Independent Statistics & Analysis
U.S. Energy Information Administration

Annual Energy Outlook 2022

with projections to 2050

Narrative

Independent Statistics & Analysis

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Introduction

Key takeaways from the Reference case and side cases

Petroleum and natural gas remain the most-consumed sources of energy in the United States through 2050, but renewable energy is the fastest growing

- Motor gasoline remains the most prevalent transportation fuel despite electric vehicles gaining market share
- Energy-related carbon dioxide (CO_2) emissions dip through 2035 before climbing later in the projection years
- Energy consumption increases through 2050 as population and economic growth outweighs efficiency gains
- Electricity continues to be the fastest-growing energy source in buildings, with renewables and natural gas providing most of the incremental electricity supply

Wind and solar incentives, along with falling technology costs, support robust competition with natural gas for electricity generation, while the shares of coal and nuclear power decrease in the U.S. electricity mix

- Electricity demand grows slowly across the projection period, which increases competition among fuels
- Renewable electricity generation increases more rapidly than overall electricity demand through 2050
- Battery storage complements growth in renewables generation and reduces natural gas-fired and oil-fired generation during peak hours
- As coal and nuclear generating capacity retire, new capacity additions come largely from wind and solar technologies

U.S. crude oil production reaches record highs, while natural gas production is increasingly driven by natural gas exports

- U.S. production of natural gas and petroleum and other liquids rises amid growing demand for exports and industrial uses
- Driven by rising prices, U.S. crude oil production in the Reference case returns to pre-pandemic levels in 2023 and stabilizes over the long term
- Refinery closures lower domestic crude oil distillation operating capacity, but refinery utilization rates remain flat over the long term
- Consumption of renewable diesel increases as a share of the domestic fuel mix

The *Annual Energy Outlook 2022* explores long-term energy trends in the United States

- Projections in the Reference case of our *Annual Energy Outlook 2022* (AEO2022) are not predictions of what will happen, but rather, they are modeled projections of what may happen given certain assumptions and methodologies. The Reference case serves as a baseline for comparison between side cases that explain alternative trends. By varying Reference case assumptions and methodologies in side cases, AEO2022 can illustrate important factors in future energy production and use in the United States.

- Energy market projections are uncertain because we cannot foresee with certainty many of the events that shape energy markets—as well as future developments in technologies, demographics, and resources. To illustrate the importance of key assumptions, AEO2022 includes a baseline Reference case and several side cases that systematically vary important underlying assumptions.

- We developed AEO2022 by using the National Energy Modeling System (NEMS), an integrated model that captures interactions of economic changes and energy supply, demand, and prices.

- We publish the AEO2022 to satisfy the Department of Energy Organization Act of 1977, which requires the EIA Administrator to prepare annual reports on trends and projections for energy use and supply.

What is the AEO2022 Reference case?

- The AEO2022 Reference case represents our assessment of how U.S. and world energy markets would operate through 2050. Our key assumptions in the Reference case provides a baseline for exploring long-term trends, based on current laws and regulations as of November 2021. The current laws and regulations included in the AEO and a paper addressing the Bipartisan Infrastructure Law are available on the AEO website.

- We based the economic and demographic trends reflected in the Reference case on the current views of leading economic forecasters and demographers. For example, the Reference case projection assumes improvement in known energy production, delivery, and consumption technologies.

- The Reference case serves as the benchmark to compare with alternative policy-based cases, so in general, it assumes that current laws and regulations that affect the energy sector, including laws that have end dates, remain unchanged throughout the projection period.

What are the side cases?

- We run eight standard side cases each year in addition to the Reference case. We also publish Issues *in Focus* analyses to explore emerging issues in the energy sector. The standard side cases are:
    - High Oil Price case
    - Low Oil Price case
    - High Oil and Gas Supply case
    - Low Oil and Gas Supply case
    - High Economic Growth case
    - Low Economic Growth case
    - High Renewable Cost case
    - Low Renewable Cost case

- Global market balances, primarily non-domestic supply and demand factors, will drive future crude oil prices. To account for these factors, oil prices are an external assumption in our analysis. In the AEO2022 High Oil Price case, the price of Brent crude oil, in 2021 dollars, reaches $170 per barrel (b) by 2050, compared with $90/b in the Reference case and $45/b in the Low Oil Price case.

- Compared with the Reference case, the High Oil and Gas Supply case assumes that the estimated ultimate recovery per well for tight oil, tight gas, or shale gas in the United States is 50% higher. This side case assumes that undiscovered resources in Alaska and the offshore Lower 48 states are 50% higher than in the Reference case. Rates of technological improvement that reduce costs and increase productivity in the United States are also 50% higher than in the Reference case. Conversely, the Low Oil and Gas Supply case assumes that the estimated ultimate recovery per well for tight oil, tight gas, or shale gas in the United States; the undiscovered resources in Alaska and the offshore Lower 48 states; and rates of technological improvement are all 50% lower.

- The High Renewables Cost case and the Low Renewables Cost case examine the sensitivities surrounding capital costs for renewable electric power generation and diurnal storage technologies. We assume capital cost reductions for an electric power-generating technology occur from learning by doing as commercialization expands and construction and manufacturing experience accelerates. The High Renewables Cost case assumes no cost reductions from learning by doing for any renewable generation or diurnal storage technologies. The Low Renewables Cost case assumes faster technology learning for renewable generation and diurnal storage technologies through 2050, resulting in a cost reduction of about 40%, compared with the Reference case, by 2050. In addition, we assume fixed operating and maintenance costs will decline along with the capital cost from technology improvement.

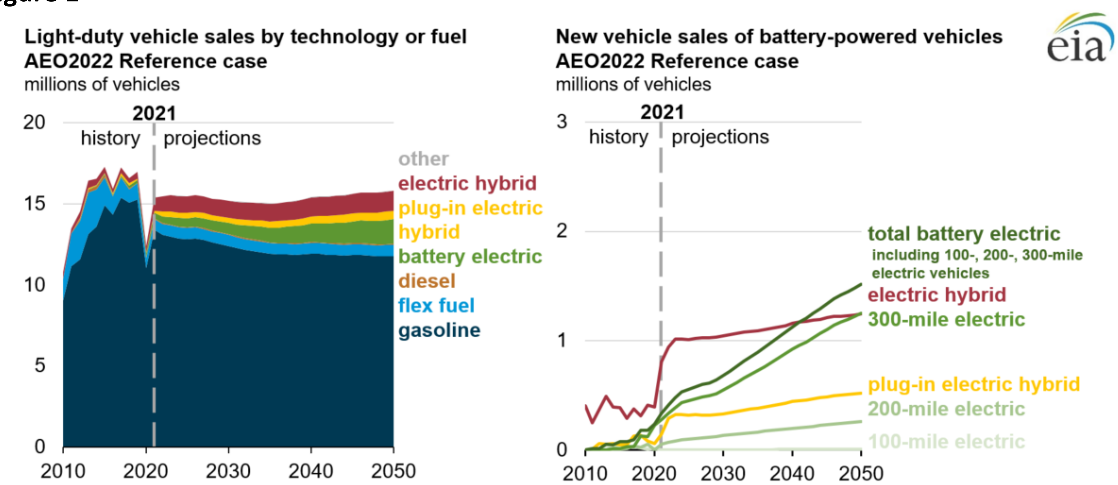
- The High Economic Growth case and Low Economic Growth case address the effects of economic assumptions on the energy consumption modeled in the AEO2022. From 2021 to 2050, the High Economic Growth case assumes the compound annual growth rate for U.S. GDP is 2.7%, and the Low Economic Growth case assumes a rate of 1.8%. However, the Reference case assumes the U.S. GDP annual growth rate is 2.2% over the projection period.

- AEO2022 cases do not include the potential effects of proposed legislation, regulations, or standards, except as specifically noted in *Issues in Focus* analyses.

Consumption

Motor gasoline remains the most prevalent transportation fuel despite electric vehicles gaining market share

Figure 1



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

Gasoline remains the dominant light-duty vehicle (LDV) fuel, but consumption does not return to pre-pandemic levels during the projection period

LDVs accounted for 54% of the energy consumed in U.S. transportation in 2021. Their share falls to 51% by 2050. LDV energy consumption generally decreases through 2038 and then increases through the end of the projection period. Total LDV sales do not return to 2019 pre-pandemic levels by 2050, and sales of conventional motor gasoline vehicles decrease through the projection period because of increasing sales of battery-electric vehicles (BEVs), hybrid-electric vehicles (HEVs), and plug-in hybrid-electric vehicles (PHEVs).

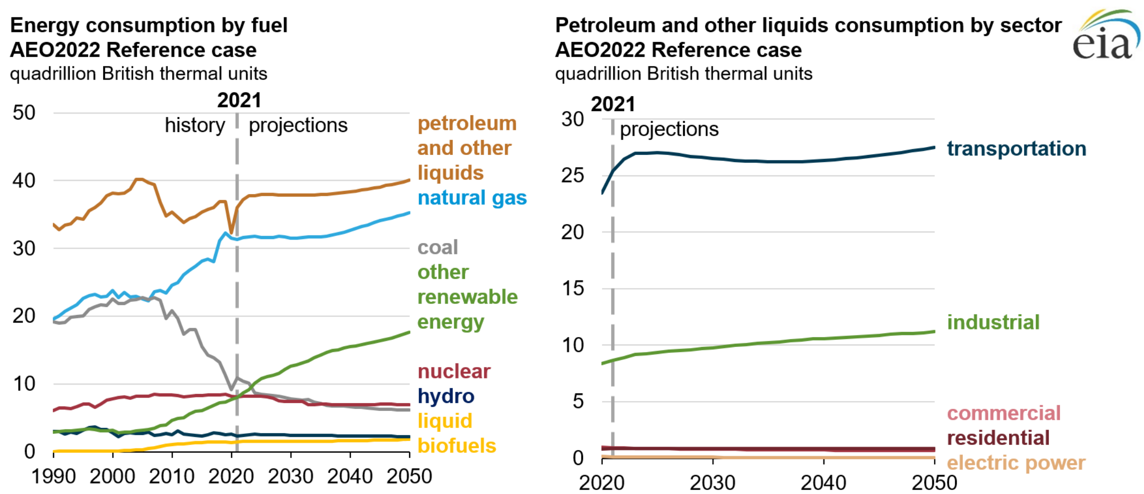
We project that the combined share of sales of internal combustion engine (ICE) LDVs—including gasoline, diesel, flex-fuel, natural gas, and propane powertrains—will decrease from 92% in 2021 to 79% in 2050 because of growth in sales of BEVs, PHEVs, and HEVs. Through the projection period, 200- and 300-mile BEV sales grow, increasing from 0.34 million in 2021 to 1.52 million in 2050, while sales of PHEVs increase from 144,000 in 2021 to 521,000 in 2050. PHEVs demonstrate fast growth and market penetration between 2021 and 2024. Growth in PHEV sales slows after 2024 as a result of declining battery prices, which pushes BEVs into the highest electric LDV market share. We project BEVs and PHEVs combined account for 13% of total LDV sales in 2050.

The on-road vehicle stock shifts more slowly than sales because electric vehicles replace older, retired ICE vehicles

We project that the total electric vehicle share—including BEVs and PHEVs—of on-road LDV stock grows from less than 1% in 2021 to 9% in 2050, based on current laws and regulations as of November 2021. This shift occurs even as the on-road LDV stock likely grows from 260 million to 288 million vehicles over that timeframe. Increased electrification of the on-road LDV fleet increases electricity consumption from less than 0.5% to more than 2% of total consumption of energy in the transportation sector between 2019 and 2050 in the Reference case.

Energy-related carbon dioxide (CO_2) emissions dip through 2035 before climbing later in the projection years

Figure 2



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case
Note: Biofuels are shown separately and included in petroleum and other liquids.

Vehicles and industrial processes are the main consumers of petroleum in the Reference case

Petroleum and other liquids remain the most-consumed fuels in the Reference case. In the United States, petroleum and other liquids, particularly motor gasoline and distillate fuel oil, are mostly consumed in transportation. In the Reference case, we assume that current fuel economy standards remain constant after 2026 for light-duty vehicles and after 2027 for heavy-duty vehicles. As travel continues to increase, consumption of petroleum and other liquids increases later in the projection period.

In the U.S. industrial sector through 2050, hydrocarbon gas liquids (HGLs) used as a feedstock drive most of the growth in demand for petroleum. Petroleum also remains a major fuel for refining processes and in nonmanufacturing industries (agriculture, construction, and mining).

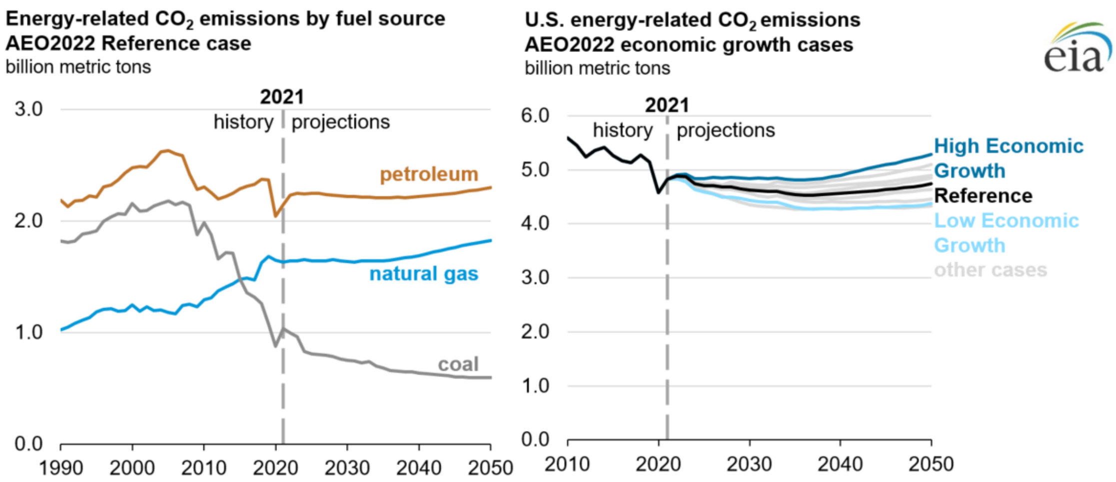
Consumption of renewable energy increases steadily as natural gas maintains a large market share and coal continues a steady decline

In all cases, we project that renewable energy will be the fastest-growing U.S. energy source through 2050. Policies at the state and federal levels continue to provide incentives for significant investment in renewable resources for electricity generation and transportation fuels. New technologies continue to lower the cost to install wind and solar generation, further increasing their competitiveness in the electricity market, even as the policy effects we assume level out over time. Federal regulations continue to provide incentives for using biofuels, primarily ethanol, as energy during the projection period. However, relatively modest increases in demand for electricity and liquid fuels limit the projected growth of renewable energy in the Reference case.

We project that consumption of natural gas will keep growing as well, maintaining the second-largest market share overall. The expected growth in natural gas consumption is driven by expectations that natural gas prices will remain low compared with historical levels. In the Reference case, the industrial sector has the largest share of natural gas consumption, starting in the early 2020s, driven by greater use of natural gas as a feedstock in the chemical industries and by increased heat-and-power consumption across multiple industries.

Changes in fuel mix reduce energy-related CO_2 emissions in the Reference case through 2037, despite steadily increasing energy consumption

Figure 3.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)
Note: Series does not include greenhouse gases other than carbon dioxide (CO_2). Industrial sector CO_2 emissions do not include process emissions, such as the emissions from cement clinker production.

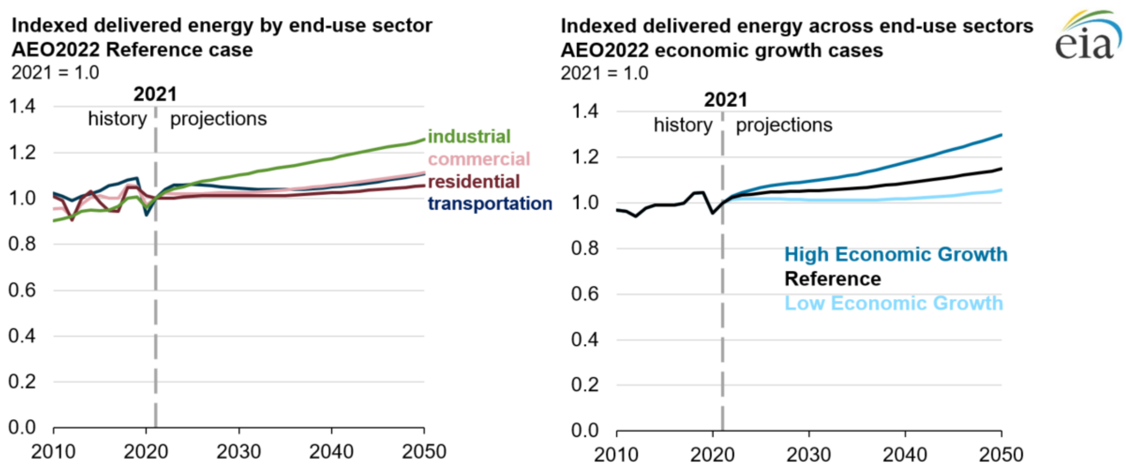
Changes over time in U.S. energy-related CO_2 emissions in the Reference case reflect shifts in the quantity and CO_2 intensity (CO_2 per unit of energy) of fuel consumption. Emissions decrease from 2022 to 2037 because of a transition away from more carbon-intensive coal to less carbon-intensive natural gas and renewable energy for electricity generation and because of an overall decrease in energy intensity (energy consumption per unit of GDP). After 2037, CO_2 emissions begin to trend upward as increasing energy consumption, resulting from population and economic growth, outpaces continuing reductions in energy intensity and CO_2 intensity. This trend occurs in all AEO2022 side cases. The High Economic Growth case has the highest level of CO_2 emissions over the projection period, and the Low Oil and Gas Supply case has the lowest. Even in the High Economic Growth case, annual energy-related CO_2 emissions through 2050 remain below the 2007 peak of 6 billion metric tons.

Energy consumption increases through 2050 as population and economic growth outweighs efficiency gains

U.S. energy consumption grows through 2050, driven by population and economic growth

Economic growth is a key driver of the longer-term trends in energy consumption, and the High and Low Economic Growth cases explore future growth trajectories in the U.S. economy. These cases modify population growth and productivity assumptions throughout the projection period to yield higher or lower compound annual growth rates for U.S. GDP compared with the Reference case. The economic growth cases show the highest and lowest levels of projected energy consumption across cases. From 2021 to 2050, the High Economic Growth case assumes a U.S. GDP compound annual growth rate of 2.7%, the Low Economic Growth case assumes 1.8%, and the Reference case assumes 2.2%.

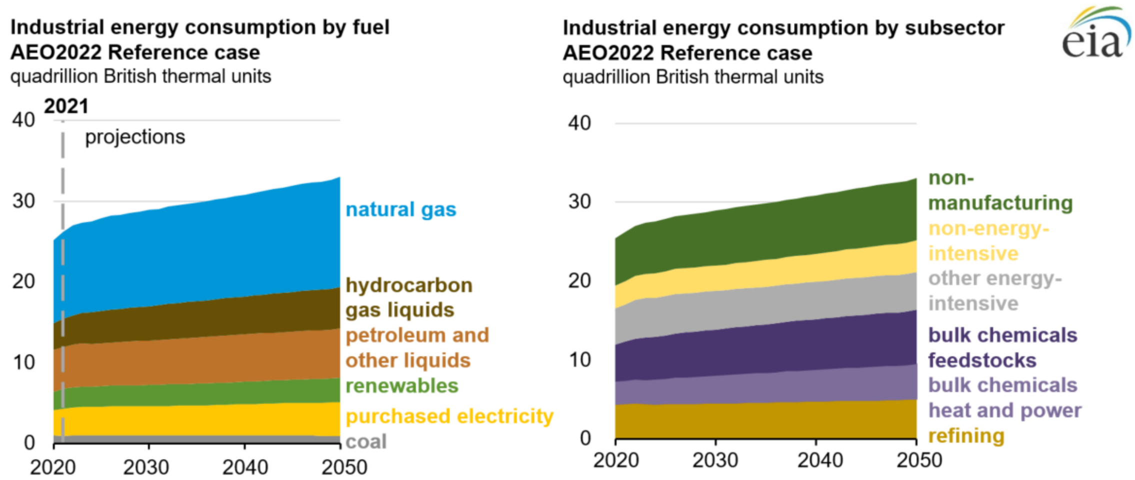
Figure 4.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)

Overall industrial energy consumption grows rapidly, but not all industries return to pre-pandemic levels

Figure 5.



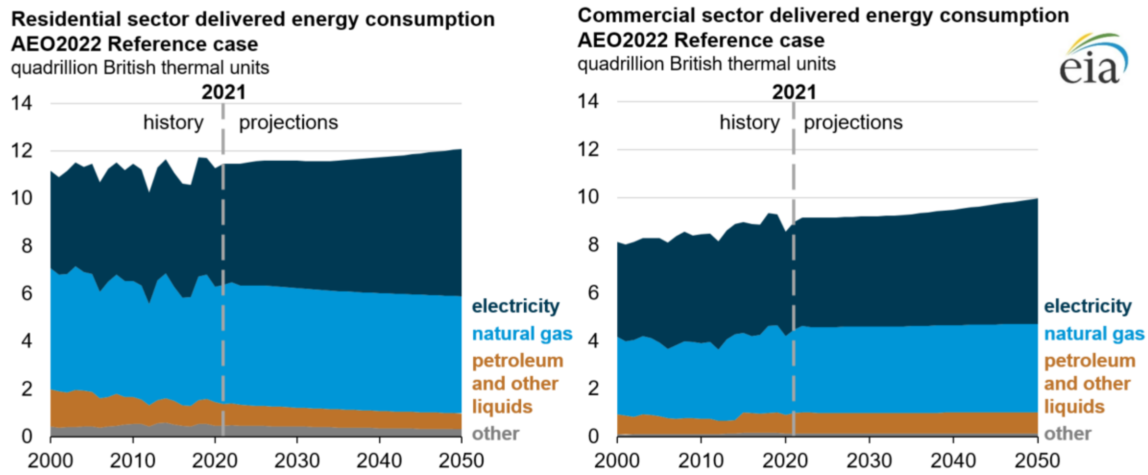
Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

In the Reference case, we project the U.S. industrial sector's energy consumption will grow more than twice as fast as any other end-use sector from 2021 to 2050. We expect industrial energy consumption in the United States to exceed pre-pandemic levels by 2022, although specific industries may remain below or take longer to return to pre-pandemic levels. For example, we do not project the glass and steel industries to return to 2019 levels of energy consumption by 2050. These industries were decreasing their energy use before the pandemic because shifts in their respective industrial production processes increased efficiencies. Moreover, U.S. steel production is more or less flat after 2025, further contributing to this industry's declining energy consumption in the long term. We assume that most major energy-consuming industries will have declines in energy intensity (the amount of energy used to produce a unit of output) as a result of efficiency gains, which results in energy consumption growth that is slower than the growth in shipments.

The U.S. bulk chemicals industry is the largest industrial energy user throughout the projection period and consumes the most energy in the industrial sector as a whole. We project that through the mid-2020s, the bulk chemicals industry will build facilities that use natural gas and HGL feedstocks to produce chemicals such as nitrogenous fertilizer and ethylene. Some chemical products derive from heavier liquid petrochemicals (mainly naphtha), but feedstock use of heavy petrochemicals does not grow during the projection period. Growth in natural gas and HGL feedstock consumption slows after the first half of the 2020s as growth in the bulk chemicals industry shifts to secondary chemical production (that is, derivative chemicals produced from commodity chemicals, as opposed to HGLs or natural gas).

Growth in residential housing stocks and commercial floorspace contributes to increasing energy consumption across the buildings sector

Figure 6.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

Housing stocks and commercial floorspace increase over the projection period and are key drivers of energy consumption in buildings. However, as a result of efficiency gains, delivered energy consumption in U.S. buildings[1] grows at 0.3% per year, more slowly than housing stocks (0.8% per year) and commercial floorspace (1.0% per year) grow between 2021 and 2050 in the Reference case.

Between 2021 and 2050, U.S. housing stocks, led by growth in single-family homes, increase by 23% in the Reference case. Single-family homes consume more energy per square foot, on average, than multifamily or mobile homes. However, efficiency gains in new homes cause energy use to grow more slowly than the U.S. housing stock overall, continuing the long-term decline in residential energy intensity per square foot.

Similarly, the commercial building stock expands by more than one-third between 2021 and 2050. However, energy consumption in commercial buildings grows more slowly than commercial floorspace. Energy efficiency improvements enable buildings to meet growing demand for energy-consuming services without a one-for-one increase in energy use. We project the energy intensity of the commercial building stock to decline at an average rate of 0.6% per year from 2021 through 2050.

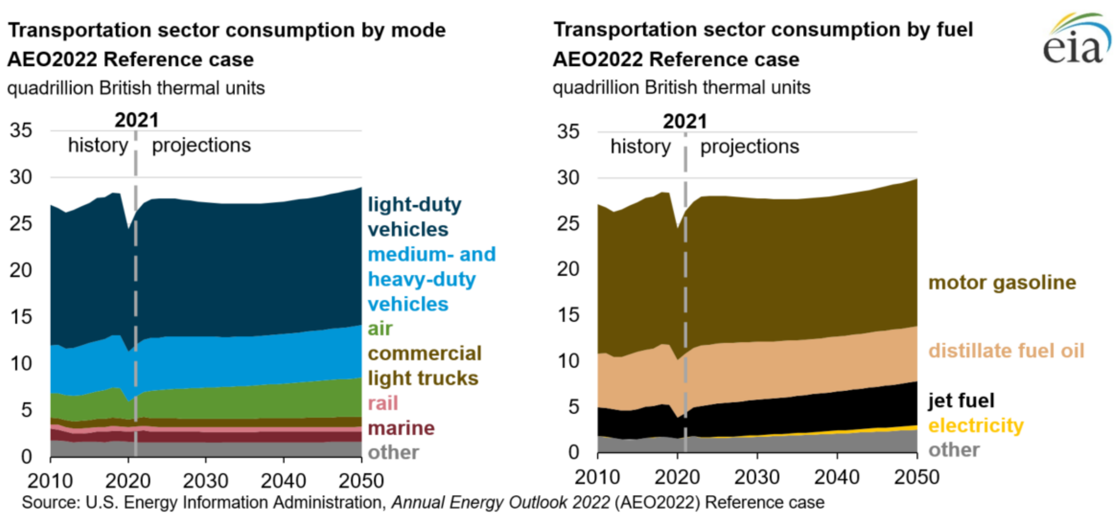
In our Reference case, we project that electricity consumption in U.S. residences will grow 22% between 2021 and 2050. Onsite generation, largely from solar photovoltaics (PV), reduces the amount of energy that must be delivered to buildings to meet energy demand. Energy consumption from onsite sources grows at an average annual rate of 6.1%. This growth occurs despite our expectation that PV system costs will decline more slowly than in the past. PV costs decline more slowly following near-term pandemic impacts and related supply constraints on materials needed to manufacture PV panels, as well as restrictions for certain PV panel imports, both of which have lasting effects through the projection period.

[1] Delivered energy excludes electricity-related losses. In addition, this measurement excludes onsite energy generated for use in a home or commercial building.

Natural gas consumption for space heating, which is the largest single contributor to both U.S. commercial and residential delivered energy consumption throughout the Reference case projection period, declines through 2050. We project that buildings will consume less energy for space heating as the United States experiences warmer winters and as the population increasingly migrates to warmer parts of the country, reducing the heating degree days we use to project space heating requirements.[2]

Despite steep declines during the pandemic, consumption of energy for transportation returns to pre-pandemic levels

Figure 7.



In the Reference case, energy consumption in the transportation sector nearly returns to the 2019 pre-pandemic level of 28.4 quadrillion British thermal units (quads) in 2025 before declining slowly through 2035. Energy consumption in the sector then rises through the remainder of the projection period to 29.9 quads. Motor gasoline, distillate fuel oil, and jet fuel account for more than 90% of the transportation sector's energy consumption throughout the projection period. Electricity is the fastest-growing fuel used for transportation, growing from less than 0.5% of total consumption in 2019 to nearly 2% in 2050.

In the Reference case, on-road passenger light-duty vehicle (LDV) travel mainly uses motor gasoline as its energy source through 2050. LDV fuel economy and projected vehicle miles traveled (VMT) are key factors that determine the level of future gasoline consumption. New vehicle fuel economy improvements are driven by increasingly stringent fuel economy standards from the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration through 2026, after which we assume that the standards remain constant and improvement in fuel economy slows. Passenger VMT grows steadily with population and income throughout the projection period, growing 26% higher in 2050 than it was in 2019. We project that the confluence of fuel economy improvement

[2] Heating degree days are a measure of how far temperatures fall below a reference temperature, indicating demand for indoor heating. Reference case projections use a 30-year trend of historical population-weighted degree days from the National Oceanic and Atmospheric Administration (NOAA).

and increasing VMT results in gasoline consumption falling through 2038 and then rising for the remainder of the projection period.

Rising diesel consumption is largely a result of projected medium- and heavy-duty freight truck travel, which accounts for around 77% of consumption of diesel in the transportation sector throughout the projection period. Both the trend and its explanation are similar to that of gasoline. After fuel economy returns to pre-pandemic levels, we project that fuel economy increases for trucks, which generally reduces consumption through 2041. Slowing gains in fuel economy and rising freight truck travel demand gradually cause consumption to rise through 2050. After returning from its 2020 pandemic low, commercial jet fuel consumption continues to grow throughout the projection period as a result of growing income and population. We project that U.S. commercial aircraft will consume 4.2 quads of jet fuel in 2050, a 32% increase from 2019.

We project that different transportation modes, and as a result, different fuels, will return to pre-pandemic (2019) levels at different rates:

- Light-duty vehicle travel as measured by VMT in 2022
- Freight truck VMT in 2021
- Air travel as measured in revenue passenger-miles (RPMs) in 2025
- Bus as measured in passenger-miles traveled (PMT) in 2028
- Passenger rail PMT in 2025

Improving efficiencies across all modes results in slower increases in consumption. Gasoline consumption does not reach its 2019 total during the projection period, diesel returns to its 2019 level in 2023, and commercial jet fuel returns to its 2019 level in 2027.

Electricity continues to be the fastest-growing energy source in buildings, with renewables and natural gas providing most of the incremental electricity supply

Over the projection period, use of electricity expands to meet a variety of needs in homes and commercial spaces

Electricity continues to be the fastest-growing source of energy used in buildings, even as lighting, air-conditioning, and other end uses see efficiency gains. In our Reference case, onsite generation from solar PV grows faster than purchased grid electricity for buildings during the projection period. We project distributed generation technologies such as solar PV will grow to supply 8% of electricity consumed in households and 6% of electricity consumed in commercial buildings in 2050, despite declining electricity prices.

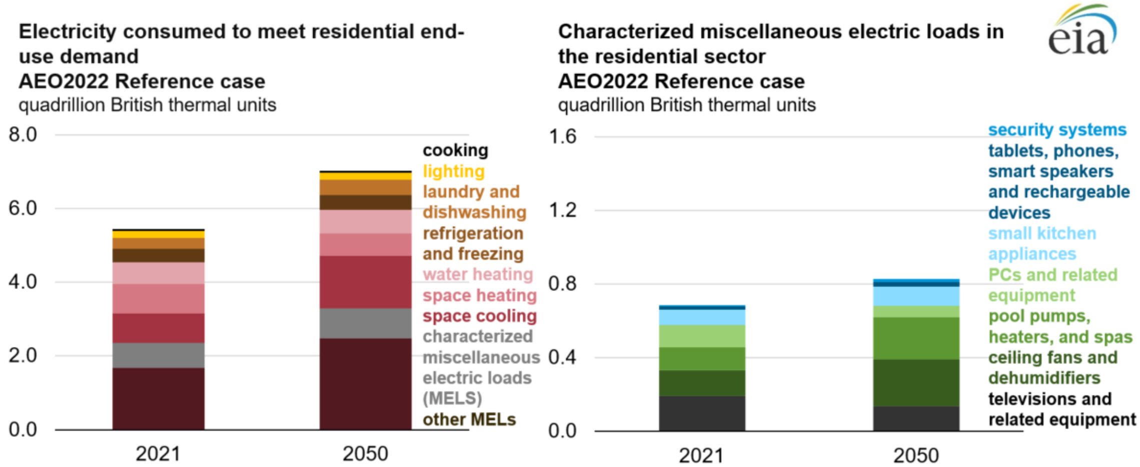
Federal minimum energy efficiency standards, the availability of subsidies for energy-efficient equipment, and technological improvements increase the efficiency of commercial equipment and household appliances in the Reference case. Incremental increases in equipment efficiency reduce consumption, offsetting the effects of household and floorspace growth.

The Reference case reflects evolving consumer demand for electricity over time

U.S. consumption of electricity for many major end uses—including space heating, water heating, refrigeration, and lighting—decreases over time. Growing adoption of space cooling equipment and increasing cooling demand in the residential sector cause associated electricity consumption to grow

77% from 2021 to 2050. At the same time, we project residential electricity used to serve *miscellaneous electric loads* (MELs) to grow 20% by 2050 for devices and technologies that we explicitly model. MELs include televisions, personal computers (PCs), smartphones, tablets, pool pumps, and other uses.

Figure 8.

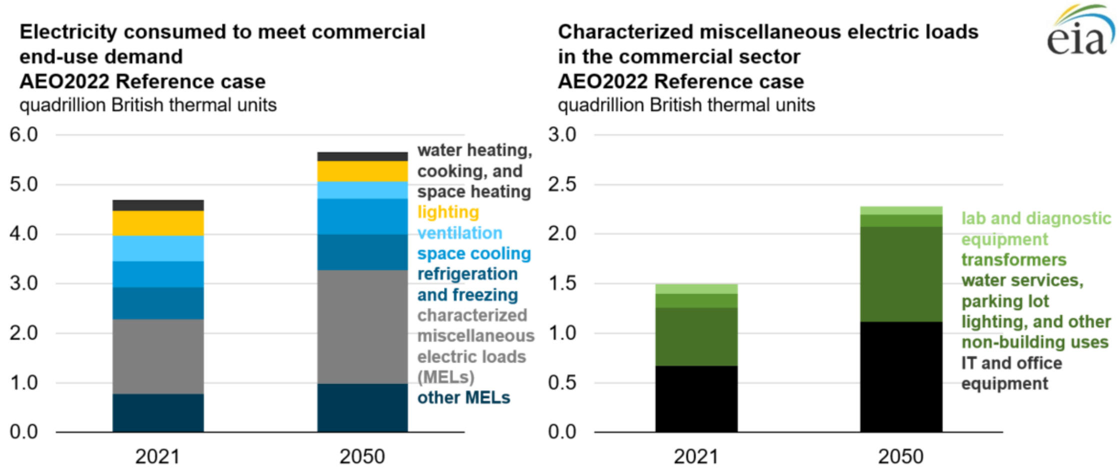


Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

We project that energy consumed by traditional computing equipment, specifically desktop PCs and laptops, will decrease through 2050, offset in part by increasing numbers of monitors per computer. We project electricity consumed by tablets to increase over time, and we project electricity used to recharge smartphones in U.S. households will grow at a faster annual rate than population. We project the average number of smartphones per household to grow 8% between 2021 and 2050, up to 2.4 phones per household, on average. In 2050, we project that an average of 2.5 people live in each U.S. household.

Projected electricity used by televisions and related equipment declines as newer models replace less energy-efficient televisions through 2050, despite increased use of video game consoles. Consumption of electricity from other MELs generally continues to increase over time as personal disposable income grows.

Figure 9.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

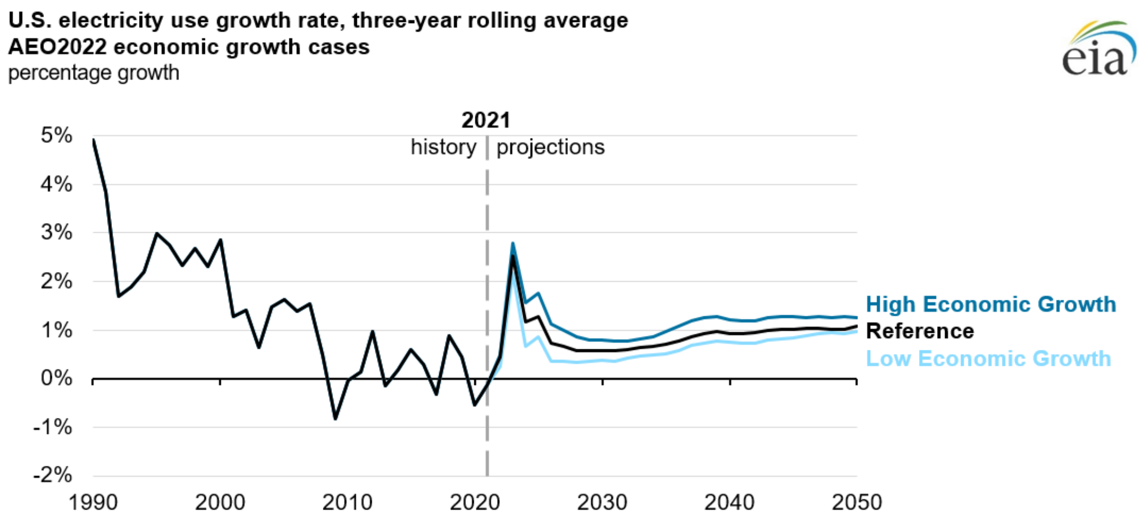
In the commercial sector, electricity for space cooling grows by 38% over the projection period. We project MELs to consume 29% more electricity in 2050 than in 2021 in U.S. commercial buildings. Not all equipment, appliances, and devices contribute to these increases. For example, we project the number of monitors per computer to increase relative to 2021 levels. However, we project the associated energy consumption to decrease by more than half in 2050 compared with 2021 as new monitors replace older models that consume more energy. Meanwhile, consumption by data center servers in commercial buildings expands through 2050. As a result, by 2050, we project energy use by commercial IT and office equipment to increase by 67% from 2021 levels. Projected increases in service sector output drives additional growth in other commercial MELs.

Electricity

Electricity demand grows slowly across the projection period, which increases competition among fuels

The U.S. annual average electricity growth rate remains below 1% for much of the projection period in the Reference case

Figure 10.

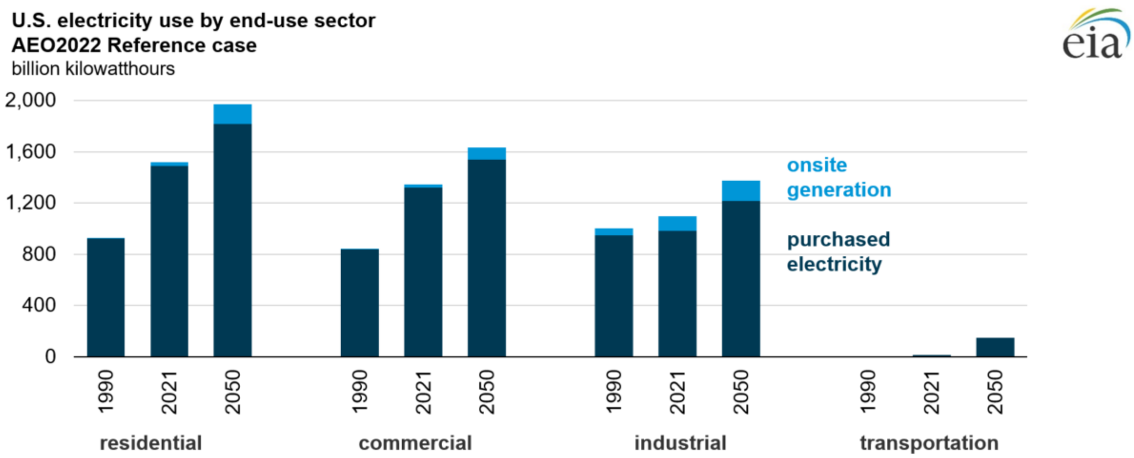


Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)

The three-year rolling average growth rate of electricity consumption in the United States peaks in 2023 as the economy returns to pre-pandemic levels of economic activity. In the short term, demand for electricity may fluctuate as a result of year-to-year weather, economic shocks, or other unpredictable events. Economic growth drives longer-term trends in electricity consumption, although the growth is somewhat offset by efficiency improvements. In the Reference case, the average annual growth rate of electricity consumption surpasses 1% but not until near the end of the projection period. Electricity demand in the AEO2022 High Economic Growth case grows about 0.25% faster than in the Reference case, and it grows about 0.25% slower in the Low Economic Growth case.

The share of onsite electricity generation increases across non-transportation sectors

Figure 11.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case
Note: Onsite generation is electricity produced onsite for own use.

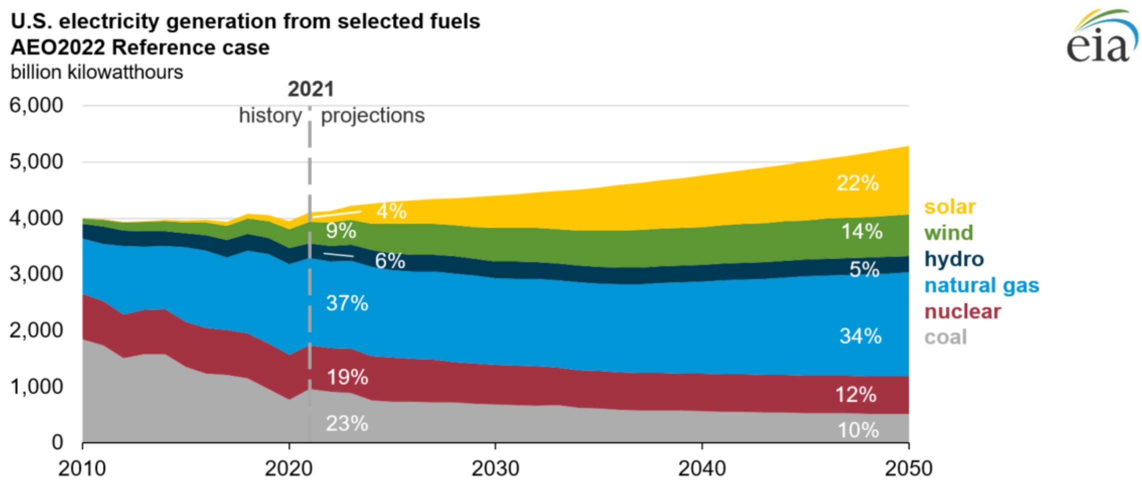
Through the projection period, onsite generation of electricity expands significantly in the U.S. residential, commercial, and industrial sectors, reducing growth in electricity purchased from centralized generators. We project that residential, commercial, and industrial sector onsite solar PV systems will account for more than 8% of total electricity generation by 2050, almost double the share held by onsite power generators in 2021.

Electricity demand in transportation remains low

We project that demand for electricity grows fastest in the transportation sector, even as consumption in that sector remains less than 3% of economy-wide electricity consumption in the Reference case. Fully electric vehicles grow from less than 1% of the on-road LDV fleet in 2021 to a little over 7% in 2050 in the Reference case. The increase in demand primarily follows evolutionary electric vehicle (EV) technology and market developments, as well as current fuel economy regulations. Both vehicle sales and utilization (miles driven) would need to increase substantially for EVs to raise electric power demand growth rates by more than a fraction of a percentage point per year. The transportation sector's share of electricity consumption is greatest in the High Oil Price case, where it reaches 5% of the total in 2050.

Renewable electricity generation increases more rapidly than overall electricity demand through 2050

Figure 12.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case
Note: Solar includes both utility-scale and end-use photovoltaic electricity generation.

Renewable electricity generation meets incremental demand growth

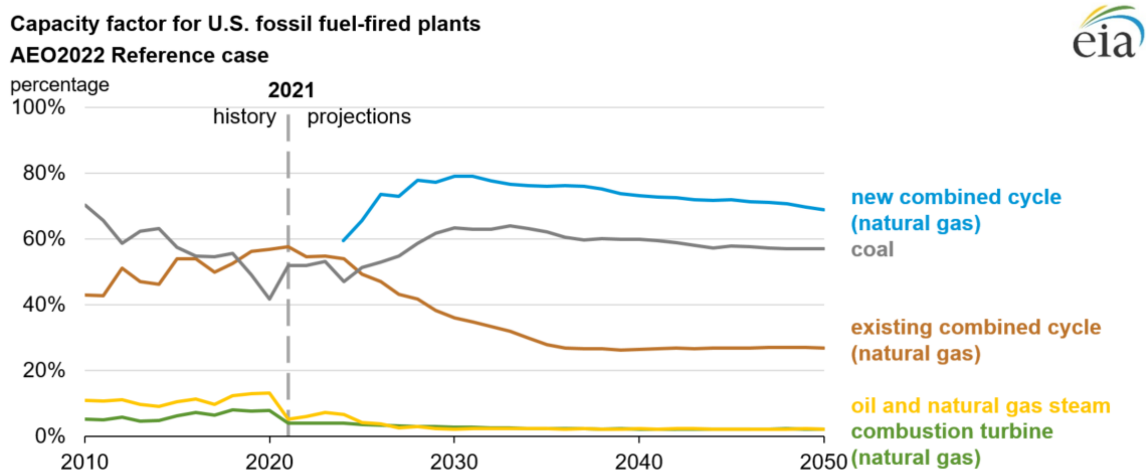
The share of renewables in the U.S. electricity generation mix more than doubles from 2021 to 2050. Wind grows more than any other renewable generation type from 2021 through 2024, accounting for more than two-thirds of those increases in electricity generation during that period. After the production tax credit (PTC) for wind phases out at the end of 2024, solar generation accounts for almost three-quarters of the increase for renewable energy. In the Reference case, we model existing legislation for the investment tax credit (ITC): solar receives a 30% tax credit through 2024, which then reduces to 26% for projects coming online in 2024 and 2025 before phasing down to a non-expiring credit of 10% starting in 2026.

Sustained low natural gas prices keep natural gas generation at the highest market share in the Reference case

The share of natural gas in the generation mix remains relatively constant, at about one-third from 2021 to 2050. Although the share remains the same, projected natural gas prices stay below $4.00 per million British thermal units (MMBtu) for most of the projection period. The natural gas share remains consistent despite significant projected coal and nuclear generating unit retirements, which cause the shares from those sources to drop by half. Generation from renewable sources increases to offset the natural gas share, largely because regulatory programs and market factors incentivize these sources.

After near-term natural gas prices stabilize, and as more solar and wind energy integrates into the electricity grid, natural gas-fired generating unit capacity factors steadily decrease. The average capacity factor of the coal fleet increases as inefficient units are retired throughout the projection period

Figure 13.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

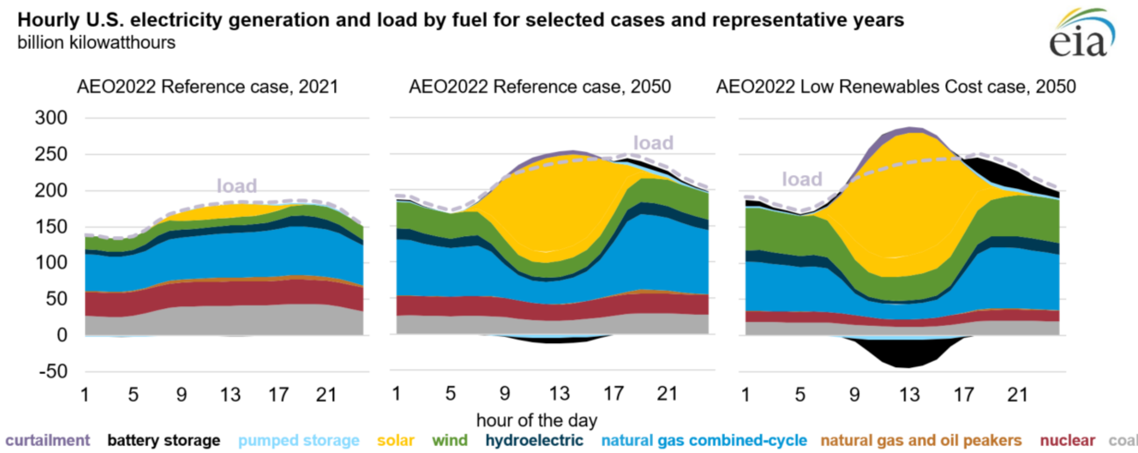
As more wind and solar capacity is added, both existing and new natural gas-fired generation is displaced, and capacity factors for existing combined-cycle units drop by nearly half from a peak of 60% in 2020. Because natural gas-fired generating capacity grows faster than natural gas-fired generation from 2020 to 2050, capacity factors for natural gas units decline steadily across all plant technology types. The average capacity factor of operating coal plants increases over the projection period as relatively old and inefficient coal plants retire and the more efficient and cost competitive plants remain. Natural gas accounts for more than 40% of cumulative capacity additions from 2020 to 2050. About half of natural gas capacity additions through 2050 are low-utilization combustion turbines, which are economically attractive when mostly used to provide infrequent peaking capacity.

Energy storage systems, such as stand-alone batteries or solar-battery hybrid systems, will compete with natural gas-fired turbines as sources of back-up capacity for nondispatchable renewable energy sources. Storage systems can act as an arbitrage tool to move solar and other generation from periods of high supply and low demand to periods of low supply and high demand, and they can provide capacity for grid reliability in times when nondispatchable generation is not available.

Battery storage complements growth in renewables generation and reduces natural gas-fired and oil-fired generation during peak hours

Battery storage complements solar capacity additions, captures solar generation that would otherwise be curtailed, and reduces nonrenewable generation to meet peak electric demand

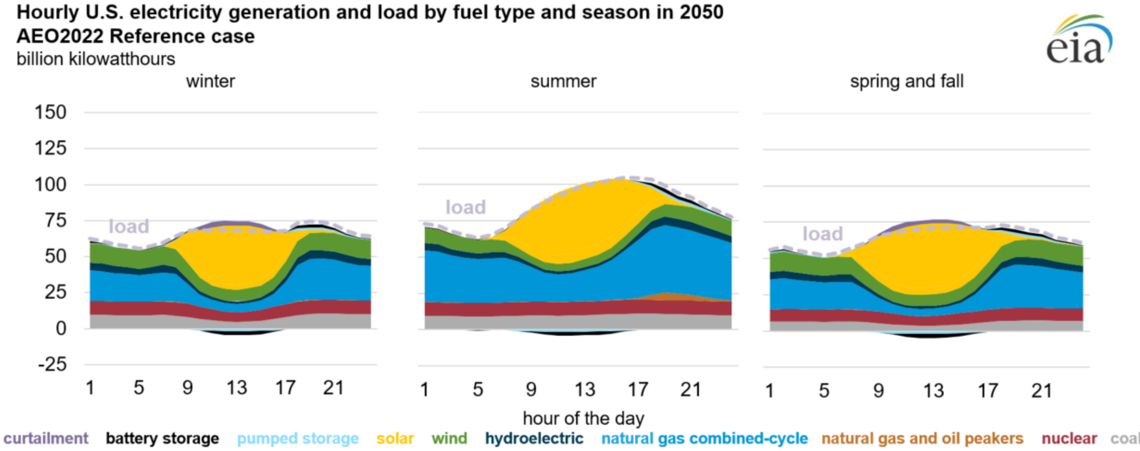
Figure 14.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)
Note: Negative generation represents charging of energy storage technologies such as pumped hydro and battery storage. Hourly dispatch estimates are illustrative and are developed to determine curtailment and storage operations; final dispatch estimates are developed separately and may differ from total utilization as this figure shows. Solar includes both utility-scale and end-use photovoltaic electricity generation.

In 2021, limited surplus generation occurred throughout all hours of the day in the Reference case; however, by 2050, the large amounts of added solar capacity cause a surplus of generation in the middle of the day. Because solar has essentially zero variable operating costs, its high midday generation levels cause a large decrease in generation from natural gas-fired combined-cycle plants during these hours, as well as a slight decrease in generation from coal and nuclear plants. Once the solar generation is not available in the evening hours, the other generators ramp back up to meet demand. Batteries are also used to move excess solar generation during the daylight hours into the evening hours when demand is still relatively high.

Figure 15.

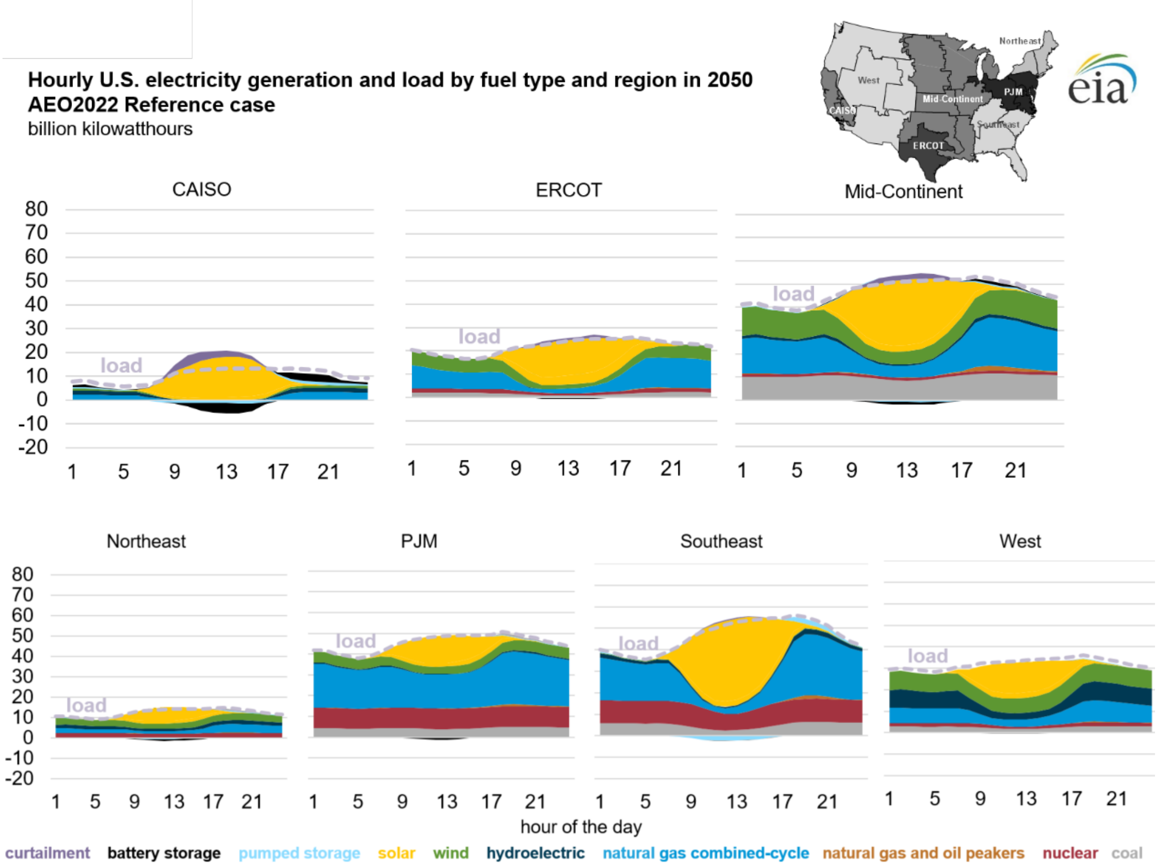


Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case
Note: Negative generation represents charging of energy storage technologies such as pumped hydro and battery storage. Hourly dispatch estimates are illustrative and are developed to determine curtailment and storage operations; final dispatch estimates are developed separately and may differ from total utilization in Figure 15. Solar includes both utility-scale and end-use photovoltaic electricity generation.

When utilities generate more electricity than needed to meet load, the excess energy can either be *curtailed* (not used) by the grid operator or stored. Because solar and wind generators are not dispatchable, curtailment often happens during very sunny and windy periods when energy storage is not economical or available. Only a small percentage of solar and wind generation is curtailed through the projection period in the Reference case. Most curtailment occurs during the winter and shoulder (spring/fall) seasons when demand is low. In the summer months, higher demand in midday hours results in less curtailment.

Daily hourly generation patterns vary widely by season and region, affecting decisions on strategies to support solar generation

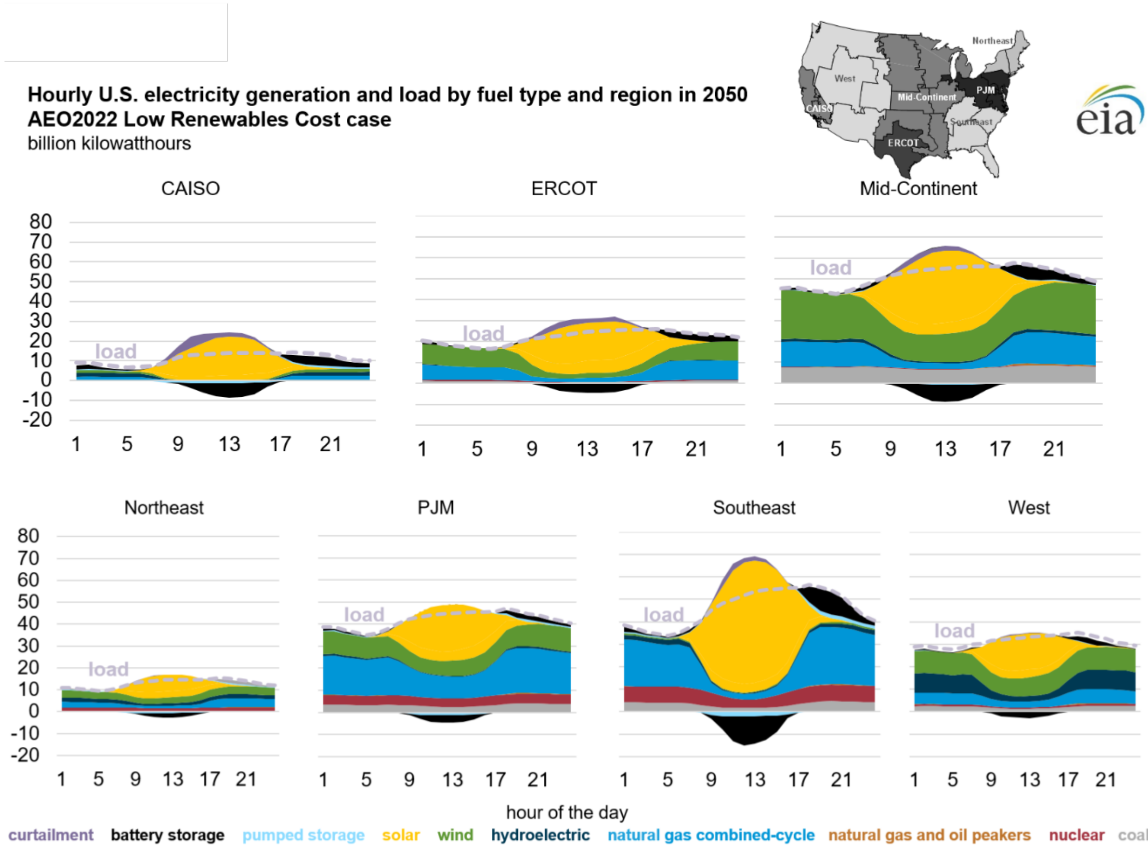
Figure 16.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case
Note: Negative generation represents charging of energy storage technologies such as pumped hydro and battery storage. Hourly dispatch estimates are illustrative and are developed to determine curtailment and storage operations; final dispatch estimates are developed separately and may differ from total utilization in Figure 16. Solar includes both utility-scale and end-use photovoltaic electricity generation.

In the Reference case, by 2050, most projected solar curtailments occur in the California ISO (CAISO), Electric Reliability Council of Texas (ERCOT), and Mid-Continent regions. These regions have a higher percentage of their load met by solar during the afternoon hours than most other regions. The Southeast region also has a relatively large percentage of load met by solar in midday hours, but it has fewer curtailments because its demand profile better coincides with solar generation than the other regions' profiles. Some of the energy that would otherwise be curtailed is used for charging pumped hydro or battery energy storage sites. In the Reference case, most of the electricity provided by battery storage is in CAISO due to the relatively larger proportion of midday solar curtailments and resulting larger price disparity between midday and evening hours. Other regions meet their respective evening ramp periods, when solar generation decreases, with natural gas units.

Figure 17.



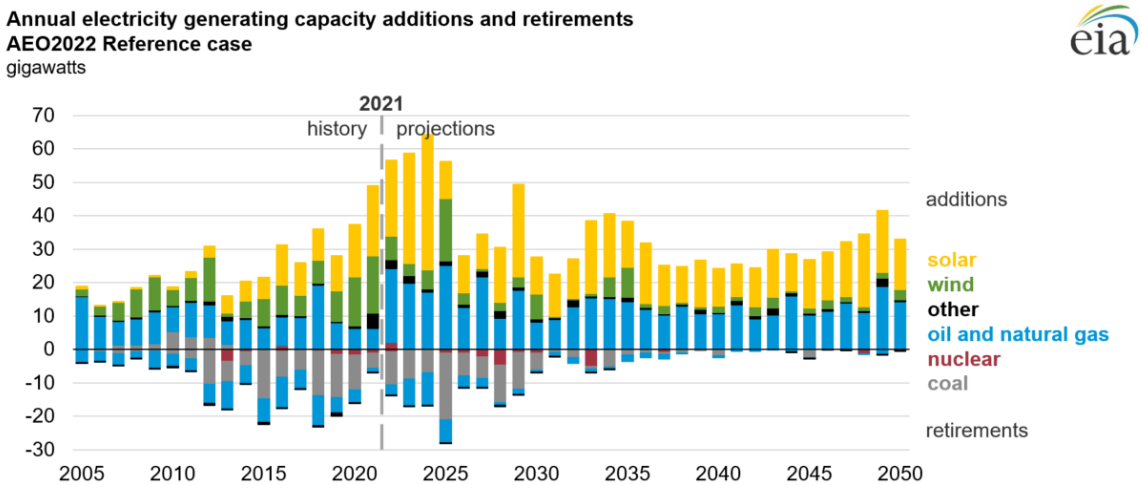
Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Low Renewables Cost case
Note: Negative generation represents charging of energy storage technologies such as pumped hydro and battery storage. Hourly dispatch estimates are illustrative and are developed to determine curtailment and storage operations; final dispatch estimates are developed separately and may differ from total utilization in Figure 17. Solar includes both utility-scale and end-use photovoltaic electricity generation.

In the Low Renewables Cost case, by 2050, lower costs for solar and battery storage signficantly affect the daily hourly electricity generation profiles in all regions. In additon to the CAISO, ERCOT, and Mid-Continent regions, the Southeast region also curtails significant amounts of generation. All regions use much more battery storage than in the Reference case, most notably in the Mid-Continent and Southeast. Use of battery storage in each of these regions surpass CAISO, the region with the largest amount of installed battery capacity in 2021.

As coal and nuclear generating capacity retire, new capacity additions come largely from wind and solar technologies

Renewable technologies account for the majority of the projected capacity additions

Figure 18.

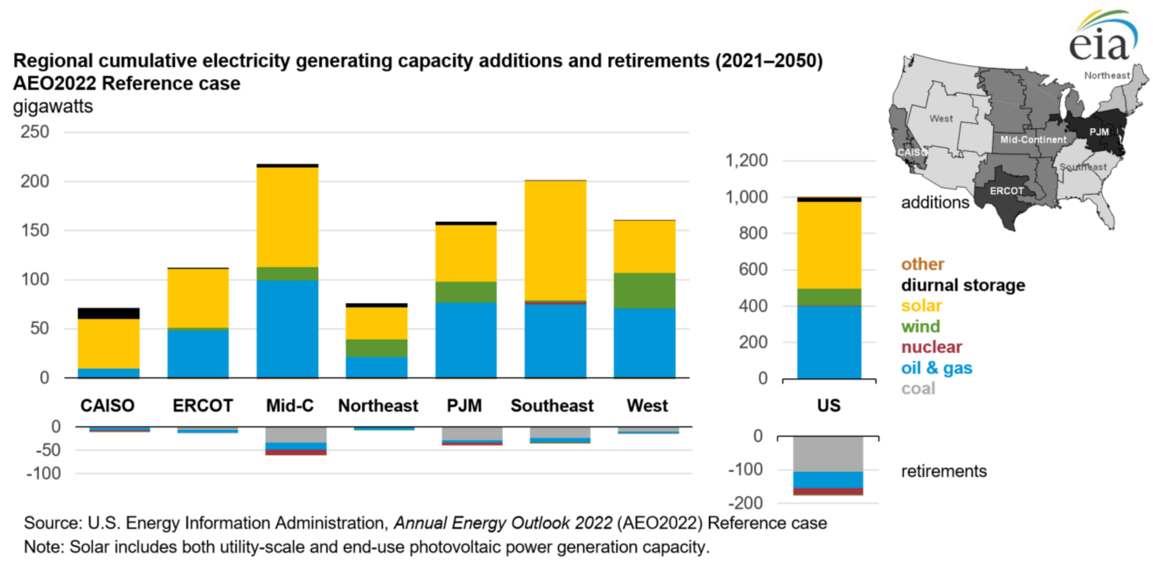


Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case
Note: Solar includes both utility-scale and end-use photovoltaic power generation capacity.

Renewable electric generating technologies account for over 57% of the approximately 1,000 gigawatts (GW) of cumulative capacity additions that we project in the Reference case from 2021 to 2050. This large share is a result of not only declining capital costs, but also continuing legislative incentives, such as state renewable portfolio standard (RPS) targets and the extension of federal and state tax credits. Although wind capacity is added steadily throughout the projection period, much less wind capacity is added than solar. Solar capacity accounts for 47% of electric generating capacity additions, and wind accounts for about 10%. Generating technologies fueled by natural gas make up most of the remaining share of new capacity additions (39%), some of which is used to generate electricity when intermittent wind and solar resources are not available.

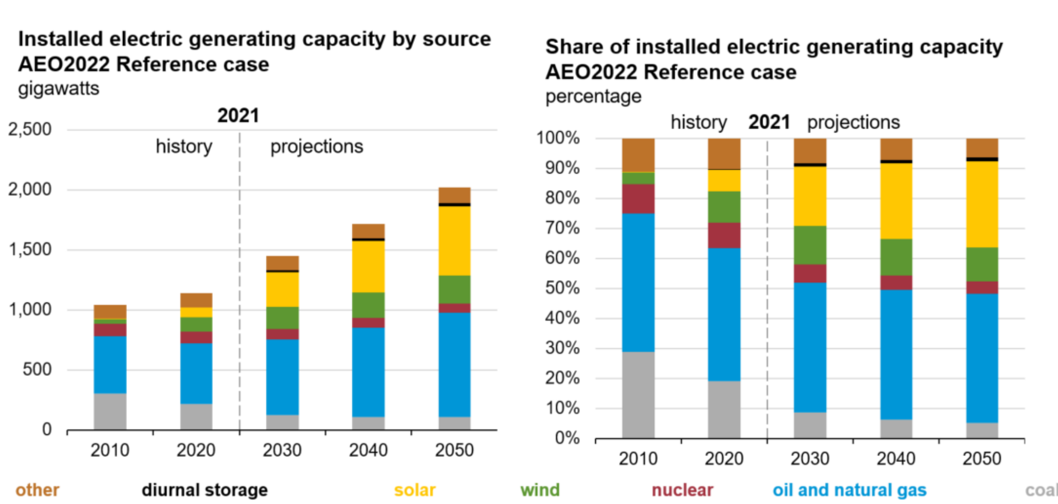
Solar accounts for the majority of U.S. capacity additions in most regions. The majority of coal and nuclear retirements come from the Mid-Continent, PJM, and Southeast regions

Figure 19.



Solar generating capacity grows steadily across all regions of the United States in the Reference case. Some regions build diurnal storage capacity to support larger daily price fluctuations from the solar capacity additions. We project that California will add nearly 13 GW of diurnal storage power capacity through 2050 in the Reference case, compared with 8.4 GW of natural gas-fired generation capacity. PJM and the West are the only regions that add more natural gas capacity than solar capacity, but these regions also show high growth in solar. Cheaper solar and wind energy, accompanied by natural gas-fired plants, replaces coal and nuclear in the Mid-Continent, PJM, and Southeast regions. Solar's share of total U.S. capacity increases from 7% in 2020 to 29% in 2050. About 70% of solar additions are utility-scale PV power plants, and 30% come from end-use PV such as residential and commercial rooftop solar installations.

Figure 20.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case
Note: Solar includes both utility-scale and end-use photovoltaic power generation capacity.

Wind additions are largely tied to policy

The Reference case assumes the production tax credit (PTC) for wind will be available through 2024, following a one-year extension in 2020. Although capital costs for wind continue to decline throughout the projection period, most projected wind additions take advantage of available federal tax credits. Nearly half of cumulative wind capacity additions from 2021 to 2050 occur before the PTC expires for projects coming online after 2025. The steadier pace of solar additions reflects, in part, the continued availability of a 10% investment tax credit (ITC), which has no fixed expiration date after 2026, when the current 30% phases out.

Natural gas continues to have the largest share of fossil fuel capacity additions in all regions

Although renewable electric-generating technologies account for about 60% of cumulative capacity additions throughout the projection period in the Reference case, natural gas-fired capacity accounts for almost the entire remaining balance of additions—about 40% through 2050. These natural gas-fired generator additions are almost evenly split between combined-cycle technologies and combustion turbines, which both provide energy and help balance the intermittent output from wind and solar generators.

Coal-fired generating unit retirements largely take place by 2030

EPA's Affordable Clean Energy (ACE) rule (84 FR 32520) was vacated by the U.S. Court of Appeals for the District of Columbia Circuit on January 19, 2021. This has been incorporated into the Reference case, leading some plants that retired in the AEO2021 Reference case to continue operating past 2025. Despite that development, the Reference case still shows substantial coal plant retirements, most of which take place by 2030. Those retirements are a result of both regulatory measures and market factors. In particular, low natural gas prices in the early years of the projection period contribute to the retirements of coal-fired plants and nuclear plants. Natural gas-fired generation sets power prices in wholesale electricity markets most of the time, and the lower natural gas prices affect the profitability of coal and nuclear units, which have high fixed costs. In addition, owners of many coal-fired plants have announced closings as part of meeting goals to decarbonize their systems.

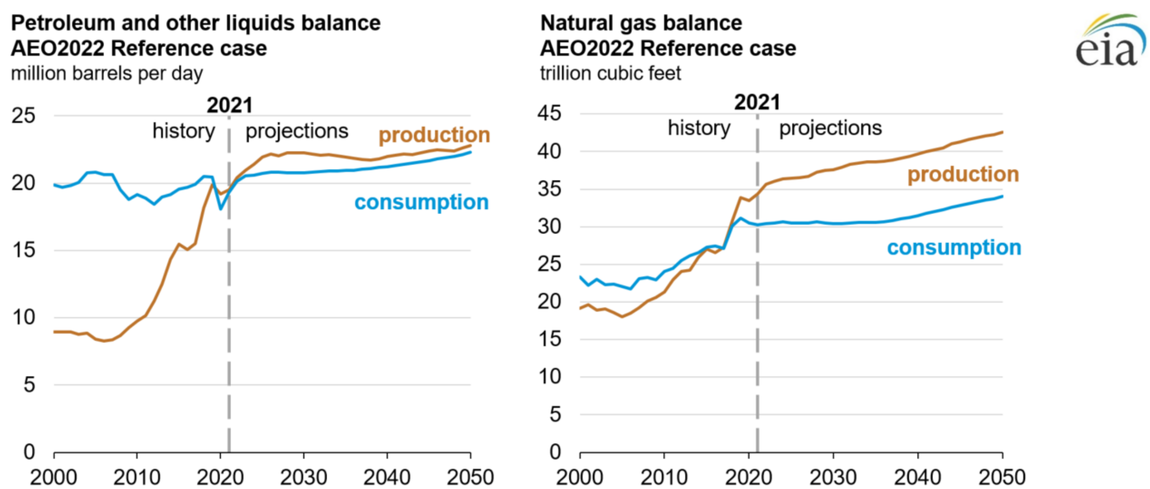
The civil nuclear credit program, passed as part of the Infrastructure Investment and Jobs Act, supports continued use of existing nuclear power facilities. This act, along with several state support programs, provides out-of-market payments that will likely keep reactors in affected regions profitable over the next 5–10 years. We project nuclear capacity retirements to occur after 2030, partially because we assume that these plants will no longer receive those credit payments when the current legislation expires.

Production

U.S. production of natural gas and petroleum and other liquids rises amid growing demand for exports and industrial uses

Oil and natural gas production in the Reference case remains at historically high levels through the projection period

Figure 21.

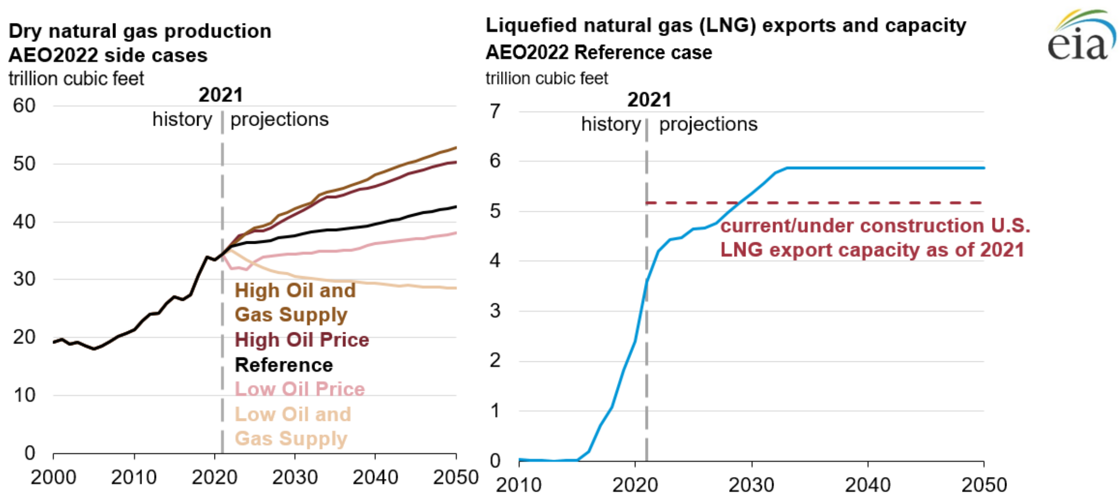


Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

We project U.S. consumption and production of petroleum and other liquids to grow through 2050. Domestic consumption and production levels of petroleum and other liquids remain relatively close to one another through most of the projection period in the Reference case. Consumption increases by 15%, and production increases by 17% from 2021 to 2050. However, consumption and production of specific petroleum products vary. We also project consumption and production of natural gas to grow through 2050. During the projection period, natural gas production grows by almost 24%, approximately twice as fast as consumption. Much of this growth in natural gas production is exported as liquefied natural gas (LNG). By 2050, we project that approximately 25% more natural gas will be produced than consumed in the United States. Together, these Reference case trends highlight the continued growth in demand for U.S. natural gas and petroleum products.

Natural gas exports increase with production, driven by global demand and continued construction of new LNG export facilities

Figure 22.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)

In the Reference case, U.S. natural gas production increases through 2050, and more than 35% of gross additions are exported. U.S. natural gas production increases in all cases except in the Low Oil and Gas Supply case. Projected U.S. natural gas exports rise through 2050, primarily driven by increased LNG capacity and growing global natural gas consumption.[3] Increases in pipeline exports to Mexico and Canada also contribute to the increase in U.S. natural gas exports.

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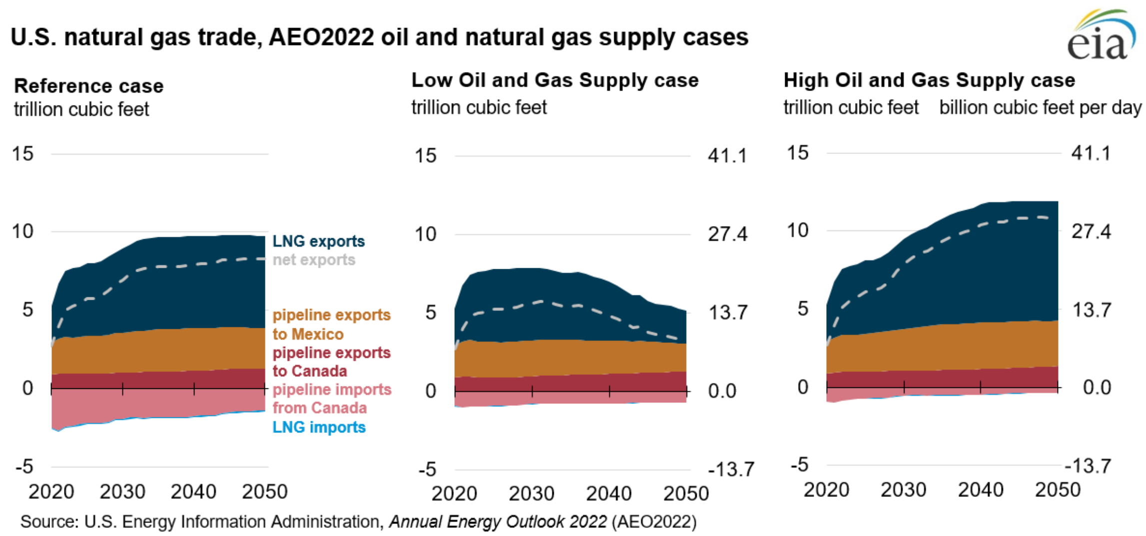
[3] According the our *International Energy Outlook 2021*, we project global natural gas consumption to continue growing through 2050 in absolute terms (and as a share of the world energy mix) because of its economics and lower carbon emissions relative to other sources of energy.

Figure 23.



In 2021, U.S. natural gas exports reached a record high. We project continued growth in natural gas exports through 2025 because of increases in LNG capacity from facilities currently under construction. LNG export facilities at Sabine Pass, Calcasieu Pass, and Golden Pass will likely enter service much earlier than we had anticipated in the AEO2021, increasing the amount of infrastructure available for converting natural gas to LNG for export. Additional completed natural gas pipeline infrastructure will also increase takeaway capacity into Mexico.

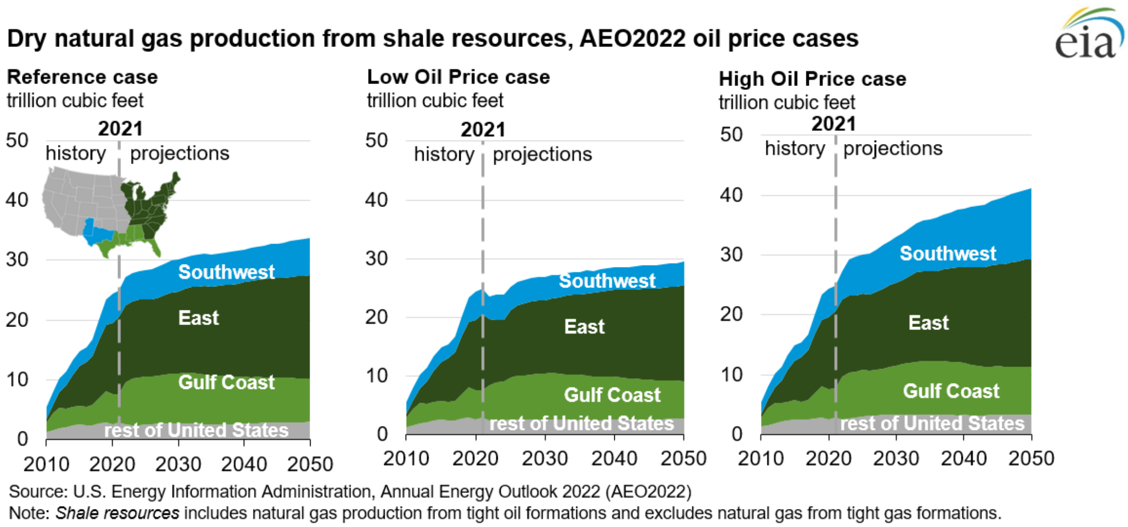
Beyond 2025, we project that natural gas production will ramp up to meet growing export demand, the majority of which will be LNG. We project global demand for U.S. natural gas to exceed current and announced LNG export capacity; therefore, additional LNG export facilities will be economical to build. These LNG capacity expansions, coupled with high demand for natural gas abroad, result in our projection of an increase in LNG exports to 5.86 trillion cubic feet (16.1 Bcf/d) by 2033 in the Reference case, prompting natural gas production growth in the medium and long term.

The oil and gas supply cases illustrate the relationship between LNG exports and production. The Low Oil and Gas Supply case assumes higher costs and less resource availability, which increases natural gas prices, so LNG exports begin to decline in the mid-2030s. In the High Oil and Gas Supply case, which assumes lower natural gas prices, LNG exports grow twice as fast as in the Reference case, leveling off during the mid-2040s.

More than half of projected U.S. natural gas production growth comes from associated natural gas produced from tight oil plays

Shale gas and associated natural gas from tight oil plays are the primary contributors to the long-term growth of U.S. natural gas production through 2050. In the Reference case, more than half of the growth in natural gas production between 2020 and 2050 is associated natural gas from tight oil plays, primarily the Wolfcamp play in the Permian Basin (Southwest region). For shale gas production during this same period, the Marcellus and Utica shale gas plays in the Appalachia Basin (East region) and the Haynesville play in the Mississippi-Louisiana Salt Basins (Gulf Coast region) account for the majority of growth.

Figure 24.

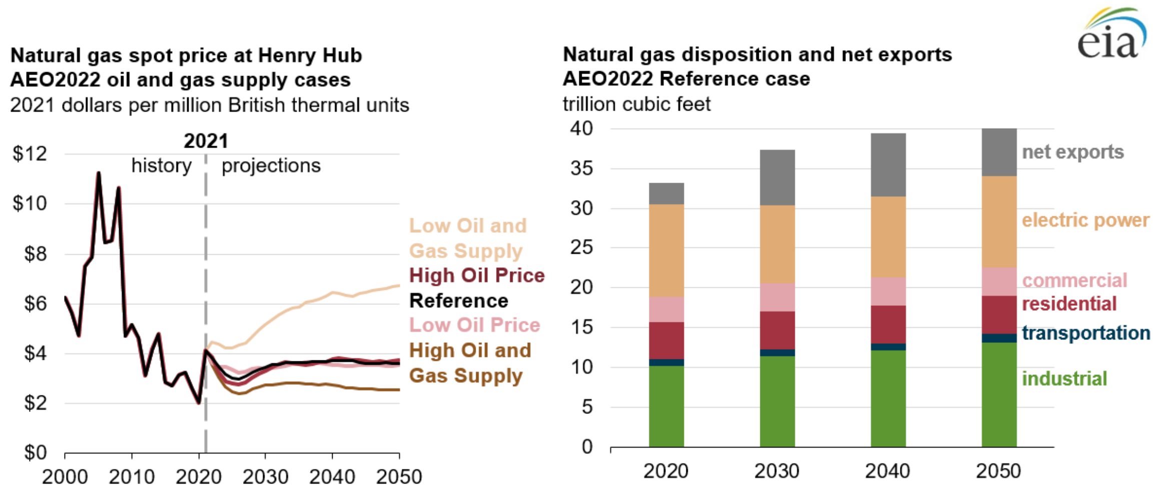


The amount of associated gas that will be available from tight oil plays in our projection is particularly sensitive to world oil price assumptions. Higher world oil prices, such as those in the High Oil Price case, increase the incentive to target oil plays, increasing the projected amount of associated natural gas. The opposite occurs in the Low Oil Price case: LNG exports are largest in the High Oil Price case, which is prompted by growth in production in the Southwest.

We project growth in natural gas production from the Wolfcamp and Haynesville plays, in part, because of these production regions' proximity to LNG export terminals. Natural gas from the Marcellus and Utica plays also reach export markets, but pipeline infrastructure constrains the Appalachia region's access to export terminals. So, natural gas production growth in the Appalachia region is predominantly driven by the region's relatively low production costs.

Despite LNG export growth and increased domestic demand for natural gas, we project that the Henry Hub price will remain below $4/MMBtu throughout the projection period in most cases

Figure 25.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)

Amid growth in LNG exports, the natural gas spot price at the Henry Hub faces upward pressure from the mid-2020s through the early 2040s across all cases except the High Oil and Gas Supply case. Steady growth in natural gas demand in the industrial sector and growing electric power sector demand for natural gas after 2035 also put upward pressure on the Henry Hub price during this time.

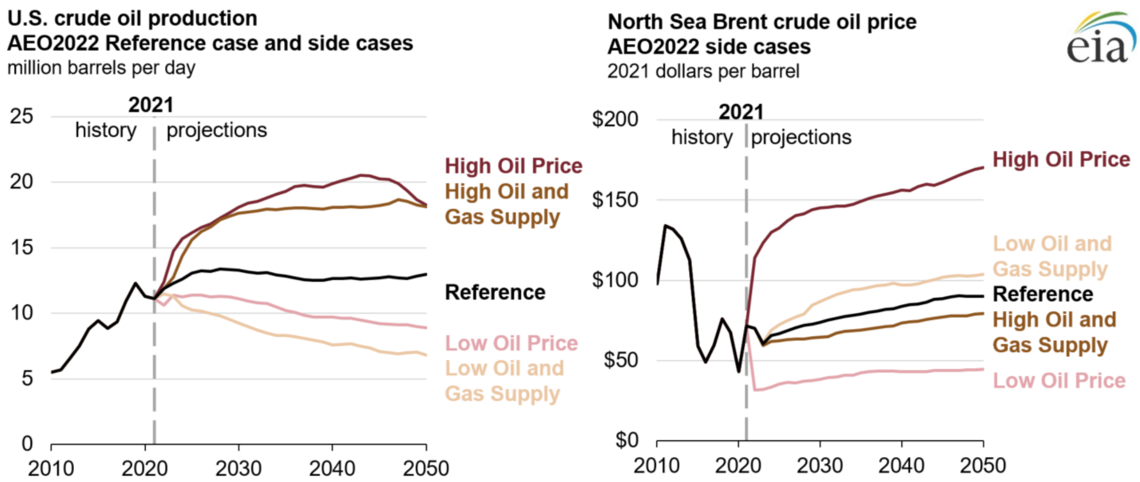
The oil and gas supply cases indicate that the natural gas spot price at Henry Hub is very sensitive to reduced supply and somewhat less sensitive to increased supply. In 2050, the projected natural gas price is almost twice as high in the Low Oil and Gas Supply case as in the Reference case, while in the High Oil and Gas Supply case, the price is approximately 29% lower than in the Reference case.

Driven by rising prices, U.S. crude oil production in the Reference case returns to pre-pandemic levels in 2023 and stabilizes over the long term

Projected U.S. crude oil production in the Reference case peaks in the late 2020s and remains near that peak through 2050

During 2021, crude oil production did not grow, even as benchmark prices increased substantially. However, as the global economy returns to pre-pandemic levels, we project that both demand and prices will remain elevated, resulting in crude oil production reaching pre-pandemic levels in the medium term.

Figure 26.

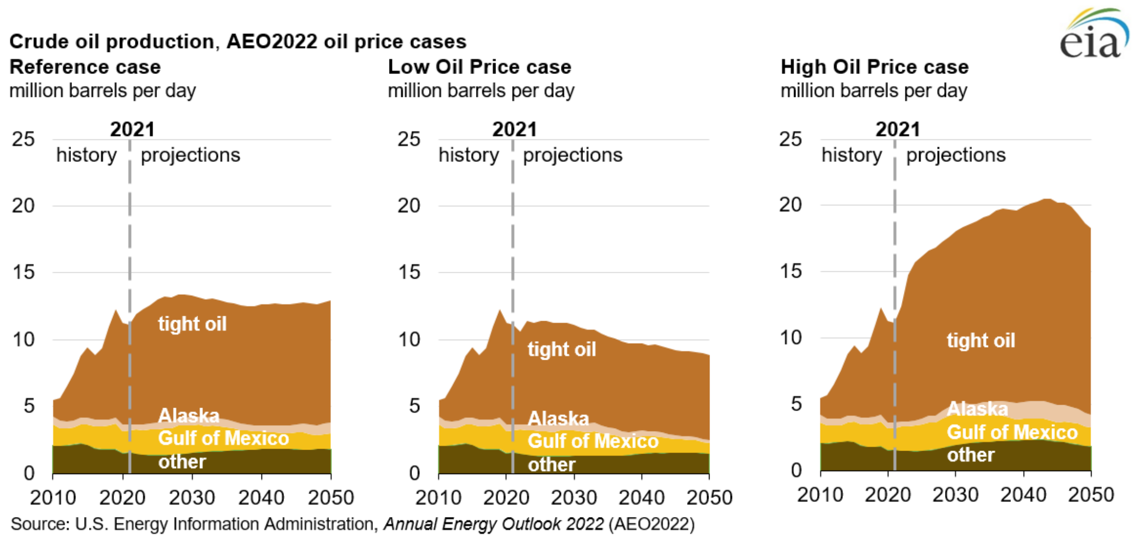


Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)

In the AEO2022, crude oil prices primarily drive drilling activity and crude oil production. In the Reference case, crude oil production returns to pre-pandemic levels in 2023 and peaks in the late 2020s. Production then remains relatively flat through 2050. The Reference case projects that prices are high enough to maintain investment at steady crude oil production levels but not high enough to elicit increasing volumes from those levels of investment. The production path involves many factors, including the amount of investment, technology change, costs of operations, and quality of resource geology.

The side cases illustrate how crude oil production responds to changing market conditions. Our analysis indicates that higher prices, such as those found in the High Oil Price case, projects more production, while the Low Oil Price case projects less production. In the High Oil and Gas Supply case, crude oil production increases by up to 40% from the Reference case, while in the Low Oil and Gas Supply case, crude oil production is almost 47% lower in 2050.

Figure 27.

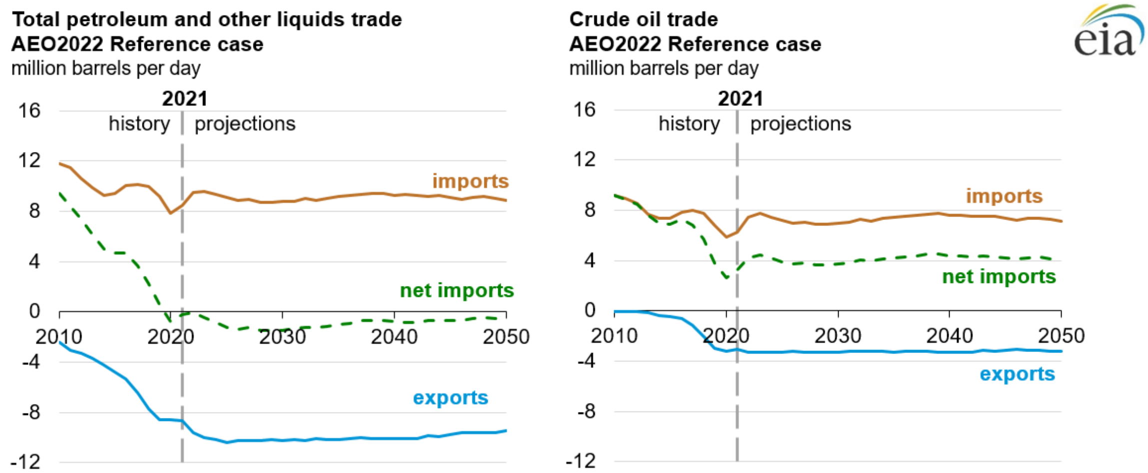


The majority of new U.S. crude oil production comes from tight oil resources. The Wolfcamp play in the Permian Basin (Southwest region) and the Bakken play in the Williston Basin (Northern Great Plains region) lead the growth in U.S. tight oil production. However, estimates of technically recoverable tight or shale crude oil resources are uncertain. The high and low price cases demonstrate the sensitivity of crude oil production to higher and lower oil prices, including tight oil. In the High Oil Price case, high crude oil prices improve the economics of drilling particularly in tight oil formations, resulting in generally increasing domestic production through most of the projection period before declining as drilling moves to less productive areas. The Low Oil Price case results in generally decreasing U.S. crude oil production because of the lack of economic incentive for producers to drill.

U.S. crude oil net imports remain relatively flat over the long run

Although U.S. crude oil production and refinery throughput was less in 2021 than in 2019, crude oil exports have mostly increased in response to growing international demand. Throughout the projection period, from 2021 through 2050, crude oil exports remain near their projected peak, and they remain fairly stable in both gross terms and as a percentage of total domestic crude oil production, according to the Reference case. Projected crude oil imports, meanwhile, rise to pre-pandemic levels by 2023 in the Reference case, and then they remain relatively flat through 2050. We project that the United States will remain a net exporter of petroleum products through 2050 as net petroleum product exports remain mostly flat through the projection period.

Figure 28.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

Refinery closures lower domestic crude oil distillation operating capacity, but refinery utilization rates remain flat over the long term

A number of U.S. refineries have closed over the last two years as a result of pandemic-related demand decreases or conversion to renewable diesel production

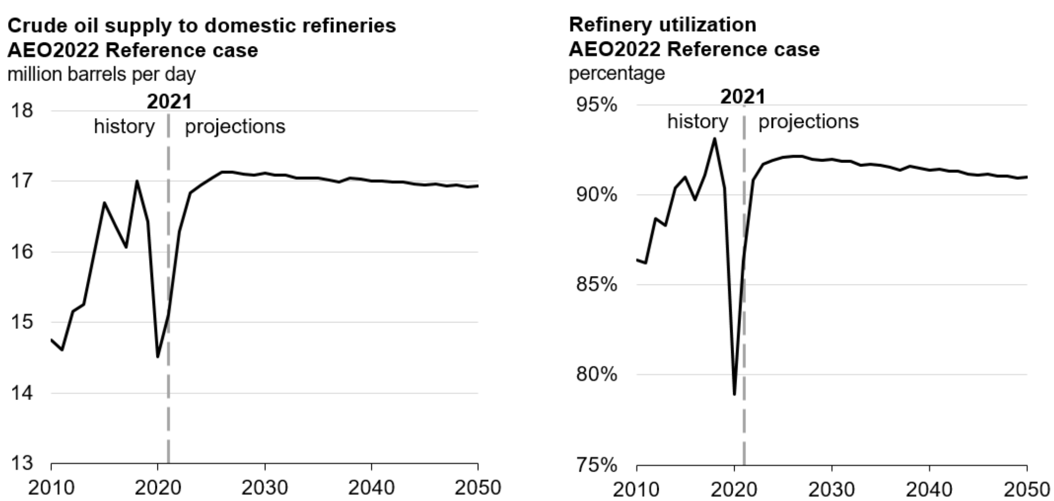
Between 2020 and 2021, six U.S. refineries closed, totaling 750,000 barrels per day (b/d) of total capacity:

- The Western Refining refinery in Gallup, New Mexico
- The Tesoro (Marathon) refinery in Martinez, California
- The Dakota Prairie refinery in Dickinson, North Dakota
- The HollyFrontier refinery in Cheyenne, Wyoming
- The Shell refinery in Convent, Louisiana
- Philadelphia Energy Solutions in Philadelphia, Pennsylvania

Some of these closures are related to decreased demand caused by responses to the global pandemic. However, other refineries, such as HollyFrontier in Cheyenne, Wyoming, and the Dakota Prairie refinery in Dickinson, North Dakota, are converting to produce renewable diesel. Cumulatively, these closures have reduced national crude oil distillation operating capacity by approximately 3.5%.

Refinery utilization rates remain stable over the long run in response to diminished demand

Figure 29.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

Despite the recent reduction in refinery capacity, we project that refinery utilization and throughput (the amount of crude oil processed at refineries) will remain relatively flat over the projection period. The refinery utilization rate (represented as a percentage) measures the volume of gross refinery inputs divided by the total operable crude oil distillation capacity. If capacity declines and utilization remains the same, production of petroleum products declines. We project that utilization rates will return to near historical averages in 2022, but it will not be cost-effective for refineries to make up for lost capacity by increasing utilization beyond this point. As a result of lower capacity and stable utilization, we expect total production of refined products to remain below peak levels over the long run.

Consumption of renewable diesel increases as a share of the domestic fuel mix

The share of renewable diesel in the biomass-based diesel market increases

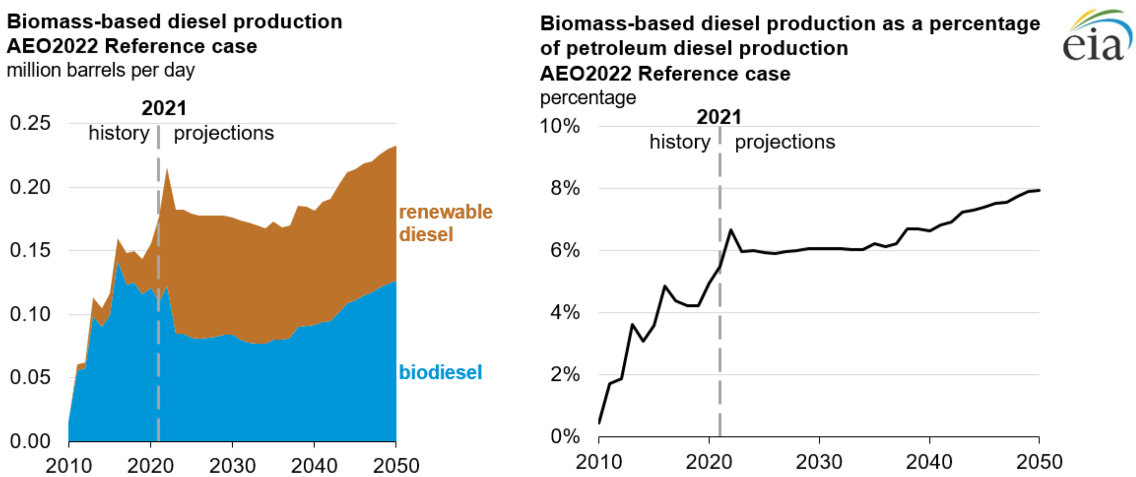
Although biodiesel has historically been the predominant biomass-based diesel fuel produced in the United States, we project a shift toward renewable diesel capacity in the medium to long term.

Biomass-based diesel fuels are fuels produced from biomass, such as waste fats and oils. These fuels are predominately used in diesel engines, but they can also be used as heating fuels.

Biomass-based diesel includes biodiesel and renewable diesel. Renewable diesel is chemically indistinguishable from petroleum diesel, meaning that it meets specifications for use in existing infrastructure and diesel engines. Biodiesel is a mixture of chemical compounds known as alkyl esters and is often combined with petroleum diesel in blends of 5% to 20%, known as B5 to B20, respectively. Renewable diesel is not subject to any blending limitations.

Renewable diesel's growth is a result of its fungibility, along with higher state and federal targets for renewable fuel production, favorable tax credits, and the conversion of existing petroleum refineries into renewable diesel refineries. These targets and incentives include the Renewable Fuel Standard, the California Low-Carbon Fuel Standard, and the U.S. biomass-based diesel blender credit, which applies through 2022 and allows qualified taxpayers to claim a credit of $1.00 per gallon for biodiesel or renewable diesel blended with petroleum diesel. In response to the improved economics of renewable diesel, capacity has increased in the form of new stand-alone facilities and converted petroleum refineries.

Figure 30.

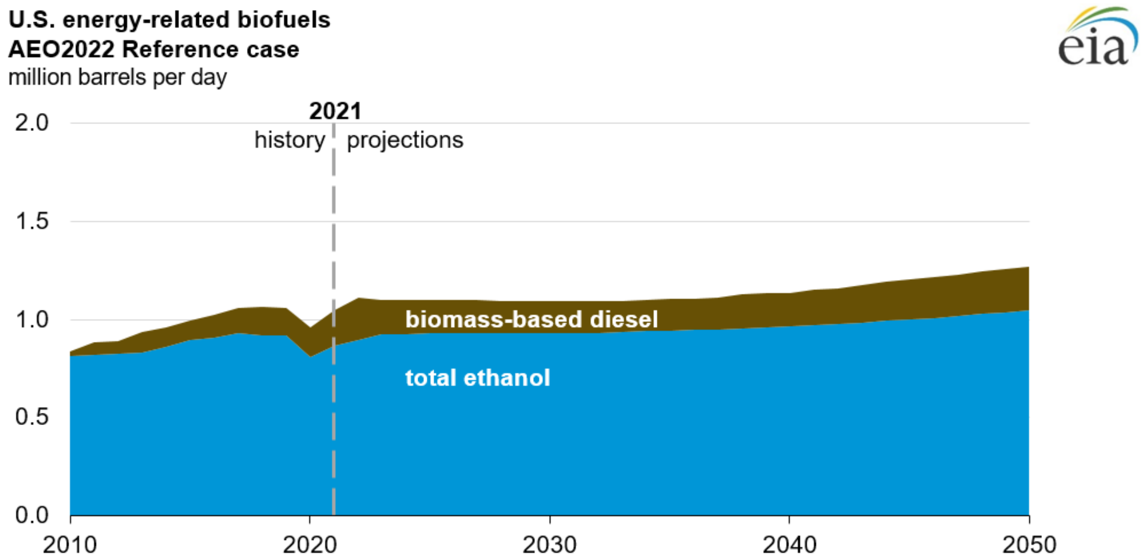


Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

The current market for biomass-based diesel fuels is constrained by a combination of capacity, feedstock availability, and economics. Because the market penetration for biomass-based diesel fuels is limited by market demand, and renewable diesel and biodiesel compete for the same feedstocks, growth in renewable diesel comes partially at the expense of new biodiesel capacity. In the Reference case, the renewable diesel supply is supported by imported renewable diesel and remains higher than biodiesel supply through 2050.

Biomass-based fuels remain a small but important part of the total fuel mix

Figure 31.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

Biomass-based diesel fuels remain a relatively small part of the total diesel market, contributing less than 8% of the total supply in 2050. By comparison, current ethanol consumption as energy in the United States approaches almost 1 million b/d in 2050, almost five times the quantity of biomass-based diesel. So, much more ethanol is consumed as energy than biomass-based diesel fuels because almost all finished motor gasoline sold in the United States is blended with 10% ethanol (E10). However, despite higher blend ratios, future growth of U.S. ethanol consumption as energy is constrained near current levels through 2050 by declining motor gasoline consumption. Renewable diesel, however, does not need to be blended, and biomass-based fuels continue to attract interest and investment because they represent a potential pathway for reducing carbon emissions in the transportation sector and provide an alternative fuel source to petroleum-based diesel fuel. We project that biomass-based diesel will continue to be a growing, but fractional, part of the total diesel fuel mix in the long term.