Taking Stock 2021: Technical Appendix

This document provides additional detail on the methods and data sources used in Rhodium Group's Taking Stock 2021 report. Direct access to all energy and emissions results from our Taking Stock 2021 baselines—including results broken down by gas and sector for all 50 US states through 2035—is available via the ClimateDeck. All historical greenhouse gas (GHG) emissions and removal estimates (1990-2019) come directly from the 2021 Environmental Protection Agency (EPA) Greenhouse Gas Inventory. Like the EPA inventory, all gases are reported in carbon dioxide (CO_2)-equivalent emissions based on the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4) 100-year global warming potential (GWP) values. To model potential future emissions scenarios, we use RHG-NEMS, a modified version of the detailed National Energy Modeling System. NEMS is developed and used by the Energy Information Administration (EIA) to produce its Annual Energy Outlook 2021 (AEO2021). We make several modifications in RHG-NEMS and project impacts for all sectors of the US economy and six key greenhouse gas categories.

Energy Market, Technology and Economic Assumptions

To construct our national Taking Stock GHG projection range, we revised multiple energy market, technology cost, policy, and behavioral assumptions in RHG-NEMS to be consistent with the most recent research and to reflect the range of market and economic uncertainties. Each year these assumptions are updated to reflect the best available data and information.

Unless otherwise stated below, we use EIA's AEO2021 Reference case assumptions in our Taking Stock projections.

Sources of Uncertainty

To construct the full range of emission projections in Taking Stock we looked at three key sources of uncertainty:

- Energy Markets: We consider a range of energy market variables that shape emissions outcomes, including natural gas and oil resource availability and prices.
- Technology Cost and Performance: We estimate ranges for key technology cost and performance variables, including capital and operating costs for clean electricity generators and battery costs for light-duty electric vehicles (EVs).
- Economic: Our emissions range is bounded by a high and a low economic growth scenario.

RHG-NEMS Inputs That are Consistent Across the Emissions Outlook

We make several revisions to input assumptions beyond EIA's AEO2021 Reference case that are consistent across our Taking Stock emissions range. The key revisions are described below.

- Announced power plant retirements and additions: We incorporate all announced coal and nuclear power plant retirements through 2030. Announced coal retirements are informed by coal plant data tracked by the Sierra Club. We account for recent state-level policy actions that will allow for continued operation of certain nuclear power plants in those states.
- Electric vehicle availability and uptake: We revise the year that several classes of light-duty electric vehicles are first available on the basis of recent automaker announcements. We also revise key

parameters to reflect recent historical EV sales as well as expectations relating to ongoing EV research and development and industry investment.

- Electric vehicle charging costs: We alter fuel costs for electric vehicles to reflect current charging behavior.

- Automated vehicle deployment: RHG-NEMs does not capture the impact of autonomous transportation technologies for personal vehicle use.

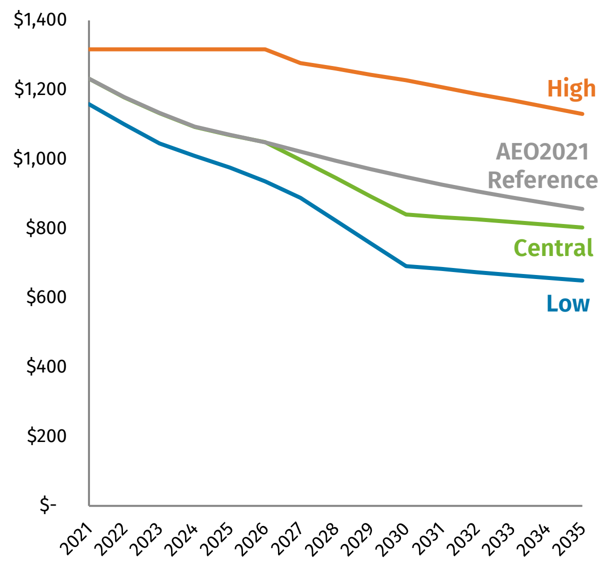
RHG-NEMS Inputs That Vary to Capture Energy Market and Technology Uncertainty

Below are the key assumptions that vary across our estimated emission range and underlying data sources. For each input, we defined a central, low and high case to reflect a range of potential market and technology cost outcomes. Charts are provided for select assumptions.

Electric generating technology costs: We generally assume capital costs for utility-scale and distributed solar photovoltaic, land-based and off-shore wind, and utility scale energy storage decline according to NREL's 2020 Annual Technology Baseline's (ATB) technology cost projections. Our central cost assumptions follow ATB's Moderate Technology Innovation Scenario, while our low- and high-cost assumptions follow the Advanced Scenario and Conservative Scenario, respectively. For onshore wind and utility-scale solar photovoltaic technologies, we retain EIA's mid, low and high cost assumptions in the early 2020s, since these cost assumptions are based on slightly different technologies than the ATB and are better aligned with technological performance during those early years. However, the ATB captures technology improvements that result in long-term aggressive cost declines, so we transition to ATB costs starting in the late 2020s.

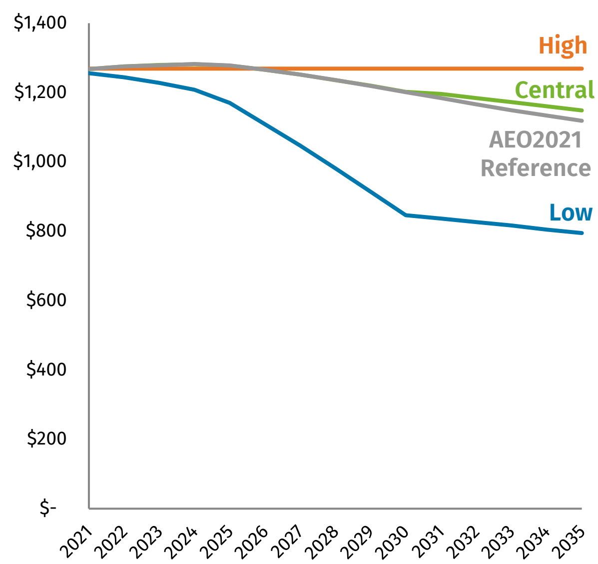
We also change relevant cost and performance parameters for power generating facilities equipped with carbon capture technology, informed by Rhodium analysis and current literature. Of particular note are revisions to costs for new-build natural gas plants with carbon capture. We adapt work from the National Energy Technology Laboratory, which details cost and performance for natural gas-fueled direct supercritical CO_2-fired power plants.

FIGURE 1
Utility-scale solar photovoltaic overnight capital costs
2020 dollars per kilowatt



Source: Rhodium Group, NREL, EIA

FIGURE 2
Land-based wind overnight capital costs
2020 dollars per kilowatt

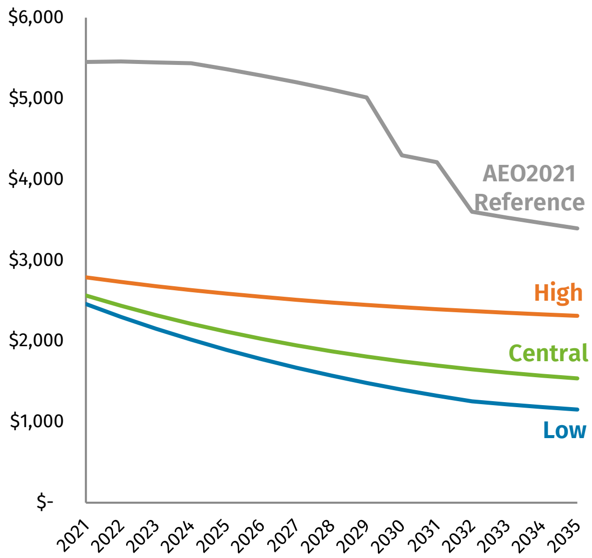


Source: Rhodium Group, NREL, EIA

FIGURE 3

Offshore wind overnight capital costs

2020 dollars per kilowatt

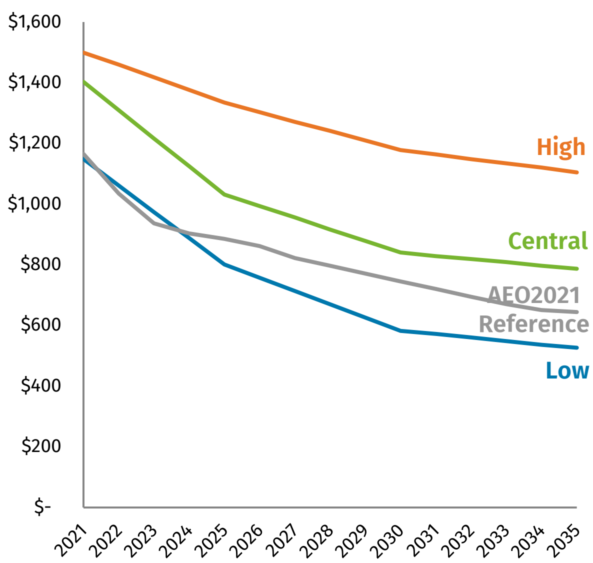


Source: Rhodium Group, NREL, EIA

FIGURE 4

Utility-scale energy storage overnight capital costs

2020 dollars per kilowatt

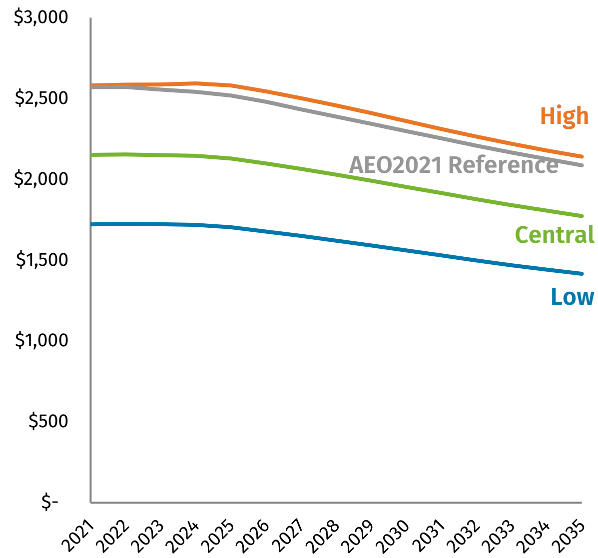


Source: Rhodium Group, NREL, EIA

FIGURE 5

Natural gas with CCS overnight capital costs

2020 dollars per kilowatt

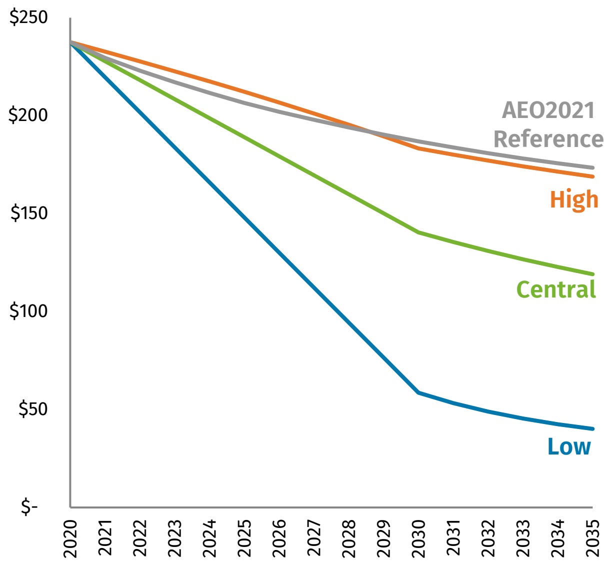


Source: Rhodium Group, NETL, EIA

Electric vehicle battery costs: For light-duty electric vehicle (EV) battery costs, we draw on the Rapid Advancement case from the National Renewable Energy Laboratory's (NREL) Electrification Futures Study (EFS) for our central case and BNEF projections for our low-cost case. In our high-cost case, we assume annual cost reductions are 50% slower than the central case. We assume battery costs for the suite of light-duty EV technologies modeled in NEMS[1] match these reduction pathways, though each starts at a different current price.

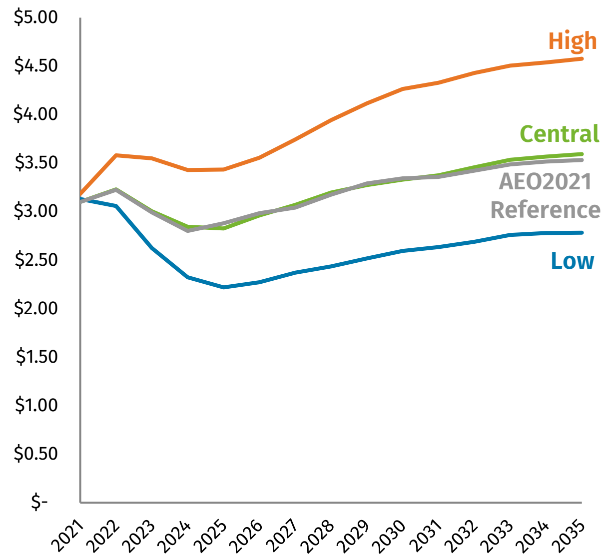
[1] EV technologies modeled in NEMs include EV100- and 200-mile range, plug-in hybrid 10 and 40-mile range, diesel hybrid, fuel cell methanol, fuel cell hydrogen, and gasoline hybrid.

FIGURE 6
Battery costs for 300-mile electric vehicles
2020 dollars per kilowatt-hour



Source: Rhodium Group, BNEF, NREL, EIA

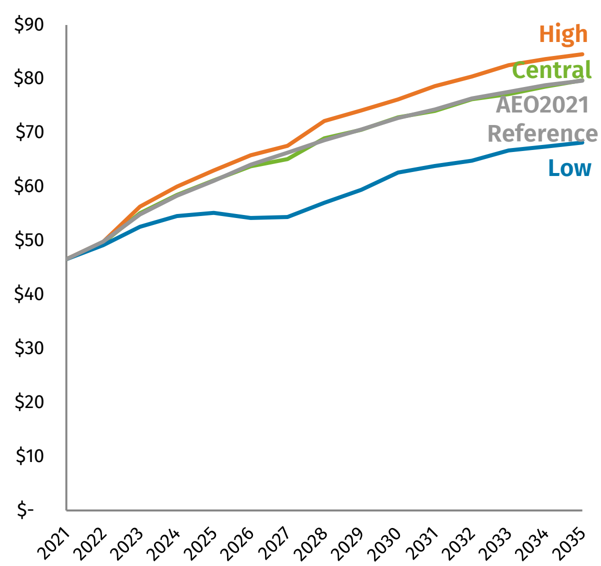
FIGURE 7
Natural gas spot price at Henry Hub
2020 dollars per million Btu



Source: Rhodium Group, EIA

Natural gas and oil resource and prices: For our central cost case we use the oil and natural gas resource and prices reflected in the AEO2021 reference case. In this case, natural gas averages $3.20/MMBtu through 2035 at Henry Hub, and Brent crude rises from $45/barrel in 2021 to $80/barrel in 2035. In our low cost case, we use the oil natural gas resource and prices reflected in the AEO2021 high oil and gas supply side case. The resulting average natural gas price is $2.60/MMBtu through 2035, and Brent crude reaches $68 per barrel in 2035. For our high cost case, we modify EIA's low oil and gas supply side case to reflect a less-constrained resource space than EIA models. This results in lower fossil production and higher prices than those projected in our central cost case, but higher production and lower prices than EIA's low oil and gas supply case. Natural gas prices in our high cost case average $4.00/MMBtu through 2035, while Brent crude rises to $85/barrel in 2035.

FIGURE 8
Brent Crude oil spot price
2020 dollars per barrel



Source: Rhodium Group, EIA

Industrial carbon capture costs: Rhodium has developed the Industrial Carbon Abatement Platform (ICAP) to assess technology deployment and emissions abatement potential in the industrial sector under a variety of scenarios. Using ICAP, we project future carbon capture retrofits at existing industrial facilities under low, medium, and high CCS cost assumptions. ICAP is integrated with the rest of RHG-NEMS such that industrial facilities see dynamic energy costs and expected revenue from CO_2 sales.

RHG-NEMS Inputs That Vary to Capture Macroeconomic Uncertainty

We model a range of future economic growth scenarios to capture the emissions impact of uncertainty in the annual growth rate of the US economy. Our baseline economic assumptions deliver a 2.4% real annual rate of growth, on average, through 2035. In our low economic growth case we model a 1.7% average annual economic growth rate through 2035 to capture the downward pressure on emissions that could arise if the economy grows at a slower rate coming out of the COVID 19 pandemic. We assume a higher 2.9% annual average growth rate in our high economic growth case, to capture the emissions impact of sustained bullish economic growth. The assumptions for the central, low and high macroeconomic growth cases match those of the AEO2021 Low, Reference, and High Macroeconomic Growth side cases, respectively.

Federal and State Policy Assumptions

Our scenarios include emission reductions from all existing federal and state policies "on the books" as of May 2021. To remain consistent with United Nations (UN) guidelines for reporting the impact of "current measures," we include only policies that have been finalized and adopted. We do not include aspirational goals or economy wide targets that have not been solidified in specific, actionable policy, nor do we explicitly include specific city-level or corporate commitments.

CO_2 Policies

Electric Power: The following national policies are reflected in our analysis: renewable energy and nuclear tax incentives in place as of May 2021, phased out based on their current statutory schedules. We also include the tax credit for carbon oxide sequestration (45Q) as amended in December 2020. We reflect the judicial vacation of the Affordable Clean Energy (ACE) rule. State and regional cap-and-trade programs, Renewable Portfolio Standards (RPS), Clean Energy Standards (CES), and zero-emission credit programs are all included. We also include state offshore wind and energy storage mandates. We incorporate all announced power plant additions and retirements through 2030 as of May 2021.

Transportation: We include the federal Renewable Fuels Standard, medium and heavy-duty vehicle GHG emissions standards, and state and federal electric vehicle incentives. All state zero-emission vehicle (ZEV) mandates and low-carbon fuel standards adopted as of May 2021 are also included. California's Advanced Clean Truck regulation (requiring 100% zero emission truck sales by 2045) and the Innovative Clean Transit regulation (requiring 100% zero emission bus sales by 2040) are also included. Additional states have announced their intention to follow California's ZEV commitments for trucks, and a number of states have set 100% ZEV sales goals in the light-duty sector. However, these are excluded from our baselines as they have yet to be finalized and adopted.

We assume light-duty Corporate Average Fuel Economy (CAFE) standards increase 1.5% annually from model year 2021 to 2026, reflecting the Trump Administration Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule finalized in February 2020, which replaces Obama-era standards. In August 2020, California finalized deals with five automakers (Ford, VW, Honda, BMW, and Volvo) committing to improve their US light-duty vehicle fuel economy 3.7% annually from 2022 to 2026. We apply this increased fuel economy to these automakers' US passenger vehicle sales.

Industry and Buildings: We include current federal minimum energy conservation standards for appliances and equipment. We also include the tax credit for carbon oxide sequestration (45Q) as amended in December 2020. State energy efficiency programs are implicitly captured in RHG-NEMS electric demand projections.

Carbon Pricing: We include the California Cap-and-Trade Program and the Regional Greenhouse Gas Initiative (RGGI), which prices electricity sector carbon emissions from 11 states. We exclude the Transportation and Climate Initiative (TCI), which was not finalized by May 2021, and the Washington Climate Commitment Act (CCA), which directs policymakers to design an economy-wide Cap-and-Trade Program to be implemented in 2023.

Non-CO_2 Policies

Methane: We assume the reinstatement of the 2012 and 2016 Oil and Natural Gas New Source Performance Standards that regulate methane emissions from the oil and gas industry. This follows a Congressional Review Act vote, subsequently signed by President Biden, to invalidate the Trump administration's Review Rule, which rolled back some of the Obama-era rules. We assume the 2016 Bureau of Land Management regulations to prevent waste of natural gas from venting, flaring and leaks on public lands—undone by the Trump administration—remains rolled back. We assume emission reductions from EPA's 2016 updated NSPS and Emission Guidelines for methane from municipal solid waste landfills rules are delayed—with enforcement starting in 2021 rather than 2016—to reflect the EPA's May 2021 update to the Obama-era rule. The following state policies are also reflected: oil and gas standards in California, Colorado, Pennsylvania, New Mexico, Ohio, Utah, and Wyoming; and California's landfill methane control measures from 2010 and updated in 2017. All estimates associated with federal and state oil and gas rules are based on modeled estimates from the Clean Air Task Force that align with oil and gas production from each of our scenarios. For landfills, we used emission reduction estimates from EPA and California's Air Resources Board.

Hydrofluorocarbons (HFCs): In all our scenarios we assume a phasedown in the production and consumption of HFCs in line with the Kigali Amendment of the Montreal Protocol, consistent with the American Innovation and Manufacturing (AIM) Act of December 2020. We reflect emission reductions from all existing state rules, including California, Colorado, Delaware, Massachusetts, Maryland, New Jersey, New York, Vermont, Virginia, and Washington's HFC control regulations. We model HFC emissions based on the California Air Resources Board's Short-Lived Climate Pollutant assessment tool, which estimates potential national and state-level HFC emission pathways associated with a range of federal and state policies.

TABLE 1

Federal and state policies included in Taking Stock 2021 baselines

Sector	Federal Policy	State Policy	State
Power			
	Renewable energy tax incentives as amended in December 2020, phased out based on their statutory schedules	Renewables Portfolio Standard (RPS)	AZ CA CO CT DE DC HI IL IA ME MD MA MI MN MO MT NV NH NJ NM NY NC OH OR PA RI TX VT VA WA WI
	Tax credit for carbon dioxide sequestration as amended in December 2020 (45Q)	Offshore Wind Mandates	CT MA MD ME NJ NY RI VA
	Judicial vacation of the Affordable Clean Energy (ACE) rule	Nuclear Zero Emission Credit (ZEC) Programs	CT IL NJ NY OH
	Cross-State Air Pollution Rules (CSAPR)	Energy Storage Mandates	CA MA NV NJ NY OR VA
	Mercury and Toxics Standards (MATS)		
	New Source Review (NSR)		
Transportation			
	The Safer Affordable Fuel-Efficient (SAFE) Vehicles rule Alternative Fuel Vehicle Tax Credits	California's Framework Agreements on Clean Cars with automakers	CA CO CT DE ME MA MD NJ NY OR PA RI VT WA
	Renewable Fuel Standard (RFS) GHG and fuel consumption standards for heavy-duty vehicles	California Light Duty Vehicle Zero Emission Vehicle (ZEV) Program	CA CO CT ME MD MA NJ NY OR RI VT WA

	Plug-in Electric Drive Vehicle (PEV) tax credit Tier 3 Motor Vehicle Emission and Fuel Standards Program International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI	Low Carbon Fuel Standard (LCFS) Medium and Heavy-Duty ZEV Policy State electric, hybrid, and alternative-fuel vehicle tax and other incentives Zero Emission Bus Mandate	CA OR WA CA AR AK CA CO CT DE DC FL GA HI ID IL LA MD MA MI MO MT NV NJ NY NC OH OR PA RI TN TX UT VA WA WI CA
Industry and Buildings	Federal minimum energy conservation standards for appliances and equipment Tax credit for carbon dioxide sequestration (45Q) as amended in December 2020 Clean Air Act Amendments of 1990 emission requirements for industrial processes	Energy Efficiency Resource Standards (EERS)	AK AZ CA CO CT DC HI IA IL LA MA MD ME MI MN MO MS NC NH NV NJ NM NY OH OR PA RI TX UT VA VT WA WI
Hydrofluorocarbons (HFCs)	Phasedown in the production and consumption of HFCs in line with the Kigali Amendment of the Montreal Protocol, consistent with the American Innovation and Manufacturing (AIM) Act of December 2020	State HFC phasedowns and management programs	CA CO DE MA MD NJ NY VA VT WA

Methane			
	Reversal of Trump-era amendments to EPA's 2012 and 2016 Oil and Gas New Source Performance Standards	State oil and gas standards	CA CO NM OH PA UT WY
	EPA Municipal Solid Waste landfill methane rule	Landfill methane regulation (LMR) and SB1383 agricultural methane targets	CA
Carbon Pricing			
		Cap and Trade Program	CA
		Regional Greenhouse Gas Initiative (RGGI)	CT DE ME MD MA NH NJ NY RI VT VA

This list is not exhaustive, but rather reflects the most meaningful state and federal policies included in our projections.

Projection and 50-state downscaling methodology

Carbon Dioxide Emissions

Projected CO_2 emissions from all energy use in RHG-NEMS are inconsistent with EPA's accounting conventions for CO_2 from fossil-fuel combustion in its GHG inventory. To address this inconsistency, we make the following adjustments to RHG-NEMS output to generate a forecast for CO_2 from fossil-fuel combustion:

- International bunker fuels: Emissions from fuel combustion by ships and airplanes that depart from or arrive in the US from international destinations are not included in EPA's inventory of total US emissions nor are they counted in US climate targets. However, they are included in RHG-NEMS CO_2 output. We subtract these emissions from our projections.

- Industrial non-energy use of fuels: Fossil fuels are used as feedstocks in the manufacture of a variety of products such as steel and chemicals. Generally, EPA accounts for CO_2 emissions generated by consumption of these feedstocks in the industrial processes categories of the GHG inventory, not under fossil-fuel combustion CO_2. We subtract CO_2 emissions from non-energy uses of CO_2 from our fossil-fuel combustion projections and account for non-energy use of fuels and feedstocks elsewhere.

- Transportation non-energy use of fuels: A small amount of petroleum fuel used in the transportation sector (largely for lubricants) is not combusted but generates CO_2 emissions through its usage. We subtract this amount from projections of petroleum CO_2 emissions in the transportation sector and account for them elsewhere as non-energy use of fuels.

RHG-NEMS does not provide an Intergovernmental Panel on Climate Change (IPCC) consistent projection output for non-fossil fuel consumption CO_2 emissions from activities such as non-energy use of fuels and industrial processes. We applied the following methods to project non-fossil fuel combustion CO_2 emissions:

- Inventory categories with emissions below 25 million metric tons (MMt): We extrapolate historical trends from EPA's latest GHG inventory in line with EPA's latest GHG projection guidance.
- Inventory categories with emissions above 25 MMt: We follow EPA's latest guidance, scaling inventory data based on category appropriate RHG-NEMS output. For example, recent historical CO_2 emissions from natural gas systems are scaled based on the projected change in dry natural gas production available at the play level from RHG-NEMS. This allows for non-combustion CO_2 emissions to change in line with changes in the economic and technology assumptions we make to account for uncertainty in our projections.

Non-CO_2 and Land Use Emissions and Removals

All projections of non-CO_2 emissions (i.e., methane, nitrous oxide, hydrofluorocarbons, perfluorocarbon, and sulfur hexafluoride) follow the same general approach as we take in projecting CO_2 emissions from non-fossil fuel combustion sources. Inventory categories with emissions less than 25 MMt CO_2e are extrapolated based on recent historical trends. Inventory categories with emissions more than 25 MMt CO_2e are scaled based on appropriate outputs from RHG- where possible. In some instances, such as agriculture, there are no appropriate outputs from RHG-NEMS to scale emissions. In these instances, we use alternative public projections such as the US Department of Agriculture (USDA)'s long-term projections. Additional modifications are made to reflect the impact of state and federal policies as discussed above.

Historical emissions and removals from land use, land-use change, and forestry (LULUCF) come directly from the 2021 EPA GHG inventory. Projected trends come from the high sequestration scenario from the 2016 Biennial Report of the United States (the most recent set of federal projections) calibrated to align with EPA's 2021 inventory. For emissions of N_2O and CH_4 from LULUCF we assume 2019 emissions from LULUCF remain constant through 2035, following the approach used in the 2016 Biennial Report.

Downscaling National Emissions Projections to the State Level

RHG-NEMS forecasts fuel consumption by sector at various levels of geographical aggregation, which is then downscaled to the state level using state-level activity data. For the power sector, generation-based emissions are taken directly from RHG-NEMS which reports individual plant-level emissions. NEMS builds new fossil-fuel fired plants to meet electricity demand and those plants and their respective emissions are attributed to individual states within an electricity market region based on historical trends. We also estimate power sector emissions associated with the consumption of electricity within a state, accounting for the carbon intensity of generation that produced that electricity.

Projections of fuel consumption by other end-use sectors, including industry, buildings (a combination of the residential and commercial sectors) and transportation, are downscaled to the state level from nine census-level regions. In the building sector, we apportion census-level GHG emissions to constituent states using each state's share of historical fuel consumption. In the transportation sector, we use historical demand to divide up fuel consumption by mode in each census region between constituent states. For example, we use the historical share of vehicle miles traveled (VMT) for light-duty vehicle fuel demand, and truck ton-miles for freight fuel demand. For industry, we use EPA's Facility Level Information on Greenhouse Gases Tool (FLIGHT) as weights to apportion census region GHG emissions to constituent states for large industrial facilities, and total value-added as weights to apportion census region fuel consumption for smaller facilities.

For non-fossil fuel combustion CO_2 emissions at the state level, all other GHG emissions and LULUCF emissions and removals we use activity data from RHG-

NEMS where available. For example, methane emissions from fossil fuel production are downscaled based on production output from RHG-NEMS which is available by fuel basin/play and can be attributed to individual states. In cases where there are no appropriate outputs from RHG-NEMS, we draw on other sources of activity data, including FLIGHT, the EIA, and USDA.

Disclosure Appendix