Technical Appendix

Working Paper: Charting an Ambitious US NDC of 51% Reductions by 2030

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Overview of GCAM-USA-CGS

The estimates of economy-wide emissions reductions in this analysis are based on a version of the Global Change Assessment Model (GCAM) with detailed representation of the U.S. energy system at the state level (GCAM-USA). We refer to the version of GCAM-USA used in this study as GCAM-USA-CGS.

The global version of GCAM is a multi-sector model that represents the energy and economic systems for 32 geopolitical regions, including the United States. GCAM represents land use and agriculture in 384 land regions nested within 235 water basins. GCAM tracks emissions of a range of GHGs and air pollutants from energy, agriculture, land use, and other systems.

GCAM-USA is a version of GCAM that disaggregates the U.S. energy and economy components into 50 states and the District of Columbia while maintaining the same level of detail in the rest of the world. The energy system formulation in GCAM-USA consists of detailed representations of depletable primary sources such as coal, gas, oil and uranium, in addition to renewable resources such as bioenergy, hydro, wind and geothermal.

GCAM-USA also includes representations of the processes that transform these resources to final energy carriers, such as refining and electric power. These energy carriers, in turn, are used to deliver services to end users in the buildings, transportation, and industrial sectors. The electric power sector includes representations of a range of power generation technologies, including those fueled by fossil fuels, renewables, bioenergy, and nuclear power.

GCAM-USA is a market equilibrium model. The market equilibrium in each period is solved by finding a set of market prices such that supplies and demands are equal to one another in all markets as the actors in the model adjust the quantities of the commodities they buy and sell. GCAM operates in 5-year time-increments, with each new period starting from the conditions that emerged in the last.

GCAM-USA-CGS is based on the open-source release of GCAM-USA 5.3[iv]. GCAM-USA-CGS has been modified to reflect updated renewable energy costs and vehicle technology costs. It also contains the updated non-CO_2 marginal abatement cost curves from the U.S. Environmental Protection Agency.

Core Assumptions and Sensitivity Analyses

The results of this study depend on many assumptions about how the U.S. and the world might evolve in the future. This study uses a set of core assumptions for drivers including economic growth, population growth, fossil fuel prices, and EV sales (Supplementary Table 1). Economic impacts associated with COVID-19 in 2020 and subsequent recovery in the following years have also been incorporated into these assumptions. Our core assumptions draw from data sources such as EIA's *Annual Energy Outlook*[v], the Federal Reserve System[vi], IMF's *World Economic Outlook*[vii], and Rhodium Group[viii].

To help understand the possible range of outcomes and contextualize the results, we generated a range of sensitivity assumptions for important drivers (Supplementary Table 1). Four sensitivity factors were taken as the focus of this exercise: population growth, economic growth, oil and gas prices, and LULUCF emissions.

While these sensitivities are not a full representation of all factors that might influence the overall emissions trajectory, they nonetheless provide insight into the range of possibilities and the level of certainty associated with the projections in this assessment (Supplementary Figure 1).

Implementing Policies in GCAM-USA-CGS

This emission reduction policy scenario projects how much GHG emissions could be reduced with renewed and comprehensive engagement from the federal government. In this scenario, the Biden-Harris Administration and Congress implement a suite of new ambitious measures across sectors to decarbonize the economy.

These various measures both build upon existing policies and authorities and introduce new policies spanning the buildings, industry, power, transportation, and lands sectors. For instance, this scenario assumes an extension of existing incentives for wind and solar through the Production Tax Credit and Investment Tax Credit through 2030, and it assumes the continuation of new, more ambitious GHG standards on fossil generation, vehicles, and appliances through existing authorities at EPA and DOE. Examples of new policies explored in the analysis include new incentives to accelerate the turn-over of inefficient existing vehicles; new incentives to retain existing nuclear generation; and more expansive incentives for CCS in the industrial sector. All policies are incorporated into this analysis by directly altering inputs to GCAM-USA-CGS, and are applied across all 50 states and the District of Columbia at the national level. Other trends beyond these policies (e.g. improvements in technology cost and performance) are also captured in the assessment, as noted elsewhere in this document.

The policies explored in this study are described in Table 1 in the Working Paper. These policies were implemented by changing specific model parameters. In some cases, where appropriate, these policies are explicitly modeled in GCAM. In other instances, where an explicit approach is not appropriate or feasible, model parameters were adjusted to meet policy goals (Supplementary Table 2).

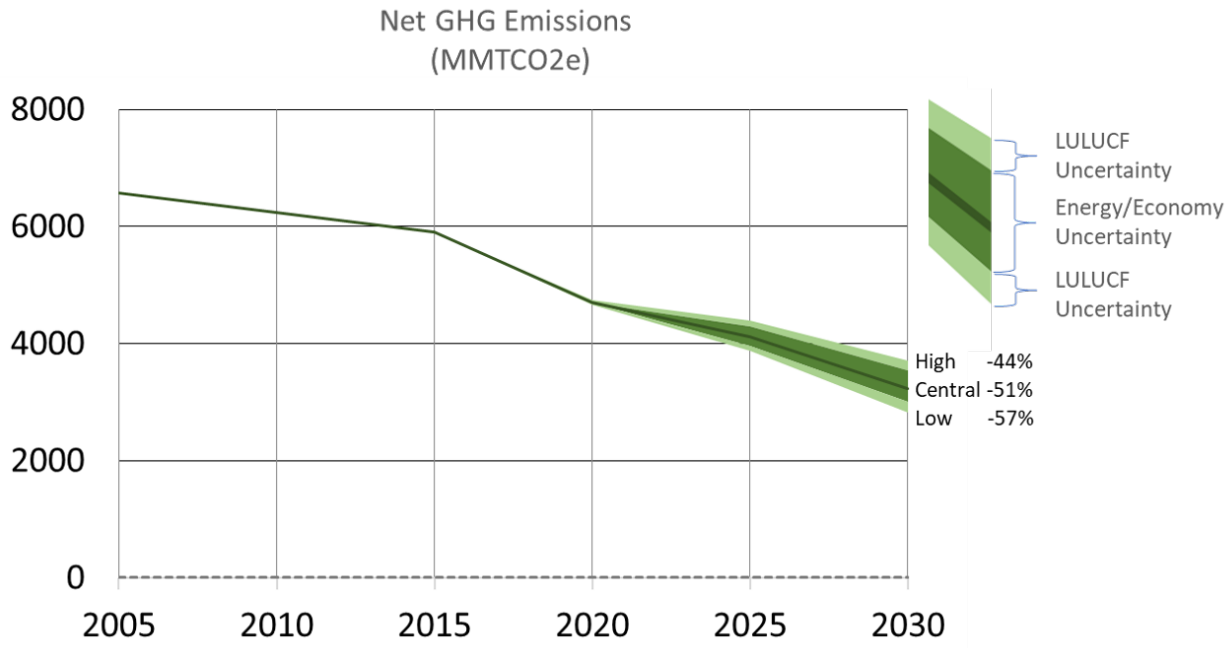
Harmonization with EPA Inventories

GCAM independently builds up historical emissions from underlying activity level and emission factors. This creates differences with the US EPA Inventory of Greenhouse Gas Emissions. To harmonize GCAM results to the EPA inventory, GCAM subsectors were first re-mapped according to EPA categories. Next, to account for remaining differences, GCAM's historical emissions were proportionally rescaled by gas, sector, and year, so that historical data for the two methods match exactly. The rescaling factors from GCAM's final calibration period (2015) were then carried forward to rescale emissions in future years by the same proportion.

CO_2 emissions were harmonized for each of the following sectors: electricity, buildings, industry, transportation, and agriculture. Emissions from international transport and U.S. territories are handled separately. In addition to energy emissions, harmonization in the industry sector applies to CO_2 from oil and gas systems, cement, fertilizer production, and industrial feedstocks. Agriculture CO_2 includes liming and urea fertilization.

Non-CO_2 harmonization covers the following: CH_4 emissions from oil and gas systems, coal mining, landfills, and livestock; N_2O emissions from croplands, livestock, and nitric and adipic acid production; and emissions of HFC, PFC and SF6. Because GCAM's non-CO_2 emissions inventory is based on the Emissions Database for Global Atmospheric Research (EDGAR), it differs from the EPA inventories used for the purposes of calculating the emission reduction in the U.S. Biennial Report. Net CO_2 removal from natural and working lands in the U.S. was estimated separately, and added to the total GHG estimates.

Supplementary Figure 1. Sensitivity Analysis Emission Range



Supplementary Table 1. Core Assumptions and Sensitivities for GCAM-CGS Analysis

Drivers	**Scenario assumptions**
Economic Growth	Overall GDP decreases by 3.5% year-on-year in 2020, then increases by 2.2% per year through 2030. (Low: 5.0% decrease in 2020, 1.0% increase through 2030 High: 2.0 % decrease in 2020, 3.3% increase through 2030)
Population Growth	Population grows by 0.65% per year through 2030. (Low: 0.53% through 2030 High: 0.76% through 2030)
Fuel Prices	Gas price is assumed to drop by 19.5% year-on-year in 2020, then increase by 4.9% per year through 2030. (Low: 2.6% increase through 2030 High: 9.3% increase through 2030) Oil price is assumed to drop by 30.8% year-on-year in 2020, then increase by 6.2% per year through 2030. (Low: 0.09% decrease through 2030 High: 13% increase through 2030)
Transportation Energy Demand	Transport sector energy demand is assumed to decrease by 14.7% from 2015 levels in 2020, with recovery through 2030.
Industry Energy Demand	Industry sector energy demand is assumed to decrease by 4.1% from 2015 levels in 2020, with recovery through 2030.
Buildings Energy Demand	Buildings sector energy demand is assumed to decrease by 1.7% from 2015 levels in 2020, with recovery through 2030.
Technology Costs	Technology costs are updated with NREL Annual Technology Baseline 2020 assumptions. Solar and wind base technology costs decrease by 49% and 42% from 2015 levels by 2030, respectively.

Supplementary Table 2. GCAM Implementation of Policy Assumptions

Sector	Modeled Policy	GCAM Implementation
Power	Renewable Energy Incentives	Investment tax credit extension is modeled by reducing investment costs by 30% by 2030. Production tax credit extension is modeled by levelized input cost reduction of 2.5 cents/KWh in 2030.
	Standards on existing coal	Federal regulations on existing coal are modeled by implementing a proxy carbon price starting at $5/ton in 2023, rising to $25/ton by 2035.
	Standards on existing gas	Federal regulations on existing gas are modeled by implementing a proxy carbon price starting at $10/ton in 2030, rising to $25/ton by 2035.
	Standards on new gas	Requirement all new gas plants be built with CCS starting in 2025 is modeled by allowing zero new gas plants without CCS starting in 2025.
	Incentives for Carbon Capture and Sequestration	45Q tax credit for CCS projects is increased to $100/ton through 2030 is modeled by exogenously adding 154 MTCO2 of gas CCS plants in the power sector.
	Nuclear Retention Incentives	Incentives to retain existing nuclear generation are modeled by exogenously specifying 680 TWh of nuclear generation by 2030.
Transport	Combustion Engine Performance	The ICE GHG performance goal is modeled by implementing fuel efficiency that reaches 118gCO2/mi for new passenger cars and 160g/mi for new light trucks and SUVs by 2030.
	LDV ZEV incentives	Increased incentives for ZEVs are modeled by GCAM preference parameters so that new EV sales of 40% by 2030 and 90% by 2035. Cash-for-clunkers incentive is modeled by reducing expected lifetime of old vintage vehicles manufactured prior to 2015.
	M/HDV ZEV incentives	2030 ZEV sales target and incentives for ZEV HDVs is modeled by exogenously specifying electric truck deployment to reach 15% for Class 2b-3 trucks, 20% for Class 4-8 straight trucks, and 15% for Class 7-8 tractors.
Buildings	Electrification	Building electrification standards and incentives are modeled by raising GCAM preference parameters for heat pumps to reach 69% of new sales in 2035 for residential buildings and 47% of new sales for commercial buildings in 2035. Electric heat pump retrofits are exogenously specified at 10% of heating service(non-electric) in existing residential buildings by 2030. For water heating, air source heat pumps reach 29% of new sales in 2035 for residential buildings and 30% of new sales for commercial buildings.
	Energy efficiency	Building energy efficiency increase is modeled by reducing building service demands to reach power demand reduction of 254 TWH and natural gas demand reduction of 440 TBTU by 2035.
Industry	Energy efficiency	Industry energy efficiency increase is modeled by implementing an energy efficiency improvement of 1% per year through 2030.
	Carbon Capture and Sequestration	45Q tax credit for CCS projects is modeled by exogenously adding 79 MTCO2 sequestration in cement and biofuel sectors.
Non-CO2 emissions	Non-CO2 emissions	Non-CO2 reductions are modeled by implementing marginal abatement cost curves for CH4, N2O, and HFCs emissions based on the EPA MAC report.
LULUCF	LULUCF	LULUCF emissions are exogenously specified to reach -1000 TgCO2e/yr of LULUCF emissions by 2030. This is based on an analysis of existing literature, including analysis that suggests that -1000 TgCO2e/yr by 2030 would be possible with $35/ton carbon price, which we use as a proxy for incentives and payment for climate beneficial practices.

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[iv] https://github.com/JGCRI/gcam-core
[v] Annual Energy Outlook 2021. U.S. Energy Information Administration (EIA). https://www.eia.gov/outlooks/aeo/tables_ref.php
[vi] Federal Open Market Committee Projections, December 16, 2020. The Federal Reserve System. https://www.federalreserve.gov/monetarypolicy/fomcprojtabl20201216.htm
[vii] World Economic OutLook, October 2020: A Long and Difficult Ascent. International Monetary Fund. https://www.imf.org/en/Publications/WEO/Issues/2020/09/30/world-economic-outlook-october-2020
[viii] Larsen, K., Hannah Pitt, John Larsen, Whitney Herndon, Trevor Houser, Hannah Kolus, Shashank Mohan, & Emily Wimberger. (2020). *Taking Stock 2020: The COVID-19 Edition*. Rhodium Group. 16 pp. Available at https://rhg.com/wp-content/uploads/2020/07/Taking-Stock-2020-The-COVID-19-Edition.pdf