Rhodium Group

Closing the Transportation Emissions Gap with Clean Fuels

JANUARY 15, 2021

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About this Report

This nonpartisan, independent research was with support from Breakthrough Energy. The results presented in this report reflect the views of the authors and not necessarily those of the supporting organization.

About Rhodium Group

Rhodium Group is an independent research provider combining economic data and policy insight to analyze global trends. Rhodium Group's Energy & Climate practice analyzes the effects of policy and market developments on energy systems and greenhouse gas emissions, and provides actionable information about the risks of climate change by sector and region around the world. This interdisciplinary group of policy experts, economic analysts, energy modelers, data engineers, and climate scientists supports decision-makers in the public, financial services, corporate, philanthropic and non-profit sectors. More information is available at www.rhg.com.

Executive Summary

Federal and state policies adopted over the past two decades have done a great deal to bend the curve of greenhouse gas (GHG) emissions from the US transportation sector. However with 1.6 billion tons of CO_2-equivalent projected to come from the transportation sector in 2030, we are still a long way from being on track to net-zero emissions by 2050, or from reducing transportation-related pollutants like NOx, particulate matter, and ozone, which disproportionately impact communities of color and low-income communities.

To achieve economy-wide net-zero emissions, we find that, in the transportation sector, a portfolio of strategies is the lowest cost and most likely to succeed. While efficiency improvements and vehicle electrification can cut transport emissions by up to two-thirds by 2050, low-GHG liquid fuels are needed to fill the remaining gap and achieve net-zero emissions in the transportation sector by mid-century.

Transportation will continue to be one of the largest sources of US emissions

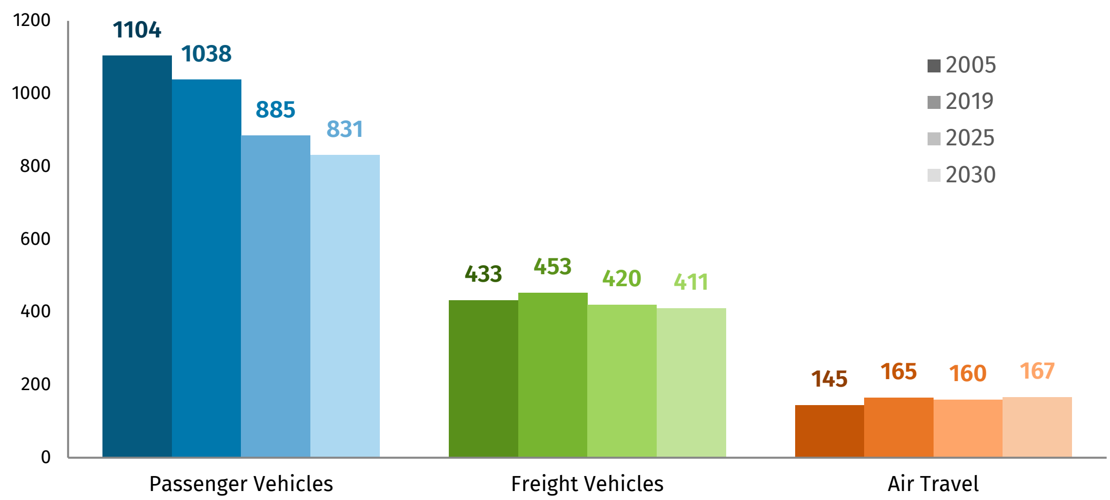
Transportation is the largest source of GHG emissions in the US, accounting for 33% of the economy-wide total in 2019. While transport emissions declined 6% between 2005 and 2019, the majority of reductions have come from the passenger vehicle fleet (light-duty vehicles). Between 2005 and 2019, emissions from freight vehicles rose 5%, and aviation emissions rose by 14%.

Looking forward, under current policy, passenger vehicle emissions are projected to be 20% lower in 2030 than they were in 2019, largely due to increased electrification. However, the same progress is not projected for freight transportation and air travel. Freight emissions are projected to decline by 9%, while aviation emissions are expected to increase by about 1% in 2030 (ES Figure 1).

ES FIGURE 1

US transportation emissions by mode, 2005-2030

Million metric tons (MMT) of CO_2-equivalent (CO_2e)



Source: Rhodium Group. Projections are from Rhodium Group's Taking Stock 2020, V-shaped economic recovery scenario.

Electric vehicles alone will not get the US to net-zero by 2050

Under a scenario of modest electrification of light-duty vehicles (LDVs), we project that over 700 million metric tons of emissions will remain in 2050, from fuels that need to be decarbonized or displaced through mobility strategies that reduce vehicle usage (low electrification in ES Figure 3). Under this scenario, electric vehicle sales come in at the lower end of aggressive projections, reaching 35% of LDV sales in 2030 and 77% in 2040. Even with increased LDV electrification (ES Figure 2), where more than half of all LDV sales nationally are electric by 2030 and nearly 90% by 2035, 525 million tons of GHG emissions, 34% of emissions still remain in the transportation sector in 2050. The remaining emission reductions will need to come from fuel decarbonization and mobility solutions. Increasing mobility will reduce vehicle miles traveled but cannot decarbonize the remaining emissions from the transportation sector. Clean fuels will be needed to close the transportation emissions gap.

A portfolio of clean fuels is needed to close the transportation emissions gap

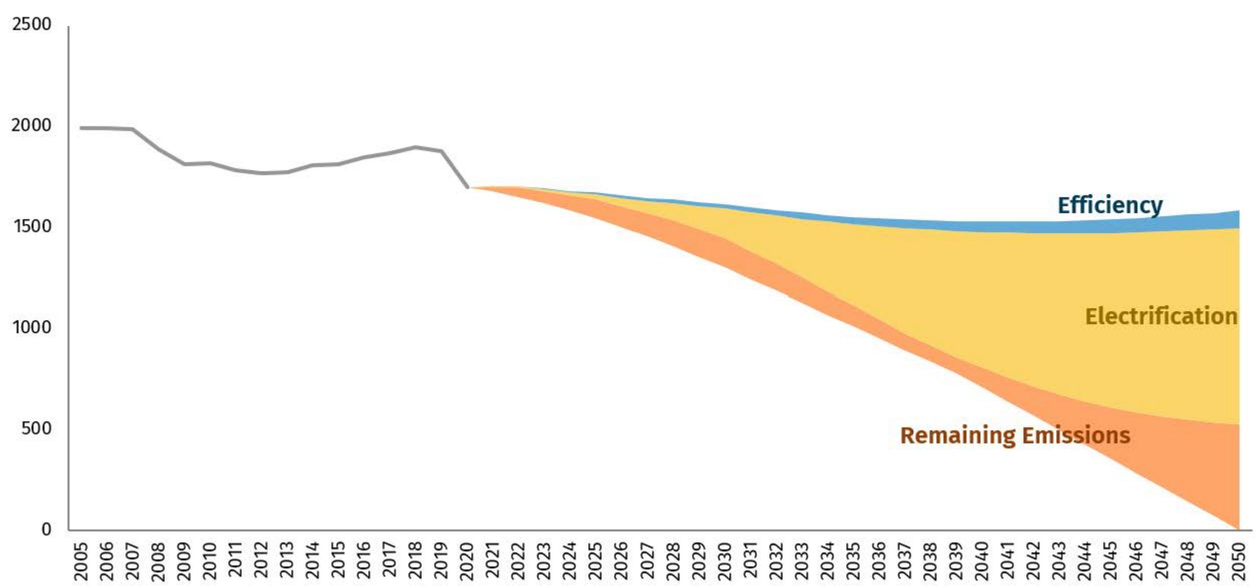
Achieving net-zero emissions in the transportation sector in 2050 will require not just electrification but other strategies as well, including aggressive federal action to deploy a portfolio of clean fuels. We find in our modeling that a combination of advanced biofuels, electrofuels, and carbon-neutral fossil fuels (defined in ES Table 1) can successfully close the transportation emissions gap and get the sector to net-zero emissions by 2050.

The optimal portfolio of clean fuels will depend on technology cost, feedstock availability and will vary regionally based on local air quality issues, availability of high-quality wind and solar resources and characteristics of the local agricultural economy.

ES FIGURE 2

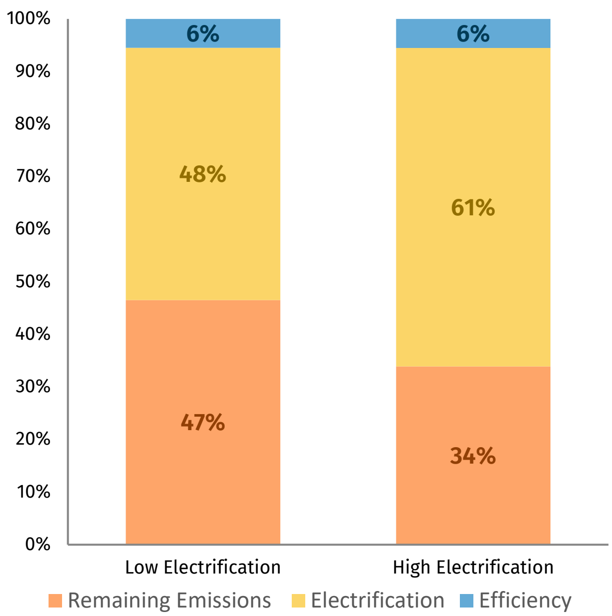
US transportation emissions with decarbonization strategies under a high electrification scenario

Million metric tons CO_2e



Source: Rhodium Group and EER

ES FIGURE 3
Transportation emissions fuel gap in 2050 under varying levels of electric penetration
Percentage in million metric tons CO_2e



Source: Rhodium Group and EER

ES TABLE 1
Clean fuel categories

Biofuels	Conventional and advanced fuels made from biomass feedstock
Electrofuels	Drop-in liquid replacement fuels made from electricity, carbon, and hydrogen
Carbon-neutral fossil fuels	Petroleum fuels whose emissions are offset with negative emissions technology

Federal policies to drive clean fuel deployment

Achieving net-zero emissions in 2050 will require aggressive federal action to reduce transportation demand, electrify vehicles, and develop and deploy clean fuels. A portfolio of policies can drive emissions reductions across transportation modes and amplify reductions from policies enacted at the state and local level. The federal government plays a large role in determining the US fuel mix. Research funding, fiscal incentives, market-based policies, and GHG and air quality targets all shape the portfolio of fuel consumed across the country. Rather than relying on existing policies, the federal government can take action to accelerate the deployment and market penetration of the clean fuels needed to achieve net-zero emissions by 2050.

Federal transportation policy should support research and development of clean fuels through funding and investments in transformational fuel technology. Moreover, the federal government can accelerate deployment and development of clean fuels through fiscal incentives aimed at fuel manufacturers and fuel consumers to incentive the production and consumption of clean fuels. Federal procurement policies can also increase market penetration as bulk purchases can increase economies of scale. Ultimately, deep market penetration of clean fuels, required to achieve net-zero emissions by 2050, will require durable price signals and robust federal policies.

This report begins with projections of transportation emissions under current policy, to identify the emission reductions that will be needed to achieve net-zero emissions by 2050. Next, we identify the portfolio of strategies that can achieve net-zero transportation emissions, including a wide range of clean fuels to complement electrification, efficiency, and increased mobility. The report then shifts to the economic and environmental merits of a wide range of clean fuels and the federal policy tools that can drive development and market penetration of clean fuels to achieve net-zero transportation emissions by 2050.

CHAPTER 1

Current Transportation Emissions Trends

Transportation is the largest source of greenhouse gas (GHG) emissions in the US, accounting for 33% of the economy-wide total in 2019. Following decades of steady growth, transport emissions peaked in 2005 at just under 2 gigatons, and declined 6% between 2005 and 2019 (Figure 1). Much of the reduction came from the drop in vehicle miles traveled (VMT) during the 2008-2009 Great Recession, but policy and technology change have played an important role. Improvements in vehicle efficiency and increased biofuels deployment reduced the carbon intensity of US transportation by 14% since 2005, enough to offset the recovery in VMT after the end of the Great Recession. Emissions of other air pollutants have declined as well. While not yet a meaningful contributor to overall transportation emission reductions, electric vehicle (EV) sales are growing quickly, from 10,000 vehicles in 2011 to 330,000 in 2019. The overwhelming majority of transportation emission reductions have come from the passenger vehicle fleet. Between 2005 and 2019 emission from freight vehicles rose 5% and aviation emissions rose by 14% (Figure 2).

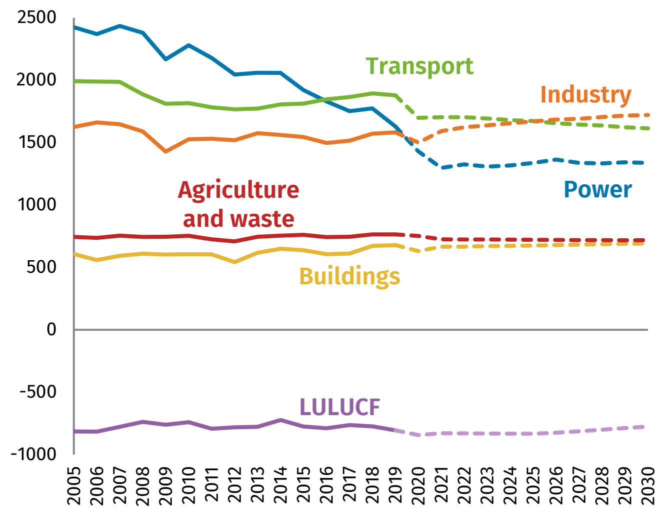
Transportation will remain a leading source of US GHG emissions through 2030.

Transportation was the sector that was most significantly impacted by the COVID-19 pandemic this year, as Americans dramatically curtailed driving and flying, particularly in the first half of 2020. Both passenger vehicle usage and air travel started to recover during the second half of the year, but the ultimate impact of COVID-19 on transportation emissions will depend on the pace of economic recovery in 2021 and beyond, and the permanence of pandemic-induced changes in mobility patterns (e.g. more working from home and more virtual conferences). In our 2020 Taking Stock report, we project US emissions by sector under a range of economic recovery scenarios. In our V-shaped recovery scenario, we expect transportation emissions to remain relatively flat between 2021 and 2030 as continued improvements in fuel efficiency and electric vehicle sales offset post-pandemic growth in vehicle miles traveled (Figure 1).

FIGURE 1

US emissions by sector

Million metric tons (MMT) of CO_2-equivalent (CO_2e)



Source: Rhodium Group. Projections are from Rhodium Group's Taking Stock 2020 V-shaped economic recovery scenario.

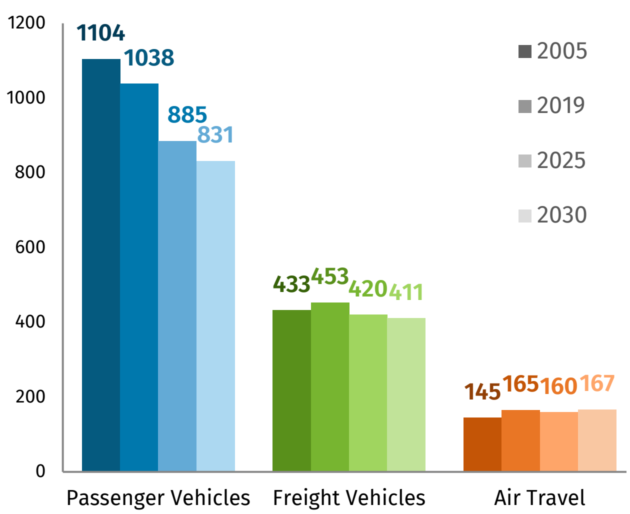
These projections include all current federal and state policy as of May 2020, including the federal Renewable Fuel Standard (RFS), updated heavy-duty vehicle GHG emissions standards, and federal vehicle incentives. We assume light-duty CAFE standards increase 1.5% annually from model year 2021 to 2026 following the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule finalized in February 2020 for all states except California and the 14 S177 states that plan to maintain more stringent Obama-era CAFE standards. Our projections also include state-level Low-Carbon Fuel Standards in California and Oregon.

As over the past decade, most of the projected reductions in transportation emissions over the coming decade come from light-duty vehicles (cars and light trucks). In our V-shaped recovery scenario, VMT grows by 9% between 2021 and 2030, but this is offset by a 15% improvement in the average efficiency of on-road vehicles as newer, higher efficiency cars and light trucks make up a larger share of the overall fleet. EVs also start to have a measurable impact on transportation emissions over the coming decade. Using battery cost projections from NREL's Electrification Futures Study (rapid advancement scenario), we project that the EV share of LDV sales grows to 17% in 2030 and that EVs account for 6% of total LDV stock that year. These are the assumptions included in our projections shown in Figure 1. Combining growing EV sales, continued improvements in vehicle efficiency, and lingering effects of the pandemic, we project LDV emissions will be 20% lower in 2030 then they were last year (Figure 2). Using more aggressive battery cost decline projections from Bloomberg New Energy Finance, EVs grow to 30% of new LDV sales by 2030 and 11% of total LDV stock. Under this scenario, LDV emissions decline by 22% instead of 20%.

FIGURE 2

US transportation emissions by mode, 2005-2030

Million metric tons (MMT) of CO_2-equivalent (CO_2e)



Source: Rhodium Group

Under current policy we expect significantly less progress in decarbonizing freight transportation and air travel over the coming decade. In our V-shaped recovery scenario, we expect both freight and aviation emissions to remain relatively flat (Figure 2). Improved efficiency in both trucks and planes helps offset growth in usage, but unlike in LDVs, it is not enough to lead to a net emissions decline.

Federal and state policy adopted over the past two decades, along with encouraging technological and market developments, have done a great deal to bend the US transportation emissions curve. But with 1.6 billion tons of CO_2e still projected to come from the transportation sector in 2030, we are still a long way from being on track to net-zero emissions by 2050—President-elect Biden's economy-wide goal—or from reducing transportation-related pollutants like NOx, particulate matter and ozone, which disproportionately impact low-income communities and communities of color. A multi-pronged policy approach that includes efficiency, vehicle electrification, and clean fuels, is needed to close the GHG emissions gap and address environmental health disparities.

CHAPTER 2

Paths to Net-Zero Emissions by 2050

To help inform a multi-pronged policy approach to decarbonizing the transportation sector, Rhodium Group partnered with Evolved Energy Research (EER) to model economy-wide pathways to achieving net-zero GHG emissions in the US by 2050. We used EER's coupled RIO/EnergyPATHWAYS modeling platform calibrated to technology cost and market inputs defined by Rhodium and consistent with Rhodium's Taking Stock 2020 baseline emission projections.

Economy-wide, we find that a six-part strategy is necessary to get to net-zero emissions:

1. **Efficiency:** Reduce the amount of energy required to fuel the economy by making appliances, buildings, equipment, and vehicles more efficiently.

2. **Zero-carbon electricity**: Decarbonize electric power generation by switching from uncontrolled coal, oil, and natural gas to renewables and nuclear and/or fossil generation with carbon capture and sequestration.

3. **Electrification**: A zero-carbon electricity grid provides a power platform for decarbonizing other sectors of the economy through electrification of appliances, equipment, and vehicles.

4. **Fuel decarbonization:** For those applications where appliance, equipment, or vehicle electrification is too costly, too slow, or faces significant barriers to adoption, decarbonized liquid and gaseous fuels made from biomass or zero-carbon electricity are necessary to close the gap.

5. **Other sectors and gases**: The energy sector accounts for 85% of US GHG emissions. The other 15%, like agricultural and methane or F-gas emissions, will need to be addressed through sector and/or gas-specific strategies.

6. **Carbon removal**: Those emissions that can't be reduced directly will need to be offset by natural (e.g., improved forest management) or technical (e.g., direct air capture) carbon removal.

An illustrative combination of these strategies is provided in Figure 3. The ultimate balance among them depends on future technological, market, behavioral and policy developments. But what's clear from our modeling is that a multi-pronged approach is both the lowest cost way to get to net-zero emissions, and the one most likely to succeed.

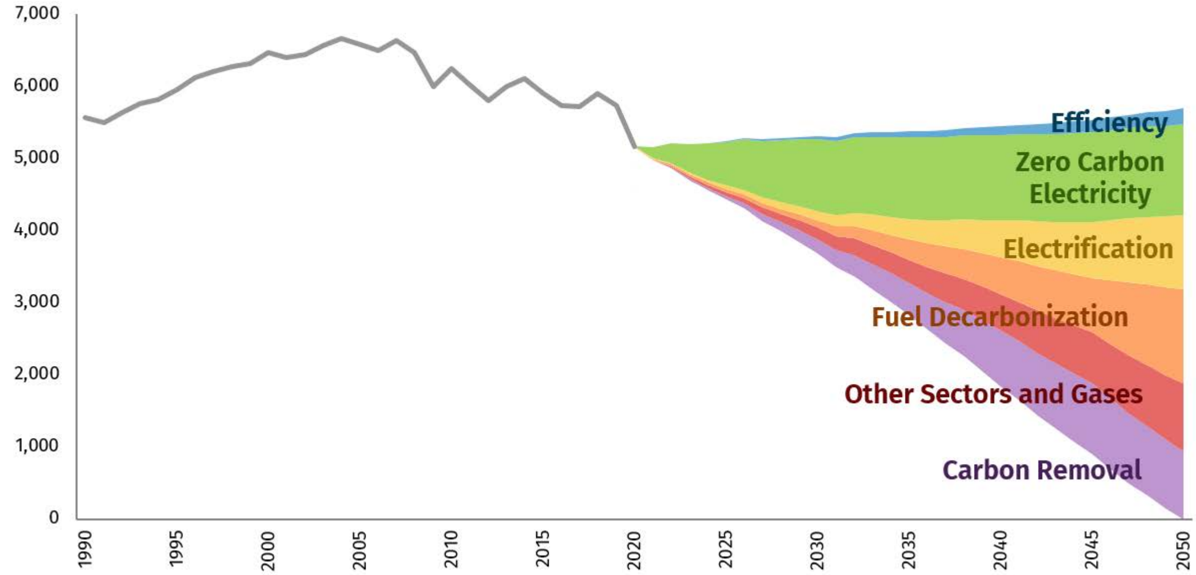
A three-pronged strategy for decarbonizing transportation

For the transportation sector, three of the six economy-wide strategies apply. The US needs to a) reduce transportation energy demand through vehicle efficiency improvements and reductions in vehicle usage, b) electrify vehicles wherever possible and affordable, and c) develop and deploy low-GHG liquid fuels to cover the remainder. In modeling paths to net-zero emissions for the transportation sector, we explore the potential role played by all three.

FIGURE 3

Paths to economy-wide net-zero emissions in the US, by strategy

Million metric tons CO_2e



Source: Rhodium Group and Evolved Energy Research

Efficient mobility

The most direct way to reduce emissions from transportation is to move people and goods more efficiently—either by improving the fuel economy of cars, trucks, buses, ships and airplanes, or reducing how many miles those vehicles need to move people or goods. For this exercise, we only model the former, but the latter is equally important. We restrict internal combustion engine sales to only the most efficient vehicles available to create an upper bound estimate on the role fuel economy improvements can play in the transition to a net-zero economy. We do not include policies or investments that reduce demand for vehicle transportation, such as those that encourage switching to public transit, biking, walking, and micromobility, and those that improve freight logistics efficiency. These measures are outside the scope of this exercise and warrant a separate analysis to understand the potential reductions from increased mobility options.

Vehicle electrification

After a couple of false starts historically, electric vehicles have finally achieved escape velocity. Lithium-ion battery prices have fallen by nearly 90% since 2010, and based on current battery price projections from Bloomberg New Energy Finance (BNEF), electric vehicles in many vehicle classes will be cheaper than internal combustion engine vehicles within the next few years, even without subsidies. BNEF projects EVs will account for 10% of US LDV sales in 2025 (up from 2% in 2019), 32% in 2030 and 60% in 2040 (Figure 4). Wood Mackenzie has a slightly less aggressive forecast, with EVs reaching 6% of US LDV sales in 2025, 17% in 2030 and 40% in 2040. The EIA has the most conservative EV sales forecast, at 3.5% of sales in 2025, 5% in 2030 and 7% in 2040. This is largely a function of relatively outdated battery cost projections. When we run Rhodium's version of the same National Energy Modeling System (NEMS) used in EIA's forecast, but with updated battery cost projections, we get sales shares in 2030 between 17% and 36% depending on the specific battery price path.

In modeling transportation pathways to net-zero emissions, we adopt a range of EV sales projections that are more aggressive than the most optimistic current market forecasts, but within the realm of technical possibility. In the most optimistic case for LDVs, we model EV sales shares as high as 56% in 2030, 88% in 2035, 98% in 2040 and 100% from 2045 onward (Figure

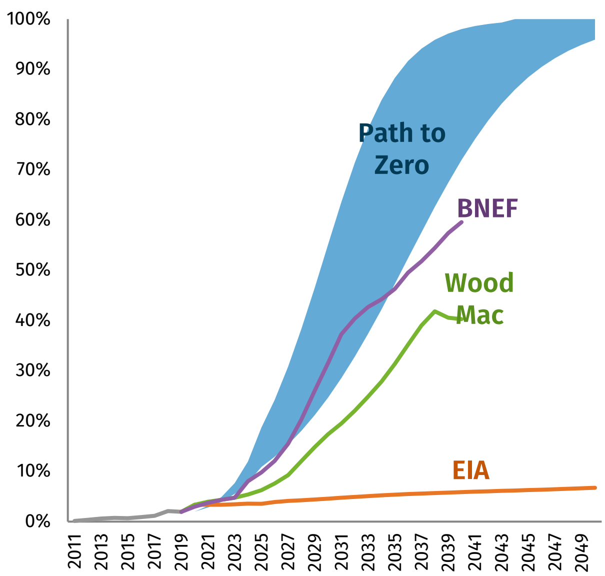
4). Because of the time it takes for vehicles already on the road to turn over, there is a significant delay in these scenarios between growth in the EV share of vehicle *sales* and commensurate growth in the EV share of vehicle *stock*. But at the upper end, this still translates into market penetration rates for EVs in the years ahead as rapid as cell phones and the internet achieved in years past (Figure 5).

Under a scenario of high EV market penetration, EV adoption rates in 2030 would need to be equivalent to adoption rates for cell phones and the internet in 2005, 10 years after take-off.

FIGURE 4

US electric vehicle sales as a share of total LDV sales

Percent



Source: Rhodium Group, EER, Bloomberg New Energy Finance, Wood Mackenzie, EIA

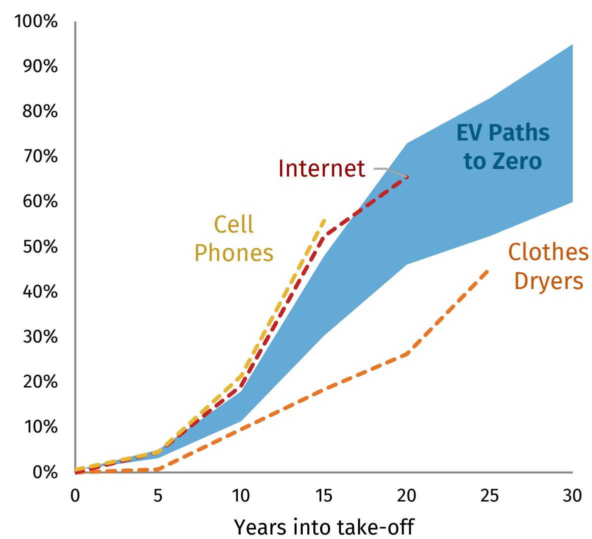
This analysis focuses on the electrification of the light-duty vehicle fleet given the current technological challenges with electrifying other transportation applications—specifically marine and aviation. Technology and cost have been barriers to development and deployment of electric airplanes and shipping vessels, which will require new policies to drive investment to achieve market penetration.

EVs face a number of barriers to wide-spread adoption that consumer electronics don't face even after they have achieved cost parity with internal combustion engines. These include infrastructure barriers like wide-spread charging station availability, behavioral barriers like range anxiety, and manufacturing scaling and supply chain barriers that are larger in the automotive industry than in consumer electronics. Aggressive action can help overcome these barriers, but not completely eliminate them. As a result, we also consider slightly less aggressive EV sales pathways in our modeling, but still more aggressive than BNEF projections from 2035 onward (Figure 4). In our slowest deployment scenario, EVs cross 50% of LDV sales in 2036 (instead of 2030 in our fastest case) and cross 90% in 2046 (instead of 2036).

FIGURE 5

EV market penetration will need to match historic consumer electronic deployment

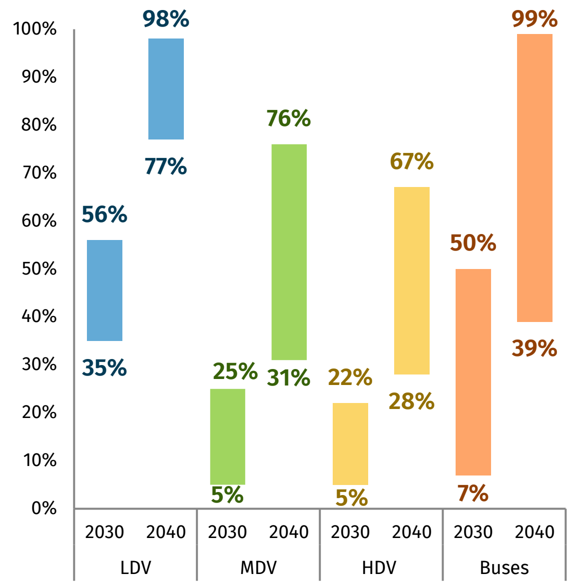
Percent of market in the years following take-off, EVs are LDV only



Source: Rhodium Group and EER

Electrification is occurring more slowly in the medium-duty vehicle (MDV) and heavy-duty vehicle (HDV) segments. For MDVs we assume between 5 and 25% of all sales are electric by 2030 and between 31 and 76% by 2040. For HDVs we assume between 5 and 22% of all sales are electric by 2030, and between 28 and 67% by 2040. We expect transit buses will be easier to electrify, and assume 7 to 50% of all sales are electric in 2030, growing to 39 to 99% by 2040 (Figure 6).

FIGURE 6
US electric vehicle sales as a share of total sales
Percent



Source: Rhodium Group and EER

Even with aggressive EV sales rates – 56% of LDV sales in 2030 and 98% of sales in 2040 - the US vehicle fleet is slow to electrify. Under our highest EV sales rates, EVs comprise only 18% of the LDV vehicle fleet in 2030 and 66% in 2040.

Fuel decarbonization

For those transportation applications where vehicle electrification is too slow, too expensive, or faces insurmountable market or behavioral barriers, low-GHG clean liquid fuels need to fill the gap. Fortunately, electrifying vehicles is not the only way to take advantage of increasingly low-cost renewable electricity to decarbonize the transportation sector. Electrolysis can be used to turn wind and solar power into hydrogen, which can be further transformed into electrofuels that can be used in existing cars, trucks, ships and planes. Advanced biofuels offer another low-GHG alternative to gasoline, diesel and jet fuel, as do carbon-neutral fossil fuels where negative emissions technologies are employed to offset emissions from conventional fossil fuels (Table 1).

To model the potential role for these different low-GHG fuels to play in reducing transportation sector emissions to zero, we explored a range of electrolyzer and direct air capture costs, as well as a range of levels of biofuels feedstock availability.

TABLE 1
Clean fuel categories

Biofuels	Conventional and advanced fuels made from biomass feedstock
Electrofuels	Drop-in liquid replacement fuels made from electricity, carbon, and hydrogen
Carbon-neutral fossil fuels	Petroleum fuels whose emissions are offset with negative emissions technology

In our modeling, we take electrolyzer cost estimates from the International Energy Agency. But we also explore a side case where electrolyzer costs are at the high end of currently available literature estimates. For direct air capture, we use technology cost estimates from a 2019 Rhodium Group report, Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology. For biomass, we assume 850 million metric tons of available supply, at cost curves specified in the US Department of Energy's 2016 Billion-Ton Report. But we also explore a side case where no energy feedstocks are used for biofuels.

The US needs a mix of all three approaches

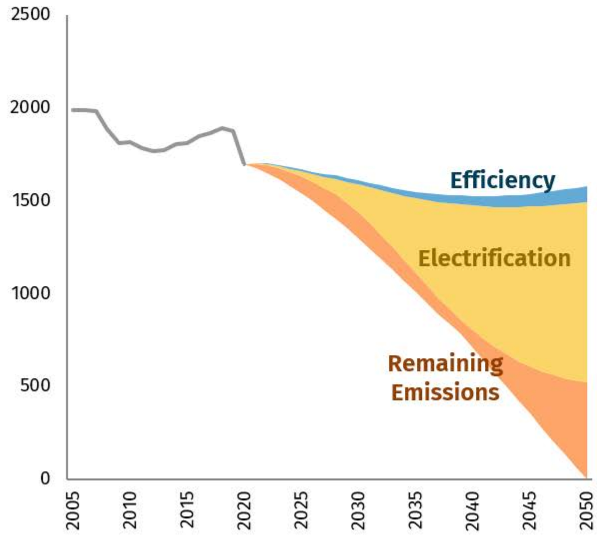
Decarbonized fuels and mobility options will need to comprise nearly half the emissions reductions needed to achieve net-zero emissions by 2050.

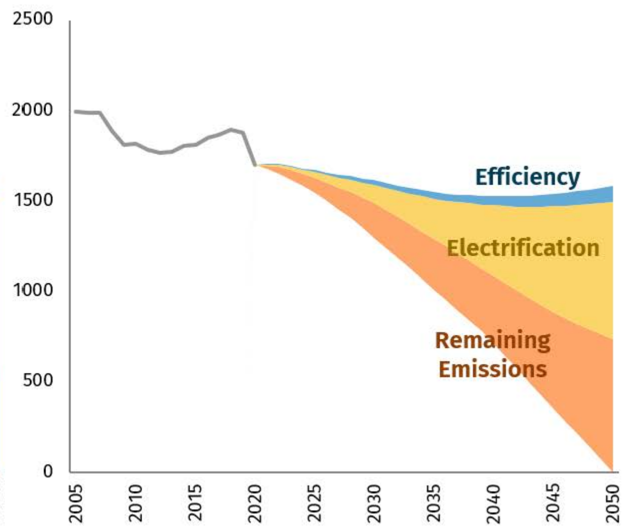
As in modeling economy-wide pathways to get to net-zero emissions, when we model what's required in the transportation sector specifically, we find that a portfolio of strategies is the lowest cost and most likely to succeed. Efficiency improvements and vehicle electrification cut transport emissions by two-thirds in 2050 in our most aggressive electrification scenario (assuming the power sector is completely decarbonized), leaving 525 million metric tons of remaining emissions (Figure 7 left).

FIGURE 7

US transportation emissions with decarbonization strategies under high and low electrification scenarios

Million metric tons CO_2e, high electrification scenario (left) and low electrification scenario (right)





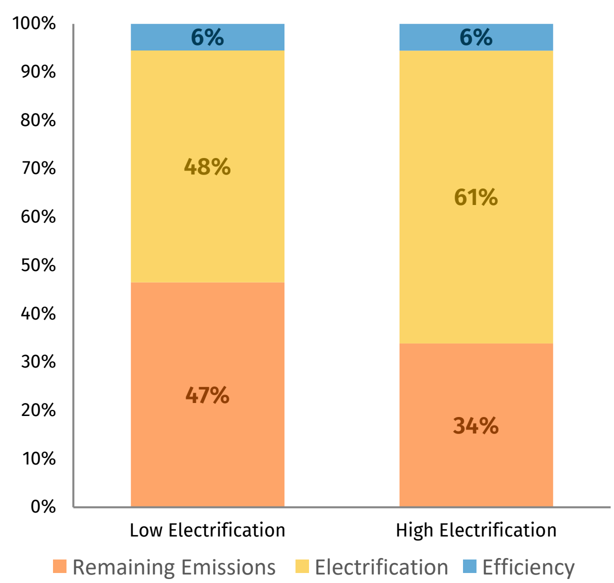
Source: Rhodium Group and EER

If electric vehicle sales come in at the lower end of our projections (but still higher than current BNEF projections), remaining emissions are 735 million tons in 2050 (Figure 7 right). Across the range of EV penetration scenarios, a gap of 34-47% of 2050 transportation sector emissions remains (Figure 8). Without low-GHG liquid fuels to fill this gap, there is little chance the US will be able to achieve net-zero transportation emissions by mid-century.

FIGURE 8

Transportation emissions fuel gap in 2050 under varying levels of electric penetration

Percentage in million metric tons CO_2e



Source: Rhodium Group and EER

CHAPTER 3

Clean Fuels

Fortunately, we find in our modeling that a combination of biofuels, electrofuels and carbon-neutral fossil fuels can successfully close the transportation emissions gap and get the sector to net-zero emissions by 2050. These low-GHG "clean fuels" all have a lower carbon intensity (CI) than fossil fuels (Text Box 1). The optimal balance among the various clean fuel options will depend on the cost of electrolyzers, the price of direct air capture and the availability of suitable biomass feedstock. It will also vary regionally within the US based on local air quality issues, availability of high-quality wind and solar resources and characteristics of the local agricultural economy.

Biofuels

Biofuels are transportation fuels made from a wide spectrum of biomass that are typically placed into two main classifications, conventional and advanced. Biofuel production is currently among the most technologically ready and cost-effective pathways to decarbonizing aviation, marine, and heavy-duty vehicle applications and achieve net-zero emissions by 2050. Conventional, or first generation, biofuels are liquid fuels that are commercially available and have reached technological maturity made from food crops and agricultural waste including corn, soybean, sugarcane, vegetable oil, and used animal fats. Advanced biofuels are derived from non-food crops and agricultural and forest residue through a variety of biologic, thermal, and chemical processes. Advanced biofuel feedstocks include algae, municipal solid waste, animal fats, and woody biomass composed of three primary elements: cellulose, hemicellulose, and lignin. Conventional and advanced biofuels can be blended with petroleum fuels, combusted in existing internal combustion engines, and distributed through existing fuel infrastructure.

The most common biofuels are ethanol and biodiesel that can be blended at various levels with gasoline and diesel, respectively. In the US, ethanol is produced mainly from corn through fermentation and biodiesel is produced from soybeans through transesterification. These fuel pathways are well-integrated in the agricultural sector with established technologies and

BOX 1

Measuring the carbon intensity of liquid fuels

Carbon intensity (CI) is defined as the amount of carbon emissions released per unit of energy produced. For transportation fuels, CI is the measure of GHG emissions emitted through the production and total life of the fuel, measured in grams of carbon dioxide equivalent (CO_2e) per megajoule (MJ). Fuel CI is based on the effects of five GHGs: CO_2, methane, nitrous oxide, volatile organic compounds, and carbon monoxide. The cumulative effect of these gases is calculated using life cycle analysis (LCA) which estimates the direct GHG emissions of fuels including emissions from: feedstock generation or extraction; conversion of feedstock to finished fuel or blendstock; distribution; storage; delivery, and final use of the fuel.

Argonne National Lab's GREET (Greenhouse Gases, Regulated Emissions, and Energy use in Transportation) model is considered the state-of-the-art model with over 100 pathways for petroleum fuels, natural gas fuels, biofuels, hydrogen, and electricity for analyzing the life cycle emissions of traditional and advanced technology fuels. The GREET model is frequently updated and is widely used by state and federal regulators and provides a uniform, transparent platform for LCA analysis with inputs from US Department of Energy, US EPA, US Department of Agriculture and other sources. GREET been used in the development of US EPA's Renewable Fuel Standard (RFS) and a California specific modification, CA-GREET was developed by the California Air Resources Board (CARB) for use in the Low Carbon Fuel Standard.

Indirect emissions, including emissions from indirect land use change (iLUC), are estimated separately and added to the CI calculation resulting in a comprehensive estimate of a fuel's lifecycle GHG emissions. As land is converted for biofuel feedstock, carbon stored in the soil and vegetation may be released. This iLUC factor is measured as the carbon emissions per unit of biofuel released due to global land use change from biofuel-induced changes in land and food prices. Both US EPA and CARB require the inclusion of iLUC factors for the CI calculations in the RFS and LCFS. There is a large body of literature estimating the iLUC factor of crop-based biofuel but fewer studies on non-crop and residual feedstock biofuels. ILUC factors and their application have been controversial and heavily litigated.

supply chains. Advancements in feedstock generation and processing continues to reduce costs, expand the range of co-products (including high quality animal feed) and improve the environmental performance of conventional biofuels.

More than 98% of gasoline in the US contains ethanol, with E10 (10% ethanol) the most common blend, used in conventional internal combustion engines. E15 (containing 10.5% to 15% ethanol) can also be used in conventional vehicles while E85 (85% ethanol) can only be used in flex fuel vehicles. In 2019, ethanol comprised 10% of US total gasoline volume, approximately 1.5 billion gallons. The energy content of ethanol is about 30% lower than gasoline, and a vehicle using E10 will on average see a decrease in vehicle fuel economy of around 3%. However, ethanol has a higher octane number than gasoline, increasing its power and performance, and researchers are investigating ways to optimize engine efficiency for higher-octane biofuel blends.

There are two main biofuels created from non-food and waste crops: renewable diesel and sustainable aviation fuel (SAF). These fuels are generated through gasification, pyrolysis, and hydrotreating processes that are in the early stages of development. When coupled with bio-energy with carbon capture and storage (BECCS), these advanced biofuels have the potential to be carbon negative.

To date, renewable diesel has gained the largest market share of advanced biofuels, and can be blended with diesel or used a drop-in replacement. In the US, five plants have a combined capacity to produce nearly 400 million gallons of renewable diesel each year. However, in 2019, about 900 million gallons of renewable diesel were consumed in the US, about 2% of total diesel volume. Nearly all US produced and imported renewable diesel was consumed in California due to the price signal of its Low Carbon Fuel Standard (LCFS).

Nearly 400 million gallons of renewable diesel are produced in the US each year.

SAF encompasses all non-petroleum jet fuels that were previously known as renewable jet fuel, alternative jet fuel, renewable aviation fuel, and biojet fuel. SAF can be blended with petroleum jet fuel at a maximum blend level of 50% across five fuel pathways. SAF has been used commercially since 2016, with 2.4 million gallons (less than 1% of aviation fuel demand) consumed in the US in 2019.

Carbon intensity of biofuels

Biofuels often rely on renewable feedstocks that could be used for other purposes—including food for human consumption, animal feed, and electricity generation. Increasing demand for biofuel feedstock can result in indirect land use change (iLUC), additional GHG emissions from the release of carbon sequestered in soil and vegetation as land is converted for biofuel feedstock. Studies vary widely in their iLUC estimates; however US EPA and CARB require the inclusion of iLUC factors in the CI calculations of biofuels.

The CI of biofuels can vary widely based on feedstock, production process, and fuel delivery, from carbon negative advanced biofuels with BECCS to ethanol that provides an incremental CI improvement due to iLUC. Conventional biofuels are largely blend fuels, limiting the fossil fuel emissions they can displace. Ethanol pathways, on average, have a CI approximately 40% lower than gasoline, while biodiesel has an average CI roughly 60% lower than diesel. Coupling conventional biofuel with soil carbon sequestration, biochar production, or BECCS does have the potential to further reduce the carbon intensity of finished clean fuels. Researchers estimate that an average corn ethanol plant can reduce the CI of ethanol by 40% through carbon capture, producing ethanol with 80% lower GHG emissions than fossil gasoline.

Advanced biofuels have a larger CI reduction potential as they can completely displace petroleum fuels. The average gallon of renewable diesel has a CI 60% lower than diesel, while SAF pathways average 65% lower than jet fuel. Advanced biofuels coupled with carbon sequestration even have the potential to be carbon negative. In September 2020, the Proceedings of the

National Academy of Sciences (PNAS) published findings that advanced cellulosic biofuel production with BECCS could achieve up to 15 times the carbon mitigation potential of forest or grassland restoration.

Corn ethanol plants can reduce the carbon intensity of ethanol by 40% through carbon capture.

Feedstock availability of biofuels

The availability of consistent feedstock has been a major factor in the supply of clean fuels. Feedstocks comprise a significant portion of the final fuel price for many fuels—up to 90% for some biofuels. Conventional biofuels have been subject to the 'fuel vs. food' debate, where critics argue that diverting cropland for fuel production increases crop prices leading to global food insecurity—often pointing to spuriously correlated movements in the price of corn and ethanol production. Advanced biofuels produced from non-food crop feedstocks do not directly compete with food crops for land use, however they can have iLUC factors due to changes in water and pesticide consumption. In addition, these advanced biofuel feedstocks often require additional processing compared to conventional biofuel feedstocks, increasing the overall cost of the final fuel.

In addition to land use changes, crop feed stocks may impact water and soil quality through use of additional fertilizer and pesticides. The Department of Energy's 2016 Billion-Ton Report estimates that the US has the potential to produce nearly 100 billion gallons of biofuel by 2030. In addition, the International Energy Agency (IEA) estimates up to 1.5 billion tons of advanced biomass (forestry resources, agricultural residue, and waste) will be available in the US in 2040. Advanced biofuels have the advantage of abundant and diverse feedstocks, but they require extensive processing relative to conventional biofuels. In addition, feedstocks may be located far from processing facilities and have immature supply chains, creating inconsistencies in quality and timing of finished fuels.

Despite the large potential for biofuel production, disagreements over iLUC factors could threaten widescale biofuel penetration. While some say sustainability standards can improve biodiversity and ecosystem benefits from biofuel feedstock, others voice concerns that increasing conversion of productive land for biofuels will divert scarce resources, causing harm. Increased demand for palm oil as a feedstock has been blamed for increased deforestation and reduced biodiversity in Indonesia. There have also been reports of human rights abuses associated with the harvesting of palm oil, leading some jurisdictions to consider banning the feedstock for use in biofuels.

Air quality impacts of biofuels

Every step in the life cycle of a fuel results in air quality impacts. For fossil fuels, this includes extraction, refining, fuel storage and transport, and combustion. Petroleum extraction, refining, and combustion releases oxides of nitrogen (NOx), particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO_2), volatile organic compounds (VOC) and carcinogens. NOx and VOCs react with sunlight to create ozone, a main ingredient in smog, while PM are fine particles that cause lung damage. Diesel particulate matter (DPM) is of particular concern as it also contains over 40 cancer-causing substances and is often emitted near highly populated areas.

Localized air pollution leads to adverse health effects including increased instances of asthma, cardiovascular disease, cancer, and premature mortality. The impact of air pollution is highly dependent on where it is emitted, and the relative impact of fuels depends on the location of feedstock production and processing and fuel combustion. Petroleum emissions can also exacerbate existing health conditions in vulnerable populations and communities of color. The average Black and Hispanic Americans are 41% and 46% more likely to be exposed to DPM than white Americans.

The emissions profiles of clean fuels vary greatly—by feedstock, processing and combustion—and quantifying air quality impacts, specifically in regions that fail to meet EPA National Ambient Air Quality

Standards for PM and ozone, is of critical importance to ensure that clean fuels result in GHG and air quality benefits.

Ethanol and biodiesel have a similar air quality profile to petroleum fuels. While studies have found some evidence that blending biodiesel with conventional diesel may lower the particulate matter of the fuel, there is a lack of consensus that blending ethanol with petroleum products results in any air quality improvements.

The air quality impacts of advanced biofuels vary by feedstock, conversion technology, and direct and indirect land use changes but generally offer lower criteria pollutant levels than petroleum fuels or conventional biofuels. The air quality impacts are separated by location of feedstock cultivation and production and fuel combustion. Combustion of advanced biofuels results in lower PM emissions than their fossil fuel counterparts which can provide health benefits in areas where the fuels are consumed. However, feedstock cultivation and processing can result in increased PM levels in regions where fuels are produced. Analyses have shown that renewable diesel in particular can have PM levels 30% lower than diesel. Renewable natural gas can also provide air quality benefits specifically when paired with low NOx engines that reduce combustion emissions relative to fossil fuels. However, there are concerns about NOx air quality impacts at production and processing facilities, which can reduce the net benefit of the finished fuel.

SAF has been shown to provide significant air quality improvements, including large reductions in sulfur oxides (SOx) and PM, across all fuel production pathways when blended with or replacing fossil jet fuel. SAF does not provide reductions in NOx emissions, however, which comprise a large portion of the overall health impact of the fuel.

Technology readiness of biofuels

Ethanol and biodiesel are largely produced using mature technological processes—hydrolysis and fermentation—that are proven on a commercial scale. Technologies to produce renewable diesel and SAF are more nascent and have been hampered by high capital costs. Advanced biofuel development has largely been driven by government support for research and development and fiscal production incentives. However, this support has not been sufficient for highly anticipated fuels, including cellulosic feedstocks, the microbial conversion of woody biomass to bioethanol and thermochemical processes to create renewable gasoline and diesel renewable gasoline, to reach production quantities. BECCS technologies, including thermochemical conversion and post-energy conversion carbon capture are also not yet mature, despite policy support.

Along with fuel development, technological advancements continue in the storage and transport of biofuels in order to maintain fuel quality across a range of climate conditions. Technological advances in conventional biofuels are now focused on efficiency, reducing overall production costs and maximizing the energy potential of feedstocks. Researchers continue to explore higher biofuel blends as well as off-road applications for drop-in biofuels.

Economic implications of biofuels

In 2019, the US imported an average of 9.1 million barrels of oil per day, a little less than half of domestic daily oil consumption. Displacing petroleum with clean fuels reduces our reliance on international oil supplies and can drive growth in domestic fuel production and distribution. Clean fuels can provide a just transition for workers and communities reliant on oil and gas extraction and production and provide direct economic benefit to low-income and historically disadvantaged communities through infrastructure investments and high-road employment opportunities. The diversity of clean fuel categories provides for economic opportunities across the US, promoting growth in urban and rural communities across occupations including science, engineering, construction, and agriculture.

Expanding consumption of biofuels will require additional feedstock and processing capacity which can drive investment and employment in agriculture, science, engineering, and construction. Research and development of higher blends of ethanol and biodiesel can also drive employment and provide investment opportunities across the US. In 2019, there were 102 operating biodiesel plants and 201 ethanol plants in the US. Biodiesel plants were forecasted to operate at 77% of nameplate capacity in 2019, while ethanol plants were forecasted to produce more than stated operable levels.

The diversity of emerging advanced biofuel feedstocks and applications also presents a large opportunity for domestic investment and employment opportunity. Historically driven by government mandates, the demand for advanced biofuels has increased in recent years across transportation modes. The global aviation industry has committed to reducing GHG emissions by 50% from 2005 levels by 2050, increasing demand for SAF. While, currently there is very limited production of SAF in the US, low oil demand has led oil companies, including Phillips 66 and Marathon, to convert refining facilities to produce biofuels including renewable diesel, renewable gasoline, and SAF.

Electrofuels

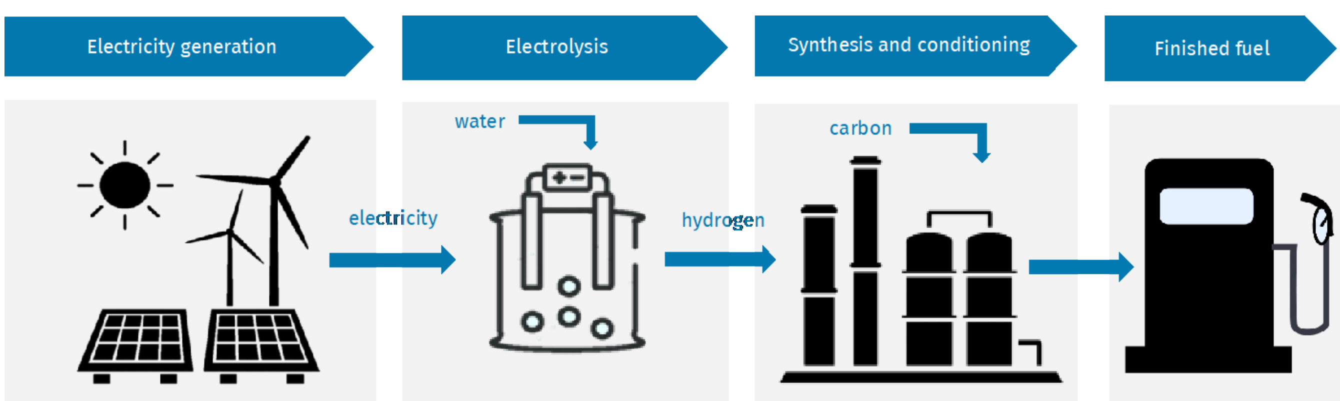
Electrofuels, or power-to-gas/liquid/fuel or synthetic fuels, are carbon-based drop-in replacement fuels produced from carbon and hydrogen, using electricity as the primary source of energy. The term electrofuels describes the process used to produce the fuel, rather than the fuel itself. Electrofuels can be similar or identical to fossil-based fuels.

> Electrofuels are fuels produced using electricity, carbon, and hydrogen, which can replace fossil fuels.

The production of electrofuels requires electricity and CO_2. Electrofuels are produced through electrolysis where electricity is used to split water into oxygen and hydrogen. The hydrogen is then combined with carbon to form liquid hydrocarbons. The final fuels produced through this process include methane, methanol, and Fischer-Tropsch fuels depending on the catalyst used in the synthesis process (Figure 9). Fischer-Tropsch fuels include synthetic gasoline, diesel, and jet fuel, which are promising pathways to displace fossil fuels and drive deep decarbonization.

The emissions profile of electrofuels is determined by the sources of electricity and carbon used to create the fuel. Coupling carbon from direct air capture or BECCS coupled with renewable electricity can result in zero-carbon, or even carbon-negative, electrofuels.

FIGURE 9
Electrofuel generation



Electrofuels have yet to see market penetration due to high production costs and energy conversion losses, but they offer potential for zero-carbon drop-in fuels across transportation modes, including aviation and marine applications.

Carbon intensity of electrofuels

There are no existing fuel pathways with a calculated CI for electrofuels in a regulatory framework. However, electrofuel technologies under development are largely focused on producing carbon-neutral fuels, and no net GHG emissions over the lifecycle of the fuel. The CI of electrofuels will largely depend on the source of the electricity and carbon used to produce the fuel. Electrofuels generated from hydrogen produced through electrolysis, and renewable electricity powered direct air capture will have a CI of zero.

Feedstock availability of electrofuels

Electrofuels require consistent supplies of carbon and renewable electricity. Assuming carbon capture technology is at scale, market penetration of electrofuels will depend on reliable sources of zero-carbon electricity. As global demand for clean electricity grows in response to net-zero carbon policies, electrofuels will have to compete with other end uses of electricity in the power and industrial sectors and for the direct supply of electricity for EVs. Drop-in electrofuels require five times more electricity generation to achieve the same distance as an EV, placing additional burdens on the supply of clean electricity. Efficiency gains as electrofuel technologies are commercialized can help mitigate this differential, and electrofuels may provide utilization or storage of surplus or curtailed variable renewable energies providing stability to the electricity grid.

Air quality impacts of electrofuels

As electrofuels are currently under development, there is uncertainty about their overall lifecycle air quality impact, which includes emissions associated with renewable electricity generation and transmission, the carbon feedstock used in fuel production, and combustion of the fuel. Electrofuels created using solar energy, for instance, will need to account for the air quality impacts associated with the manufacturing of photo-voltaic cells. However, the air quality impacts occurring from the generation of renewable electricity will be small relative to the air quality impacts of fossil fuel extraction and combustion. As electrofuels are produced synthetically, there may be ways to significantly reduce combustion emissions through the fuel generation process. However, while combustion of electrofuels may provide air quality improvements over fossil-based fuels, research is nascent and work is on-going to assess the impact of electrofuels across a variety of applications.

Technology readiness of electrofuels

There are no commercially viable electrofuels on the market. Electrofuel technologies that use microorganisms to directly use energy from electricity and produce fuels are still in the research and development phase. Demonstration projects have produced electrofuels from renewable energy sources but continue to advance technologies to improve efficiency and reduce costs. Technologies for generating and transporting consistent, pure streams of zero-carbon electricity are also required for deployment of zero-carbon electrofuels across transportation modes. Federal funding has provided initial support for in the development of these fuels, but additional support will be required to achieve commercially viable finished electrofuels.

Economic impacts of electrofuels

While electrofuels have yet to achieve commercialization, their potential for efficiency gains, GHG reductions, and air quality improvements provide a great potential for long-term market penetration given federal economic and policy support. Since 2009, the Department of Energy has provided federal funding for electrofuel research through the ARPA-E program, funding 13 active projects to create liquid transportation fuels. The Department of Energy estimates that a mature domestic electrofuel industry has the potential to contribute billions of dollars to the US economy.

Carbon-neutral fossil fuels

Carbon-neutral fossil fuels are petroleum fuels whose GHG emissions are offset with negative emissions technologies, resulting in net-zero GHG emissions. Within this clean fuel category, the GHG emissions of petroleum fuels can be offset by technical negative emissions technologies that capture carbon during the extraction and production of the petroleum fuel (Table 2). Technical negative emissions technologies including carbon from steam generators and combined heat and power plants and carbon captured from steam methane reforming at a refinery. GHG emissions can also be offset by projects unrelated to the production of the petroleum fuel, where the fuel producer purchases verified offset credits from another party. The CI of carbon-neutral fossil fuels is then calculated by adding the life cycle GHG emissions of the negative emissions technology offset (including land use and storage emissions) to the life cycle emissions of the finished fuel.

TABLE 2
Examples of negative emissions technologies

Natural	Technical
Afforestation and reforestation Trees take up and store carbon from the atmosphere	**Carbon capture and storage** Carbon is captured during industrial processes and power generation and stored
Soil carbon sequestration Atmospheric carbon is stored in soil	**Ocean fertilization** Nutrients are added to the ocean to increase photosynthesis and reduce atmospheric carbon
Biochar Soil amendment that may enhance soil carbon sequestration	**Direct air capture** Captures carbon directly from the air where large fans push air through filters generating a stream of pure CO_2

Carbon-neutral fossil fuels require a regulatory framework in which negative emissions technologies have a verified credit value and mechanisms for assigning offset credit to specific fuels. In 2018, California added a CCS protocol to the LCFS, allowing fuels produced with carbon capture to be used for compliance in California through low carbon fuel pathways, refinery investments, innovative crude, and direct air capture. However to date, no fuels produced with carbon capture have been used in California's LCFS program.

Beginning in 2018, fuels produced with carbon capture can be used for compliance in California's Low Carbon Fuel Standard (LCFS).

Carbon-neutral fossil fuels have been controversial with advocates who do not support continued fossil fuel combustion. In addition, carbon-neutral fossil fuels combustion does not improve air quality, water quality, or reduce adverse health outcomes in communities across the US. Carbon-neutral fossil fuels also do not avoid environmental degradation from fossil fuel extraction, specifically in natural and working lands across the US.

Carbon intensity of carbon-neutral fossil fuels

The CI of carbon-neutral fossil fuels is a function of the CI of the fuel pathway and any offsetting CI reduction from carbon capture projects. Under the LCFS, the reductions associated with CCS projects are calculated on a project or a fuel pathway basis. In this fuel category, we assume that sufficient negative emissions credits are bundled to completely offset the emissions of the fossil fuel. Thus, by either purchasing credits or generating credits through on-site carbon capture, fossil-based fuels including gasoline, diesel, and jet fuel can be net-carbon neutral.

Feedstock availability of carbon-neutral fossil fuels

The feedstock for carbon-neutral fossil fuels is negative emissions technology. The availability of that feedstock will be determined by the relative value of the GHG reduction from the negative emissions technology. To achieve net-zero emissions by 2050, the US will need hundreds of millions to more than a gigaton of negative emissions. As sectors vie to reduce emissions under varying regulatory and legislative frameworks, the negative emission reductions will go to the sector where it can receive the highest value. Therefore, a strong regulatory framework with a high credit value can work to ensure feedstock availability. However, a low-price signal for the value of captured carbon would reduce the availability of feedstock and limit the potential market penetration of carbon-neutral fossil fuels.

Air quality impacts of carbon-neutral fossil fuels

Carbon-neutral fossil fuels have air quality impacts related to the production and combustion of fuel as well as any air quality impacts related to carbon capture and sequestration. Carbon-neutral fossil fuels will have the same combustion emissions as fossil fuels, with the net air quality impact determined by the impact of the offsetting carbon capture. As the carbon capture likely occurs in a different location than fuel combustion, the health impacts of the combustion of these fuels are likely to be the same as fossil fuels, assuming similar driving patterns.

Carbon capture projects can have a beneficial impact on air quality as air pollutants are captured and stored along with carbon. They may capture criteria pollutants that would otherwise be emitted as the carbon is captured and sequestered. Carbon captured in the extraction or production of the fossil fuel may result in lower localized air pollution relative to traditional fossil fuels. Carbon that is captured off-site from the production of the fossil fuel may result in air quality improvements at the site of the carbon capture—resulting in no localized air quality benefit at the point of fossil fuel production.

Technology readiness of carbon-neutral fossil fuels

Negative emissions technology will play a critical role in achieving net-zero carbon emissions by 2050. While carbon capture opportunities at ethanol facilities are commercially viable and present opportunity in the near-term to offset the GHG emissions of fossil fuels, promising categories for carbon removal have not yet reached commercialization. Lack of large-scale carbon transport networks and distance from energy production facilities to storage location have hampered adoption. Additional research and development is needed to deploy BECCS technologies at reduced cost and scale, and regulatory frameworks are not yet fully deployed to provide the market signal required for carbon capture market penetration.

Economic implications of carbon-neutral fossil fuels

Carbon capture technologies present large domestic economic opportunity both for project-based industrial direct air capture (DAC) and carbon capture at existing ethanol and fossil fuel facilities. In previous work, we estimate that full-scale DAC deployment required for net-zero emissions in 2050 can generate at least 300,000 new jobs across the DAC supply chain. Market penetration of fuels produced with carbon capture can increase DAC demand and can provide employment in communities across the US, specifically low-income and historically disadvantaged communities located near industrial facilities.

CHAPTER 4

Policy Recommendations

The federal government plays a large role in determining the US fuel mix. Research funding, fiscal incentives, market-based policies, and GHG and air quality targets all shape the portfolio of fuel consumed across the country. Even with aggressive electrification throughout the sector, there will still be a substantial need for transportation fuel in 2030 and beyond. Transportation fuel demand can be filled with petroleum, or the federal government can take action to accelerate the deployment and market penetration of clean fuels. The question for policymakers, then, is what is the optimal portfolio of fuels in 2030, and what are the policy tools to get there?

Here we focus on three categories of federal policy levers that can be deployed by federal policymakers to develop and deploy a spectrum of clean fuels, in order to put the transportation sector on a path to net-zero emissions by 2050.

Research and development

The majority of clean fuel technologies have not yet reached commercialization, and there is a significant need for continued federal support in the research and development of advanced technology fuels. Federal funding has been critical in the development and advancement of commercial biofuels, and the government should increase funding and investment for the development of advanced fuel technologies. In the US, the ARPA-E program has been the traditional funding source for transformational fuel technology development. While it has faced funding challenges and roadblocks, ARPA-E type funding should be continued and expanded to explore high-risk fuel pathways that can transform the transportation sector and result in commercially viable products. In addition to direct funding of clean fuel technologies, the federal government should prioritize investments in training a diverse cohort of scientists and engineers through university grants and federal internships. Reinvigorating investments in science and human capital can drive innovation in breakthrough technologies.

> Federal grants and incentives can drive development and commercialization of transformational fuel technologies.

Deployment and validation

The federal government can accelerate the development and deployment of clean fuels through fiscal incentives and procurement requirements. Fiscal incentives targeting fuel manufacturers can increase the supply of clean fuels by providing tax credits and loan guarantees to accelerate innovation and reduce costs related to feedstocks and processing of clean fuels. Production incentives can drive deployment of clean fuels and increase market penetration and improve transport and storage of clean fuels. Fiscal incentives directed at industry and consumers can stimulate demand for clean fuels by providing rebates and tax credits for the purchase of clean fuels.

Federal procurement policies can increase demand for clean fuels and stimulate the development of clean fuel supply chains, which can reduce costs for clean fuel storage and transportation and lead to clean fuel penetration in the private sector.

> Federal procurement of clean fuels can drive down production costs and drive market penetration.

Federal fiscal incentives and procurement policies can be coupled with state and local incentives to amplify their impact. These federal polices can be technology-neutral and drive innovation across clean fuel categories or can target specific technologies or fuel types. Technology-neutral incentives and procurement could be based on the carbon intensity of clean fuels, providing larger incentives for the lowest CI fuels. Targeted policies could provide incentives for the commercialization of a specific clean fuel or processing technology.

Deep market penetration

Deploying clean fuels in the volumes required to achieve net-zero emissions by 2050 will require a durable price signal and a robust federal policy framework. Currently, the framework for federal fuel policy is the Renewable Fuel Standard (RFS) implemented by US EPA under the authority of the Clean Air Act. The RFS is a volumetric mandate across four fuel categories—biomass-based diesel, cellulosic biofuel, advanced biofuel, and total renewable fuel—and is designed to reduce GHG emissions and expand the portfolio of renewable fuels in the US. The currently specified fuel volumes end by 2022, and EPA has discretion as to the best path to modify the RFS. The RFS has been plagued by low volumes of advanced biofuels and in December 2019, used the cellulosic biofuel waiver to reduce the volume requirements across cellulosic biofuel, advanced biofuel, and total renewable fuels.

Given the failure of the RFS to drive deployment of advanced fuels, many stakeholders are calling for significant revisions to the program. Some policymakers suggest adding additional fuel categories to include electricity from qualifying renewable fuels or "eRIN". Other advocates suggest that federal policymakers create a Clean Fuel Standard (CFS), leveraging successful design elements from existing state LCFS programs across all clean fuel categories. California and Oregon have implemented LCFS programs that will reduce the CI of their state fuel portfolios. The LCFS programs have driven investment in clean fuel production and supported ZEV penetration through electricity and hydrogen fuel pathways.

The specific design of a federal CFS will dictate the clean fuels that are developed and deployed across the US. A technology-neutral federal CFS should include all clean fuel categories and direct electrification and include all transportation modes, including aviation and marine applications, to the extent feasible. A federal CFS should also account for regional variability in fuel production and combustion, providing compliance flexibility for states and regions with additional air quality, equity, and economic considerations.

In addition to incorporating design elements that address potential disbenefits of clean fuels, a federal CFS could be coupled with additional federal, state, and local policies. Carbon pricing, through a carbon tax or cap-and-trade system, could complement a CFS and drive additional demand for the lowest carbon fuels by adding additional costs to carbon intensive fuels. Air quality policies could set additional limits on fuel combustion in regions with poor air quality, focusing on ensuring that low-income communities and communities of color see direct air quality benefits from the CFS. Economic policies can complement a federal CFS to ensure that drive domestic production of clean fuels and support the creating of high paying jobs across the clean fuel supply chain in communities across the US.

> A Clean Fuel Standard can drive deep market penetration of the lowest carbon fuels.

A technology-neutral CFS can drive large-scale deployment of the lowest carbon fuels, including electricity. Under a federal CFS modeled on the LCFS programs implemented at the state level, the federal government sets annual CI targets that decline each year, requiring the increasing use of clean fuels over time in line with net-zero emissions by 2050. Fuels with CI above the target generate deficits, while fuels below the CI target generate credits. Fuel producers comply with the CFS by generating or buying credits to offset any deficits generated by their portfolio of fuels.

A CFS can also complement transportation policies that drive emissions reductions through direct electrification and efficient mobility. Achieving net-zero emissions in 2050 will require aggressive federal action to reduce transportation demand, electrify vehicles, and develop and deploy clean fuels. A portfolio of policies can drive emissions reductions across transportation modes and amplify reductions from policies enacted at the state and local level. A CFS can also support policies driving emissions reductions in other sectors, including the energy and agricultural and waste sectors.

A portfolio of aggressive federal transportation policies is needed to achieve net-zero emissions by 2050.

Achieving net-zero emissions in the transportation sector will require aggressive federal policies across decarbonization pathways. Given future demand for transportation fuel, the US needs policies that promote development and wide-spread deployment of clean fuel, alongside electrification and efficiency measures. Clean fuel policies should focus on the comprehensive impacts—providing the largest incentives for the highest performing fuels across attributes and ensuring that deep decarbonization can be achieved across all modes of transportation.

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