Low-Carbon Pathways for Transportation

Ramping up vehicle electrification and phasing out petroleum

Executive summary available at
www.ucsusa.org/resources/low-carbon-pathways-transportation

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CONTENTS

Chapter 1 Introduction 4

Chapter 2 Summary of Findings 6

Chapter 3 Phasing Out Petroleum 8

Figure 1. Evolution of Total US Transportation Energy, 1950-2020 8

Figure 2. Transportation Energy Changes from Fuel-Switching for the Core Scenario, from 2020 to 2050 10

Chapter 4 Transformative Pathways to a Decarbonized Future : Scenario Assumptions 12

Chapter 5 Reducing Emissions 15

Figure 3. Economy-Wide CO_2 Emissions Reductions in the Core Scenario Relative to Reference Scenario, by Sector, 2020-2050 16

Figure 4. Economy-Wide CO_2 Emissions for the Reference and Core Scenarios in 2020, 2030, and 2050 17

Chapter 6 Electrification Must Move Fast for All Vehicle Types 18

Figure 5. Shares of New Vehicle Sales and Stock by Fuel Type for the Core Scenario, 2020–2025 19

Figure 6. Electricity Generation by Fuel and End-Use Energy Demand for the Core Scenario, 2020–2050 20

Chapter 7 Decarbonizing the Remaining Transportation Liquid Fuels 22

Figure 7. Reduction in Use of Transportation Liquid Fuels for the Core Scenario, 2020-2050 23

Two Kinds of Biofuels 23

Synthetic Fuels 25

Chapter 8 The Low Energy Demand Scenario 26

Chapter 9 Carbon Capture and Storage Plays a Small but Important Role 27

Chapter 10 Modest Costs Pay Off 29

Figure 8. Cost of Core Scenario, 2020–2050 29

Chapter 11 Policy Opportunities 31

Vehicle Electrification and Charging Infrastructure 31

Clean Fuel Standards 32

Global Warming Emissions and Fuel Economy Standards 32
A Power Grid Based on Renewable Energy 32
The Deployment of Carbon Capture and Storage 33
Batteries and Energy Storage 33
Behavioral Change and Improved Mobility 33
Sustained and Equitable Investments 33

Chapter 12 Conclusion 35

Appendix 40

Model Topology for RIO and EnergyPATHWAYS 40
CO2 and Greenhouse Gas Emissions Budget for Core Scenario 41
Zero-Emission and Battery-Electric Vehicles Sales Shares and Fleet Shares 42
Fuel Economy of Internal Combustion Engines 43
Low Energy Demand Scenario VMT Reductions Relative to Core Scenario 43
Energy Flows in Core Scenario in 2030 44
Energy Flows in Core Scenario in 2050 45

Chapter 1 Introduction

The world is facing a climate change emergency. The Intergovernmental Panel on Climate Change (IPCC) special report *Global Warming of 1.5°C* makes it clear that the world's economies need to be carbon neutral by midcentury to limit the worst impacts of climate change (IPCC 2018). *The Sixth Assessment Report* of the IPCC indicates that fossil fuels are the primary source of increased carbon dioxide (CO_2) and a critical destabilizing factor for the planet's climate system (IPCC 2021). As became evident during the 26th annual summit of the United Nations' Conference of the Parties, current national pledges are insufficient to avert catastrophic global warming. The United States is a major consumer of global energy and, after China, is currently the world's second-largest producer of global warming emissions; therefore, this country bears a large share of responsibility in reducing current emissions. Furthermore, because of their early industrialization and accumulation of wealth relative to developing countries, the United States and other countries with high-income economies also bear a disproportionate historic responsibility for cumulative emissions and anthropogenic climate change. According to a study, based on the cumulative global warming emissions from 1850 to 2012, the United States has the largest share of responsibility, with approximately 20 percent of the cumulative emissions in the world, followed by the European Union at 17 percent, and China at 12 percent (Rocha et al. 2015),[1] and must, therefore, do its fair share for the planet and for future generations who will inherit the consequences of our actions as well as our inaction. Solutions are at our disposal, but we must choose to use them to avoid the very high cost of inaction.

A 2021 study from the Union of Concerned Scientists (UCS), in collaboration with consulting firm Evolved Energy Research (EER) and an expert advisory committee, examined economy-wide alternative energy pathways from 2020 through 2050, which result in US global warming emissions reductions of at least 50 percent below 2005 levels in 2030, on the way to net-zero emissions in 2050. These emissions reduction targets are consistent with the Biden Administration's commitment under the Paris Agreement and provide the level of ambition required to meet a 1.5°C target (UCS 2021; The White House 2021c).[2] The study covered all sectors of the economy, while this report focuses on the transportation sector.

We modeled a total transformation of the energy system that underpins the US economy with fundamental changes in how energy is both produced and consumed and in how the energy sector currently operates. Economy-wide CO_2 emissions reduction targets and carbon budget constraints are set covering emissions from electricity generation, transportation, buildings, and industry.[3] To achieve our goals, major transformational energy-related shifts must take place in the entire economy, such as the rapid growth of end-use electrification (electrification of transportation, home heating, and other services currently provided by fossil fuels),[4] a shift toward zero- or low-carbon liquid fuels, more progress on energy efficiency, and a significant increase in renewable electricity generation primarily from wind and solar power. In the transportation sector, the phaseout of petroleum is the backbone of the transition.

The object of this study is to provide guidance to policymakers, businesses, and communities in face of the many trade-offs and uncertainties in this transition. A 30-year transition to clean energy has far-reaching implications, as the energy system deeply affects many aspects of society. These include economic growth, increased and higher-quality employment, cleaner air and improved health, and the dramatic reduction of the inequity and injustice firmly entrenched in our energy and transportation systems. Not only is assessing the alternatives critical, as we have a truly unique opportunity to make lasting systemic changes in the energy and transportation systems, but we also have the opportunity to make changes that affect all of society, going beyond the energy system and the reduction of emissions.

Chapter 2
Summary of Findings

The study shows that it is possible for the United States to transition to a decarbonized and equitable future by midcentury. In the transportation sector, decarbonization entails the phaseout of petroleum. Our results show it is economically feasible to cut fossil-based liquid fuel use by half in 2040 and by almost 85 percent in 2050, based on today's levels. On the technology front, this transition calls for three main strategies: (1) rapid vehicle electrification, including the build-out of an extensive charging infrastructure to support the growing electric fleet, and rapid transition of the power grid to renewable energy; (2) strengthening vehicle efficiency for both electric vehicles (EVs) and internal combustion engines; and (3) reducing emissions associated with the production and use of the remaining liquid fuel in hard-to-decarbonize sectors, such as aviation, shipping, and some heavy-duty on-road transportation. With these decarbonization strategies, the model reports that by midcentury we are able to reduce transportation CO_2 emissions by 98 percent relative to today's levels.

The findings for the later decades provide important context and help inform the decisions and actions to be taken in the next 10 to 15 years, a critical period for achieving our 2050 climate targets. Delaying action has high costs from a financial perspective, as it could close the door to the least-cost pathways, but also has high costs from the perspectives of climate impact and human health.

The pathways from our findings are economically viable, with modest net costs relative to the size of the economy. All forecast energy needs in the economy are met at a net cost of less than 1 percent of GDP, and novel technologies were not found to be necessary to meet the carbon reduction targets. Moreover, these costs are easily outweighed by the benefits of avoided impacts on climate change and health as well as from the formation of a more equitable society, estimates that were beyond the scope of this study (see chapter 10).

However, a transition to a decarbonized and equitable transportation system goes beyond the technological solutions needed to meet the growing energy demand from a growing fleet of vehicles. This transition must include a comprehensive reinvention of the transportation system and broader energy system. The future of transportation must be multimodal, with expanded and improved mobility for all (Brumbaugh 2018; Buehler and Hamre 2015). There must be a fair distribution of both costs and benefits, taking into account the historical responsibility for widespread and deeply embedded injustices permeating our current transportation system. An equitable and people-centered transition of this nature will require changes that go beyond the necessary technological shifts and must focus also on overcoming significant social, institutional, and behavioral barriers. In other words, technological solutions are necessary but not sufficient.

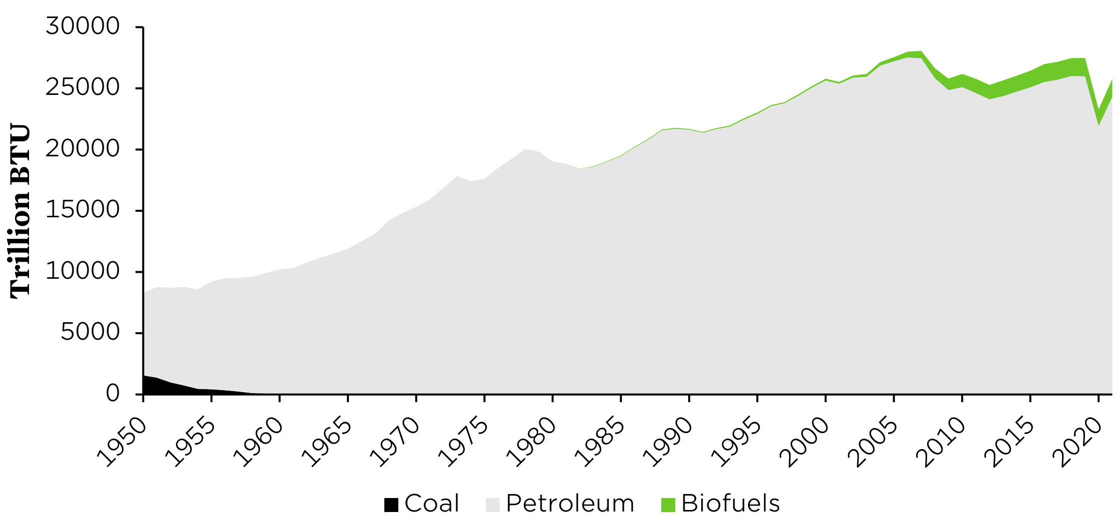
How can we model the profound changes needed to build a clean and equitable transportation system, changes that go beyond technological shifts? How can we examine the implications of deeper social and behavioral changes on the decarbonization trajectory? The model used in this study provides a range of detailed energy system configurations to deliver projected energy service demands at least cost. By modeling changes in demand, we were able to simulate various worlds where behavioral changes and successful policies lead to the particular outcomes of each energy pathway, or scenario. Aside from the main scenario (the Core scenario described in chapter 4), we designed an alternative Low Energy Demand scenario where there is a reduced demand for energy services throughout the economy. In the transportation sector, driving is reduced in all types of vehicles, with walking, biking, and public transportation use simultaneously increased. The Low Energy Demand scenario illustrates the implications of a more comprehensive reinvention of the transportation and energy systems, including what reduced demand for energy services could mean for the energy transition, and is consistent with a more holistic view of climate action. This scenario helps to envision a viable trajectory of decarbonization in a world where the necessary social, institutional, and behavioral shifts are met to some degree, showing that we can decarbonize our transportation system to achieve our emissions reduction targets by midcentury while also addressing equity and driving deep systemic change (see chapter 8).

Chapter 3
Phasing Out Petroleum

This study examines scenarios that achieve a clean and equitable transportation system within an economy swiftly transitioning away from fossil fuels. A transition that rapidly phases out petroleum as the primary source of transportation fuel is paramount in the decarbonization effort, as the transportation sector is responsible for the largest share of economy-wide emissions in the United States, at 29 percent of the country's global warming emissions[5] and 37 percent of energy-related CO_2 emissions (EIA 2020b).

For decades, the transportation sector has been the least diversified of all end-use sectors, with petroleum as the primary energy source. Petroleum accounted for 80 to 97 percent of all transportation energy from 1950 to 2007. Transportation energy use tripled between 1950 and its peak in 2005. However, since 2005, energy use in the sector has been roughly constant owing to improved vehicle efficiency. Additionally, petroleum use has fallen slightly as biofuels have supplied a growing share of transportation energy, corresponding to slightly more than 5 percent today (EIA 2022e) (see Figure 1).

Figure 1. Evolution of Total US Transportation Energy, 1950-2020



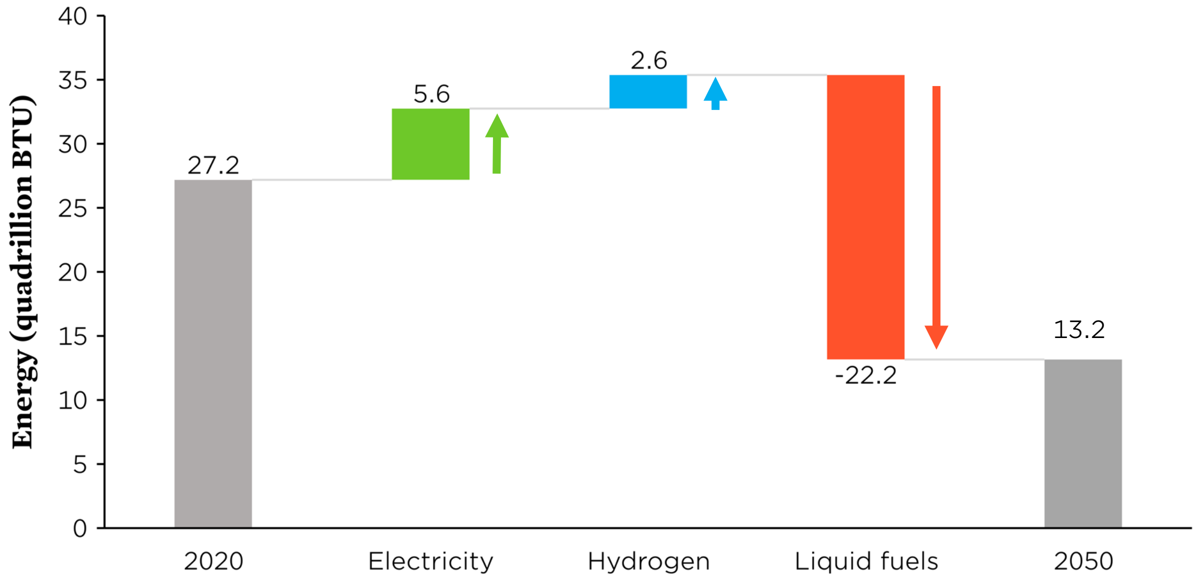
Our transportation system has been primarily based on petroleum for over half a century, but biofuels have supplied a growing share of transportation energy.
Note: Natural gas use for vehicles is not included in this chart, as it is less than 0.25 percent of total energy use in the transportation sector (excluding natural gas for pipelines and distribution).[6] *Electricity use for vehicles has experienced significant growth in the last decade but is also not included, as it is currently small relative to other energy sources.*
Source : EIA 2022e.

Petroleum also has a major role in certain other economic sectors. It is used as a feedstock in the petrochemical industry, and, to a lesser degree, in the buildings sector and for electricity generation, but currently the transportation sector consumes almost two-thirds of all petroleum (EIA 2022a). Historically, its abundance and high energy density have made petroleum highly attractive from financial and technical perspectives,[7] but challenges associated with climate change, air quality and public health, environmental impacts, price volatility, and geopolitics have motivated the need to phase out petroleum wherever possible and replace it with clean alternatives.

In 2013, UCS released a study showing that cutting projected petroleum use in the transportation sector by half through 2035 could be achieved with electrification, efficiency, clean fuels, and other policies (UCS 2013). Our current study shows that with similar approaches we can go beyond the original "half-the-oil" strategy and effectively phase out petroleum by 2050 using vehicle and fuel technologies already or close to becoming commercially available to meet the energy demand forecast for the next three decades at the lowest possible cost.

Our current results show it is possible to phase out petroleum by 2050 while also significantly reducing end-use transportation energy, with a 50 to over 60 percent drop, depending on the scenario. Reducing energy use from all fuel types — even from cleaner fuels — is important, because less demand contributes to reducing not only emissions but also infrastructure needs, such as for battery storage, the transmission and distribution of renewable electricity, and resources such as critical minerals for EV batteries. Figure 2 shows this dramatic energy transformation.

Figure 2. Transportation Energy Changes from Fuel-Switching for the Core Scenario, from 2020 to 2050



The deployment of electric vehicles, with the consequent decrease in use of liquid fuels, is a major strategy in the decarbonization of transportation, and a significant contributor to an approximately 50 percent reduction in total transportation energy by midcentury relative to 2020.

The most significant strategy is the shift away from liquid fuels (see orange bar in Figure 2) toward EVs, both battery-electric vehicles (green bar) and hydrogen-powered fuel-cell vehicles (blue bar). There are several reasons why EV deployment contributes significantly to the drop in energy use seen in 2050 relative to 2020. EVs are on average three to four times more efficient than gasoline-powered cars[8] because electric-drive technologies are significantly more efficient than internal combustion technology,[9] the regenerative braking systems of electric-drive engines result in less wasted heat, and these engines do not produce idling losses. The transition to electric vehicles from 2020 to 2050 results in an associated dramatic reduction of global warming emissions because operating a battery-electric vehicle produces zero tailpipe emissions. In fact, manufacturing and operating an EV emits significantly less compared to manufacturing and operating the average new gasoline vehicle everywhere in the United States,[10] especially as the power grid used to charge the fleet relies progressively more on wind, solar, and other renewable energy sources (Reichmuth 2021b; Reichmuth, Dunn, and Anair 2022).

In this analysis, we examine the opportunities and implications of a future where the vast majority of passenger cars sold in 2050 are battery-electric vehicles. However, a role for hydrogen is considered for vehicles not well suited for electrification, such as long-haul heavy trucks. Hydrogen fuel cells can potentially fill gaps in these hard-to-electrify applications, but the magnitude of this future role is uncertain. We include some role for hydrogen in the model's input assumptions to help understand the implications of this technology for the energy system by midcentury. The model finds a least-cost path to decarbonize the electricity and hydrogen used by the fleet. We assume that electrolytic hydrogen takes on an increasingly important role over time as a transportation fuel, and by 2050, sales of medium- and heavy-duty trucks running on hydrogen fuel cells are 30 percent and 38 percent, respectively, of all vehicle sales. In the Core scenario, by midcentury, half of the country's production of electrolytic hydrogen is used as a fuel in the transportation sector while the remaining half is used in industry and other processes.

Chapter 4 Transformative Pathways to a Decarbonized Future: Scenario Assumptions

Economy-wide pathways, or scenarios, were designed to illustrate the effect of technology and societal choices, emissions targets, and resource constraints on various decarbonization strategies for the energy system. The scenarios achieve sectoral emissions reductions at different paces, with various challenges, trade-offs, and uncertainties associated with the various pathways in which primary energy[11] can be produced (e.g., petroleum), converted (e.g., refining and electricity generation), and consumed in end uses (e.g., electricity and fuels). The scenarios illustrate how different energy sources can be used to meet the same needs. For example, while petroleum can be refined to produce gasoline or diesel to power a vehicle with an internal combustion engine, solar radiation can be used to generate electricity used to charge an EV that provides the same transportation service.

In all scenarios, modeling clearly confirms that rapid electrification, strengthened energy efficiency, clean fuels, and reduced driving are critical strategies to transition to a decarbonized transportation system. These scenarios do not provide precise solutions or forecasts but provide guidance for making choices.

Energy system modeling is a powerful tool that can be used to illustrate alternative energy pathways toward a net-zero economy in 2050. We used the Regional Investment and Operations (RIO) and EnergyPATHWAYS modeling platforms developed by EER to study large-scale energy system transformations (EER 2022b; 2022a). These coupled models can identify synergies and trade-offs in the economy that sector-specific models cannot. The EER models produce energy, CO_2 emissions, and cost data over the 30-year study period (2020 to 2050).

We modeled all energy flows throughout the economy, from primary energy inputs, such as petroleum, through energy conversion processes, such as refining and electricity generation, to final energy (end use) in the economic sectors. The demand-side model, EnergyPATHWAYS, is a bottom-up, stock-rollover model that accounts for the emissions and costs associated with producing, transforming, delivering, and consuming energy in an economy. In the transportation sector, the model uses the number of miles driven (service demand), efficiency of vehicles, and fuel switching (electrification and fuel cell adoption rates, biofuels, and synthetic fuels). The supply-side model, RIO, is an optimization model that meets economy-wide emissions constraints at least cost, co-optimizing across 14 geographical zones (see appendix). The model in this study uses as exogenous input a database of the US energy economy based on high geographical resolution of technology stocks, cost and performance, built infrastructure and resource potential, and high temporal resolution electricity loads (UCS and EER 2021).[12]

The paired EER models account for interactions across various sectors of the economy, also referred to as sector-coupling, including interactions among electricity generation, fuel production, and carbon capture. The models have specific strengths in infrastructure accounting and electricity operations, making them particularly useful for examining the impact of vehicle electrification on the power grid.

We summarize below the key assumptions of three scenarios: the Reference scenario, the Core scenario, and the Low Energy Demand scenario.[13] The results for these scenarios will be addressed in more detail later in the report.

Reference Scenario

The Reference scenario is a business-as-usual scenario, with no emissions constraints, where no new policies are introduced as of 2020.[14] It was developed for comparison with the decarbonization scenarios, in terms of energy demand, energy mix, infrastructure requirements, CO_2 emissions, and cost. Assumptions are primarily from EIA's Annual Energy Outlook 2019 and 2020, and NREL's Annual Technology Baseline (EIA 2019, 2020a; NREL 2019).

Core Scenario

The Core scenario[15] illustrates a decarbonization pathway that achieves economy-wide emissions reduction targets at least cost. Carbon emissions constraints are applied so that GHG emissions are 50 percent below 2005 levels by 2030 and are at net zero by 2050, with land sinks fixed at current levels.[16] CO_2 emissions are reduced 48 percent below 2005 levels by 2030 and decline to zero by 2050. No cumulative carbon emission constraints or carbon taxes are applied in the model. Carbon emissions constraints result in cumulative CO_2 emissions of 76 GT in the 2020 to 2050 period.

For this scenario, an aggressive adoption of high-efficiency and electric technologies in all economic sectors is assumed; the use of wind, solar, and other renewables in electricity generation grows from 20 to 90 percent by 2050, with nuclear and natural gas providing the remaining 10 percent; coal is phased out by 2030;[17] and electricity use roughly doubles between 2030 and 2050.

In the transportation sector, the scenario assumes all new light-duty vehicle (LDV) sales are zero emissions by 2035, including passenger cars and light trucks, and all new medium- and heavy-duty vehicle (M/HDV) sales are zero emissions by 2040. It assumes a biomass supply from the *2016 Billion-Ton Report* by the Department of Energy (DOE) (Langholtz, Stokes, and Eaton 2016). A sensitivity analysis was also performed for this scenario assuming half the DOE billion-ton biomass supply (see the section, Two Kinds of Biofuels, in chapter 7).

Low Energy Demand (LED) Scenario

Societal and behavioral changes are crucial aspects of a cleaner and more equitable future. This alternative scenario, the Low Energy Demand (LED) scenario, illustrates how it is possible to go beyond the technological pathways produced by the energy model by showing the implications of coupling broader societal and behavioral changes with technological strategies.

The demand side of an energy system has significant potential for efficiency gains. While the Core scenario relies on energy forecasts from the Energy Information Administration (EIA), the LED scenario simulates the implications of overall lower energy demands for the supply side of the energy system.

This scenario examines the scaling down of energy demand resulting from increased adoption of shared mobility and active transportation modes, such as walking and biking. A 40 percent reduction in driving compared to the EIA assumptions used in the Core scenario is assumed.[18] A doubling of miles from transit, rail and school buses, and a 20 percent reduction in flying and goods movement are also assumed.

To help develop a shared understanding of the implications, opportunities, and challenges that would follow from our modeling choices, we worked with an external expert advisory board throughout the modeling.[19] The design of the LED scenario and the quantitative choices of the energy demand reductions were informed by discussions with the expert advisory board and with modeling experts from UCS and EER, and by existing studies (Grubler et al. 2018; IEA 2021; IPCC 2022b).

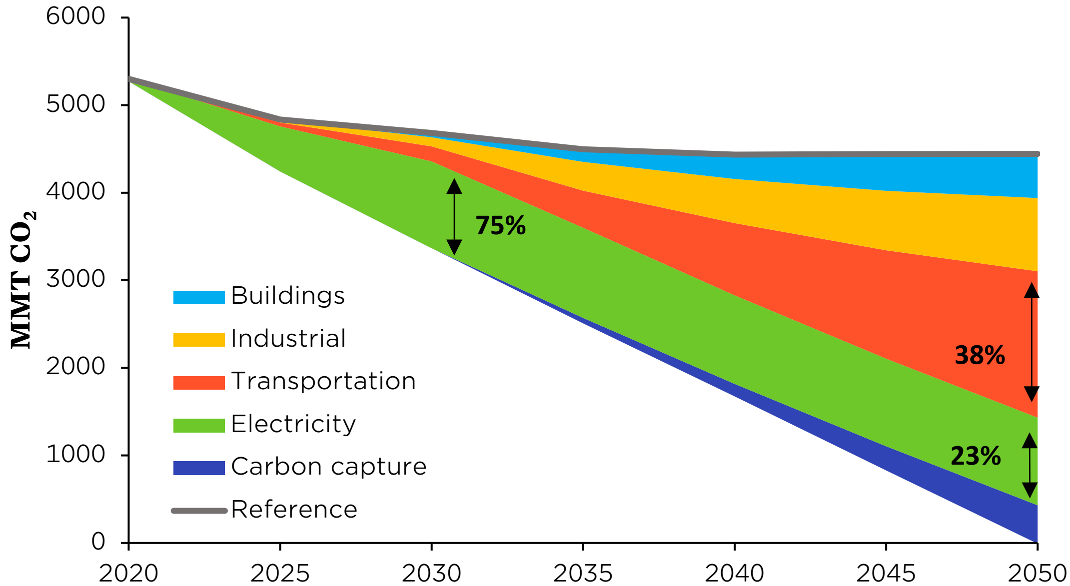
Chapter 5
Reducing Emissions

Three main factors contribute to CO_2 emissions associated with fuel use in vehicles: carbon intensity of the fuel, fuel efficiency of the vehicle, and distance driven. These contributions vary throughout the period considered in the analysis because of elements such as degree of displacement of carbon-intensive liquid fuels with progressively cleaner electricity and advances in vehicle and clean fuel technologies.

The transportation sector's contribution to economy-wide reductions within the first decade of the period is modest. In 2030, the power sector accounts for three-quarters of CO_2 reductions, since until then most of the economy-wide emissions reductions come from decarbonizing electricity, as coal-fired and natural gas generation are reduced (natural gas drops from 40 percent today to 25 percent in 2030) and fossil sources are replaced with solar and wind energy. But over time, a major shift occurs in the relative contribution to emissions reductions from the transportation and electricity sectors as EV sales grow rapidly and electrification sets in. Beyond 2030, economy-wide reductions are increasingly from transportation, with the largest potential for the emissions reduction coming from EVs powered by renewable energy and other low-carbon electricity. By 2050, transportation accounts for 38 percent of emissions reductions, and electricity accounts for 23 percent. Figure 3 shows the contributions of each sector to emissions reductions (colored wedges) relative to the Reference scenario (gray line at top).

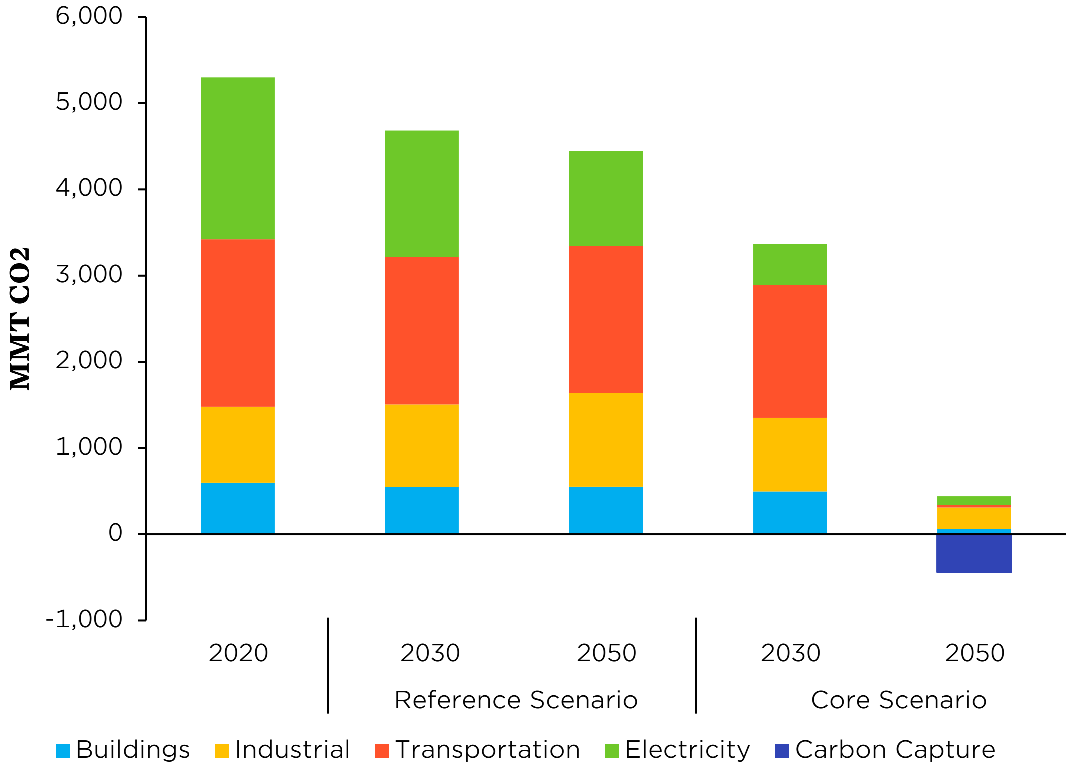
In the Core scenario, the transportation sector is close to being fully decarbonized, with a 98 percent emissions reduction from 2020 to 2050. Figure 4 shows actual economy-wide emissions, with transportation emissions almost eliminated by 2050. As will be discussed, the remaining emissions in 2050 come from the small volume of liquid fuels remaining at that time. It should be noted that transportation emissions reported by the model are likely to be slightly underestimated as a consequence of model design, so this emissions reduction could be slightly less, at approximately 94 percent.[20]

Figure 3. Economy-Wide CO_2 Emissions Reductions in the Core Scenario Relative to Reference Scenario, by Sector, 2020-2050



Most of the near-term reductions in emissions are in the electricity sector, from phasing out coal and replacing it primarily with wind and solar, but the reductions contribution from transportation grows steadily as electrification is deployed and by 2050 almost 40 percent of the reductions come from transportation.

Figure 4. Economy-Wide CO_2 Emissions for the Reference and Core Scenarios in 2020, 2030, and 2050



The transition away from a fossil fuel–based economy to one powered by clean energy achieves net-zero CO_2 emissions by midcentury. The transportation sector is close to being fully decarbonized.

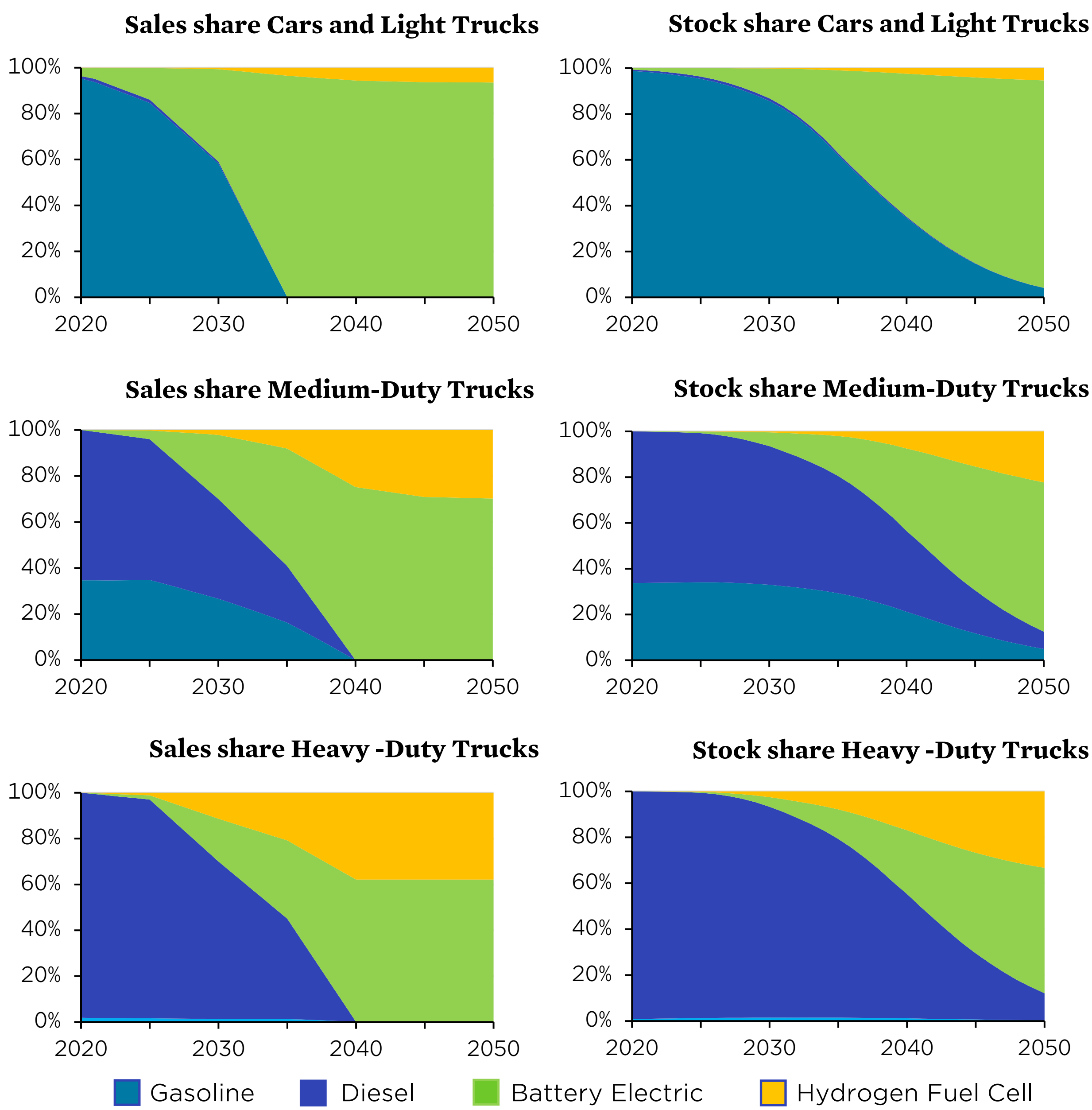
Chapter 6 Electrification Must Move Fast for All Vehicle Types

Rapid electrification of all vehicle types is a key strategy to reduce emissions from the transportation sector. The large fleet of US LDVs bears the largest share of responsibility for global warming emissions in the transportation sector, at 57 percent.[21] M/HDVs also bear a large share of responsibility.[22] While these vehicles currently make up only 10 percent of the nation's fleet, they contribute 28 percent of global warming emissions in the sector. Their contribution to local air pollution is also highly disproportionate, as heavy-duty vehicles are responsible for 45 percent of on-road nitrogen oxides (NO_x) and 57 percent of on-road fine particulate matter ($PM_{2.5}$) emissions (EPA 2014; O'Dea 2019).

In the Core scenario, it is assumed as model input that the transition of all new LDV sales to zero emissions technology is complete by 2035, and all new M/HDV sales by 2040 (see Figure 5). This complete transition to zero-emissions vehicle (ZEV) technologies by 2035 and 2040, focused on battery-electric EVs and hydrogen fuel-cell technology, is necessary to achieve the needed fleet shares in 2050 (Den Boer et al. 2013; Fulton and Miller 2015). We assume the share of battery electric EV sales grows fastest and becomes the largest share in all vehicle classes, whereas fuel-cell vehicles feature most prominently in heavy-duty applications. Out of all ZEVs, in 2050, fuel-cell vehicles make up 38 percent of heavy-duty trucks and 30 percent of medium-duty trucks, versus 5 percent and 9 percent of passenger cars and light trucks, respectively.[23]

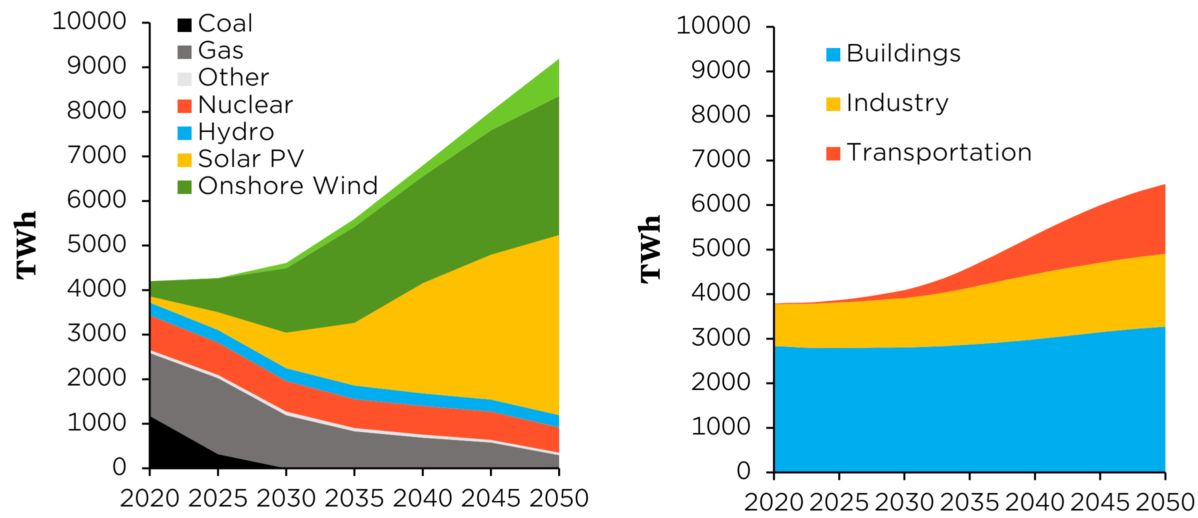
The significant growth of electricity demand, driven primarily by vehicle electrification, has important implications for the power grid. The share of electricity in the economy for use powering EVs increases from less than 0.1 percent in 2020 to about 25 percent in 2050. Overall, the increased electrification of the economy results in a more than doubling of economy-wide electricity generation in the Core scenario between 2020 and 2050, even with significant investments in energy efficiency.[24] Figure 6 (left) shows the evolution of the combination of fuels for electricity generation in the 2020–2050 period, with the share of zero-carbon sources growing from 38 percent of our electricity today, to 74 percent in 2030, and to 97 percent in 2050. The share of renewables for the same years are 20, 59, and 91 percent, respectively. These achievements will require an unprecedented build-out of wind and solar capacity, plus related grid infrastructure.

Figure 5. Shares of New Vehicle Sales and Stock by Fuel Type for the Core Scenario, 2020–2025



As electric and fuel-cell vehicles are deployed, gasoline and diesel vehicles comprise a declining share of both new vehicle sales (left column) and vehicle fleets (right column) over time, across all vehicle types, with sales ending in 2035 for passenger cars and light trucks, and in 2040 for medium- and heavy-duty trucks.

Figure 6. Electricity Generation by Fuel and End-Use Energy Demand for the Core Scenario, 2020–2050



The rapid decarbonization of the power sector is critical for the increase in electrification to provide maximum benefit in emissions reductions. By 2050, the transportation sector accounts for almost a quarter of economy-wide power demand (right). Nearly three-quarters of electricity generation is carbon-free by 2030, and by 2050, this share is 97 percent (left). Wind and solar play a dominant role in decarbonizing the power sector. Coal is phased out in 2030, and by 2050 there is a small remaining share of natural gas and nuclear energy (3 percent and 6 percent of total generation, respectively).

Note : The difference between generation and end-use energy demand in 2050 can be explained, as demand represents 78 percent of generation (hydrogen electrolysis, 16 percent; electric boilers, 5 percent; and biomass conversions, 2 percent). The remainder of the difference is from transmission and distribution losses.

Figure 6 (right) shows the growth of the transportation sector's use of electricity in the economy. The power sector must be rapidly decarbonized for this increase in electrification to provide maximum benefits of emissions reduction. Increased investment in renewable energy along with a corresponding increase in transmission and energy storage capacity are key in the transition to clean transportation. If vehicle electrification grows together with renewable power, the mitigation benefits of EVs will grow over time.[25]

The study highlights the demands on the electric sector to meet the energy needs of a growing fleet of EVs while simultaneously decarbonizing power generation. Potential also exists in the transportation-electricity sectoral coupling for EVs to support the integration of renewable energy and help decarbonize the electric sector. For example, charging loads can be managed in a way that takes advantage of the flexibility most drivers have to maximize the amount of charging during times of abundant wind and solar (O'Connor and Jacobs 2017). Indeed, studies have shown that the shape of the new load demand curves is as important as the expected load growth (Muratori and Mai 2021). EVs set up for power export can effectively act as battery storage, charging up on renewable energy and discharging some of that electricity back to the power grid when it is not needed to power the vehicle. Electrolytic hydrogen production can provide an additional variable load that can be timed to coincide with abundant renewable energy generation. This renewably powered hydrogen, called green hydrogen, can then be used for transportation or other end uses.

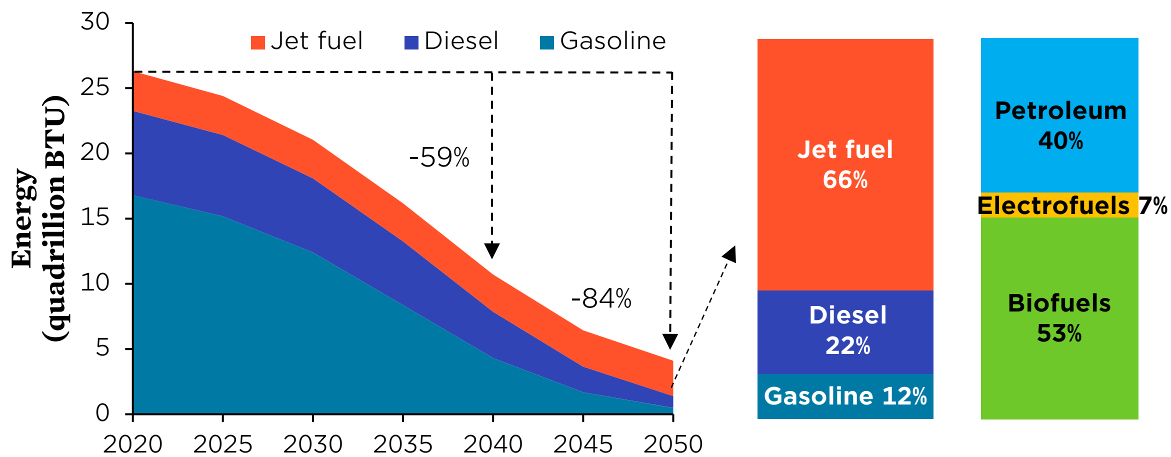
Chapter 7
Decarbonizing the Remaining Transportation Liquid Fuels

With rapid vehicle electrification and improved efficiency, the model results show it is possible to achieve a highly significant reduction in the use of liquid fuel in the transportation sector. In the Core scenario, the use of gasoline, diesel, and jet fuel is cut 20 percent by 2030, 59 percent by 2040, and a drastic 84 percent by 2050, relative to today's levels of fuel use (see Figure 7). This reduction is economically feasible and can be achieved with moderate cost using existing and emerging technologies, such as battery and fuel-cell technologies (see chapter 10).

However, in spite of the extreme reduction in the use of liquid fuels by 2050, a not insignificant volume of liquid fuels will still be needed, equivalent to 16 percent of current use. In our Core scenario, all new passenger car and light truck sales are electric by 2035, and all medium- and heavy-duty truck sales are electric by 2040, but because vehicles stay on the road for around 15 years, a declining share of the fleet will still be based on internal combustion engines through 2040 and beyond. In 2050, one in five heavy trucks on the road will still depend on diesel, as heavy-duty electrification progresses more slowly. These remaining vehicles, together with the vehicles of hard-to-electrify sectors, such as aviation, shipping, and some heavy-duty land transportation, will still rely on liquid fuels in 2050.

The rates of reduction in gasoline and diesel use reflect the different rates at which electrification is deployed in the light- and heavy-duty vehicle sectors. Gasoline use declines the fastest, with a drastic reduction of 97 percent in 2050 relative to 2020, with diesel a close second with an 86 percent reduction. The use of jet fuel, in contrast, does not decrease much and accounts for the bulk of liquid fuels used in the transportation sector by 2050, from the current 12 percent to two-thirds of all liquid fuels.

Figure 7. Reduction in Use of Transportation Liquid Fuels for the Core Scenario, 2020-2050



With rapid deployment of electric vehicles and improved vehicle efficiency, it is possible to cut liquid fuel use by almost 60 percent in the next two decades and by almost 85 percent by midcentury, relative to 2020 levels. The remaining liquid fuels in 2050 are from the hard-to-decarbonize sectors, with jet fuel accounting for almost two-thirds of this remainder. More than half of the remaining liquid fuel will be produced from non-petroleum sources.

Note. The columns on the right show the shares of the types of liquid fuels used in 2050 (gasoline, diesel, and jet fuel) and how these fuels are produced (biofuels, synthetic fuels or electrofuels, and petroleum). See endnote 20.

For the decarbonization target to be reached by midcentury, it is critical to reduce carbon emissions associated with the production and use of the remaining liquid fuels required for transportation, mainly jet fuel and diesel. Three primary strategies are employed by the model to address these emissions. In our Core scenario, just over half of the demand can be met with biofuels and about 7 percent can be met with synthetic fuels produced from hydrogen and captured carbon (see right column in Figure 7). This leaves at most 40 percent of liquid fuels still being produced from petroleum, equivalent to about 6 percent of 2020 petroleum consumption (see endnote 20). Emissions from any remaining petroleum use are addressed by carbon capture and storage.

In the next two sections biofuels and synthetic fuels are discussed in more detail.

Two Kinds of Biofuels

In 2020, biofuels powered a much larger share of transportation energy than electricity, at 5.6 percent and 0.1 percent, respectively (EIA 2022f). In the Core scenario, by 2050 the situation is reversed, with electricity becoming the primary source of transportation energy. But while rapid electrification, and efficiency to a lesser extent, are the main drivers leading to the 84 percent reduction in liquid fuel use, biofuels are currently the main alternative to petroleum and continue to play an important role in displacing petroleum from the remaining liquid fuels used in transportation.[26]

The Core scenario assumes the biomass supply[27] from the *Billion-Ton Report* (Langholtz, Stokes, and Eaton 2016), which results in over half of the remaining liquid fuels in the economy being produced from biofuels by midcentury (see Figure 7, right column). With the objective of examining the implications of biomass use for energy, we performed a sensitivity analysis where the biomass supply is halved relative to the Core scenario and all other assumptions remain unchanged. With a reduced biomass supply, the model increases the amount of petroleum needed to meet the remaining liquid fuel demand in a direct trade-off between petroleum and biomass. Also, the reduced biomass decreases the opportunity for carbon removal through bioenergy with carbon capture and storage (BECCS). Given the overall carbon constraint, the result is an increasing reliance on direct air capture for carbon removal.[28] The share of liquid fuels in the economy that can be produced from biofuels is reduced from 53 percent to 40 percent, while the share of petroleum-based liquid fuels increases from 40 percent to 54 percent relative to the Core scenario (see endnote 20 and chapter 9).

The model used in this analysis is primarily an energy systems model that includes a small but representative sample of biofuel production technologies (it does not, however, include a detailed treatment of the complex interactions of biofuel production with agriculture, food markets, and land use). Below, we describe the two types of biofuels considered by the model, corn ethanol and biofuels made from nonfood biomass, and make observations along the way about technologies not considered by the model.

First, the model considers corn ethanol for blending with gasoline. Ethanol produced by the fermentation of corn starch is currently the most widely used biofuel, accounting today for 10 percent of gasoline and approximately 4 percent of transportation energy (EIA 2022e). In the Core scenario, a substantial decline occurs in the consumption of corn-based ethanol fuel as gasoline passenger cars and light trucks give way to EVs. Corn consumption for fuel declines by more than 95 percent compared to current levels, in line with the reduction in gasoline use. The model does not consider pathways for biofuel production technologies that could extend the demand for corn-based biofuels beyond the current market for ethanol used for gasoline blend. One such example is the corn-to-jet conversion technology, which could gradually redirect the production of ethanol away from its role in mixtures of finished motor gasoline toward the production of aviation fuel (Spaeth 2021).

Second, the model considers the use of nonfood biomass to produce renewable hydrocarbon fuels, including diesel,[29] in conjunction with the capture of carbon dioxide for sequestration as part of BECCS. The model does not include consideration of the conversion of vegetable oil or other lipids to hydrocarbon fuels, even though this application has grown rapidly in recent years (EIA 2022f). Scaling up the use of these feedstocks could lead to significant uncertainty because of the high cost, limited supply, and sustainability risks associated with diverting vegetable oil from food uses or scaling up their production (O’Malley et al. 2022).

The model does not consider the use of biomethane[30] or fossil natural gas as transportation fuels, which accounts for a small share of transportation energy. We do not anticipate this share will grow substantially.

Synthetic Fuels

Synthetic hydrocarbon fuels produced from hydrogen and CO_2 can provide alternative liquid transportation fuels without the use of petroleum or biomass. For this reason, the technology has attracted a great deal of recent attention, particularly regarding synthetic fuels produced from captured carbon and electrolytic hydrogen,[31] which are often referred to as electrofuels or e-fuels.[32] Within our modeling results, synthetic fuels account for a small share of alternative liquid transportation fuel, just 7 percent of the mix of liquid transportation fuel in 2050 (see Figure 7, right column), which reflects an underlying assumption that the technology is too expensive to compete with other mitigation strategies at larger scale. Within our modeling, two-thirds of the hydrogen produced in the economy is produced from electricity, but scaling up the production of electrolytic hydrogen to produce additional synthetic fuels would require increased electricity generation compared to the direct use of electricity to charge a battery or hydrogen fuel cell in an electric vehicle. Making a liquid fuel from hydrogen is much more energy intensive than using the electricity directly to power an EV (most efficient) or to use the hydrogen directly to power a fuel-cell EV (second-highest in efficiency). Because of this inefficiency, when direct electrification is not feasible, the model deploys synthetic fuels only on a limited scale.

Chapter 8
The Low Energy Demand Scenario

The LED scenario reduces the demand for energy services compared to the Core scenario and involves a significant amount of decoupling of energy demands from economic growth. It illustrates how the same climate targets can be met with a less energy-intensive lifestyle, achieved through broad societal and behavioral shifts, and a consequent reduced level of technology and infrastructure investment. For instance, there would be reduced demand for EV batteries and charging infrastructure, reduced carbon capture and CO_2 pipeline infrastructure, and a more manageable, slower rate of renewable deployment, electricity transmission, and storage build-out.

This scenario allows us to examine the balance between changes in behavior and investments in technology, as a broader view of energy use goes beyond vehicle and fuel technology. Structural shifts in society include expanded mobility strategies, such as reduced driving, improved public transit, shared transportation services (Anair 2020), active transportation such as biking and walking, and a reformulation of land use planning. An integrated and equitable transportation system can reduce dependence on private cars and lower overall energy demand while improving air quality and public health.

As in the Core scenario, emissions in the transportation sector in 2050 are reduced by 98 percent relative to 2020 (see endnote 20). The largest potential for emissions reduction comes from EVs powered by renewable electricity, as with the Core scenario. However, the societal and behavioral changes simulated in the LED scenario lead to reduced liquid fuels consumption and electricity demand compared to the Core scenario. By 2050, liquid fuel use is cut by 8 percent, electricity generation by 34 percent, and hydrogen use by 30 percent.

Chapter 9
Carbon Capture and Storage Plays a Small but Important Role

The Core scenario relies on a limited amount of carbon capture and storage (CCS) to offset the remaining emissions in the economy and achieve carbon neutrality. The model does not require mitigation to occur in the same sector where emissions originate, and CCS is deployed based on cost. Most of this CCS is deployed as BECCS for the production of biofuels (associated mainly with emissions from liquid fuels in hard-to-decarbonize sectors, such as aviation, shipping, and some heavy-duty land transportation), while the remainder is used in the cement, chemical, and steel industries. The modeled cost of BECCS is low relative to other carbon capture technologies, so the model results show a significant contribution of this technology in 2050, approximately 440 million metric tons of CO_2, equivalent to about 8 percent of the total US CO_2 emissions in 2020, or 10 percent of Reference scenario levels in 2050.

CCS is responsible for about 13 percent of economy-wide emissions reduction relative to the Reference scenario,[33] split between BECCS (10 percent) and fossil-based CCS (3 percent) (see Figure 3). In the LED scenario, this share is slightly smaller at 10 percent. The model also deploys a small amount of direct air capture in the scenario where the biomass supply is halved.

The use of these technologies in the energy model reflects the current understanding that various forms of carbon capture may be required to reach net-zero emissions. This thinking is in alignment with the IPCC's *Sixth Assessment Report*, which states that "the deployment of CDR (carbon dioxide removal) to counterbalance hard-to-abate residual emissions is unavoidable if net-zero CO_2 or GHG emissions are to be achieved" (Anderson 2019; IPCC 2022a).

However, carbon capture and storage technologies are not free of substantial uncertainties and risks. Perhaps the most significant concern is that moving CO_2 at the scale anticipated will require the construction of a network of CO_2 pipelines connecting CO_2 sources to sequestration sites. CO_2 pipelines are susceptible to serious accidents, and there are currently many deficiencies and gaps in federal regulation governing CO_2 pipelines, which must be addressed (Kuprewicz 2022). There are also growing concerns that leakage from geological sequestration of CO_2 may contaminate groundwater supplies (Gupta and Yadav 2020). Public support for investments in CCS technology should be reserved for technologies that are required for long-term decarbonization and should not support CCS at oil refineries or other fossil fuel facilities that will be rendered obsolete as electrification reduces demand for petroleum fuels.

Most importantly, however, CO_2 removal is not aligned with the objective of replacing all fossil-based transportation fuel with cleaner alternatives as quickly as possible. In the absence of strong policies, the expansion of CCS could be used as a loophole by industries to avoid making the necessary investments to cut oil use and emissions, including health-damaging local air pollution. The implementation of CCS could delay or deter urgently needed mitigation (which refers to preventing CO_2 release in the first place), thus extending the lifetime of the oil industry, increasing the risk of a temperature overshoot scenario, and deepening severe climate impacts, some of which are irreversible.

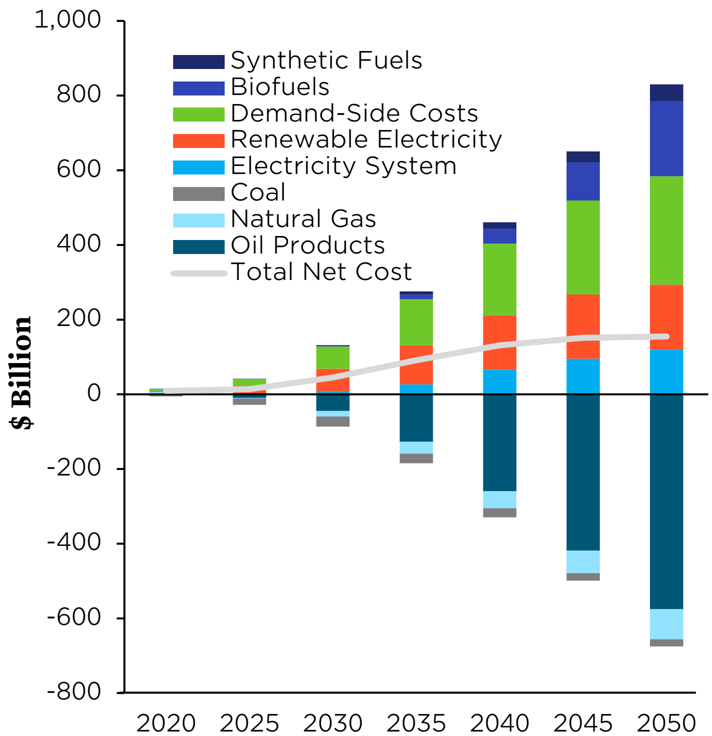
Instead of CCS, biofuels, low- and zero-emission hydrogen, and synthetic fuels are the best options to mitigate these remaining emissions in the transportation sector. Because of the potential ongoing need for a not insignificant volume of liquid fuels by midcentury, equivalent to 16 percent of current use (see Figure 7), continued efforts to develop and scale up low- and zero-carbon fuels are critical to completely phase out petroleum and fossil-based fuels by 2050. Technologies are currently available to produce liquid fuels directly from biomass and synthetic fuels directly from captured CO_2 and electrolytic hydrogen. The exact future mix of biofuels, synthetic fuels, and petroleum-based liquid fuels is highly uncertain and depends on policy choices and the progress of technology.

In brief, it is key to replace the combustion of petroleum-based liquid fuels with zero-emission technologies to the maximum extent possible, replacing these fuels with cleaner alternatives. Only after these opportunities have been exhausted should CCS be used to address remaining emissions.

Chapter 10
Modest Costs Pay Off

The annual net cost under the Core scenario is $45 billion by 2030 and $155 billion by 2050 (see Figure 8). That year, significant investments of $830 billion are needed for the power grid, in the deployment of renewables, for zero-carbon fuels, and for other investments. These investments, which will benefit the economy and clean up energy industries, are mostly offset by $675 billion in savings from reduced fossil fuel use.[34]

Figure 8. Cost of Core Scenario, 2020–2050



The net system costs of decarbonizing the US economy are modest. The net cost in the Core scenario is $45 billion by 2030 and $155 billion by 2050 compared to the Reference scenario. These net costs are easily outweighed by the benefits of avoided climate and health impacts (estimating these was beyond the scope of this study).

The pathways from our findings are economically viable, with modest net costs relative to the size of the economy. All forecast energy needs in the economy are met at a net cost of less than 1 percent of GDP, and novel technologies were not found to be necessary to meet the carbon reduction targets. Moreover, these costs are easily outweighed by the benefits of avoided climate change impacts, such as hurricanes, heat waves, droughts, fires, and flooding, as well as the avoided costs of adverse health effects from polluted air caused by the combustion of petroleum-based liquid fuel, estimates that were beyond the scope of this study. A recent assessment by the US Office of Management and Budget finds that GDP in the United States could be reduced by 3 to 10 percent by the end of the century, an equivalent of $2 trillion per year in today's dollars at the upper end, as a result of climate change (Vahlsing and Yagan 2022). A study by the American Lung Association finds that a transition to 100 percent sales of zero-emissions passenger vehicles by 2035 and medium- and heavy-duty trucks by 2040 (the same assumptions made in our study), coupled with a shift to renewable electricity, would lead to cleaner air that avoids up to 110,000 premature deaths, almost 3 million cases of asthma, and over 13 million lost workdays. These co-benefits of electrification would generate over $1.2 trillion in public health savings between 2020 and 2050. Findings from the same report show that the shift to decarbonized transportation and electricity generation will yield avoided global climate impacts of over $1.7 trillion (ALA 2022). With the avoided costs of climate change and health impacts factored in, there is no question that making smart investments in the next 30 years will yield economic as well as climate and health benefits.

Chapter 11
Policy Opportunities

Transportation is a vital service that connects people to jobs, medical care, education, leisure, and other opportunities, and sustains the economy through the movement of goods and services. Yet it is a major source of global warming pollution as well as local air pollution, which is harmful for public health. To address these impacts, we must fundamentally transform our highly inequitable and fossil fuel–based transportation system.

How do we achieve this transition in a way that meets the needs of both people and the planet? A suite of policies and regulations at all administrative levels is required to phase out petroleum and achieve a zero-carbon and equitable transportation system by 2050. Policies must be designed with broad goals in mind and must address the harms inflicted on underserved and overburdened communities. Multiple actions must be taken simultaneously by various actors, as isolated actions are not likely to lead to the necessary emissions reductions and investments. Overlapping action at different levels of government can result in more successful outcomes and can act as backup for one another in case one action is delayed or fails (Larsen et al. 2021). It is imperative for stakeholders—consumers, communities, labor, automakers, utilities, regulators, policymakers and leaders at all levels of government, and others—to understand the central role of policies on vehicle electrification and clean fuels, as well as on mobility to support decreased personal vehicle use, less overall driving, and increased public and active transportation. Specific opportunities for policymaking follow.

Vehicle Electrification and Charging Infrastructure

The vehicle electrification and charging infrastructure landscape in the United States has changed considerably in just a few years, and EVs are now the fastest-growing segment of the US auto market (Cox Automotive 2022). The Biden administration set a target whereby half of all passenger cars sales in 2030 would be electric (The White House 2021b). In November 2021, President Biden signed into law the Infrastructure Investment and Jobs Act, which supports the deployment of EV charging infrastructure across the country and the transition to electric school and transit buses. In August 2022, the Inflation Reduction Act (IRA) was signed into law (The White House 2021d, 2022b). The IRA includes tax credits and investments that could help electrification grow. The maximum tax credit of $7,500 for new EVs is the same as before, but the IRA changed requirements for new EVs to qualify for the tax credit. Phasing out the credit after the manufacturer reached a US sales limit of 200,000 EVs has been eliminated, all auto manufacturers are now eligible, and the credit is now assignable to a car dealer so that buyers can use it as part of their down payment without needing to wait until filing taxes. Additionally, for the first time, buyers of used EVs may claim a credit of $4,000 or 30 percent of the sales price, whichever is lesser (Reichmuth 2022). Successful implementation of these laws is critical for supporting the very rapid pace of electrification needed to achieve the transition to a decarbonized transportation sector by midcentury.

Consumers have an increasing number of more affordable models to choose from in a growing number of vehicle types and sizes, from more automakers and in more locations (Doll 2022; Lutsey and Nicholas 2019; Reichmuth 2021a). In 2021, EVs made up an average of 3.4 percent of US sales, and this share is at least double in areas where regulations and incentives are in place, such as California, showing there is potential for increased sales in areas where policies and regulations are in effect (EIA 2022d).

Clean Fuel Standards

Clean fuel standards hold fuel producers accountable to steadily reduce the life-cycle emissions of transportation fuels. Existing clean fuel standards in California and Oregon are being strengthened while a new standard is implemented in Washington. Clean fuel standards go beyond biofuel policies such as the federal Renewable Fuel Standard in recognizing the central role of EVs and renewable electricity in decarbonizing transportation, because compliance with these standards is measured by reduced emissions rather than increased biofuel production. Thoughtful policy design of these standards is needed to ensure that benefits and burdens are equitably shared and to avoid harmful land use changes associated with biofuel expansion.

Global Warming Emissions and Fuel Economy Standards

Global warming emissions and fuel economy standards for passenger vehicles through model year 2026 have recently been strengthened by the Biden administration, which must move quickly to set a new round of standards for model years 2027 and beyond, charting the course to a fully electric passenger vehicle market (Cooke 2022). Zero- and low-emissions vehicle standards have been adopted in many states (CARB 2022). After setbacks in the Trump administration, California is pushing forward in reducing emissions from vehicles, with proposed regulations that require 35 percent of model 2026 cars for sale in the state to be ZEVs, on the way to 100 percent by 2035, in line with the assumptions in our modeling (UCS 2022).

In 2021, four states[35] followed California and approved the Advanced Clean Truck rule, requiring a growing share of truck sales to be zero emissions (O'Dea 2020). Also, the administration has an opportunity to spur electrification through an upcoming rulemaking that sets multipollutant emissions standards for M/HDVs for model years 2030 and beyond.

A Power Grid Based on Renewable Energy

Deployment of renewable energy in the power grid should be accelerated, as should investment in transmission capacity. Both are critical for electrification to unleash its full potential for reducing emissions. The IRA includes long-term tax credit incentives for a broad array of clean energy technologies. As of the end of 2021, 31 states and the District of Columbia had renewable portfolio standards or clean energy standards (EIA 2022c).

The Deployment of Carbon Capture and Storage

Even with the ambitious adoption of preferred solutions such as electrification, energy efficiency, clean fuels, and demand management, our modeling shows that some CCS and negative emissions technologies will in all likelihood be necessary to keep the global temperature change below 2oC. There will be challenging trade-offs and decisions to be made. Affected communities, particularly those that have long been burdened by fossil-based pollution, must be provided with a voice when options and safeguards regarding CCS deployment are being evaluated and implemented.

Batteries and Energy Storage

Strategies must be executed to address availability as well as reusing, repurposing, and recycling of batteries and other energy storage systems (Ambrose and O'Dea 2021; Dunn 2022), as energy storage is vital for supporting the unprecedented amount of renewables being added to the power grid (Pereira 2022). The price of batteries and of renewable sources such as wind and solar are declining rapidly (Lutsey and Nicholas 2019), but continued effort needs to be made to lower the costs of new technologies and ensure the responsible sourcing of critical minerals. Investments in research and development are crucial in driving innovation and must also be given priority.

Behavioral Change and Improved Mobility

Changing travel behavior is a long-term goal that can be achieved through various measures and incentives. Among other measures, mode choice can be influenced by the following:

- improved efficiency of public transportation and infrastructure for walking and biking;
- enhanced services that encourage active transportation, such as shuttles, bike storage, bike repair stations, company bikes, work buses, and bus stops;
- integration of public transportation with walking and biking;
- access to transportation and mobility information through advertisement and awareness campaigns;
- personalized travel assistance and ecodriving;
- carpool schemes and ridesharing;
- reorganization of working practices, such as flexible opening hours and teleworking; and
- parking and congestion management.

Sustained and Equitable Investments

Sustained and equitable investments are indispensable to ensure a smooth transition in the economy and to protect people from possible disruptive changes during the foundational transition needed to achieve a clean and equitable transportation system. Communities that have been historically underserved through lack of mobility access and overburdened by local air pollution from roads, ports, warehouses, and other sources must be given full consideration, with policies structured to reduce air pollution in the vicinity of these communities and to increase economic opportunity for residents and businesses (Pinto de Moura and Reichmuth 2019; Reichmuth 2019). The Justice40 Initiative presents one potential opportunity for progress in this area, with its goal of 40 percent of benefits from certain federal investments going to marginalized, underserved, and overburdened communities (The White House 2022a).

Policies must include provisions to assess and prevent environmental justice impacts and must be developed with meaningful engagement from affected stakeholders. One example is managing the decommissioning of refineries to support and retrain workers and to address this transition safely and equitably. As a consequence of the petroleum phaseout, it is likely that roughly half of all US oil refineries will be decommissioned by 2040 and half the remaining refineries by 2050. In addition, mechanisms intended to hold the petroleum industry accountable, such as clean fuel standards, must be designed to avoid harm to communities (Martin 2020).

Chapter 12
Conclusion

In the transition to a decarbonized transportation sector, vehicle electrification must happen at a very rapid pace. Electrification is the main strategy to mitigate GHG emissions, as EVs produce about half the emissions of gasoline or diesel vehicles. The magnitude of the build-out of new energy infrastructure in this transition, including vehicle-charging infrastructure and electricity generation and transmission, is unprecedented. To eliminate emissions from the remaining liquid fuels in hard-to-decarbonize sectors, there must be an understanding of the trade-offs and risks associated with the use of biofuels, e-fuels, carbon capture and storage, and negative emissions technologies.

The relative benefits and costs of the various decarbonization technologies will change over time, so there must be a constantly renewed understanding of underlying factors in available choices. Transportation options in cities, suburbs, and rural areas must be improved and expanded, going beyond vehicle and fuel technologies toward equitable and efficient mobility, thus eliminating historical inequities, improving health through cleaner air, and raising living standards for all while reducing the demand for energy services.

With effective and sustained investments, a robust policy environment, community participation, consumer awareness, and much commitment and resolution, it is possible to achieve a decarbonized transportation system where renewable electricity and zero- or low-carbon fuels are the primary sources of energy for the sector, where the need for driving is reduced, and where mobility is expanded and improved for all.

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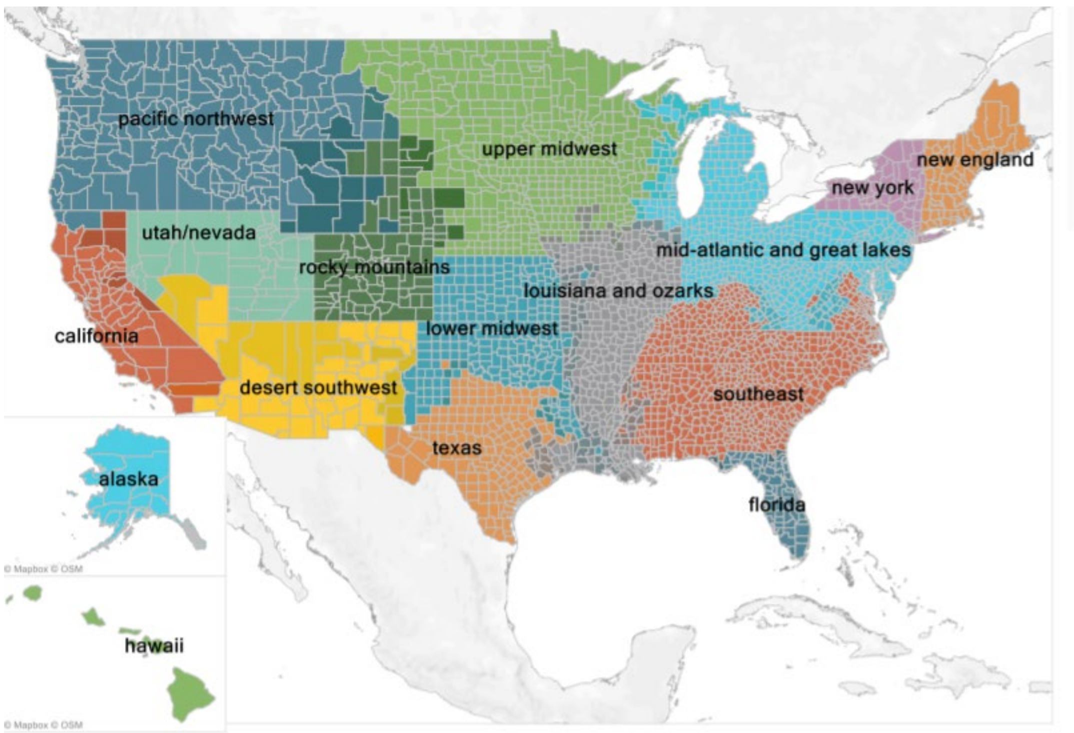
Appendix

Model Topology for RIO and EnergyPATHWAYS



Source: UCS and EER 2021.

CO_2 and Greenhouse Gas Emissions Budget for Core Scenario

Year	Energy & Industry CO_2 (Gt CO_2) [1]	Total Non-CO_2 (Gt CO_2e)[2]	Land Sink (Gt CO_2e) [2]	Total Net CO_2e (Gt CO_2e) [2]	Total Net CO_2e (% below 2005)
2005[3]	6.14	1.29	-0.79	6.64	n/a
2020[3]	5.02	1.30	-0.79	5.54	17%
2025	4.10	1.08	-0.79	4.39	34%
2030	3.19	0.83	-0.79	3.23	51%
2035	2.39	0.79	-0.79	2.37	64%
2040	1.60	0.76	-0.79	1.57	76%
2045	0.80	0.76	-0.79	0.77	88%
2050	0	0.76	-0.79	-0.03	100%

Notes:

1. *Annual emissions constraints in RIO, including all energy and industrial process CO_2 in the United States not directly related to energy exports.*

2. *Total non-CO_2 and land sink are exogenous to model. Total non-CO_2 gases include methane, nitrous oxide, and fluorinated gases. Land sink assumed to stay constant at current levels. CO_2e refers to the CO_2 equivalent, the measure used to compare the emissions from other greenhouse gases on the basis of their global warming potential (GWP), by converting amounts of other gases to the equivalent amount of CO_2 with the same GWP. Units are gigatons.*

3. *2005 and 2020 levels based on 2021 EPA US Greenhouse Gas Inventory, with 2019 levels assumed for 2020; 2020 CO_2 emissions based on EIA Short-Term Energy Outlook.*

Zero-Emission and Battery-Electric Vehicles Sales Shares and Fleet Shares

		2020	2025	2030	2035	2040	2045	2050
Sales Share of ZEV	**Cars**	6.0%	17%	45%	100%	100%	100%	100%
	Light-duty trucks	0.8%	10%	35%	100%	100%	100%	100%
	Medium-duty trucks	0.0%	4%	30%	59%	100%	100%	100%
	Heavy-duty trucks	0.0%	3%	30%	55%	100%	100%	100%
Stock/Fleet Share of ZEV	**Cars**	1.1%	5%	16%	40%	68%	87%	96%
	Light-duty trucks	0.1%	2%	10%	32%	60%	82%	95%
	Medium-duty trucks	0.0%	1%	6%	19%	44%	69%	88%
	Heavy-duty trucks	0.0%	1%	7%	21%	45%	71%	88%
BEV Sales Share of ZEV Sales	**Cars**	98.5%	100%	99%	97%	96%	95%	95%
	Light-duty trucks	85.4%	98%	98%	95%	92%	91%	91%
	Medium-duty trucks	0.0%	94%	93%	86%	75%	71%	70%
	Heavy-duty trucks	0.0%	62%	62%	62%	62%	62%	62%

Note: Sales refer to new vehicles.

Fuel Economy of Internal Combustion Engines

	Annual improvement in fuel economy
Light-duty cars	2.70%
Light-duty trucks	2.61%
Medium-duty trucks	1.39%
Heavy-duty trucks	1.43%
Aviation	1.50%

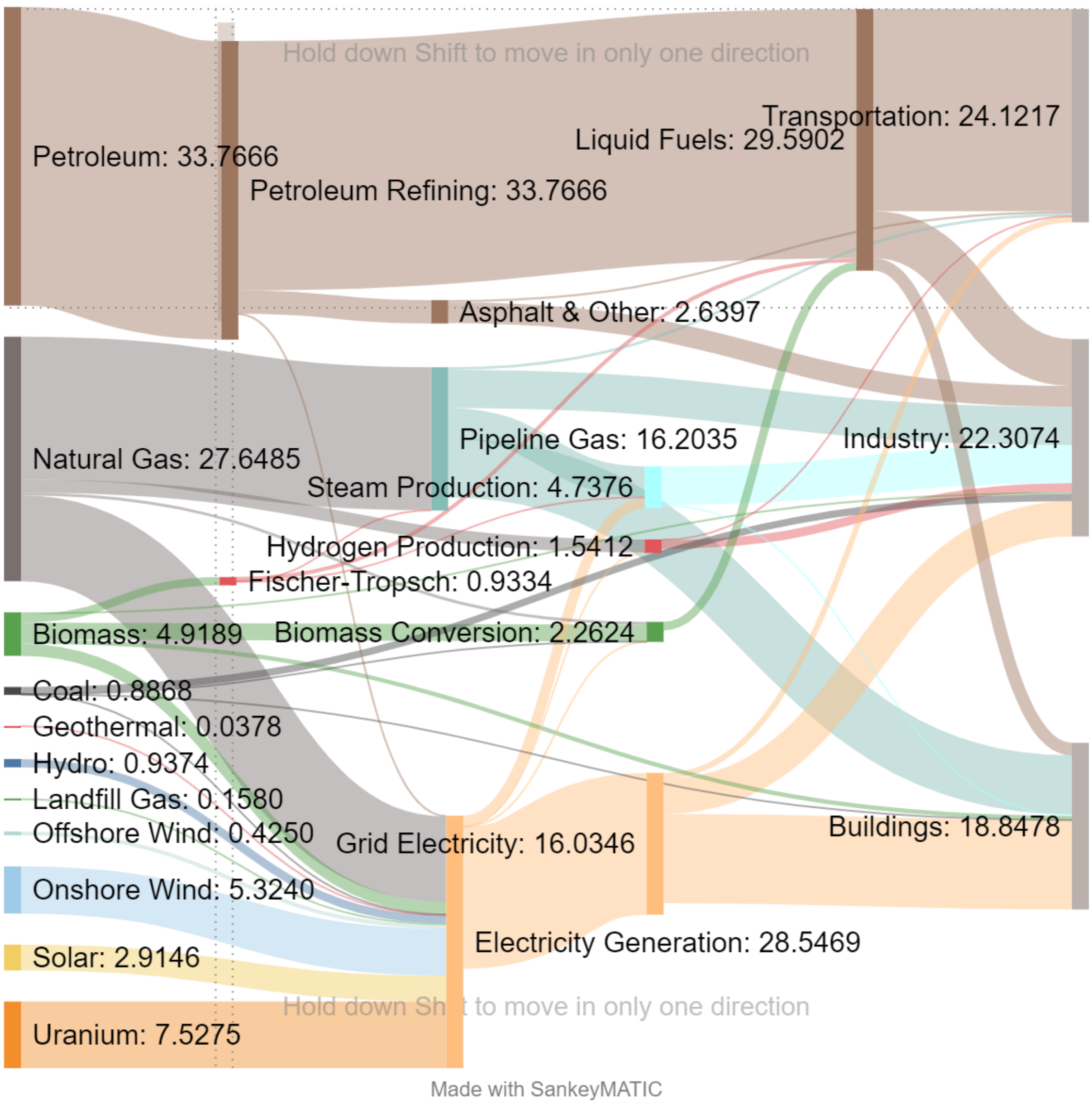
Source: UCS and EER 2021.

Low Energy Demand Scenario VMT Reductions Relative to Core Scenario

Aviation	-20%
Domestic shipping	-20%
Freight rail	-20%
Heavy-duty trucks	-20%
International shipping	-20%
Light-duty autos	-40%
Light-duty trucks	-40%
Lubricants	-20%
Medium-duty trucks	-20%
Military use	-20%
Motorcycles	-20%
Passenger rail	100%
Recreational boats	-20%
School and intercity buses	100%
Transit buses	100%

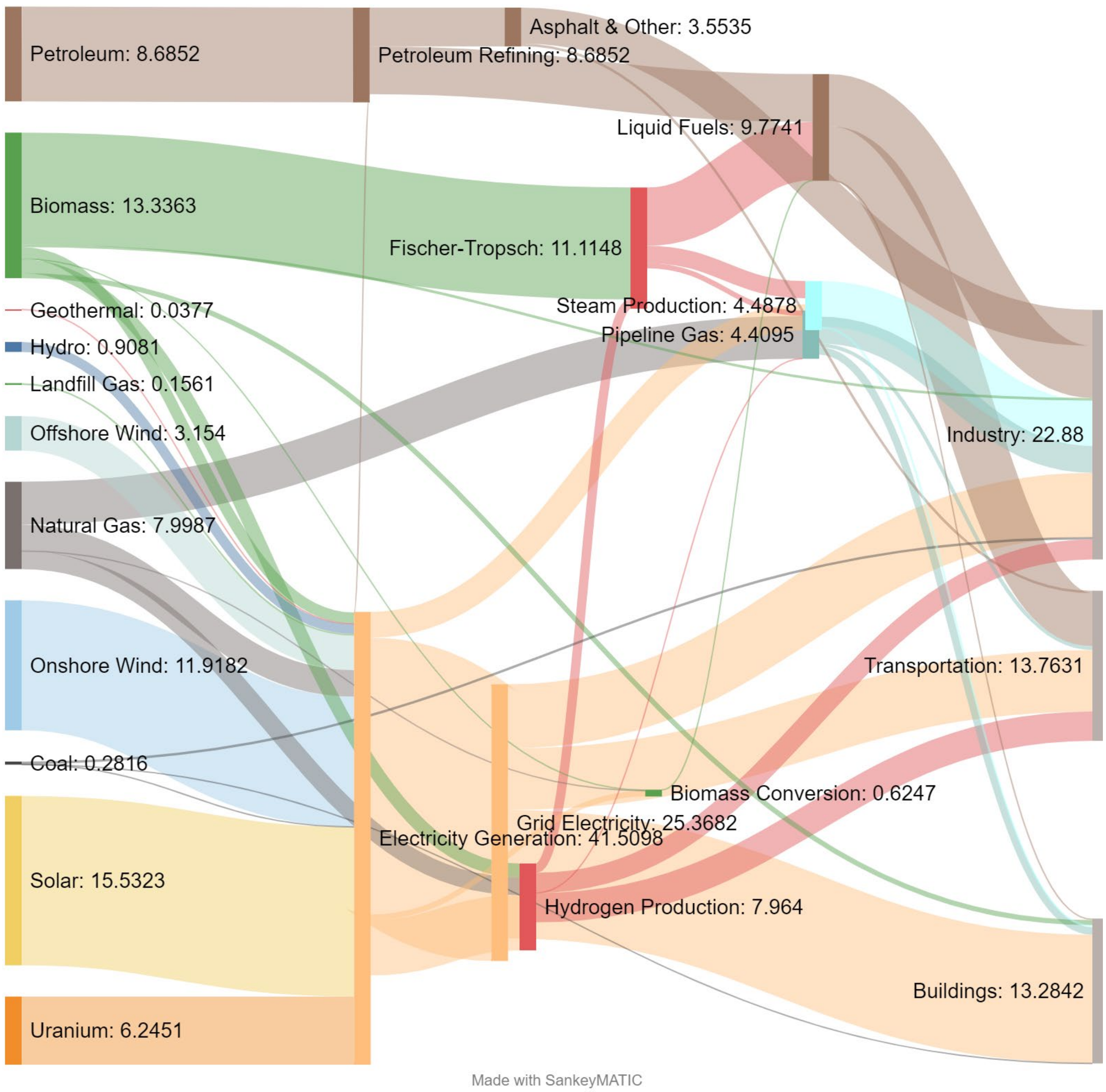
Source: UCS and EER modeling input assumptions.

Energy Flows in Core Scenario in 2030



Source: UCS and EER modeling.

Energy Flows in Core Scenario in 2050



Source: UCS and EER modeling.

ENDNOTES

1 Besides cumulative emissions, another climate index based on temperature increase can be used to measure the impact of global warming on the planet and is especially instructive for measuring relative historical responsibility from countries. CO_2 emissions contribute to an overall 0.784°C increase in global surface temperature in 2100. The US contribution to this total is the largest, at 0.172°C, followed by the EU at 0.140°C, and China at 0.100°C (Rocha et al. 2015).

2 These targets are in line with the Biden administration's commitment to rejoin the Paris Agreement (White House 2021a).

3 The agriculture and forestry sectors are considered exogenously in the model. Non-CO_2 emissions reductions and land sink assumptions are derived from published data.

4 End-use energy is energy consumed directly by the end-use sectors, which are the transportation, industry, residential, and commercial sectors. In this study, we use the term buildings to refer jointly to the residential and commercial sectors.

5 Greenhouse gas emissions by sector: transportation, 29 percent; electricity, 25 percent; industry, 23 percent; agriculture, 10 percent; commercial, 7 percent; and residential, 6 percent (EPA 2022).

6 EIA annual reports of total natural gas use in the transportation sector include natural gas for uses that are not exclusively vehicular, such as for pipelines and distribution (e.g., compressors and pushing fluids through pipelines). Vehicular natural gas use in 2021 was about 5 percent of total natural gas use in the transportation sector as reported by the EIA (Table 2.5, Transportation Sector Energy Consumption).

7 Electricity is quickly proving superior when measured on its own merits, largely because of the efficiency of electric-drive engines compared to internal combustion engines.

8 The specific energy efficiency ratio (EER) depends on the vehicle type and use case. CARB uses different EERs depending on the application, with 3.4 for cars and a 5.0 for battery-electric trucks. See Table 5, page 73 of California's Low Carbon Fuel Standard Regulation (CARB 2020).

9 EVs convert over 77 percent of the electrical energy to power at the wheels. Conventional gasoline vehicles convert only about 12 to 30 percent of the energy stored in gasoline to power at the wheels (EERE 2022).

10 Over its lifetime (from manufacturing to operation to disposal), the average new battery-electric vehicle produces about half the greenhouse gas emissions compared to a gasoline or diesel vehicle. See Figure ES-2 from Reichmuth, Dunn, and Anair 2022.

11 Primary energy is "energy in the form that it is first accounted for in a statistical energy balance, before any transformation to secondary or tertiary forms of energy." For example, coal (primary energy) can be converted to synthetic gas (secondary energy), which can be converted to electricity (tertiary energy) (EIA 2022b).

12 The demand model EnergyPATHWAYS makes use of many of the same input files used to populate the National Energy Modeling System used by the EIA to forecast their Annual Energy Outlook.

13 The economy-wide study modeled over a dozen scenarios. The three chosen to be presented here are the most relevant for the transportation sector.

14 The Infrastructure Investment and Jobs Act and Inflation Reduction Act were not considered in any of the scenarios.

15 The Core scenario is called the "Zero CO_2 2050 scenario" in the economy-wide report released in 2021.

16 We modeled only CO_2 emissions. Reductions of other GHG emissions such as methane, nitrous oxide, hydrofluorocarbons, and the land sink are exogenous to the model and based on a literature review. Our assumption that the land sink stays constant at current levels is conservative. One factor is the potential increases in land emissions from wildfires, which could offset reductions from reforestation and afforestation, and from increased soil carbon (Phillips 2022).

17 The Biden administration has set a target of 100 percent clean energy from power plant generation by 2035 (The White House 2021a).

18 The LED scenario assumes a slightly slower adoption of EVs. All LDV sales are zero emission by 2040, and M/HDV sales are zero emission by 2045. In our next round of modeling updates, the same rate of electrification will be used for all scenarios.

19 The external expert advisory board consists of Monica Unseld, Founder, Until Justice Data Partners; Ted Boettner, Senior Researcher, Ohio River Valley Institute; Shelley Welton, Assistant Professor, University of South Carolina School of Law; Chandra Farley, Energy Justice Advocate; Brett Isaac, Founder, Navajo Power; and Jackson Koeppel, Founder of Soulardarity.

20 Our modeling results allocated most of the available biofuels and synthetic fuels to transportation uses, resulting in very little remaining petroleum used in the transportation sector relative to other end uses of petroleum products. Because the production of various petroleum products (e.g., transportation fuels asphalt and liquefied petroleum gas) are tightly integrated, it is likely that the most efficient or probable allocation of alternatives may be different from our model results, which are not based on a detailed model of the refining sector. (The model estimates the shares of biofuels, synthetic fuels, and petroleum for the entire economy but does not reliably disaggregate within each of the economic sectors.) If we assume that the share of petroleum remaining in 2050 is the same for transportation liquid fuels as for other sectors, petroleum would constitute 40 percent of remaining liquid transportation fuel use in 2050, rather than the 10 percent from our modeling results. This is a 94 percent reduction of petroleum use from 2020 rather than a 98 percent reduction from the model results and leads to transportation emissions of 120 $MMtCO_2$ instead of the 32 $MMtCO_2$ reported in the model. However, overall petroleum use and economy-wide emissions are unchanged; only the allocation to the different sectors changes.

21 US transportation sector's GHG emission by vehicle type follows: light-duty vehicles, 57 percent; medium- and heavy-duty trucks, 26 percent; aircraft, 8 percent; other, 5 percent; rail, 2 percent; and ships and boats, 2 percent (EPA 2022).

22 Vehicles are categorized into classes based on their gross vehicle weight rating (GVWR), which range from Class 1 (cars and most SUVs) to Class 8 (semitrucks and transit buses). Emissions data on heavy-duty vehicle cited here includes Class 2b vehicles (GWVR of 8,501 to 10,000 lb) (O'Dea 2019).

23 Plug-in hybrid passenger cars and light trucks are a very small share that increase until around 2030 and then decrease quickly after the next two decades. Likewise with propane passenger cars, which are an insignificant share throughout the time period.

24 Electricity use in the building sector decreases from 75 percent to 51 percent. Industry use stays approximately constant at 25 percent. The contribution from these sectors stays constant or is reduced primarily because of the much greater increase in transportation electrification, in spite of some improvement in energy efficiency.

25 According to a recent UCS study, if 95 percent of electricity generation is renewable by 2035, emissions from driving an EV would be reduced to less than one-third of current EV emissions (Reichmuth, Dunn, and Anair 2022).

26 Aside from their important role in decarbonizing the remaining liquid fuels, bioproducts are important in displacing petroleum in other sectors of the economy as well.

27 Most of the biomass supply is from agricultural residues and herbaceous energy crops, such as switchgrass. A relatively small part of the supply comes from forest and logging residues.

28 In the Core scenario, in 2050, the model utilizes 439 MMT CO_2 of carbon removal, mostly from BECCS from biofuels. In the scenario where the biomass supply is halved, this same amount of carbon removal is addressed with a smaller amount of BECCS from biofuels (347 MMT CO_2) and direct air capture (125 MMT CO_2). See Modeling Results from UCS 2021.

29 Renewable diesel is a so-called drop-in fuel, which has the advantage of being chemically and functionally equivalent to fossil-based fuels and therefore does not require the adaptation of internal combustion engines, unlike biodiesel, which at higher blends often requires the adaptation of engines. Both renewable diesel and biodiesel can be produced from vegetable oils and lipids as well as from nonfood sources, such as herbaceous biomass. In 2021, biodiesel and renewable diesel combined accounted for 5 percent of diesel used in vehicles and approximately 1 percent of transportation energy (EIA 2022e).

30 Biomethane, also known as renewable natural gas, consists of methane produced from anaerobic digestion at landfills, dairies and other livestock operations, and wastewater treatment facilities. It can be used in natural gas vehicles in the form of compressed or liquefied natural gas.

31 Eletrolytic hydrogen is produced from the electrolysis of water, a process by which water is split into hydrogen and oxygen using electricity. If the electricity is from renewable sources, the hydrogen is referred to as green hydrogen.

32 Synthetic fuels include fuels obtained from biomass, waste, coal, natural gas, and through various processes of conversion, such as gasification, steam methane reformation, Fischer-Tropsch conversion, and other processes (Ridjan, Mathiesen, and Connolly 2016). In the model, the main technology used to produce e-fuels is Fischer-Tropsch.

33 This is associated with sequestered CO_2. A small amount is utilized and is not included in this total.

34 Since the costs of many future technologies are quite uncertain, we should exert caution when interpreting exact cost model results. Overall costs in more recent studies are generally lower than studies just five years ago, mainly because the cost of batteries and of solar and wind power have decreased more than expected. The study assumes cost reductions in technologies such as advanced nuclear, CCS, and hydrogen from natural gas reformation (NETL 2022; NREL 2018). As a result, a minimal amount of these technologies is still present in 2050. Some studies assume larger cost reductions that result in much larger build-outs of these technologies.

35 As the time of publication of this report, Oregon, Washington, New York, New Jersey, and Massachusetts have followed California in adopting the Advanced Clean Truck rule.

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