail Transport: Lessons from the Road Sector," *Sustainability* 11, (2019): 904, https://doi.org/10.3390/su11030904.

[13] Reuters, "U.S. to join effort to curb climate-warming emissions from shipping," April 2021, https://www.reuters.com/business/environment/us-join-global-effort-decarbonize-shipping-industry-kerry-2021-04-20.

[14] Lloyd's Register and University Maritime Advisory Services (UMAS), "Zero-Emission Vessels 2030. How do we get there?" 2018, https://www.lr.org/en/insights/global-marine-trends-2030/zero-emission-vessels-2030.

4 Benefits of Low-Carbon Fuels

Despite steady improvement in vehicle and fuel technologies and efforts to curb demand for travel over the past decades, GHG emissions from transportation have continued increasing by 20 million metric tons per year, except during global recessions and pandemics.[15] Low-carbon fuels were introduced to the market with the goal of reducing the carbon footprint of the transportation sector, and they have generally been effective. For instance, by lowering the carbon intensity of transportation fuel in California, LCFs helped reduce CO_2e emissions by 47.1 million tons and petroleum diesel consumption by nearly 3.3 billion gallons from 2011 to 2018.[16]

Some LCFs have benefits beyond curbing GHG emissions as well. Electrification of the transportation sector and the proliferation of some low-carbon fuels could also reduce toxic emissions. This is important because transportation contributes significantly to ambient air pollution in urban areas, which poses a threat to public health. Exposure to vehicle emissions has been linked to adverse health outcomes, including cardiovascular diseases, lung cancer, and asthma.[17, 18, 19, 20, 21, 22] Racial and ethnic minorities and low-income communities are more likely to be exposed to dangerous concentrations of transportation air

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15 U.S. Environmental Protection Agency, "Fast Facts on Transportation Greenhouse Gas Emissions," 2022, EPA-420-F-22-018.

16 Congressional Research Services, "A Low Carbon Fuel Standard: In Brief," 2021.

17 Allen et al. "Fine Particulate Matter Air Pollution, Proximity to Traffic, and Aortic Atherosclerosis," *Epidemiology* 20, no. 2 (March 2009): 254-264, https://doi.org/10.1097/EDE.0b013e31819644cc.

18 Brugge, D., Durant, J.L., Rioux, C., "Near-highway pollutants in motor vehicle exhaust: A review of epidemiologic evidence of cardiac and pulmonary health risks," *Environmental Health* 6, no. 23 (August 2007), https://doi.org/10.1186/1476-069X-6-23.

19 Franco Suglia, S., Gryparis, A., Schwartz, J., Wright, R.J., "Association between Traffic-Related Black Carbon Exposure and Lung Function among Urban Women," *Environmental Health Perspectives* 116, no. 10 (October 2008): 1333-1337, https://doi.org/10.1289/ehp.11223.

20 Gan, W.Q., Davies, H.W., Koehoorn, M., Brauer, M., "Association of Long-term Exposure to Community Noise and Traffic-related Air Pollution With Coronary Heart Disease Mortality," *American Journal of Epidemiology* 175, no. 9 (May 2012): 898-906, https://doi.org/10.1093/aje/kwr424.

21 HEI, "Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects," Health Effects Institute, Boston, MA, Special Report 17 (2010).

22 McConnell et al., "Traffic, Susceptibility, and Childhood Asthma," *Environmental Health Perspectives* 114, no. 5 (May 2006): 766–772, https://doi.org/10.1289/ehp.8594.

pollution than white and/or high-income communities.[23, 24, 25, 26, 27, 28, 29, 30, 31] While 19.3% of the U.S. population lives near major highways, for example, the number is 27.4% for people of color. Similarly, the average median household income of census blocks near major roadways is $1,221 lower than the national median household income.[32, 33]

The introduction of LCFs in California, mainly through the use of electric vehicles, is estimated to have saved the state $1.84 million in public health impacts and helped to avoid more than 200 premature deaths due to reduced toxic air pollution from vehicles between 2011 and 2018.[34] Similarly, the introduction of LCFs into British Columbia's market has helped to reduce GHG emissions by 12 million tons between 2010 and 2020.[35]

In addition to contributing to climate change and affecting air quality, transportation has economic impacts on consumers. In 2020, transportation was the second-largest expenditure for American households,

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[23] Bullard, R.D., "Environmental Justice in the United States," in *International Encyclopedia of the Social & Behavioral Sciences (Second Edition)*, ed. Wright, J.D., (Oxford, 2015): 756-762, https://doi.org/10.1016/B978-0-08-097086-8.91013-4.
[24] Carrier, M., Apparicio, P., Séguin, A.M., Crouse, D., "The application of three methods to measure the statistical association between different social groups and the concentration of air pollutants in Montreal: A case of environmental equity," *Transportation Research Part D: Transport and Environment* 30, (July 2014): 38-52, https://doi.org/10.1016/j.trd.2014.05.001.
[25] Chakraborty, J., "Automobiles, Air Toxics, and Adverse Health Risks: Environmental Inequities in Tampa Bay, Florida," *Annals of the Association of American Geographers* 99, no. 4 (September 2009): 674-697, https://doi.org/10.1080/00045600903066490.
[26] Clark, L.P., Millet, D.B., Marshall, J.D., "National Patterns in Environmental Injustice and Inequality: Outdoor NO2 Air Pollution in the United States," *PLOS ONE* 9, (April 2014) e94431, https://doi.org/10.1371/journal.pone.0094431.
[27] Hajat, A., Hsia, C., O'Neill, M.S., "Socioeconomic Disparities and Air Pollution Exposure: a Global Review," *Current Environmental Health Reports* 2, (September 2015): 440-450, https://doi.org/10.1007/s40572-015-0069-5.
[28] Lipfert, F.W., "Air pollution and poverty: Does the sword cut both ways?" *Journal of Epidemiology & Community Health* 58, no. 1 (January 2004): 2-3, https://doi.org/10.1136/jech.58.1.2.
[29] Rivas, I., Kumar, P., Hagen-Zanker, A., "Exposure to air pollutants during commuting in London: Are there inequalities among different socio-economic groups?" *Environment International* 101, (April 2017): 143-157, https://doi.org/10.1016/j.envint.2017.01.019.
[30] Rowangould, G.M., "A census of the U.S. near-roadway population: Public health and environmental justice considerations," *Transportation Research Part D: Transport and Environment* 25, (December 2013): 59-67, https://doi.org/10.1016/j.trd.2013.08.003.
[31] Stuart, A.L., Zeager, M., "An inequality study of ambient nitrogen dioxide and traffic levels near elementary schools in the Tampa area," *Journal of Environmental Management* 92, no. 8 (August 2011): 1923-1930, https://doi.org/10.1016/j.jenvman.2011.03.003.
[32] Rowangould, G.M., "A census of the U.S. near-roadway population: Public health and environmental justice considerations," *Transportation Research Part D: Transport and Environment* 25, (December 2013): 59-67, https://doi.org/10.1016/j.trd.2013.08.003.
[33] Analysis based on median household income obtained from the 2000 census.
[34] California Delivers – Low Carbon Fuel Standard, 2018, https://greenpowersystems.com/resources/financial-incentives-2/lcfs.
[35] Government of British Columbia, "Low-carbon fuel expansion cuts emissions, creates jobs," news release, May 2022, https://news.gov.bc.ca/releases/2022EMLI0032-000730.

costing them $9,862 that year.[36] While vehicle purchases account for the highest share of the costs, fuel and motor oil account for 16.3% and maintenance and repair account for 8.6%. The share of income that a household spends on transportation is higher for low-income households and other disadvantaged households,[37] which is why it is important to understand the equity impacts of the transportation sector as well.

4.1 Lowering Carbon Intensity

Carbon intensity (CI) is the main metric used to determine whether GHG emission reduction targets for LCFs are achieved. CI is estimated through a life cycle assessment (LCA) that evaluates carbon emissions related to extraction, cultivation, land-use conversion, processing, transportation and distribution, fuel use, recycling, and disposal. This section will examine the CI-reducing potential of various low-carbon fuels.

Biofuels are liquid and non-liquid fuels that are produced through industrial processes from biomass obtained from plants and raw materials, wastes, and residues from agricultural, commercial, domestic, and/or industrial activities. Corn ethanol, for example, the most common biofuel used in the U.S.,[38] is produced by converting hydrocarbons in corn to sugars, and then sugars into ethanol, in the presence of microorganisms. Ethanol has one of the highest market shares among low-carbon fuels. By 2018, about 21 million flex fuel vehicles (FFVs) registered in the U.S.[39] were capable of running on an 85% blend of ethanol, not counting traditional internal combustion engine vehicles that use conventional gasoline blended with 10% ethanol.[40]

Biomass-based diesels include biodiesel and renewable diesel. Both types achieve similar CI but differ in other characteristics. Biodiesel can be produced through the transesterification method by purifying the oils and fats, cannot be used in its pure form (B100) in unmodified diesel vehicles, and is blended with regular diesel at 5% (B5) and at 20% (B20). Renewable diesel, on the other hand, is produced by hydrotreating vegetable oil and can be directly used in engines.

Input feedstock can be used to classify liquid biofuels into three generations. Food crops such as corn and molasses are the most common inputs for first-generation ethanol. Energy crops such as corn stover and switchgrass are the leading sources for second-generation, or lignocellulosic, ethanol. Rapeseed and soybean are the main food crop feedstock for first-generation biodiesel, and used cooking oil and

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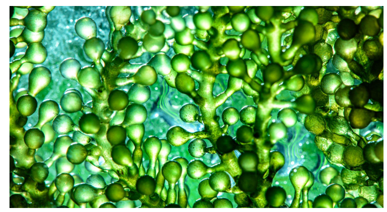
[36] U.S. Department of Transportation, Bureau of Transportation Statistics, “Transportation Economic Trends,” 2020.
[37] U.S. Department of Transportation, Bureau of Transportation Statistics, “Household Spending on Transportation: Average Household Spending,” 2020, https://data.bts.gov/stories/s/Transportation-Economic-Trends-Transportation-Spen/ida7-k95k.
[38] U.S. Department of Agriculture, “U.S. Bioenergy Statistics,” 2022, https://www.ers.usda.gov/data-products/u-s-bioenergy-statistics.
[39] U.S. Department of Energy, “Flexible Fuel Vehicles,” 2022, https://afdc.energy.gov/vehicles/flexible_fuel.html.
[40] Not all the FFVs use E-85 and less than 10 percent of such drivers use E85. https://www.fuelfreedom.org/is-your-car-a-flex-fuel-vehicle-use-this-tool-to-find-out/#:~:text=This%20tool%20is%20long%20overdue,of%20such%20drivers%20use%20E85.

camelina are energy crop sources for second-generation biodiesel. More recently, algae has been used to produce third-generation biodiesel.

Table 4-1 Three Generations of Biofuels

First Generation	Second Generation	Third Generation
Edible crop	Non-Edible crop/Residues	Microalgae
Corn, sugar beet, soybean …	Agricultural residue, organic waste, forestry waste …	





Images: Getty Images

Natural gas is an inexpensive fuel in the U.S. due to the shale gas revolution, which was driven by recent technological progress in hydraulic fracturing and horizontal drilling. Natural gas can be stored in vehicle tanks in compressed natural gas (CNG) and liquefied natural gas (LNG) forms and used in engines similar to gasoline and diesel engines, mostly for medium and heavy-duty vehicles. Renewable natural gas (RNG) is identical to natural gas but can be produced from captured methane that would otherwise leak into the air from decomposition of organic waste, landfills, sewage treatment, and livestock manure. Therefore, RNG is a much cleaner alternative for gasoline and diesel compared with fossil-derived natural gas.

Electricity is another LCF that has dominated the light-duty vehicle market. While electric vehicles produce no tailpipe GHG emissions, carbon intensity of electricity includes the emissions of producing and transporting fuel to power plants, the emissions from generating electricity (such as through burning coal and natural gas, if not renewable), and transmission line losses.

Another LCF is hydrogen, which can be used as fuel in hydrogen fuel cell (HFC) vehicles. HFCs produce only water vapor and electricity. Hydrogen, however, has to be extracted from fossil fuels, or from water and other sources using nuclear, fossil, and renewable energies.

4.1.1 Measuring Carbon Intensity

Life cycle assessment (LCA) is the main tool used to evaluate the environmental sustainability of biofuels. LCA of a fuel's carbon footprint includes estimating carbon emissions through all relevant phases of fuel production and use, including extraction of raw materials, transport routes, production and refining processes, production of co-product, as well as its use in the vehicle (Figure 4-1).

Several factors affect LCAs, including region (e.g., domestic vs. international, because farming and land-use processes vary by region), feedstock (e.g., corn vs. sugar beet), farming practices, type of fertilizers, fuel used in biorefinery process, type of biofuel, type of LCA, goal and scope of LCA, and inclusion of the co-products. Depending on the boundary definitions, assumptions, and input data from raw materials, there are uncertainties inherent in CI estimates, which makes using LCFs with CI close to those of fossil fuels uncertain choices in achieving GHG emissions reduction goals.

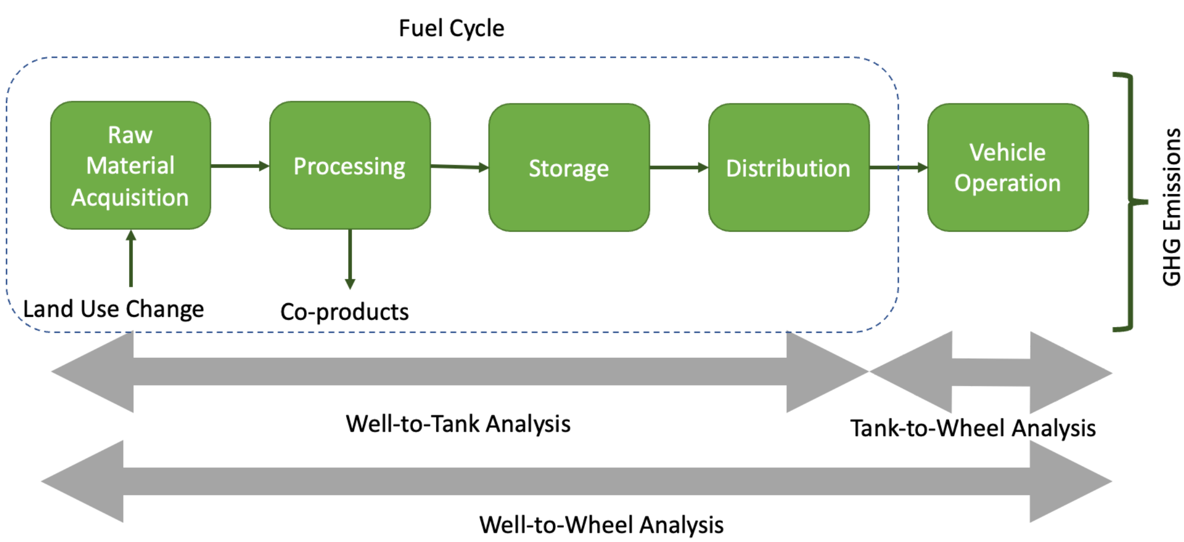


Figure 4-1 Schematic Flowchart for Life Cycle Assessment of Low-Carbon Fuels

LCA analyses enable the comparison of various low-carbon fuels based on their gram per mile Well-to-Wheel GHG emissions. Figure 4-2 shows, for example, that clean electricity from California can compete with ester-based biodiesel,[41] while many other low-carbon fuels, such as CNG and non-plug-in hybrid electric vehicles (HEVs), may not meet more stringent carbon intensity reduction targets. Some LCFs can achieve negative CI, in fact, because in addition to generating zero tailpipe emissions, their

[41] These are traditional biodiesels obtained from the transesterification process of vegetable oils such as soybean and must be blended with diesel to be used in diesel engines.

production eliminates other sources of carbon emissions. Producing biogas from waste fields, for example, eliminates methane emissions.

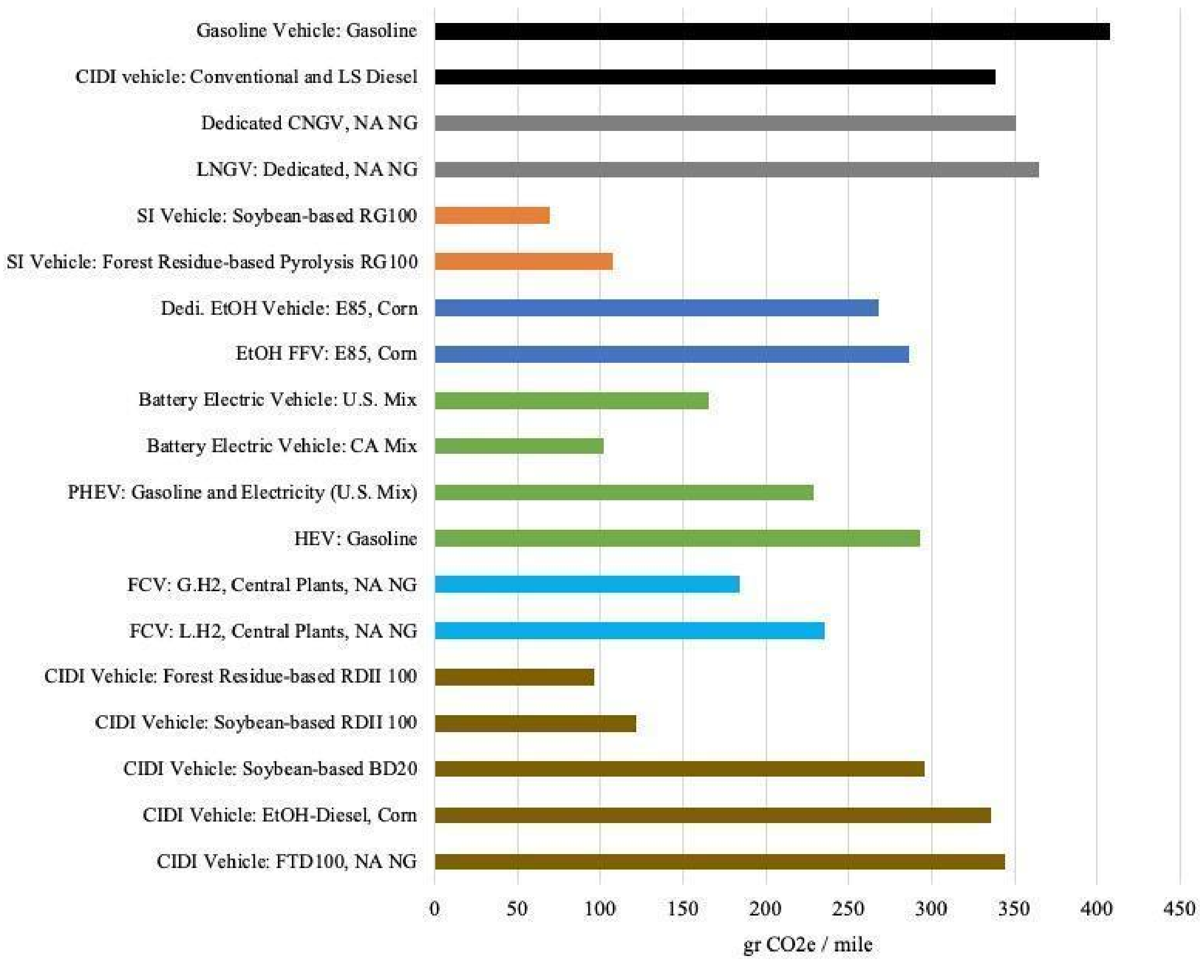


Figure 4-2 Well-to-Wheel GHG Emissions Comparison of Different Vehicle and Fuel Technologies from GREET Model[42, 43]

[I] Compression ignition direct injection (CIDI)—known as diesel—engines, which have higher thermal efficiency than spark ignited direct injection (sidi) engines used in light-duty vehicles run on gasoline.

[II] North American natural gas/compressed natural gas (NA NG/CNG).

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[42] Wang et al., "Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model® (2021 .Net)," computer software, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), 2021, https://doi.org/10.11578/GREET-Net-2021/dc.20210903.1.
[43] Wang, M., "CA-GREET3.0: Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model," computer software, 2019, https://ww2.arb.ca.gov/resources/documents/lcfs-life-cycle-analysis-models-and-documentation.

[III] North American natural gas/liquefied natural gas (NA NG/LNG).

[IV] Soybean-based mono alkyl esters (RG100), which are a type of renewable diesel obtained by refining vegetable oils or animal fats.

[V] Ethanol fuel (EtOH).

[VI] Flexible fuel vehicle (FFV) is a vehicle with a modified internal combustion engine that can operate on any blend of gasoline and ethanol up to 83%.

[VII] North American natural gas to gaseous hydrogen (NA NG to GH2) in central plants.

[VIII] North American natural gas to liquid hydrogen (NA NG to LH2) in central plants.

[IX] Renewable Diesel 2 (100% by volume) (RDII 100).

[X] Fischer-Tropsch diesel on 100% natural gas from North America (FTD100, NA NG). Fischer-Tropsch is a process to synthesize fuels from coal, natural gas, or biomass.

4.1.2 Carbon Intensity of Biofuels

Overall, while ethanol has the potential to reduce CI compared with fossil fuels, first-generation bioethanol may not be the most reliable choice in reducing GHG emissions from transportation. For instance, sugarcane and sugar beet are among the feedstocks that can achieve a 45% to 50% CI reduction, but the CI for corn- and wheat-based ethanol can be higher than regular gasoline. Compared with regular gasoline, second-generation ethanol can reduce CI by 225% or increase it by 73%, while forest residue-based fuel could achieve the lowest CI. The CI range for biodiesel varies from almost -100% to +400%, compared with regular diesel. [The highest estimates assume palm oil-based biodiesel from tropical forest and/or peat land in Malaysia and Indonesia.][44] A similar pattern can be seen for second-generation biodiesel. CI values range from 120% lower to no change compared to regular diesel for biodiesel made from jatropha, camelina, and used cooking oil.[45] The uncertainties around technological assumptions, however, can alter the results when the products are commercialized. The uncertainties around third-generation biodiesel, including different production designs, system boundaries, feedstock inputs, and potential co-products, make the results highly sensitive to assumptions and result in estimates ranging from -2,300% to +2,780% of the regular gasoline.[46]

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[44] Jeswani, H.K., Chilvers, A., Azapagic, A., "Environmental sustainability of biofuels: a review," *Proceedings of the Royal Society A* 476, no. 2243 (November 2020), 20200351, https://doi.org/10.1098/rspa.2020.0351.
[45] Jeswani et al., 2020.
[46] Jeswani et al., 2020.

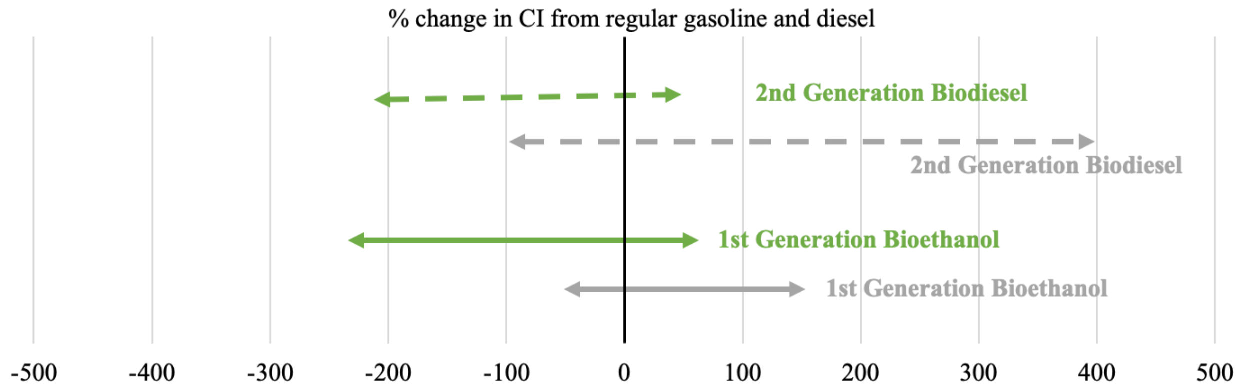

Figure 4-3 Range of Changes in Carbon Intensity for Biofuels Compared With Regular Gasoline and Diesel Depending on Their Generation[47] (Third-generation biodiesels are excluded from the graph due to the high uncertainty in their CI estimation.)

In the next several sections, we look closely at the CI estimates for various biofuels in the U.S. market.

4.1.2.1 Corn Ethanol

Corn ethanol is the most common low-carbon fuel[48, 49] in the U.S. market. Figure 4-4 depicts the production process of corn ethanol. The process involves breaking the feedstock molecules to free sugar molecules, or glucose. Then the ethanol is produced during the biochemical process in which the yeast breaks down the glucose molecules.

[47] Jeswani et al., 2020.
[48] U.S. Energy Information Administration, "EPA finalizes Renewable Fuel Standard for 2019, reflecting cellulosic biofuel shortfalls," December 2018, https://www.eia.gov/todayinenergy/detail.php?id=37712.
[49] California Air Resources Board, LCFS Data Dashboard, https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard.

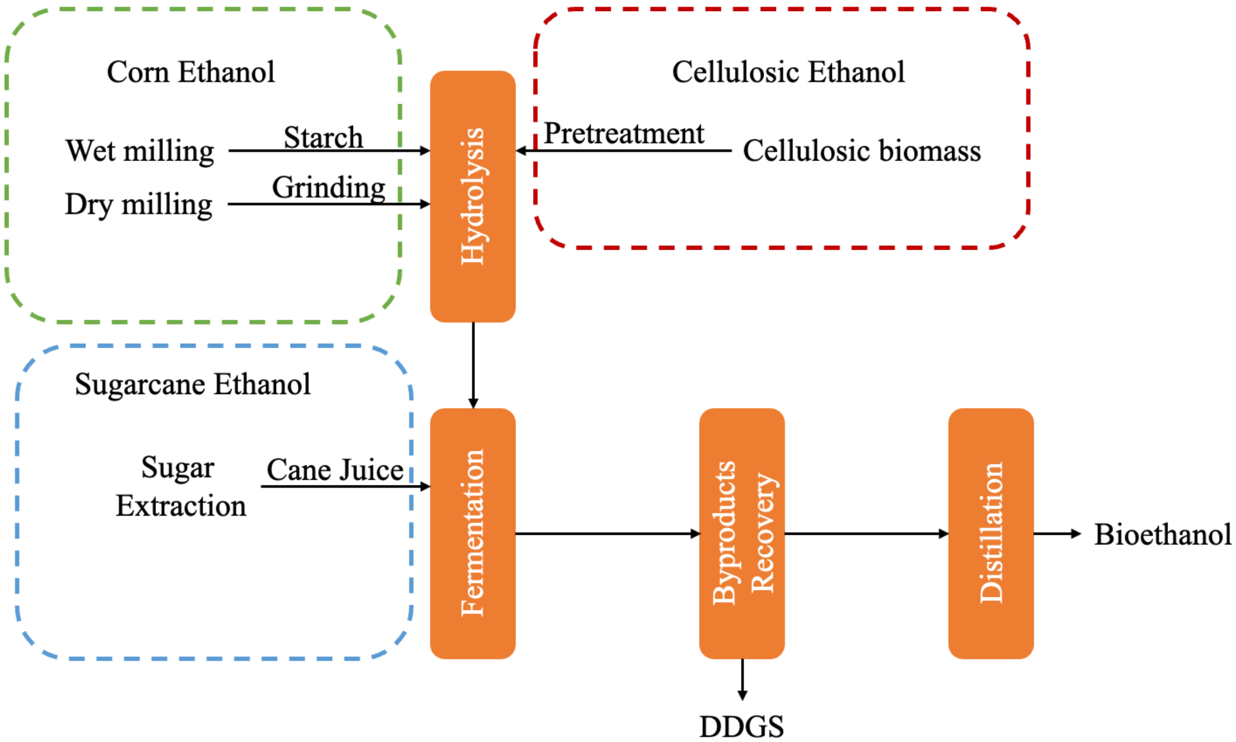

Figure 4-4 Four Main Steps in Production Framework for Corn, Sugarcane, and Cellulosic Ethanol[50, 51]

Over the past decades, the CI estimates for corn ethanol have decreased by almost 50%, to approximately 45% lower than regular gasoline.[52, 53] Depending on the type of feedstock and type of land-use change analysis—direct vs. indirect[54]—ethanol's CI can range from -60% to +150% of regular gasoline or diesel CI.[55]

The changes in CI estimates are mainly attributed to more accurate modeling with more recent input data, and also to more efficient farming and production practices, including decreased use of fertilizers and

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[50] Dried distillers grains (DDGS) are a co-product from ethanol production processes and are used as an animal feed.
[51] Gavahian et al., "Emerging techniques in bioethanol production: from distillation to waste valorization," *Green Chemistry* 21, no. 6 (2019): 1171-1185, https://doi.org/10.1039/C8GC02698J.
[52] Scully, M.J., Norris, G.A., Falconi, T.M.A., MacIntosh, D.L., "Carbon intensity of corn ethanol in the United States: state of the science," *Environmental Research Letters* 16, no. 4 (March 2021), 043001, https://doi.org/10.1088/1748-9326/abde08.
[53] Rosenfeld, J., Kaffel, M., Lewandrowski, J., Pape, D., "The California Low Carbon Fuel Standard: Incentivizing Greenhouse Gas Mitigation in the Ethanol Industry," U.S. Department of Agriculture, Office of the Chief Economist, 2020.
[54] Direct land use change refers to converting a previous land use to bioenergy crop production. On the other hand, indirect land use change (ILUC) refers to converting grassland and forest to biofuel feedstocks.
[55] Jeswani et al., 2020.

fossil fuels, more efficient refineries using natural gas and other cleaner electricity sources instead of coal, and market-based analyses of land-use change (LUC). Between 1990 and 2010, the CI from LUC has decreased by 54%, due to more accurate modeling[56] enhancements in the productivity land (via yield improvement, for example) and multiple cropping. More recent LUC emission estimates from Argonne National Lab and U.S. Department of Agriculture show that it can account for 8% of the total CI of corn ethanol.[57] Despite recent advances in life cycle assessment analysis and overall reduction in the estimates, CI estimates of LUC are still uncertain, showing 94% variation between the lowest and highest estimates (Figure 4-5).

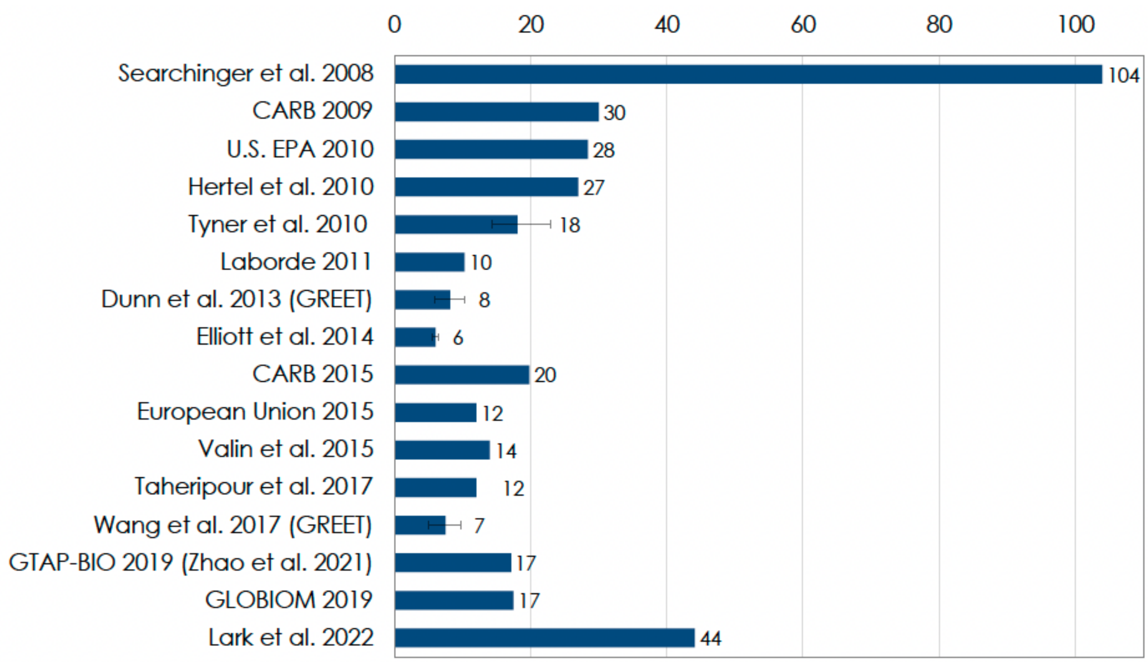

Figure 4-5 Corn Ethanol LUC GHG Emissions (gCO_2e/MJ^{-1})[58]

The second component of ethanol's CI comes from the corn production processes, including using fertilizers, disturbance of farming soils, and fossil fuel and electrical energy use on farms, which either generates GHG emissions through chemical processes or limits the ability of soil to harvest CO_2. These CI estimates have been reduced significantly over decades due to decreased use of fertilizers, cleaner ammonia production process, and more efficient farming techniques. For instance, conservation tillage, reducing nitrogen fertilizer use, and planting cover crops[59] all helped to reduce CI compared with using

[56] For instance, more accurately estimating the efficiency of feedstock production via a metric known as YDEL, the percentage change in crop yield per unit of land per percentage change in price.
[57] Scully et al., 2021.
[58] Wang, M., "Biofuel Life-cycle Analysis with the GREET Model," Presented at UC Davis ITS Center on March 16, 2022.
[59] Planting crops during fall and winter seasons not for the harvesting purposes but to protect soil fertility and erosion.

higher emitting practices.[60] And the credits from co-products of the production process, including distillers grain solubles (DGS)[61] and corn oil, can further reduce the CI by 13% compared with regular gasoline. Using renewable energy resources such as wind and solar for ethanol production could further decrease the CI. Finally, other categories, including fuel and feedstock transport, tailpipe, and denaturant emissions, all contribute to an additional 4.7% reduction compared with regular gasoline.[62]

Figure 4-6 breaks down the carbon intensity of corn ethanol by its different parts.

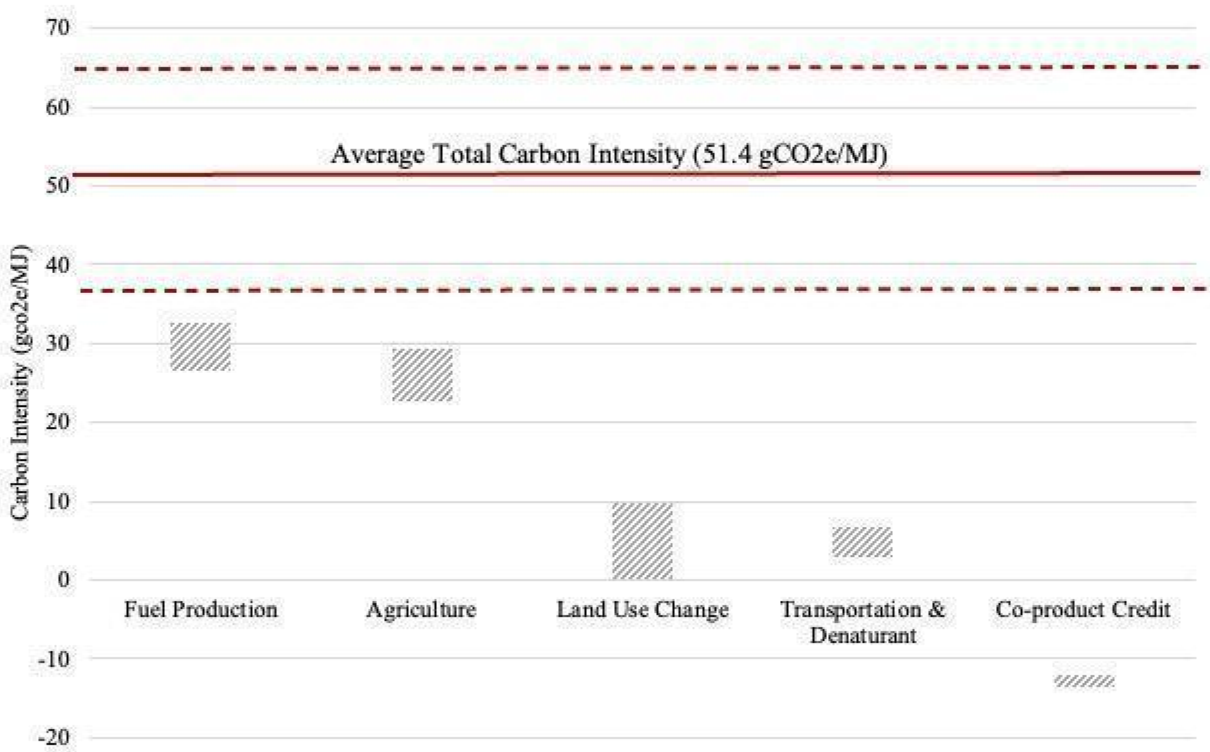

Figure 4-6 Average Corn Ethanol Carbon Intensity and Emissions Breakdown From Different Parts[63]

[60] Liu, X., Kwon, H., Northrup, D., Wang, M., “Shifting agricultural practices to produce sustainable, low carbon intensity feedstocks for biofuel production,” *Environmental Research Letters* 15, (2020) 084014.https://doi.org/10.1088/1748-9326/ab794e
[61] DGSs are co-products of biofuels production processes that can be used as feed sources for domestic livestock.
[62] Scully et al., 2021.
[63] Scully et al., 2021.

4.1.3 Natural Gas

The use of liquefied natural gas and compressed natural gas could change carbon intensity of transportation between -46% to +13%, compared with regular gasoline.[64, 65]

Renewable natural gas (RNG), on the other hand, is a biofuel that can be produced from captured methane that would otherwise leak into the air from decomposition of organic waste, landfills, sewage treatment, and livestock manure. Depending on the RNG source, the CI can be 376% to 54% lower than regular gas.[66] RNGs, however, are still produced on a small scale due to limited input sources and are used onsite at farms and waste treatment plants.

4.1.4 Electricity

Carbon intensity of electricity includes the emissions of producing and transporting fuel to power plants; the emissions from generating electricity if, as with coal and natural gas, the sources are not renewable; and transmission line losses. Carbon intensity estimates of electricity, therefore, can vary significantly depending on the energy mix. Figure 4-7 compares the emission per mile of BEVs, depending on each state's electricity sources (coal-fired and gas-fired power plants compared with solar and hydroelectric power plants), with the average CI for an ICE vehicle running on average U.S. gasoline, the red bar.

Depending on the source, electricity can be cleaner than gasoline in the U.S. In addition, BEVs are more efficient than internal combustion engine (ICE) vehicles. In an EV, about 77% of electrical energy from the grid converts to energy at the wheels. This ratio is called the energy efficiency ratio (EER). For an ICE vehicle, EER is about 12% to 30%.[67]

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[64] California Air Resources Board, "CA-GREET3.0 Supplemental Document and Tables of Changes," March 2018, https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2018/lcfs18/appc.pdf.
[65] Tong, F., Jaramillo, P., Azevedo, I.M.L., "Comparison of Life Cycle Greenhouse Gases from Natural Gas Pathways for Medium and Heavy-Duty Vehicles," *Environmental Science & Technology* 49, (May 2015): 7123-7133, https://doi.org/10.1021/es5052759.
[66] Jaffe et al., "The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute (No. UCD-ITS-RR-16-20)," Institute of Transportation Studies, University of California, Davis, 2016.
[67] U.S. Department of Energy, "All-Electric Vehicles," 2022a, http://www.fueleconomy.gov/feg/evtech.shtml (accessed 2.25.22).

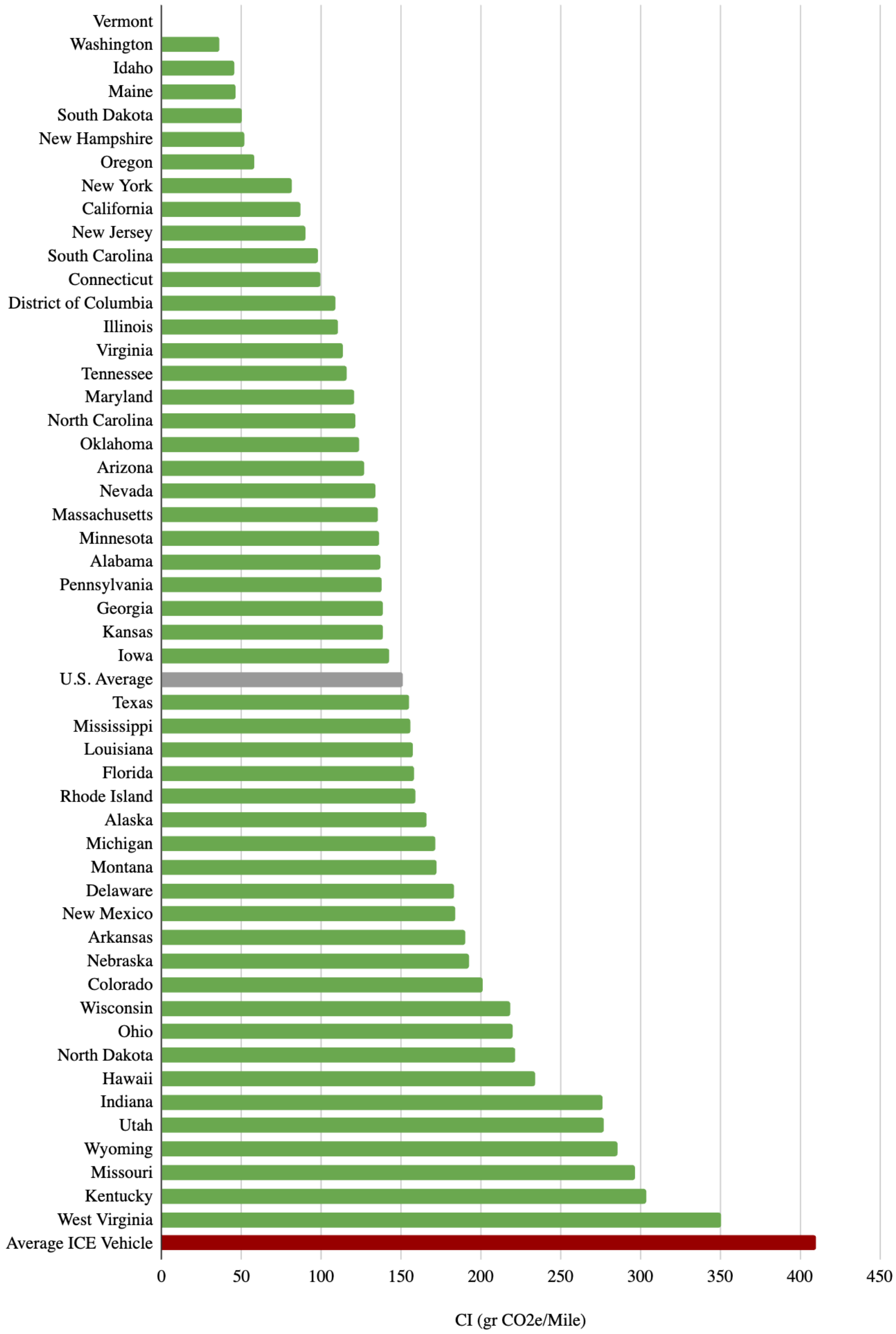

Figure 4-7 Electricity Carbon Intensity for 2021 by State[68, 69]

[68] The data is based on the average 44.4 mpg for BEVs and annual driving of 11,824 miles calculated by U.S. Department of Energy.

[69] U.S. Department of Energy, “Emissions from Electric Vehicles,” 2022f, https://afdc.energy.gov/vehicles/electric_emissions.html#wheel.

4.1.5 Hydrogen

There exist several technological paths to produce hydrogen fuel, including thermochemical, electrochemical, biochemical, thermo-electrochemical, photo-biochemical, and electro-photonic methods. Depending on the energy source and the technological pathway, and the resulting carbon footprint, hydrogen fuel is categorized as either gray, brown, blue, or green. Gray hydrogen, the most common form, uses natural gas as feedstock. Blue hydrogen follows a path similar to that of gray hydrogen, except that carbon dioxide is captured and stored in the process of producing blue hydrogen. Hydrogen fuel produced using coal is brown hydrogen—which, due to its high carbon footprint, is an inauspicious pathway. Green hydrogen, although not fully commercialized yet, is produced through electrolysis, whereby water is split into hydrogen and oxygen using electricity from renewable sources.

As with BEVs, hydrogen fuel cell vehicles are more efficient than ICE vehicles. On average, their grams per mile of emission is 40% lower compared with an ICE vehicle running on regular diesel. Depending on the hydrogen source, however, it can be 98% lower or 188% higher.[70]

4.1.6 Sustainable Aviation Fuel (SAF)

SAF can be made from corn oil, tallow, used cooking oil, agricultural and forestry residuals, municipal solid waste streams (MSW), and miscanthus. Carbon intensity of SAFs can range from 150% lower to 100% higher than regular gasoline depending on the feedstock, where the use of 100% bio MSW can achieve negative carbon intensity.[71] Overall, starch, sugar, and vegetable oil-based SAFs have higher CIs due to their land-use impacts, compared with cellulosic pathways such as miscanthus, which can achieve a negative carbon footprint from land-use changes due to the credits for co-products.

4.1.7 E-fuels

E-fuels are synthetic liquid and gaseous hydrocarbon fuels such as e-methanol, e-methane, e-diesel, e-ammonia, and e-hydrogen.[72, 73] They are manufactured through a multistep process. First, water is split into hydrogen (H_2) and oxygen using high-temperature electrolysis powered by sustainable sources. Then the hydrogen reacts with carbon dioxide (CO_2) to form a synthesis gas that later can be converted into fuel. While the process is theoretically efficient in producing zero-emission fuels, e-fuels currently have a

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[70] Rinawati, D.I., Keeley, A.R., Takeda, S., Managi, S., “A systematic review of life cycle assessment of hydrogen for road transport use,” *Progress in Energy* 4, no. 1 (December 2021), 012001, https://doi.org/10.1088/2516-1083/ac34e9.
[71] Pavlenko, N., Searle, S., “Assessing the sustainability implications of alternative aviation fuels,” *The International Council on Clean Transportation* 11, (March 2021): 1-17.
[72] Baldino, C., Berg, R., Pavlenko, N., Searle, S., “Advanced alternative fuel pathways: Technology overview and status,” *The International Council on Clean Transportation* 13, (July 2019): 1-31.
[73] Service, R.F., “Ammonia—a renewable fuel made from sun, air, and water—could power the globe without carbon,” *Science*, July 2018, https://www.science.org/content/article/ammonia-renewable-fuel-made-sun-air-and-water-could-power-globe-without-carbon.

negligible market share due to challenges in industrializing the production process and competing with lower-cost fossil-based fuels and other, more established alternatives.

Debates over the GHG reduction benefits of biofuels are ongoing. Uncertainties associated with direct and indirect land-use impacts of biofuel production, pressure on food production, and degradation of land and forests have called into question the GHG emission reduction benefits of biofuels. These concerns are the driving force behind investments into second- and third-generation biofuels, which have lower CI. However, these biofuels are still largely in the research phase and are not yet commercially feasible alternatives.

5 Potential Challenges

Despite the benefits of LCFs, there are still challenges in scaling up their role in the transportation sector.[74] Some of the most significant challenges to the expansion of LCFs are economic in nature, rather than technical, which has led some to question the potential benefits of low-carbon fuels.[75] In this section, we look more closely at the economics of LCFs, and in particular at the consumer costs associated with them. We also examine several other potential challenges to the expansion of LCFs, including their availability, public awareness of and support for them, and their equity impacts.

5.1 Cost of Low-Carbon Fuels

The cost of LCFs appears to be a factor from the consumer perspective. Though CR's 2022 nationally representative survey did not explore the extent to which consumers would use LCF if they cost more or less than traditional fuels, 67% of Americans do say they would be "very likely" or "somewhat likely" to use LCFs if the cost per gallon was the same as the cost for traditional fuel.[76]

Historically, natural gas and electricity have been cheaper than regular gasoline and diesel on the gasoline gallon equivalent (GGE) basis. (GGE is the amount of fuel it takes to equal the energy content of one liquid gallon of gasoline, and it is used to compare costs of fuels.) As shown in the graph below (Figure 5-1), when the price of crude oil is relatively high and when LCFs are being subsidized (as is currently the case), low-carbon fuels cost about as much as gasoline and diesel. (The exception is pure biodiesel [B100], which is typically more expensive.) However, the price of crude oil is highly volatile, and the price of gas and diesel has at times dipped below that of most LCFs.

The relationship between the price of gas/diesel and the price of LCFs, however, is not consistent. The spike in oil prices during 2022, for instance, was accompanied by broad inflationary pressure, which affected LCF prices as well.

In order to accurately compare the costs of LCFs with those of regular gasoline, it's important to consider the differences in energy content of the fuels. While the volumetric price of E85 is lower than the volumetric price of 100% gasoline, for example, flex fuel vehicles (FFVs) running on E85 tend—because of the lower energy content of ethanol—to get 10% to 27% lower miles per gallon (mpg) compared with

[74] Scott, W., "Low carbon fuel standards in Canada," Smart Prosperity Institute, February 2017, https://institute.smartprosperity.ca/sites/default/files/lowcarbonfuelstandards-web.pdf.
[75] Myers, T., "HB 1091, to impose a costly and ineffective Low Carbon Fuel Standard (LCFS) on the people of Washington state," Washington Policy Center, March 2021.
[76] Consumer Reports, "Battery Electric Vehicles and Low Carbon Fuel Survey: A Nationally Representative Multi-Mode Survey," press release, April 2022, https://advocacy.consumerreports.org/press_release/more-americans-would-definitely-get-electric-vehicles.

vehicles running on pure gasoline.

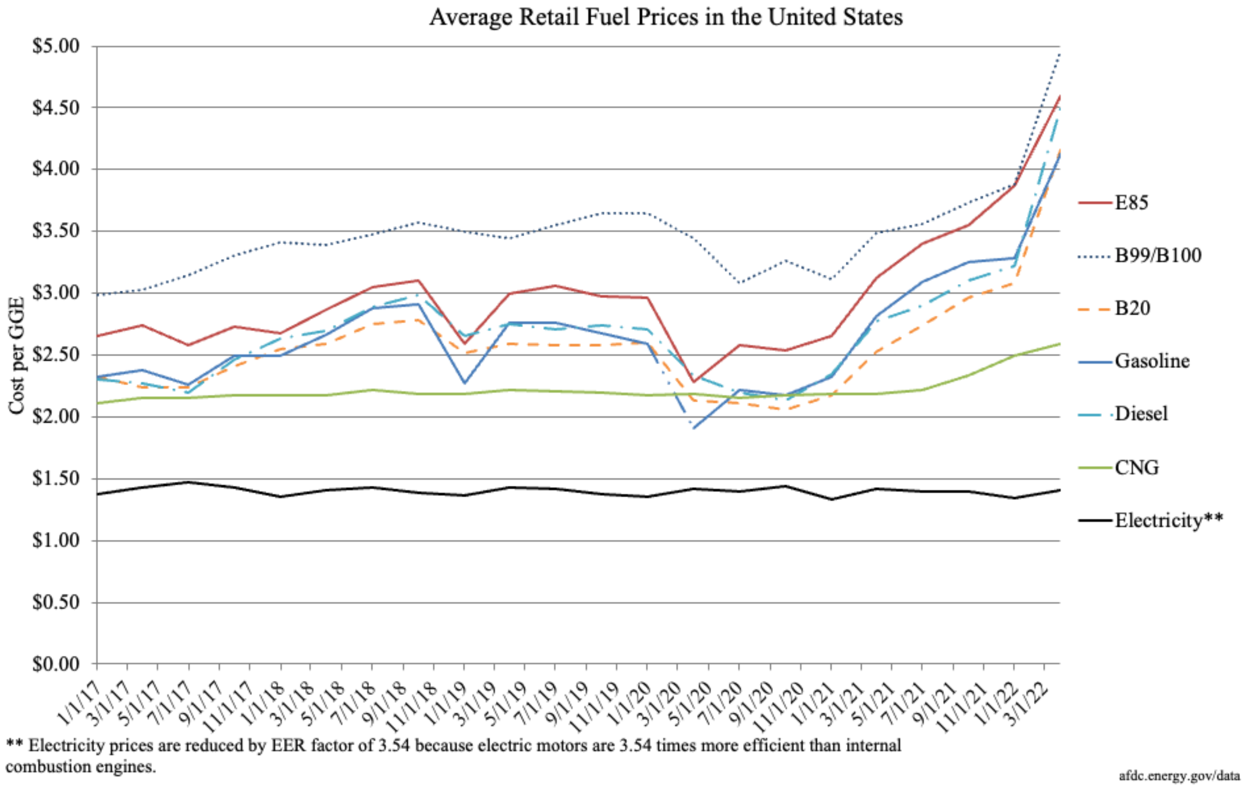

Figure 5-1 Gasoline and LCF Prices Over Time[77]

5.1.1 Biofuels

For biodiesel, current analysis at the national level reveals slightly higher costs for B99/B100, $0.46 more per GGE, compared with diesel. B20, a blend of biodiesel and regular diesel, costs $0.34 less than diesel per diesel gallon equivalent (DGE).[78, 79] Table 5-1 summarizes price of biofuels as of April 2022[80] and enables direct comparison between biofuels and gasoline/diesel prices in the market.

[77] U.S. Department of Energy, "Retail fuel price with electricity," June 2022, available at: https://afdc.energy.gov/data.
[78] DGE, similar to GGE, is the amount of fuel it takes to equal the energy content of one liquid gallon of diesel and used to compare the cost of fuels.
[79] B20 is cheaper than diesel and B100 due to the Renewable Identification Numbers (RIN) discount effect under RFS where selling credits of B100 enables fuel producers to lower/offset higher price of the commodity (B20).
[80] U.S. Department of Energy, "Clean Cities: Alternative Fuel Price Report," April 2022. https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_april_2022.pdf

Table 5-1 Average Biofuel Price as of April 2022

	Per Gasoline Gallon Equivalent ($/GGE)	Per Diesel Gallon Equivalent ($/DGE)	Per Million British Thermal Units ($/MBtu)[81]
Gasoline	$4.13	$4.66	$36.13
Diesel	$4.50	$5.06	$39.32
Ethanol (E85)	$4.60	$5.20	$52.51
Biodiesel (B20)	$4.16	$4.71	$32.91
Biodiesel (B99/B100)	$4.96	$5.56	$42.36

5.1.2 Battery Electric Vehicles (BEVs)

A BEV can cost between 10% and 40% more than a similar ICE vehicle. However, EVs tend to have lower total ownership costs, which include the cost of fueling, operating, and maintaining a vehicle over its usable lifetime, as well as its initial purchase price. As a result, according to recent CR calculations, EV owners can be expected to save between $6,000 and $10,000 over a 15-year or 200,000-mile vehicle lifetime of the car (Harto, 2020).[82] In addition to the maintenance costs, the cost of fueling is also lower in battery electric vehicles (BEVs) than in ICE vehicles. Assuming 2.7 miles per kWh[83] as the power efficiency for EVs, and charging costs of about $0.14 per kWh,[84] the cost of operating an EV is $0.054 per mile. The comparable cost for operating a 2020 ICE vehicle that gets the average 25.4 mpg,[85] if you assume gas prices will range from $3 to $6 per gallon, is between $0.12 and $0.24 per mile.

[81] Price per million British thermal units used to compare the cost of fuels based on amount of energy they provide.
[82] The analysis was done in 2020. Thus, the results may be different considering higher gas prices and also higher EV and ICE vehicle prices in 2022.
[83] U.S. Department of Energy, “Charging Electric Vehicles at Home,” 2022, https://afdc.energy.gov/fuels/electricity_charging_home.html (accessed 2.25.22).
[84] U.S. Energy Information Administration, “Electric Power Monthly,” 2022, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a (accessed 5.01.22).
[85] U.S. Environmental Protection Agency, “The EPA Automotive Trends Report,” 2021, https://www.epa.gov/automotive-trends.

5.1.3 Natural Gas

Natural gas vehicles (NGVs) are similar to conventional vehicles in terms of horsepower, acceleration, cruise speed, and mile-per-gallon efficiency. But because CNG and LNG cost less per gallon than gasoline and diesel, NGVs cost less to operate than ICE vehicles do.[86] A scarcity of natural gas fueling stations and higher maintenance costs are the two main barriers of NGV adoption. Other challenges include limited vehicle availability, higher vehicle purchase price,[87] and limited cargo space. Table 5-2 compares the costs per gasoline and diesel gallon equivalent for CNG, LNG, and regular gasoline and diesel.

Table 5-2 Average Difference Between Natural Gas, Gasoline, and Diesel Price as of April 15, 2022[88]

	Per Gasoline Gallon Equivalent ($/GGE)	Per Diesel Gallon Equivalent ($/DGE)	Per Million British Thermal Units ($/MBtu)
Gasoline	$4.13	$4.66	$36.13
Diesel	$4.50	$5.06	$39.32
CNG	$2.59	$2.93	$22.66
LNG	$2.82	$3.16	$24.55

86 U.S. Department of Energy, "Clean Cities: Alternative Fuel Price Report," April 2022.https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_april_2022.pdf
87 Ghadikolaei et al., "Why is the world not yet ready to use alternative fuel vehicles?" *Heliyon* 7, no. 7 (July 2021), e07527.
88 U.S. Department of Energy, "Clean Cities: Alternative Fuel Price Report," April 2022, https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_april_2022.pdf.

5.1.4 Hydrogen

With miles per kilogram ranging from 56 to 72 for hydrogen,[89] and assuming $10 to $17/kg costs of hydrogen,[90, 91, 92] the average cost of driving ranges between $0.14 and $0.30 per mile. Despite the high efficiency of hydrogen fuel cell vehicles (HFCVs), the average 15-year cost of driving per mile is higher than both ICE and HEVs due to higher vehicle purchase costs and the relatively high price of hydrogen.[93] Technological advancements triggered a sharp 60% reduction in the price of hydrogen over the past decade, but experts currently project that the cost of ownership of HFCVs will decrease by no more than 20% over the next 30 years, which is unlikely to make hydrogen a competitive fuel.[94]

5.2 Availability and Accessibility of Low-Carbon Fuels

Recently there has been an increase in light-duty vehicle models that run on low-carbon fuels. Figure 5-2 shows the overall increase in the number of available models. In particular, while there are fewer biofuel-based models, electric vehicle models including all-electric and plug-in hybrid electric vehicles

[89] U.S. Department of Energy, "Vehicles Fuel Economy," 2022, https://www.fueleconomy.gov/feg/fcv_sbs.shtml.
[90] California Fuel Cell Partnership, "Cost to refill," 2019, https://cafcp.org/content/cost-refill (accessed 3.1.22).
[91] California Hydrogen Business Council, 2017, https://californiahydrogen.org/resources/hydrogen-faq.
[92] H2 View, "New California hydrogen station retailing at $13.14/kg," 2021, https://www.h2-view.com/story/new-california-hydrogen-station-retailing-at-13-14-kg (accessed 3.1.22).
[93] Burnham et al., "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains (No. ANL/ESD-21/4)," Argonne National Laboratory (ANL), 2021, https://doi.org/10.2172/1780970.
[94] Staffell et al., "The role of hydrogen and fuel cells in the global energy system," *Energy & Environmental Science* 12, no. 2 (2019): 463-491.

tripled from 2015 to 2020.

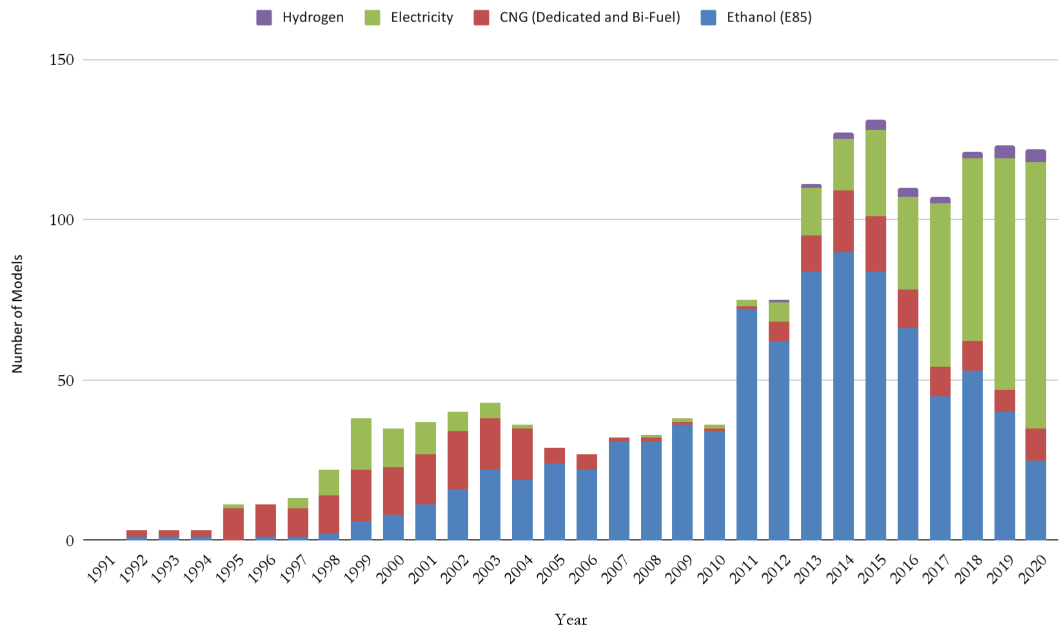

Figure 5-2 Low-Carbon Fuel Light-Duty Vehicles Model Offering[95]

In addition to availability of models, charging and refueling the vehicles is another aspect of accessibility. Among LCFs, electric vehicles have the largest network of public charging infrastructure. However, DC fast chargers that enable drivers to charge EVs to 80% in 20 to 30 minutes are still not readily available in many areas.[96] Unlike ICE vehicles that are typically refueled at gas stations, EV and PHEV owners have the ability to charge their vehicles at home. However, home charging may not be an option for many owners, especially those who reside in multi-family housing structures.

The second-largest distribution network belongs to ethanol (E-85), with 4,230 stations located mostly in the Midwest as of October 2022 (Figure 5-3). Some 827 biodiesel (B-20 and above) stations are, again, located mostly in Midwestern states. Numerous states, including New Mexico, Wyoming, Nevada, Idaho, Montana, and Mississippi, do not have a single station, and several others have very few. About 821 CNG stations are located mostly in California, Oklahoma, Pennsylvania, Texas, and Utah. But there are only 53 LNG stations, mainly located in California and Texas. Hydrogen fueling is currently limited to only 54 publicly available stations located in California.

[95] U.S. Department of Energy, Alternative Fuels Data Center, "Alternative Fuel Vehicle Model Offering," 2022, https://afdc.energy.gov (accessed 2.25.22).
[96] U.S. Department of Energy, "Ethanol Fueling Station Locations," 2022, https://afdc.energy.gov/fuels/ethanol_locations.html#/find/nearest?fuel=E85 (accessed 2.25.22).

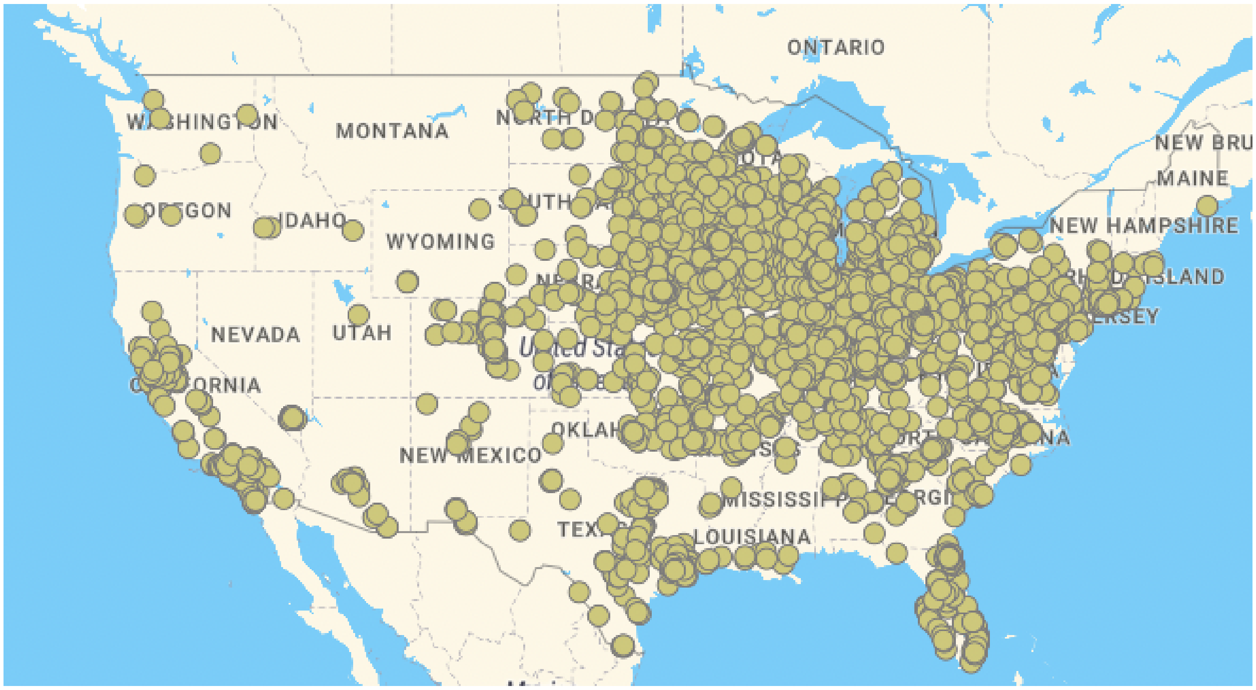

Figure 5-3 E-85 Fueling Station Locations[97]

Despite recent investments in home and public charging networks, concern about charging logistics are still impeding Americans from buying BEVs. A nationally representative survey of 8,027 U.S. adults, conducted by CR in January and February 2022, found that 61% of Americans say charging concerns—such as where and when they'd be able to charge their vehicles—would prevent them from buying or leasing a BEV.[98]

5.3 Awareness and Likelihood of Use

Public awareness and support are vital to the success of any policy, and LCF-related policies are no exception. Even if such policies were implemented without public support, their chance of success would be very low because the market is driven by public demand.

One impediment to public support for LCFs appears to be awareness and understanding of their technological and practical capabilities. CR's nationally representative survey found that only 25% of Americans have heard about drop-in low-carbon fuels before taking the survey. After we explained what these fuels are, however, 67% of these respondents said they would be somewhat or very likely to use these fuels if they were priced the same as traditional fuel.

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[97] U.S. Department of Energy, "Ethanol Fueling Station Locations," 2022, https://afdc.energy.gov/fuels/ethanol_locations.html#/find/nearest?fuel=E85 (accessed 2.25.22).
[98] Consumer Reports, "Battery Electric Vehicles and Low Carbon Fuel Survey: A Nationally Representative Multi-Mode Survey," press release, April 2022, https://advocacy.consumerreports.org/press_release/more-americans-would-definitely-get-electric-vehicles.

Socioeconomic and demographic factors also appear to have a significant effect on levels of public support for LCFs. Both awareness of and likelihood of using drop-in low-carbon fuels vary by age, race, ethnicity, and educational attainment.[99] Notable examples of such findings include the following:

- Thirty-four percent of young Americans, ages 18 to 29, are aware of drop-in low-carbon fuels, compared with only 19% of older Americans, ages 60-plus.
- A larger percentage of English-speaking Asians, 35%, say they have heard of using drop-in low-carbon fuels in vehicles, compared with white, Black, and Hispanic Americans (23%, 25%, and 30%, respectively).
- Midwesterners are not more aware of drop-in low-carbon fuels, even though the ethanol industry is based in the region.
- English-speaking Asians are more likely to support drop-in low-carbon fuels compared with Black, Hispanic, and white communities (74% vs. 60%, 64%, and 68%, respectively).
- Support for drop-in low-carbon fuels is higher among individuals with a postgraduate or professional degree than among individuals with no high school diploma (80% vs. 55%).

Finally, we found that attitudes toward climate change and air quality are related to support for low-carbon fuels. Americans who say that climate change is personally important to them are more likely to say they would use low-carbon fuels in their personal vehicles.

5.3.1 Awareness of and Support for Electric Vehicles

BEVs have recently accounted for most sales among vehicle types that use low-carbon fuels.[100] A closer look at the components of their public support may therefore provide insights into consumer attitudes toward other low-carbon fuels and barriers to their widespread adoption.

Consumers have been growing more familiar with BEVs over the past decade, and analysis reveals a statistically significant relationship between awareness of and support for BEVs. In the 2022 CR survey,[101]

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[99] Likelihood of using here means Americans who answered that they would be “very likely” or “somewhat likely” to use low-carbon fuels in their personal vehicle if they cost the same as regular fuels.
[100] Fuels Institute, “Tomorrow’s Vehicles: An Overview of Vehicle Sales and Fuel Consumption Through 2025,” https://www.fuelsinstitute.org/getattachment/Research/Tomorrows-Vehicles/Tomorrows-Vehicles-An-Overview-of-Vehicle-Sales-and-Fuel-Consumption-Through-2025.pdf?lang=en-US.
[101] Consumer Reports, “Battery Electric Vehicles and Low Carbon Fuel Survey: A Nationally Representative Multi-Mode Survey,” press release, April 2022, https://advocacy.consumerreports.org/press_release/more-americans-would-definitely-get-electric-vehicles.

40% of Americans said they were very or somewhat familiar with the fundamentals of BEVs,[102] which is similar to the share of Americans (44%) who have seen a BEV in their neighborhood in the past month. More direct experience with BEVs, however, was lower. Only 2% of Americans currently own or lease a BEV, 7% have driven one in the past 12 months, and 17% of people have ridden in one in the past 12 months. This appears to present an opportunity: We can expect to see more support for BEVs as awareness of them increases.

The consumers who own or lease a BEV, though a small percentage of all consumers, are satisfied with their choice, which may also signal strong future support for BEVs. A 2022 nationally representative CR survey[103] found that 79% of current BEV owners say they would "definitely" or "seriously consider" buying or leasing another electric-only vehicle if they were to buy or lease a vehicle today.

Beyond satisfying technical demands, BEVs also appear to satisfy a range of social and emotional needs. For instance, a larger percentage of current BEV owners (51%) than those who have never owned a BEV (26%) say reducing their impact on the environment is one of the most important social/emotional factors in determining what vehicle they would get if they were to buy or lease a vehicle today. Current BEV owners (18%) are also more likely than those who have never owned one (5%) to report that "being one of the first to adopt new/advanced technology" is one of the most important social/emotional factors when purchasing a vehicle. Other research has reported similar findings. For instance, protecting the environment, lower operating costs, good performance, and innovative technology were among factors that make EV users happy with their experience, according to a 2021 study by Song et al.[104]

All these factors—combined with the fact that consumers are currently more aware of electricity than they are of other low-carbon fuels—suggest that an opportunity exists to increase acceptance of and support for LCFs by making the public more aware of, knowledgeable about, and familiar with these technologies.

5.4 Low-Carbon Fuels and Equity Concerns

Equity—in terms of who benefits from LCFs and who has access to them—may significantly affect public and political acceptance of LCFs. Much attention has recently focused on the equity impacts of climate policies in general and tax policies in

[102] Respondents in the survey were asked about their familiarity with BEVs regarding charging vs. fueling, the frequency of maintenance/repairs, costs involved with buying, owning, and maintaining the vehicle, etc.

[103] Consumer Reports, "Battery Electric Vehicles and Low Carbon Fuel Survey: A Nationally Representative Multi-Mode Survey," press release, April 2022, https://advocacy.consumerreports.org/press_release/more-americans-would-definitely-get-electric-vehicles.

[104] Song, M.R., Chu, W., Im, M., "The effect of cultural and psychological characteristics on the purchase behavior and satisfaction of electric vehicles: A comparative study of U.S. and China," *International Journal of Consumer Studies* 46, (2022): 345-364, https://doi.org/10.1111/ijcs.12684.

particular,[105] but to date there are very few detailed studies on accessibility to LCFs among underserved communities and also environmental impacts of LCFs on those communities.

5.4.1 Electric Vehicles

EV adoption can benefit overburdened communities[106] in two ways: 1) by providing cheaper[107] (Harto, 2020) transportation options and 2) by improving air quality for the communities most impacted by air pollution and GHG emissions.

Incentive programs such as federal tax credits, rebates, and reduced electricity rates focus on reducing the cost of EV ownership. All such programs are shown to be effective in increasing EVs market share in general. That may be especially true when these programs are targeted at disadvantaged communities, as with California's Clean Vehicle Rebate Project (CVRP) incentive program, which has spent over $926 million since 2010. CVRP provides $1,000 to $7,000 incentive for the purchase or lease of a new eligible plug-in hybrid or zero-emission vehicle for low- and moderate-income households at or below 400 percent of the federal poverty level.[108] However, studies show that people with higher income and education are the majority of new and used PHEV buyers in California,[109] which is consistent with data from around the world.[110] One study, for example, shows that while disadvantaged communities account for 21.3% of households in California, only 5.7% of new-PHEV purchases were made by residents in those communities.[111]

Familiarity with the fundamentals of BEVs is one factor that can affect their adoption. CR's 2022 nationally representative survey on public awareness of low-carbon fuels reveals that those consumers who are more familiar with BEVs are more likely to choose them as their next vehicle.

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105 Bhardwaj, C., Axsen, J., Kern, F., McCollum, D., "Why have multiple climate policies for light-duty vehicles? Policy mix rationales, interactions and research gaps," *Transportation Research Part A: Policy and Practice* 135, (May 2020): 309-326, https://doi.org/10.1016/j.tra.2020.03.011.
106 These are communities that most suffer from a combination of economic, health, and environmental burdens.
107 Harto, C., "Electric Vehicle Ownership Costs: Today's Electric Vehicles Offer Big Savings for Consumers," Consumer Reports, October 2020.
108 California Clean Vehicle Rebate Project, 2022, https://cleanvehiclerebate.org/en/cvrp-info.
109 Tal, G., Nicholas, M.A., Turrentine, T.S., "First Look at the Plug-in Vehicle Secondary Market," University of California, Davis, Institute of Transportation Studies, Working Paper – UCD-ITS-WP-16-02, January 2017.
110 Vassileva, I., Campillo, J., "Adoption barriers for electric vehicles: Experiences from early adopters in Sweden," *Energy* 120, (February 2017): 632-641, https://doi.org/10.1016/j.energy.2016.11.119.
111 Canepa, K., Hardman, S., Tal, G., "An early look at plug-in electric vehicle adoption in disadvantaged communities in California," *Transport Policy* 78, (June 2019): 19-30, https://doi.org/10.1016/j.tranpol.2019.03.009.

5.5 Other Barriers to LCFs

In addition to barriers that consumers face in adopting low-carbon fuels, there exist legislative barriers to state and federal adoption of LCFs.

Critics have argued that because GHG emissions, unlike criteria air pollutants such as particulate matter (PM), do not have local impacts, it is unfair to burden local users with the costs of policies such as Low-Carbon Fuel Standards. Critics also note that, in contrast to gasoline and diesel taxes, the money paid to adopt LCF-related policy is not necessarily controlled by the local agencies and may be captured by fuel providers. As a result, the critics maintain, it can be unclear how the revenues associated with LCF-related programs are being used—unless credits generated by the public utility entities are dedicated to building more equitable low-carbon fuels infrastructure, as California did when the state revised its LCF related policy in 2020.[112]

[112] California Air Resources Board, "Low Carbon Fuel Standard (LCFS) Guidance 20-03: Electricity Credit Proceeds Spending Requirements," 2020b, https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/guidance/lcfsguidance_20-03_ADA.pdf.

6 Status Quo

This section provides the current state of practice of low-carbon fuels.

6.1 U.S.

6.1.1 California

California was the first state to adopt a low-carbon policy to reduce the carbon intensity from its transportation fuel pool. While the annual CI reduction was frozen at 1% from 2013 to 2015 due to legal challenges, by 2021 the average CI in California had been reduced by 9.36% compared with the 2010 level, slightly higher than the projected 8.75% reduction.[113] The California Air Resources Board (CARB) extended the goal to a 20% reduction in CI level by 2030.[114] CARB recently announced its plan for a more stringent standard to align the program with California's long-term climate change goals.

6.1.2 Oregon

Oregon is aiming for a 10% reduction in CI from 2015 levels by 2025 and is on track to achieve this goal.[115] In Oregon, bio-ethanol and biodiesel are the main clean fuels in the market.

6.1.3 Washington

Washington state recently announced that it will adopt its low-carbon fuel policy by winter 2022, aiming to reduce the GHG emissions from transportation, which currently account for 45% of the state's total GHG emissions. The program aims for a 20% CI reduction by 2038 compared with 2017 levels.[116] As in other states, concerns have been raised over the program's potential effect on fuel prices for consumers.[117] In response to concerns, an ex-ante economic analysis has been ordered.[118]

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[113] California Air Resources Board, LCFS Data Dashboard, 2022, https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard.
[114] California Air Resources Board, LCFS Basics, 2020, https://ww2.arb.ca.gov/resources/documents/lcfs-basics.
[115] State of Oregon Department of Environmental Quality, "Oregon Clean Fuels Program: Program Review," February 2022, https://www.oregon.gov/deq/ghgp/Documents/CFP-ProgramReview.pdf.
[116] State of Washington Department of Ecology, "Clean Fuel Standard," 2021, https://ecology.wa.gov/Air-Climate/Climate-change/Reducing-greenhouse-gases/Clean-Fuel-Standard (accessed 2.7.22).
[117] Myers, T., "HB 1091, to impose a costly and ineffective Low Carbon Fuel Standard (LCFS) on the people of Washington state," Washington Policy Center, 2021.
[118] State of Washington Department of Ecology, "Clean Fuel Standard," https://ecology.wa.gov/Air-Climate/Climate-change/Reducing-greenhouse-gases/Clean-Fuel-Standard (accessed 6.8.22).

6.2 Federal Level

The revised Renewable Fuel Standard (RFS) under the Energy Independence and Security Act (EISA) of 2007 required the use of 36 billion gallons of biofuels per year by 2022. The production of corn ethanol, therefore, has been dramatically increased to 15 billion gallons in 2022 from 10.5 billion in 2009.[119] Over the years the Environmental Protection Agency has updated the volume mandates, and most recently set 20.63 billion gallons for 2022 for total renewable fuels, which is lower than the trend values because demand for transportation fuels declined during the COVID-19 pandemic.[120] As mentioned above, there have been some concerns over the true effect of RFS on GHG emissions, mainly due to its indirect land-use impacts.[121] This volume-based regulation was initially designed to reduce the need for fossil fuels amid gas price spikes, and not aimed at reducing the carbon footprint of transportation.

6.3 International

6.3.1 Canada

British Columbia has aimed to reduce CI by 10% by 2020 when compared with a 2010 benchmark and required a 5% annual average renewable content blend in gasoline and a 4% renewable content blend in diesel. While a 9% reduction by 2020 did not meet the initial target, British Columbia has extended the plan to 2030 with a 20% reduction goal.[122]

6.3.2 Europe

In 2009, the European Parliament adopted the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD) that set a target for a minimum of 10% renewable fuels to be used in the transportation sector by 2020.[123] The FQD required fuel suppliers to reduce life cycle GHG emissions by 6% by 2020. Later, through a series of amendments, the EU fuel policy deviated from being fuel-neutral and capped food-based biofuels at 7% of total transportation fuels. In addition, to encourage more use of second-generation biofuels and discourage use of first-generation biofuels, revised regulations set a minimum for low-carbon fuel use as a percentage of total CI reduction.

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[119] U.S. Environmental Protection Agency, "Overview for Renewable Fuel Standard," https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard.

[120] U.S. Environmental Protection Agency, "Renewable Fuel Standard Program," 2022, https://www.epa.gov/renewable-fuel-standard-program/final-volume-standards-2020-2021-and-2022 (accessed 6.8.22).

[121] Lark et al., "Environmental outcomes of the U.S. Renewable Fuel Standard," PNAS, 119 (9) e2101084119, 2021.

[122] Government of British Columbia, "BC-LCFS Requirements," 2022, https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/renewable-low-carbon-fuels/requirements (accessed 2.7.22).

[123] European Council, "European Parliament legislative resolution of 17 December 2008 on the proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources," *Official Journal of the European Union, 2010.*

6.3.3 South America

In 2019 Brazil adopted targets in its RenovaBio program of a 10.2% reduction in CI over 10 years by adding biofuels (mainly sugarcane-based ethanol and soybean-based biodiesel) into its fuel pool.[124]

[124] U.S. Department of Agriculture, "Implementation of RenovaBio - Brazil's National Biofuels Policy," 2021, https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Implementation%20of%20RenovaBio%20-%20Brazil%27s%20National%20Biofuels%20Policy_Sao%20Paulo%20ATO_Brazil_02-25-2021.

7 Policy Principles

Low-carbon fuels are essential tools for achieving ambitious climate change mitigation goals. Existing state LCFs have demonstrated that GHG emissions can be reduced from the transportation sector. The challenges that should be addressed in order to increase market penetration of the low-carbon fuels are: GHG emission reduction from some of the fuels considered low-carbon may not actually be significant due to their indirect land-use impacts, effects on food crops and food prices, fraudulent activities to meet the reduction targets, and lack of investment in the next generations of low-carbon fuels. In order to eliminate the weaknesses of the current policies regarding LCFs, future policies can benefit from the following recommendations:

- Transportation accounts for 27% of greenhouse gas (GHG) emissions in the U.S.[125] To address this, there should be a strategy to decarbonize transportation fuels by increasing consumers' options for affordable low GHG-emitting transportation fuels. This will be most effectively accomplished by steadily growing market opportunities for low-carbon fuels with transparency, scale, and fair competition. Any such markets or programs must include safeguards to protect and enhance consumer benefits, and ensure equitable distribution of these benefits.

- In 2020, emissions from light-duty vehicles represented the highest emissions from the transportation sector at 57%.[126] In order to achieve emissions reductions at the scale needed to mitigate the impacts of climate change, LCF policies should be used as a tool to rapidly scale down emissions in the light-duty vehicle market.

- In 2020, heavy-duty vehicles comprised 26% of total transportation GHG emissions[127] while comprising only 11% of total vehicle miles traveled.[128] LCF policies should therefore identify opportunities to ensure emissions reductions in these highest-emitting vehicle classes and fleets to maximize emissions benefits. LCF policies should also identify opportunities to reduce emissions in sectors that are hardest to electrify, such as aviation and maritime transportation.

- Any LCF policy should be technology neutral and be able to account for future low-carbon fuel technologies that have not yet reached the marketplace.

- LCF policies should be complementary to, and not conflict with, other greenhouse gas and pollution reduction policies, goals, and strategies.

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[125] U.S. Environmental Protection Agency, "Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020," EPA 430-P-22-001, 2022.
[126] U.S. Environmental Protection Agency, "Fast Facts on Transportation Greenhouse Gas Emissions," EPA-420-F-22-018, 2022.
[127] Ibid.
[128] U.S. Department of Transportation, Bureau of Transportation Statistics, "U.S. Vehicle-Miles," https://www.bts.gov/content/us-vehicle-miles (accessed 5.03.2022).

- It is critical that regulators take a transparent, uniform, and traceable approach to measuring the life cycle emission performance of low-carbon fuels. But this approach alone is not sufficient to get significant reductions in carbon intensity. There must be stringent standards contained in any LCF policy to achieve emissions reductions in the transportation sector. These standards must ensure the best possible technology is being used to support carbon intensity reduction, including with respect to life cycle analysis and standardization of applicable verification and reporting.

- States or regions should be able to implement their own low-carbon fuels programs that are at least as stringent as any federal program and are designed to steadily decarbonize transportation fuels.

- In addition to individual state efforts, the federal government and the states can and should make a sustained effort to expand the research, development, and deployment of low- and zero-carbon fuels technologies and practices, including demonstration projects and technical assistance.

- Any LCF policy must prioritize justice and equity by recognizing that those communities most affected by transportation GHG emissions are low-income and communities of color. To do so, policies should identify opportunities to invest a significant portion of credit revenues into overburdened communities to fund infrastructure projects to support the emergence of more LCFs.

- In recognition that low-income communities spend disproportionately more of their income on transportation fuel, policymakers should work to ensure that any LCF policy does not significantly raise the cost of transportation fuel, including both LCFs and traditional transportation fuels.

8 Appendices

Table A1. Breakdown of CA Gas Price Components as of October 10, 2022[129]

	Branded	Unbranded
Distribution Costs, Marketing Costs, and Profits	$1.45	$1.50
Crude Oil Costs	$2.30	$2.30
Refinery Cost and Profit	$1.53	$1.48
State Underground Storage Tank Fee	$0.02	$0.02
State and Local Tax	$0.14	$0.14
State Excise Tax	$0.539	$0.539
Federal Excise Tax	$0.184	$0.184
Retail Prices	$6.16	$6.16

[129] California Energy Commission, “Estimated Gasoline Price Breakdown and Margins,” 2022, https://www.energy.ca.gov/data-reports/energy-almanac/transportation-energy/estimated-gasoline-price-breakdown-and-margins (accessed 4.15.22).

Table A-2 Low-Carbon Fuels Properties[130]

	Gasoline (E10)	Low Sulfur Diesel	Electricity	Biodiesel	Ethanol (E100)	Compressed Natural Gas (CNG)	Hydrogen
Gasoline or Diesel Gallon Equivalent (GGE)*	1 gal. = 1.00 GGE	1 gal. = 1.12 GGE	1 kWh = 0.030 GGE	B100 1 gal. = 1.05 GGE B20 1 gal. = 1.11 GGE	1 gal. = 0.67 GGE	1 lb. = 0.18 GGE	1 kg = 0.50 GGE
Pump Octane Number	84–93	N/A	N/A	N/A	110	120+	130+

*GGE = Gasoline gallon equivalent is the amount of a fuel that it takes to equal the energy content of 1 gallon of regular gasoline.

[130] U.S. Department of Energy Alternative Fuels Data Center, "Fuel Properties Comparison," 2021, https://afdc.energy.gov/fuels/properties.