RHODIUM GROUP

Taking Stock 2018: Technical Appendix

This document provides additional detail on the methods and data sources used in Rhodium Group's Taking Stock 2018 report produced for the US Climate Service.

NATIONAL GHG EMISSIONS AND PROJECTIONS

All historical greenhouse gas (GHG) emissions and removal estimates (1990-2016) come directly from the 2018 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) 4^{th} 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 used by the Energy Information Administration (EIA) to produce the Annual Energy Outlook 2018 (AEO2018) and maintained by Rhodium Group.

Carbon Dioxide emissions

Projected CO_2 emissions from all energy use in RHG-NEMS is 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 based on applicable RHG-NEMS output.

- **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 US dry natural gas production 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-NEMS (e.g., scaling hydrofluorocarbon emissions with economic growth) unless additional modifications are necessary to reflect the impact of state and federal policies as discussed below. 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.

Historical emissions and removals from land use, land-use change, and forestry (LULUCF) come directly from the 2018 EPA GHG inventory. Projected trends come from the 2016 Biennial Report of the United States (the most recent set of federal projections) calibrated to align with EPA's 2018 inventory. For emissions of N_2O and CH_4 from LULUCF we assume 2016 emissions from LULUCF remain constant through 2030, following the approach used in the 2016 Biennial Report.

FEDERAL AND STATE POLICY ASSUMPTIONS

Our Baseline scenario includes emission reductions from all existing federal and state policies "on the books." To remain consistent with United Nations (UN) reporting guidelines, we include only policies that have been finalized and adopted. We do not include aspirational goals 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 June 2018, phased out based on their statutory schedules. All conventional pollutant regulations such as the Mercury Air Toxics Standards (MATS) are included. State cap-and-trade programs, Renewable Portfolio Standards (RPS), fuel standards, and zero-emission credit programs are all included.

Transportation – We include the federal Renewable Fuels Standard, light-duty Corporate Average Fuel Economy (CAFE) standards, recently updated heavy-duty vehicle GHG emissions standards, and federal electric vehicle incentives. All state vehicle emission standards and zero-emission vehicle (ZEV) mandates are also included.

For light-duty federal CAFE standards, our Baseline scenario includes a range of potential rollback options to bound potential outcomes in the absence of a formal administration proposal (as of June 2018). Our federal rollback scenario assumes CAFE standards freeze at model yearl (MY) 2021 levels nation-wide to reflect the potential for the Trump Administration to revoke California's waiver under the Clean Air Act. At the most ambitious end of our range, we assume an only partial rollback of Obama-era fuel economy standards, decreasing the annual incremental improvement in the regulations by 33% starting with MY 2022. We apply this rollback to all states except California and the 12 other states that plan to maintain the original Obama-era CAFE standards.

Industry and Buildings – We include federal building codes and appliance standards. State energy efficiency programs are implicitly captured in electric demand projections.

Non-CO_2 policies

Methane – The following recent national policies are reflected in our analysis: EPA's 2016 New Source Performance Standards (NSPS) and permitting rules for methane from oil and gas; EPA's 2016 Control Techniques Guidelines (CTGs) for volatile organic compounds (VOCs) from oil and natural gas; 2016 Bureau of Land Management regulations to prevent waste of natural gas from venting, flaring and leaks on public lands; and EPA's 2016 updated NSPS and Emission Guidelines for methane from municipal solid waste landfills. The following state policies are also reflected, taking care to avoid double-counting when federal and state policies overlap: oil and gas standards in California, Colorado, Pennsylvania and Wyoming as of June 2018; and California's landfill methane control measures from 2010 and updated in 2017.

We model two policy scenarios to bound potential outcomes for methane. The most ambitious scenario for emissions reductions assumes all the federal policies listed above are maintained and enforced. The federal rollback scenario assumes that all are rescinded or not enforced. 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 our analysis, we incorporate EPA's estimated emission reductions associated with its Significant New Alternatives Policy (SNAP), including Rule 20 (2015) and Rule 21 (2016). In our most ambitious policy scenario, we also reflect a potential emission reduction pathway associated with the Kigali Amendment to the Montreal Protocol based on a modeling approach conducted by the California Air Resources Board in its 2017 assessment of the potential impact of Kigali on California's HFC emissions. We assume the relationship between an HFC phasedown and eventual emission reductions follows a similar path to the US phasedown of HCFC-22. In our federal rollback scenario, the SNAP Rule 20 remains vacated and the Kigali Amendment is not implemented, but we reflect emission reductions from California's 2018 High GWP Refrigerant Emissions Reductions regulation.

ENERGY MARKET, TECHNOLOGY AND ECONOMIC ASSUMPTIONS

To construct our national Taking Stock GHG projection scenarios, we revised multiple energy market, technology cost 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. To examine how different outcomes for our key energy market and economic variables could shape US emissions in the years ahead, we also model additional scenarios exploring a range of potential market and economic outcomes, holding our policy assumptions constant.

Unless otherwise stated below, we use EIA's AEO2018 reference case assumptions in each Taking Stock scenario.

Scenarios in Taking Stock

To construct the full range of emission projections in Taking Stock we looked at five scenarios:

- **Baseline**: Our primary scenario consisting of input assumptions that in our judgment reflect moderate cost and price projections based on a review of markets and available literature. This range is bounded by two subcases: one analyzing full rollbacks of targeted federal policies, and an alternate scenario of moderate rollbacks.

- **High**: Similar to the Baseline's full federal rollback scenario, but with more conservative energy market and technology input assumptions. The total interaction of these inputs leads to higher economy-wide emissions relative to the Baseline scenario.

- **Low:** Similar to the Baseline's moderate rollback scenario but with more optimistic energy market and technology input assumptions, resulting in lower economy-wide emissions relative to the Baseline scenario.

- **High Macro:** Our High scenario but with greater economic growth than in the Baseline scenario.

- **Low Macro:** Our Low scenario but with lower economic growth than in the Baseline scenario.

RHG-NEMS inputs that are consistent across scenarios

We make several revisions to input assumptions beyond EIA's AEO2018 Reference case that are consistent across all Taking Stock scenarios. The key revisions are described below.

- Announced power plant retirements/additions: We incorporate all announced coal and nuclear power plant retirements through 2030. We account for recent state-level policy actions that will allow for continued operation of certain nuclear power plants in those states.

- Global oil prices: We assume global oil prices from AEO2018 reference case, and allow for feedback between global and domestic oil markets.

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

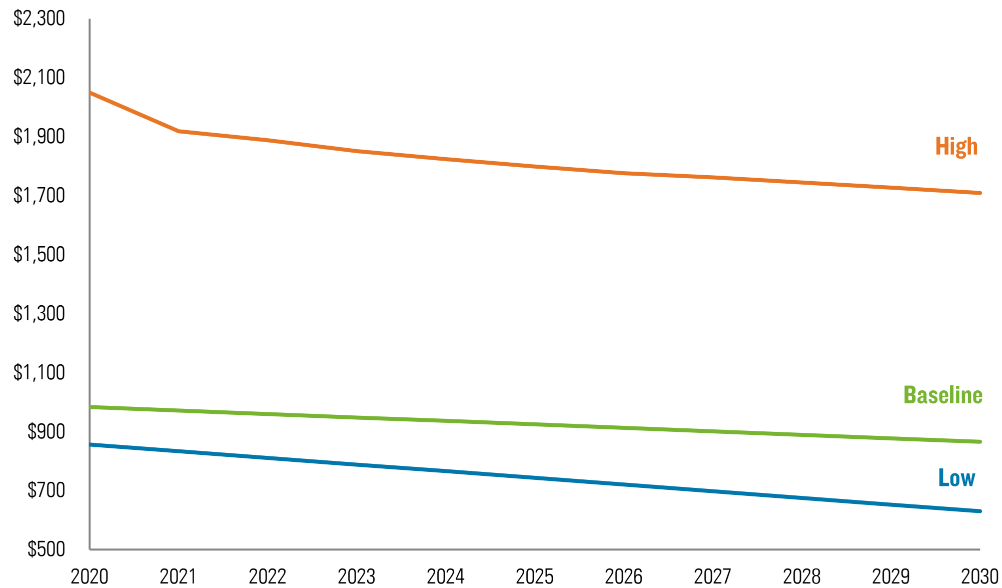
RHG-NEMS inputs that vary to capture energy market uncertainty

Below are the key assumptions that vary across our scenarios and underlying data sources. Charts are provided for select assumptions to illustrate differences across scenarios.

- **Renewable energy technology costs**: In the Baseline scenario, we assume capital costs for utility-scale and distributed solar photovoltaic and land-based wind decline according to NREL's 2017 Annual Technology Baseline's (ATB) mid-cost projections, while our low emissions scenario mirrors the ATB's low-cost projections. In the high emissions scenario, we assume cost declines consistent with EIA's AEO2018 reference case assumptions.

Figure 1: Utility-scale solar photovoltaic overnight capital costs

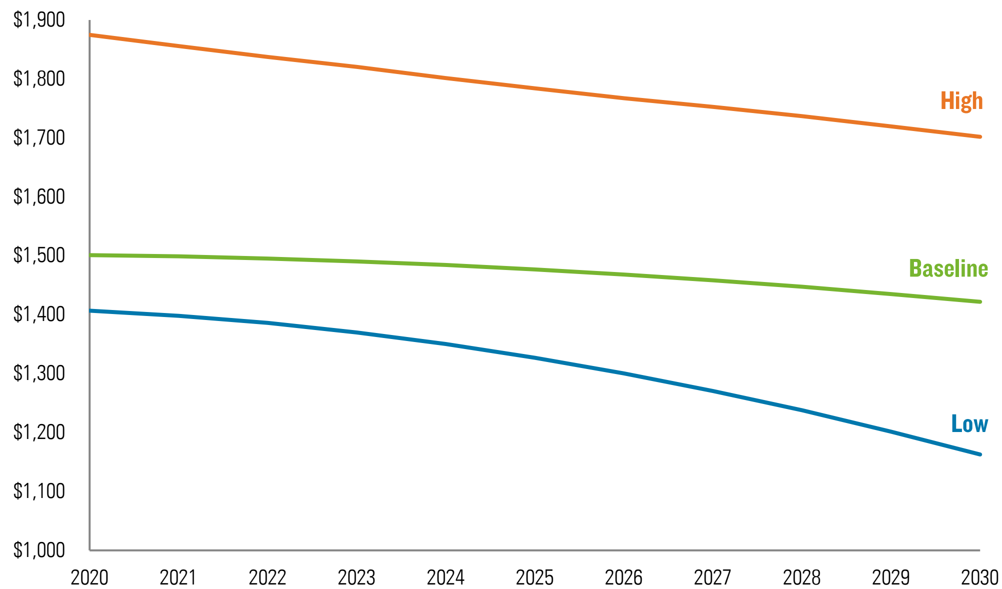
2017 dollars per kilowatt



Source: EIA AEO2018, National Renewable Energy Laboratory

Figure 2: Land-based wind overnight capital costs

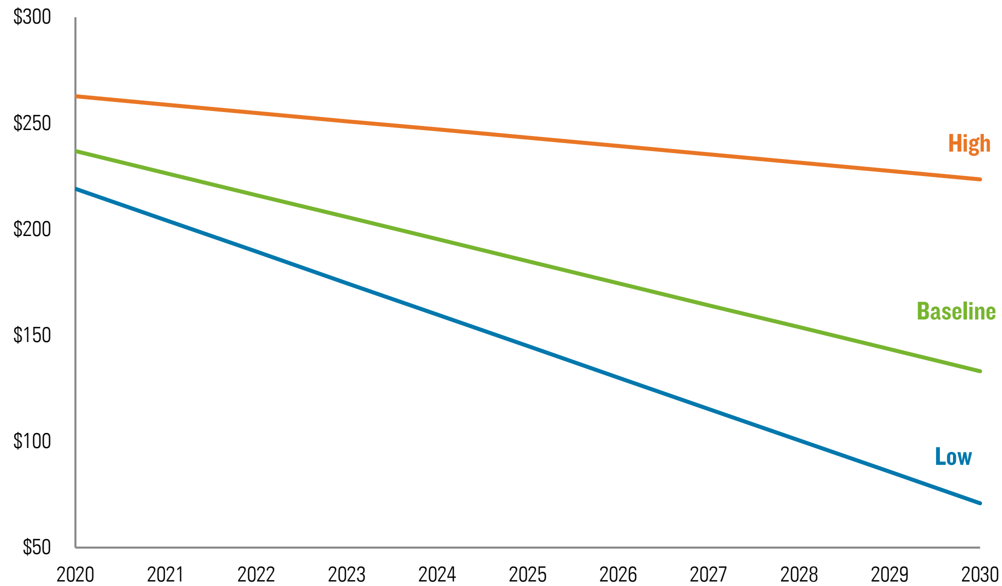
2017 dollars per kilowatt



Source: EIA AEO2018, NREL

- **Utility scale energy storage costs**: For the Baseline scenario, we assume energy storage costs follow the cost reductions of lithium-ion nickel cobalt aluminum oxide batteries in IRENA's reference case scenario in their 2017 Electricity Storage and Renewables report. We assume energy storage cost reductions match Bloomberg New Energy Finance's (BNEF) forecast in our Low emissions scenario and follow EIA's AEO2018 reference case assumptions in the High emissions scenario.

Figure 3: Utility scale energy storage overnight capital costs
2017 dollars per kilowatt-hour

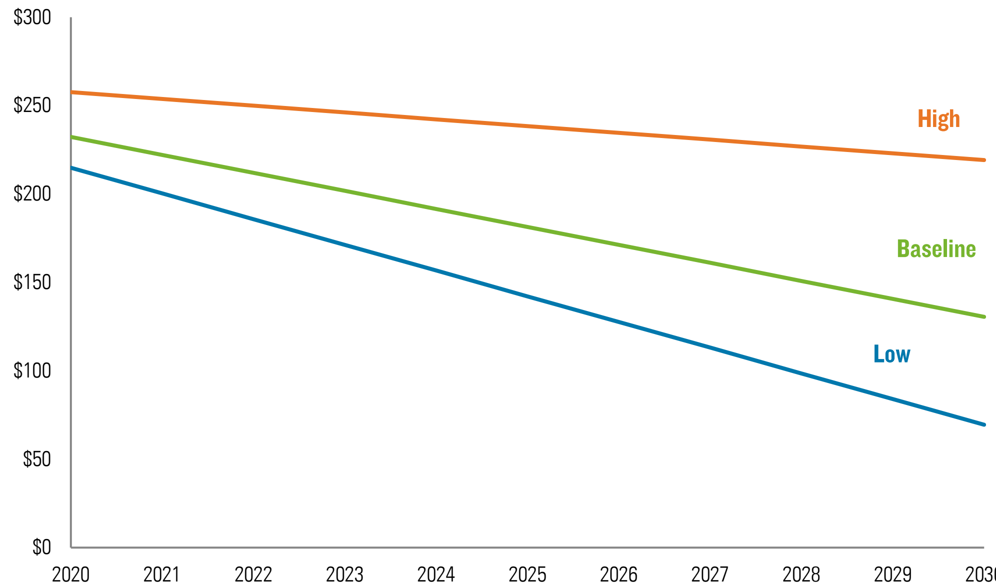


Source: EIA AEO2018, International Renewable Energy Association, BNEF

- **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 Baseline scenario, EFS's Slow Advancement case in our high emissions scenario, and BNEF projections for the low emission scenario. EFS cost curves are constructed using linear interpolations between predicted future costs, while BNEF's are not. For consistency across scenarios, we assume our low emissions battery costs for an EV 300-mile range (EV300) follow a linear cost decline consistent with BNEF cost reductions over the same period. For each scenario, we assume battery costs for other light-duty EV technologies modeled in NEMs[1] fall linearly by the same percentage decrease as they do for EV300 batteries. We adjust initial battery costs for these technologies by the percent difference in 2016 EV300 battery costs between the AEO2018 reference case and BNEF or EFS.

[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.

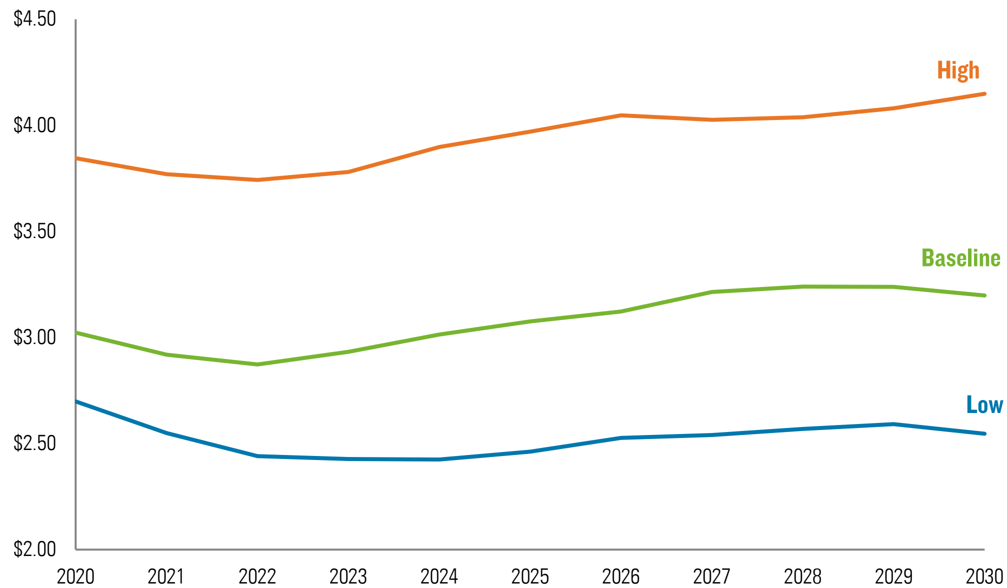
Figure 4: Electric vehicle battery costs
2017 dollars per kilowatt-hour



Source: NREL, BNEF

Natural gas resource and prices: For our Baseline scenario we use the natural gas resource and prices reflected in the AEO2018 high resource and technology side case, resulting in a price of about $3/MMBtu. We choose this as our Baseline reflection of natural gas resource and prices for two reasons: 1) AEO2018 reference natural gas prices tend to be revised down every year, ending up close to the previous year's high resource and technology side-case and 2) near-term natural gas prices from the EIA Short-term Energy Outlook (STEO) as well as other market insight providers are more closely aligned with the prices in the high resource and technology side case from EIA. The natural gas prices in our high scenario are about a $1/MMBtu higher and are based on the natural gas resource and prices in the AEO2018 reference case. For our low scenario, we used a similar methodology to the one used by EIA in the high resource and technology side case to construct a forecast with higher natural gas production and lower prices than those projected in our Baseline scenario. The natural gas prices in our low scenario are approximately $2.50/MMBtu, 50 cents cheaper than our Baseline scenario.

Figure 5: Natural Gas Spot Price at Henry Hub
2017 dollars per million Btu



Source: EIA AEO2018, Rhodium's US Climate Service

RHG-NEMS inputs that vary to capture macroeconomic uncertainty

For the Baseline, High and Low scenarios, we assume a real annual rate of 2.1%, on average, over the next decade, in line with EIA's reference case projections. Our High Macro emissions scenario assumes an average growth rate of 2.6% over the next 10 years, based on the AEO2018 High Macroeconomic Growth side case and closer to the Administration's more optimistic growth assumptions. For our Low Macro scenario, we model a 1.6% average annual economic growth rate for the next 10 years to capture the downward pressure on emissions that could arise if the economy grows at a slower rate than in the Baseline scenario. The assumptions for macroeconomic growth in this scenario match those of the AEO2018 Low Macroeconomic Growth side case.

UNDERSTANDING THE CHANGE FROM TAKING STOCK 2017

For our comparison of results from Taking Stock 2017 and 2018, we conducted a decomposition analysis to assess how differences in input assumptions explain the differences between these two projections. We estimated the relative contribution of changes in gross domestic product (GDP), the energy intensity of the economy, and the carbon intensity of energy. Emissions can be represented as the product of these three factors (Equation 1). We then approximate the relative contribution of each input as a percent change by taking the natural logarithm of the ratio of each factor in 2018 and 2017 (Equation 2).

$$Emissions = GDP * \left(\frac{Energy\ Consumption}{GDP}\right) * \left(\frac{Emissions}{Energy\ Consumption}\right) \quad \ldots Equation\ 1$$

$$Energy\ Intensity \qquad Carbon\ Intensity$$

$$\ln\left(\frac{Emissions_{TS\ 2018}}{Emissions_{TS\ 2017}}\right) = \ln\left(\frac{GDP_{TS\ 2018}}{GDP_{TS\ 2017}}\right) + \ln\left(\frac{Energy\ Intensity_{TS\ 2018}}{Energy\ Intensity_{TS\ 2017}}\right) + \ln\left(\frac{Carbon\ Intensity_{TS\ 2018}}{Carbon\ Intensity_{TS\ 2017}}\right) \quad \ldots Equation\ 2$$

We compared the 2020-2030 average annual CO_2 emissions from fossil fuel combustion from our 2017 Taking Stock Baseline to this year's Baseline. Real GDP and energy consumption projections were taken from RHG-NEMs outputs.

DISCLOSURE APPENDIX