Core Model Proposal #254:
Add Air Pollutant Emissions to GCAM-USA

Product: Global Change Analysis Model (GCAM)

Institution: Joint Global Change Research Institute (JGCRI)

Authors: Steve Smith, Maridee Weber, Brinda Yarlagadda, Catherine Ledna, Wenjing Shi, Dan Loughlin, Chris Nolte, and Yang Ou

Reviewers: Matthew Binsted, Ellie Lochner, Ryna Cui

Date committed: June 3rd, 2022

IR document number: PNNL-34410

Related sector: Emissions

Type of development: Code, Data

Purpose: To incorporate air pollutant emissions in GCAM-USA.

Background

An initial version of non-CO2 implementation was developed for GCAM v4.3 and implemented and tested in collaboration with US EPA ORD collaborators and documented in a journal paper (Shi et al. 2017). This implementation has now been updated and incorporated into gcamdata.

Note that the air pollutant representation in GCAM-USA takes a different paradigm than in core GCAM. Air pollutant emissions are implemented as a CLE (Current LEgislation) scenario, reflecting current rules and legislation with no assumptions for additional controls, although the impact of any endogenous technology changes are taken into account. This is done to support work on energy-emissions interactions over the next 20-30 years (out to 2050). Some emissions start to increase again by that point. This behavior is especially seen in non-road/other transportation due to minimal legislation represented that impacts future year emissions as well as a lack of GDP control. If we wanted a longer-term reference scenario going past 2050 (comparable to the GCAM-core) we'd want to add some additional emission control assumptions, but that is not done in this proposal. Table 0.1 below reflects the CLE approach by sector.

Overview

This core model proposal adds non-GHG pollutants to the electricity, buildings, industry, transportation, process, and refining sectors in GCAM-USA for the base years (1990-2015). Emission factors are calibrated in all historical years to the US National Emissions Inventory (NEI), allowing for state-level representations of pollutant emissions. National totals for historical years are scaled to Community Emissions Data System (CEDS) values for most sectors at the national level both for consistency over time and with the global GCAM model, and because CEDS values are updated annually, providing up to date estimates. Future emission factors are set, by vintage where available in GCAM, according to current air pollution control regulations (a "current polices" scenario). The following pollutant species are included in this proposal: BC, OC, CO, NH_3, NMVOC, NO_x, PM_{10}, $PM_{2.5}$, and SO_2. Note that $PM_{2.5}$ (particulate matter smaller than 2.5 *u*m) and PM_{10} are emission species not currently included in other GCAM regions. These are included in GCAM-USA because these species are important for analysis of air pollution. BC and OC are subcategories of $PM_{2.5}$. Outlier emission factors are re-set to national median values to avoid spurious results.

Table 0.1: Policy assumptions summary table.

Sector	Assumptions
Electricity	New Source Performance Standards (NSPS) applied to 2020 - 2100 for all pollutants except NH_3.

Buildings	Code of Federal Regulations Standards of Performance for New Residential Wood Heaters applied to 2020 - 2100 for $PM_{2.5}$, PM_{10}, BC, and OC.
Transportation (on road)	A combined set of federal and state policies as implemented in EPA's MOVES2014 model. For example, including: Tier 3 standards Heavy Duty GHG Rule (Phase I), and Light Duty GHG Rule.
Other Transportation (non-road)	EPA Category 3 marine engine sulfur limit of 1,000 ppm for marine fuels applied to 2015 - 2100 for SO_2 for domestic shipping.
Industrial Energy	A combined set of federal and state policies as implemented in Argonne National Laboratory's GREET 2014 model.
Process (industry, urban, cement)	A GDP control is applied to 2015 - 2100 for all supplysectors and technologies. The reasoning for this is explained further in Section 2.6 under Maximum Reduction and Steepness.
Refining and related	N/A

1. Emissions Data Sources

The emission data used in GCAM-USA is derived from several data sources as described below.

U.S. National Emissions Inventory (NEI) (US EPA)

The US NEI provides a highly detailed emission dataset that is produced every three years. The NEI contains non-point source emission at the level of US county disaggregated into almost 7,000 Source Classification Codes (SCCs), along with millions of point sources. Data from the NEI 2008 v3, 2011 v2, 2014 v2, and 2017 v1 was aggregated and processed by year to produce data corresponding to the fifty U.S. states and the District of Columbia.

Data was reformatted and combined the level of state, tribe, and NEI Source Classification Codes (SCC). Data was mapped to an intermediate level sector and fuel definitions used by the CEDS project. This data format was used so that the data processing codes developed for this ORD project can be readily used with updated data produced by the CEDS project in the future. Because the CEDS sectors are defined at a higher level of disaggregation than GCAM sectors, this also allows a more accurate assignment of emissions from SSC codes where fuels could not be identified.

In some cases, the fuel used is not identified. In these cases, the fuel is mapped to “other”, and this fuel is re-allocated to specific fuel types using the distribution of fuels that could be identified. This issue only applies to combustion emissions, not process emissions. Table 1.1 shows the percentages of emissions from “other” fuels for the relevant air pollutants for each NEI year. An example of a fuel "not identified" and assigned to "other" happens for NOx emissions from CEDS_Sector 1A2_Industrial_fuel_combustion. This CEDS_Sector includes several different EPA Tier 1 Criteria Air Pollutants (CAPS) descriptions, including **Tier 1**: Fuel Comb. Industrial **Tier 2**: Internal Combustion **Tier 3**: Other. This specific EPA Tier 1 CAPS description is mapped to multiple SCC codes that are associated with different fuels, but because the fuel assignments are done at the EPA Tier 1 CAPS level and not the SCC level, it must be assigned to "other".

Table 1.1: Percent of emissions assigned "other" fuels

	2008	**2011**	**2014**	**2017**
NH_3	8.6	9.0	9.5	9.6
CO	2.1	2.4	3.0	3.6
NOx	7.9	9.1	9.6	12.0
PM_{10}	1.0	1.1	1.5	1.9
$PM_{2.5}$	3.4	4.2	5.1	5.7
SO_2	3.8	4.0	4.2	9.8
NMVOC	2.0	2.4	3.2	5.3

Due to the NEI data files being large and numerous, this data is aggregated into state/sector/fuel summary files outside of gcamdata.

Air Pollutant Trends (U.S. Environmental Protection Agency EPA)

Annual data at the state level, but with a coarse sectoral resolution (US EPA Tier 1 categories), for all pollutants from 1990 forward is available in the EPA State Tier 1 CAPS trends excel spreadsheets, April 29th, 2020, version, was used to scale some of the processed NEI data. We do this scaling to get a more accurate distribution of emissions at the state level for years in between (or before) NEI years in chunk L169.nonghg_NEI_scaling_USA.R.

2008-2017: non-NEI years within 2008 - 2017 are interpolated from NEI years (2008, 2011, 2014, 2017) or scaled to EPA State Tier 1 CAPS trends data, publicly available from the EPA website. The tier 1 sectors that are scaled to state level data are HIGHWAY VEHICLES, OFF-HIGHWAY, and FUEL COMB. ELEC. UTIL. since these sectors are more likely to have actual annual estimates in the TRENDS data at the state level. All other tier 1 sectors are linearly interpolated as this is also the case in the TRENDS data. The data is then mapped to GCAM sectors according to CEDS sector.

1990-2007: For previous base years in which we have not processed NEI data (1990-2007), NEI 2008 data is scaled to either EPA State Tier 1 CAPS or CEDS. Most sectors are scaled to EPA State Tier 1 CAPS, except for domestic shipping, which is not included in the EPA State Tier 1 CAPS. Instead, domestic shipping emissions are scaled to CEDS. This data is then mapped to GCAM sectors according to CEDS sector.

This gives us a table (L169.NEI_1990_2017_GCAM_sectors_unscaled) containing non-GHG emissions by state, sector, and fuel from 1990-2017, which is processed further in L170.nonghg_ceds_scaling.R, detailed below.

Composite, scaled emissions data used in GCAM-USA

The primary dataset used in GCAM-USA starts with the state level interpolated and scaled NEI data as described in the above section. We then scale this dataset at a national level to CEDS trends within *gcamdata*. This is performed by chunk L170.nonghg_ceds_scaling.R, and output as L170.NEI_1990_2017_GCAM_sectors.csv. This is the data used throughout GCAM-USA for historical base-year calibration unless explicitly stated otherwise below. This step ensures consistently between GCAM-USA and core GCAM (which is also calibrated to CEDS). This also allows us to capture some nuances in emission trends that are not captured in the NEI (such trends in the last few years after an NEI in combustion emissions).

Road sector emissions in the NEI have a discontinuity due to a change in methodology by EPA, so additional processing is done for this sector. The process is detailed in Section 2.3 Transportation Sector.

For most other sectors and non-GHG's, NEI is scaled to CEDS. The first exception is that CEDS does not have $PM_{2.5}$ or PM_{10} emissions, so emissions from these species are not scaled to CEDS. For other sectors, where solid fuels are used, the relationship between BC, OC, and PM is more complex (because PM emissions can contain significant amounts of mineral compounds) and, therefore, there can be some inconsistency between GCAM USA BC/OC emissions and $PM_{2.5}$ emissions. In practice this is usually not a significant issue because most analysis uses either BC/OC (climate-focused analysis) or $PM_{2.5}$ (air pollution focused analysis) emissions, but not both. Given the considerable uncertainty in these primary PM emissions, it was felt that this was acceptable at the present time. If CEDS is expanded later to provide $PM_{2.5}$ emissions this can be made consistent. The second exception is that biodiesel and ethanol production do not have emissions in CEDS, so these sectors use emissions straight from NEI. Additionally, petroleum refining is in CEDS, but we use emissions straight from NEI because the scaling reduced these emissions too much.

2. Detailed Methodology by Sector

The methods for implementing emission factors or emissions in different sectors at the state level are described below.

2.0 Creating Sectoral Inputs

Scripts: L270.nonghg_NEI_to_GCAM_USA.R

Overview: This script uses the NEI_to_GCAM function to produce 6 tables (L270.nonghg_tg_state_elec_F_Yb, L270.nonghg_tg_state_refinery_F_Yb, L270.nonghg_tg_state_bld_F_Yb, L270.nonghg_tg_state_indenergy_F_Yb, L270.nonghg_tg_state_othertrn_F_Yb, and L270.nonghg_tg_state_prc_F_Yb) by sector. This function allows the user to specify what GCAM sectors should be filtered from the NEI data, maps to GCAM fuels and pollutants, converts from TON to Tg, and aggregates emissions by state, sector, fuel, year, and pollutant. Each of the 6 outputs of this script is used in a corresponding sector-specific chunk.

2.1 Electricity Sector

Scripts: L272.nonghg_elc_USA.R

Overview: Emission factors for model base-years in this sector are generally calculated by dividing inventory emissions by fuel, state, and sector by GCAM fuel consumption (input-driver). Future vintages are assigned emission factors set by regulatory standards, termed New Source Performance Standards (NSPS).

Structure: The structure of the electric generation sector in GCAM-USA differs from that of GCAM-core. In GCAM-USA, the non-CO_2's are associated with specific technologies instead of assigned to the aggregate electricity sector. This was done to take advantage of GCAM's vintaging structure, where historical vintages are calibrated to inventory data but emissions for future vintages are assigned NSPS emission factors. Only the GCAM-USA configuration with water technologies is supported, as this is the version used in almost all GCAM-USA analysis at present.

Table 2.1.1: Electricity Sector Technologies with corresponding non-GHG emission factors

Nesting Subsector	Subsectors	Cooling Technologies
Coal	Conv pul IGCC IGCC CCS Conv pul CCS	Seawater Once through Recirculation Cooling pond* Dry cooling
Biomass	Conv Conv CCS IGCC IGCC CCS	Seawater Once through Recirculation Cooling pond** Dry cooling

Refined liquids	CC CC CCS Steam/CT	Seawater Once through Recirculation Cooling pond*** Dry cooling
Gas	CC CC CCS	Once through Recirculation Cooling pond*** Dry cooling

[*] This technology only applies to conv pul subsector.

[**] This technology only applies to conv subsector.

[***] This technology only applies to CC subsector.

Table 2.1.1 shows the possible combinations of electric generation nesting subsectors, subsectors, and cooling technologies. For example, Biomass has four possible subsectors, and each of those subsectors has five possible cooling technologies, aside from the exceptions noted above.

Geothermal, wind, solar, and nuclear technologies were not given emission factors at this time.

Files Involved: Two exogenous files are used in non-GHG electricity emission factor processing. They are described further in the *Data Sources* section below.

- EPA_state_egu_emission_factors_ktPJ.csv
  - Emission factor data at the state and fuel level, used for filling in missing values
- EPA_state_egu_emission_factors_ktPJ_post2015.csv
  - Emission factor data at the electricity technology level, reflecting New Source and Performance Standards

Data Sources:

GCAM-USA Data Sources

Base-year emission factors were calculated from the composite state, fuel, technology level emissions dataset described above. Emission factors for BC and OC were calculated using fractions of $PM_{2.5}$ as described below in the methods section.

Future year (2020-2100) emission factors were provided by Dan Loughlin at EPA-ORD. Two main data sources were used.

1. EPA_state_egu_emission_factors_ktPJ_post2015.csv: Data was provided that reflected New Source Performance Standards for different electricity generation technologies. These were assumed to be constant across states and for all future years. These factors were derived from the base case scenario and modeled in the EPA's Power Sector Modeling Platform v5.14, finalized in Spring 2015. They were provided for BC, OC, CO, NO_x, SO_2, PM_{10}, $PM_{2.5}$, and NMVOC.
2. EPA_state_egu_emission_factors_ktPJ.csv: Additional emission factor data was provided by Dan Loughlin at the state and fuel level for multiple years, for use when technology-specific emission factors were unavailable. This was used for NH_3 in practice.

Methods:

Base Year Emission Factors: For the base years, emission factors were calculated based on the composite, scaled emissions data described in section 1 above and calibrated fuel input from GCAM-USA, with the aim of having national emissions in GCAM in the base years equal national emissions in CEDS. These emission factors were computed for CO, NH_3, NMVOC, NO_x, PM_{10}, $PM_{2.5}$, and SO_2.

BC and OC emission factors were computed as fractions of $PM_{2.5}$ emission factors using assumptions from Bond et al (2004). These fractions are listed in Table 2.1.2.

Table 2.1.2: BC and OC Emission Fractions, Electricity Sector

Sector	Fuel	Year	BC Fraction	OC Fraction	Source/Justification
Electricity	Biomass	1990	0.1531	0.7951	Klimont et al; Residential - biomass
Electricity	Biomass	2005	0.1682	0.7752	Klimont et al; Residential - biomass
Electricity	Biomass	2010	0.1754	0.7649	Klimont et al; Residential - biomass
Electricity	Coal		0.006	0	Bond et al (Table 5); hard coal, pulverized
Electricity	Gas		0.06	0.5	Bond et al (Table 5); for all natural gas
Electricity	Refined liquids		0.3	0.09	Bond et al (Table 5); middle dist. oil, industry/power

Note: BC/OC fractions without a year associated with them are assumed constant in all years. 2010 values are carried forward to 2015, unless 2015 is specified.

Missing Values: In some cases, there were missing values for emission factors at the state/fuel level. These fell into three categories.

Case 1: There was pollutant emissions data in the NEI, but no calibrated fuel input data in GCAM.

This occurred for several states, fuels, and pollutants in all base years. A national median emission factor was assigned as a placeholder, though there are no emissions in GCAM for these state/fuel combinations in historical years, this assures reasonable emissions in future years.

Case 2: There was calibrated fuel input data in GCAM, but no corresponding NEI emissions.

This could be due to the approximations made in developing the GCAM state-level base-year dataset, or due to missing emissions in the NEI. This happens primarily for biomass and refined liquids-related pollutant emissions in several states and years, and for gas-related NH3 emissions in West Virginia in 2015. In these cases, a national median emission factor was also used to calibrate the model. Biomass-fueled technologies in particular have a large number of missing values.

Case 3: There was no calibrated fuel input data in GCAM or corresponding NEI emissions.

This is the case for refined liquids-related pollutant emissions in DC in 2015, and biomass-related pollutant emissions in Alaska in 1990, 2005, and 2010, Wyoming in 2010 and 2015, West Virginia in 1990 and 2010, and Kansas and Oklahoma in 1990 and 2005. In these cases, a national median emission factor was also used to calibrate the model.

The national median emission factor also replaced existing emission factors outside a threshold for all technologies. This method is further described below.

Future Year Emission Factors: Emission factors for future year vintages were provided for individual fuel/technology/pollutant combinations and assumed constant across all states and years (2020-2100), reflecting minimum new source performance standards (EPA_state_egu_emission_factors_ktPJ_post2015.csv). This data was obtained from the IPM v5.13 for NO_x and SO_2 emission factors for coal, gas, and biomass and from GREET 2014 for all other emission factors (EPA, 2013 Table 3-12; and ANL, 2014) (Table 2.1.3). It is assumed that biomass (IGCC) and biomass (IGCC CCS) technologies have the same emission factors as gas (CC) and gas (CC CCS) technologies. (**TODO**: In the future, this assumption should be revisited as more information becomes available to differentiate conventional and CCS emission factors.) In circumstances where no emission factor data at the technology level was available, a second data source containing state/fuel emission factor data for 2015 to 2050 was used (EPA_state_egu_emission_factors_ktPJ.csv). This data source was also provided by Dan Loughlin and was used for NH_3 emission factors for all technologies. If emission factor data was not present for a state/technology combination in this second data source, a national median was computed. In practice, missing values existed only for NH_3 emissions across all technologies.

Table 2.1.3: Electricity Sector Emission Factors, 2020-2100[a]

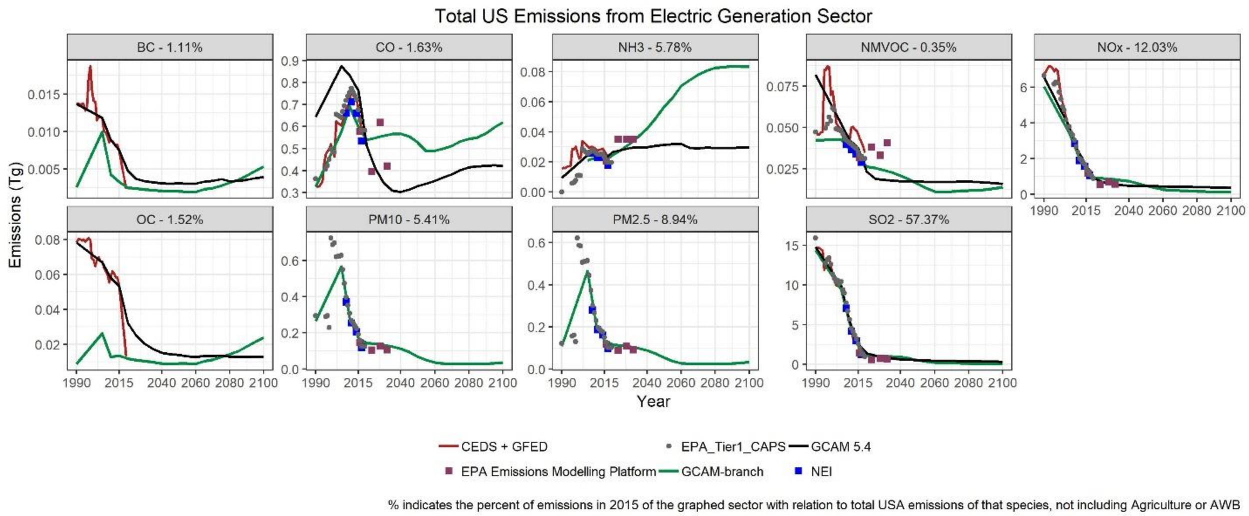
	NO_x	SO_2	BC	CO	OC	PM_{10}	$PM_{2.5}$	VOC
Coal (conv pul)	3.0E-02	2.6E-02	6.9E-04	1.2E-02	1.3E-03	2.1E-02	1.6E-02	1.4E-03
Coal (conv pul CCS)	3.0E-02	2.6E-02	6.9E-04	1.2E-02	1.3E-03	2.1E-02	1.6E-02	1.4E-03
Coal (IGCC)	5.6E-03	6.5E-03	3.0E-03	2.1E-03	5.6E-03	2.4E-01	7.0E-02	1.2E-04
Coal (IGCC CCS)	5.6E-03	6.5E-03	3.0E-03	2.1E-03	5.6E-03	2.4E-01	7.0E-02	1.2E-04
Biomass (conv)	8.6E-03	3.4E-02	4.3E-03	2.7E-01	1.1E-02	3.5E-02	3.1E-02	7.6E-03
Biomass (conv CCS)	8.6E-03	3.4E-02	4.3E-03	2.7E-01	1.1E-02	3.5E-02	3.1E-02	7.6E-03
Biomass (IGCC)	4.7E-03	0	3.7E-06	1.4E-02	8.6E-05	1.3E-04	1.3E-04	2.5E-04
Biomass (IGCC CCS)	4.7E-03	0	3.7E-06	1.4E-02	8.6E-05	1.3E-04	1.3E-04	2.5E-04
Gas (CC)	4.7E-03	0	3.7E-06	1.4E-02	8.6E-05	1.3E-04	1.3E-04	2.5E-04
Gas (CC CCS)	4.7E-03	0	3.7E-06	1.4E-02	8.6E-05	1.3E-04	1.3E-04	2.5E-04
Gas (steam/CT)	4.7E-03	0	9.8E-05	3.9E-02	2.3E-03	3.4E-03	3.4E-03	1.0E-03
Refined liquids (CC)	2.4E-01	3.1E-02	3.7E-04	1.5E-03	2.5E-04	2.5E-02	6.2E-03	2.5E-04
Refined liquids (CC CCS)	2.4E-01	3.1E-02	3.7E-04	1.5E-03	2.5E-04	2.5E-02	6.2E-03	2.5E-04
Refined liquids (steam/CT)	2.4E-01	3.1E-02	3.7E-04	1.5E-03	2.5E-04	2.5E-02	6.2E-03	2.5E-04

[a] NO_x and SO_2 emission factors for coal, gas, and biomass technologies are derived from IPM v5.13. All other emission factors are derived from GREET 2014 assumptions. This data is located in EPA_state_egu_emission_factors_ktPJ_post2015.csv.

Validation:

Figure 2.1 presents comparisons between CEDS + GFED from the GCAM data system (core model), EPA 2016 v1 emissions modeling platform, the GCAM-formatted NEI input, GCAM 5.4, and GCAM-USA values from our branch for pollutant emissions.

Note that there are definitional issues to be considered when comparing emissions data. The GCAM emission values in these graphs only represent electricity generation and not CHP. We note also that only NSPS have been included in these model runs. Other policies, such as the cross-state air pollution rule (CSAPR), are not included.



General Note: The EPA Modeling Platform data plotted on these figures are future projections used by EPA for regulatory and scientific analysis. We include those data for comparisons of near-term GCAM-USA results. In some cases, we find differences between NEI and the EPA modeling platform in historical values, which indicates there is some difference in sectoral definitions between the two datasets. NEI is the more definitive dataset, given its greater detail, for use in evaluating historical GCAM emissions values. The EPA_Tier1_CAPS data was plotted to explain the apparent increase in PM emissions and lack of historical NH3 emissions from GCAM-branch. This is due to a methodology issue with the EPA_Tier1_CAPS, which the NEI is being scaled to, resulting in this behavior in GCAM. This behavior is before 2005 and the impacted pollutants are not the focus of this sector.

2.2 Buildings Sector

Scripts: L274.nonghg_bld_USA.R

Overview: Emission factors for model base-years in this sector are generally calculated by dividing inventory emissions by state, supplysector, subsector, and stub-technology by GCAM fuel consumption (input-driver).

Files Involved: One exogenous file is used in non-GHG building emission factor processing. It is described further in the *Data Sources* section below.

- EPA_resid_wood_furnace_PM_EF_future_factors.csv
  - Emission factor scaling factors, used to linearly decrease emissions from residential wood furnaces out to 2030.

Data Sources:

GCAM-USA Data Sources

Base-year emission factors were calculated from the composite state, fuel, technology level emissions dataset described above. Emission factors for BC and OC were calculated using fractions of $PM_{2.5}$ as described in the methods section.

Future year emission factors for residential wood furnaces are computed based on EPA_resid_wood_furnace_PM_EF_future_factors.csv. This file was created by Dan Loughlin at EPA-ORD based on USA EPA 40 CFR Part 60 and Abt Associates.

CEDS sector 1A4ai_Commercial-institutional-stationary, "Other Combustion - Structural Fires", is mapped to commercial buildings and assigned "Other_Fuels", rather than being considered open burning or waste incineration emissions.

Methods:

Base Year Emission Factors: For the base years, emission factors were calculated based on the composite, scaled emissions data described in section 1 above and calibrated fuel input from GCAM-USA, with the aim of having national emissions in GCAM in the base years equal national emissions in CEDS. These emission factors were computed for CO, NH_3, NMVOC, NOx, PM_{10}, $PM_{2.5}$, and SO_2 in residential and commercial buildings. The input data were available at the state, sector, fuel, and pollutant level. The sector specifications were residential and commercial. The fuel specifications were based on an aggregation from the NEI to CEDS fuel categories: biomass, diesel oil, heavy oil, light oil, hard coal, brown coal, and natural gas. These are mapped to GCAM-USA fuel categories as shown in Table 2.2.1. There is no corresponding category in GCAM for “Process” fuels; therefore, this category is omitted in processing. In 1990, process emissions accounted for 0.21% of total emissions from the buildings sector, in 2005 they were 0.08%, in 2010 they were 0.16%, and in 2015 they were 0.07%.

Table 2.2.1: CEDS to GCAM-USA Mapping

CEDS Fuel	GCAM-USA Fuel
Biomass	Biomass
Diesel oil	Refined liquids
Heavy oil	Refined liquids
Light oil	Refined liquids
Hard coal	Coal
Brown coal	Coal
Anthracite Lignite	Coal
Natural gas	Natural Gas
Process	No correspondence

In GCAM-USA, fuel use in buildings is broken out into several sectors and many technologies. Emission factors were assigned to these technologies based on technology shares computed by dividing the technology fuel use by the corresponding fuel use in the aggregated sector/fuel combination at the same level of specification as the NEI emissions data. This calculation was performed for each state as follows:

$$EmissionFactor_{tech} = \frac{Emissions_{sector,fuel} \times \frac{FuelUse_{tech}}{FuelUse_{sector,fuel}}}{FuelUse_{tech}}$$

For some state/technology combinations with fuel use in the GCAM-USA base year, there were no corresponding emissions. In these cases, the medians of the emission factors in states with both emissions and fuel input data were used in place of emission factors directly calculated from state-level NEI data.

BC and OC emission factors were computed as fractions of $PM_{2.5}$ emissions, using the assumptions listed below. Table 2.2.2 presents a full listing of these fractions and their sources.

- Liquid-fueled residential heating, hot water, appliances, and ‘other’ technologies are assumed to have BC and OC fractions corresponding with LPG and kerosene fuels. This is based on CEDS data and NEMS modeling of residential fuel consumption, which assumes a high proportion of kerosene used in liquid-fueled technologies (AEO, 2017).
- Liquid-fueled commercial technologies are assumed to use distillate fuel oil, also based on data from CEDS and NEMS.
- For coal-fueled commercial heating technologies, fractions for hard coal are used.
- BC and OC fractions for the ‘wood furnace’ technology in the residential sector are computed from $PM_{2.5}$ emissions modeled in the NEI. $PM_{2.5}$ emissions are broken down into PEC (BC), POM and ‘other $PM_{2.5}$’ emissions categories in the NEI. The Residential Wood Combustion Tool is used to model emissions for the NEI (HTAP, 2015).
- Natural gas-fueled technologies currently use the same fractions and could be refined further if better data becomes available, but primary particulate emissions from these technologies is generally low.

Like the electricity sector, in some cases, there were missing values for emission factors at the state/fuel level. In these cases, described under “Missing Values” in section 2.1, a national median emission factor was calculated from existing values and applied to the missing entries. The national median emission factor also replaced existing emission factors outside a threshold. This method is further described below.

Table 2.2.2: Commercial and Residential BC and OC Fractions

Sector	**Fuel**	**Technology**	**Year**	**BC Fraction**	**OC Fraction**	**Source/Justification**
Comm cooking	gas	gas stove		0.06	0.5	Bond et al (Table 5); for all natural gas

Comm cooling	Gas	Gas cooling		0.06	0.5	Bond et al (Table 5); for all natural gas
Comm heating	Biomass	Wood furnace	1990	0.1531	0.7951	Klimont et al; Residential - biomass
Comm heating	Biomass	Wood furnace	2005	0.1682	0.7752	Klimont et al; Residential - biomass
Comm heating	Biomass	Wood furnace	2010	0.1754	0.7649	Klimont et al; Residential - biomass
Comm heating	Coal	Coal furnace		0.2	0.04	Bond et al (Table 5); hard coal, stoker
Comm heating	Gas	Gas furnace / hi-eff		0.06	0.5	Bond et al (Table 5); for all natural gas
Comm heating Comm hot water Comm other	Refined liquids	Fuel boiler / hi-eff Fuel water heater Refined Liquids	1990	0.5869	0.2653	Klimont et al; Residential - other fuels
Comm heating Comm hot water Comm other	Refined liquids	Fuel boiler / hi-eff Fuel water heater Refined Liquids	2005	0.6061	0.3939	Klimont et al; Residential - other fuels
Comm heating Comm hot water Comm other	Refined liquids	Fuel boiler / hi-eff Fuel water heater Refined Liquids	2010	0.602	0.398	Klimont et al; Residential - other fuels
Comm hot water	Gas	Gas water heater / hi-eff		0.06	0.5	Bond et al (Table 5); for all natural gas
Comm other	Gas	Gas		0.06	0.5	Bond et al (Table 5); for all natural gas

Resid. appliances	Gas	Gas appliances		0.06	0.5	Bond et al (Table 5); for all natural gas
Resid. appliances Resid. heating Resid. hot water Resid. other	Refined liquids	Fuel appliances Fuel furnace / hi-eff Fuel water heater / hi - eff Refined Liquids	1990	0.5869	0.2653	Klimont et al; Residential - other fuels
Resid. appliances Resid. heating Resid. hot water Resid. other	Refined liquids	Fuel appliances Fuel furnace / hi-eff Fuel water heater / hi - eff Refined Liquids	2005	0.6061	0.3939	Klimont et al; Residential - other fuels
Resid. appliances Resid. heating Resid. hot water Resid. other	Refined liquids	Fuel appliances Fuel furnace / hi-eff Fuel water heater / hi - eff Refined Liquids	2010	0.602	0.398	Klimont et al; Residential - other fuels
Resid. heating	Biomass	Wood furnace		0.4	0.27	EPA Residential Wood Combustion Tool and NEI 2011 v 1.5 (HTAP, 2015)
Resid. heating	Gas	Gas furnace / hi-eff		0.06	0.5	Bond et al (Table 5); for all natural gas

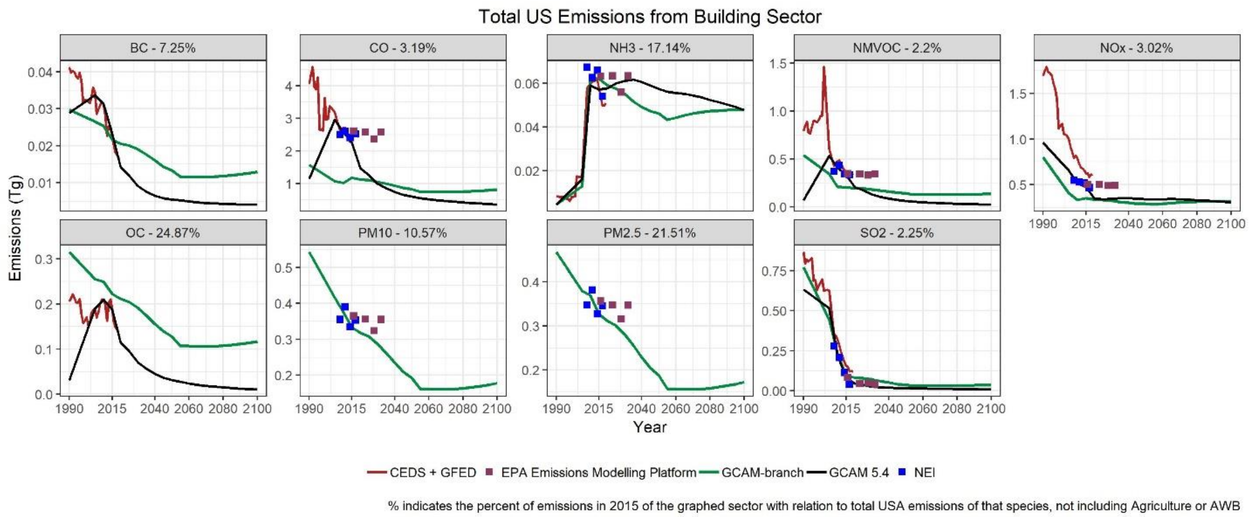
Resid. hot water	Gas	Gas water heater / hi-eff		0.06	0.5	Bond et al (Table 5); for all natural gas

Note: BC/OC fractions without a year associated with them are assumed constant in all years. 2010 values are carried forward to 2015, unless 2015 is specified.

***Future Year Emission Factors*:** At this time, most future year emission factors are assumed constant in the buildings sector. This assumption may be updated as better data or projections become available. The exceptions are BC, OC, $PM_{2.5}$, PM_{10} emission factors for the resid. heating sector wood furnace technology for 2020 – 2030. For these, the corresponding 2015 emission factor is multiplied by a factor to linearly decrease it by 27% in 2030 based on Nonpoint Source Emissions Inventory Tools - Residential Wood Combustion Tool, available at: http://envr.abtassociates.com/nonpoint_nei/index.html.

Validation:

Figure 2.2 presents comparisons between CEDS + GFED from the GCAM data system, EPA 2016 v1 emissions modeling platform, the GCAM-formatted NEI input, GCAM 5.4, and GCAM-USA values from our branch for pollutant emissions.



2.3 Transportation Sector

Scripts: L271.nonghg_trn_USA.R

Overview: Emission factors for model base-years in this sector are primarily from MARKAL for LDV and HDV, and from MOVES for 2W and 3W vehicles, with a couple exceptions detailed below, with some scaling to match inventory emission values. These emission factors are processed to better represent comprehensive fleet emission factors.

Files Involved: Several exogenous files are used in non-GHG transportation emission factor processing. These files are described below.

Data Sources:

GCAM-USA Data Sources

The composite state, fuel, technology level emissions dataset described above is used to scale emissions derived using MARKAL emission factors. This process involves calculating inferred emissions using MARKAL emission factors and GCAM service output. Scaling factors are then calculated using the NEI emissions and inferred MARKAL emissions, and these scaling factors are applied to the MARKAL emission factors.

There are PM2.5 and PM10 non-combustion dust emissions from the on-road sector. These emissions are apportioned to fuels based on on-road combustion emissions, and aggregated with the combustion emissions before being scaled to the EPA State Tier 1 CAPS. This is done in L169.nonghg_NEI_scaling_USA.R (detailed above under *Air Pollutant Trends*), and there is an option to include or exclude these dust emissions via the "gcamusa.DUST" variable in constants.R.

Road sector emissions in the NEI have a discontinuity due to a change in methodology by EPA. For most emission species scaling to CEDS, which does not contain this discontinuity, takes care of this issue. Because $PM_{2.5}$ is not currently estimated in CEDS, and we wish to have consistent BC, OC, and $PM_{2.5}$ emissions for the road sector, we use a different scaling approach for BC, OC, and $PM_{2.5}$ than we do for all other sectors and pollutants. We calculate a CEDS road sector $PM_{2.5}$ estimate by setting two conversion constants (OC to OM and PM_1 to $PM_{2.5}$) broadly applicable to liquid fuels and applying these to CEDS BC and OC emissions. From 2008 forward, we use the NEI values for $PM_{2.5}$ (effectively scaling CEDS to NEI), and the CEDS split between BC and OC. From 2007 back, we obtain a national trend by scaling CEDS. This is done by using the 2008 NEI to CEDS scaling factor and linearly interpolating to a constant value in 1990, and then scaling state level emissions from NEI to the CEDS national trend. This results in national BC, OC, $PM_{2.5}$, and PM_{10} emissions trends that are consistent with the US NEI. We note that this procedure can be used with reasonable accuracy for road transport because small particulate emissions are predominantly from BC and OC because only liquid (or gaseous) fuels are used in this sector. This approach is not applied to PM_{10}, as these emissions are primarily from tire and brake wear.

Emission Factor Data Sources: (gcam-usa/emissions):

- MARKAL_HDV_EFs_gpm.csv**,** MARKAL_LDV_EFs_gpm.csv: Emission factors for HDV and LDVs (originally derived from MOVES)
- MOVES_EV_Efs_ORD.csv: PM_{10} and $PM_{2.5}$ emission factors for light duty electric vehicles (BEV and FCEV).
- GREET2014_LDV_CNG_EFs_tgEJ.csv: LDV CNG emission factors
- MOVES_motorcycle_data.csv: Emissions and distance data for motorcycles to be used for EF calculations

- MOVES_source_type_pop.csv**,** MOVES_VMT_dist.csv, MOVES_src_type_reg_class_fractions.csv**,** MOVES_vehicle_age_fractions.csv: Files used to construct VMT weighted age fractions

Mapping Files: (gcam-usa/emissions):

- MARKAL_MOVES_class.csv: MARKAL to MOVES vehicle classes
- trnMARKAL_UCD_mapping.csv: MARKAL mode, class, and fuel to UCD mode, class, and fuel
- MARKAL_GCAM_mapping.csv: MARKAL vehicle class to GCAM transportation sector
- MOVES_VMT_dist_missing_mapping.csv: Maps VMT distributions from similar vehicle source classes for needed types that are missing
- MARKAL_UCD_HDV_fuel.csv: MARKAL to UCD fuels HDVs
- MARKAL_UCD_LDV_fuel.csv: MARKAL to UCD fuels for LDVs

Methods:

Because of inconsistencies between different data sets we cannot simply estimate state level transportation emissions by dividing emissions by fuel consumption. This is because there can be substantial mismatches between EPA estimated state-level activity data (based on vehicle-miles) and EIA fuel consumption (used in GCAM), which is based on fuel sales by state. Also, there are mismatches between the vehicle categories used in the NEI as compared to the vehicle categories used in GCAM. The methods described below were developed to provide a reasonable state and technology level emissions estimate for GCAM given these issues.

Base Year Emission Factors: Non-GHG emissions in the transportation sector of GCAM-USA use emission factors developed for MARKAL, provided by Dan Loughlin at EPA-ORD. For light duty vehicles using compressed natural gas (CNG), emission factors came from the GREET1-2014 spreadsheet model, prepared by Argonne National Laboratory (ANL, 2014, and Wang & Elgowainy, 2014). BEV and FCEV vehicles are developed using a single MARKAL fuel, "ELC", as they are not distinguished further.

Emission factor data was provided for vehicle vintages over 2005-2050. Data was provided in grams per vehicle-mile traveled for nine U.S. Census regions, seven unique light-duty vehicle classes (mini car, compact car, full size car, minivan, small SUV, large SUV, and pickup), 13 unique vehicle fuels, and eleven unique species of pollutant (BC, OC, CO, NH_3, SO_2, NO_x, VOC, $PM_{2.5}$, PM_{10}, CH_4, CO_2, and N_2O). Similarly, emission factor data was provided for four unique heavy-duty vehicle classes (bus, commercial truck, heavy duty short haul truck, and heavy-duty long-haul truck), with six corresponding unique fuels. Emission factors were assumed to be constant among states within each census region.

Emission factor data from GREET1-2014 for light-duty vehicles using CNG included the following vehicle technologies: spark injection internal combustion engine (SI ICE), SI hybrids (SI HEV), fuel cells (FCV), and SI plug-in hybrids (SI PHEV). Data was provided in mg per vehicle-mile traveled and mg/MJ.

Although GCAM-USA's transportation sector is vintaged, a composite emission factor is developed for the base years that takes into account emission factors of all vehicles that are on the road in those years. To develop this composite emission factor, weights are computed that consider the population and activity of vehicles in the base years by age as derived from MARKAL/MOVES data. The data used to compute these weights are taken from the MOVES model.

Vehicle age fractions were developed for each vehicle technology in the base years. These age fractions were grouped into classes of 0-4, 5-9, 10-14, and greater than 15-year-old vehicles. Age fractions were then multiplied by a VMT weight, calculated as the ratio of the VMT of a vehicle of a certain age divided by the VMT of a vehicle aged 0-4 years using data from MOVES_VMT_dist.csv. For MARKAL categories using more than one MOVES source type ID (buses and long and short-haul trucks), these VMT-weighted age fractions were then multiplied by the share of each source type ID in the total MARKAL category.

Vintaged MARKAL emission factors were weighted by these VMT-weighted age fractions to produce a composite emission factor for the base years. All emission factors were converted to output-based units (Tg / million pass-km for LDVs, and Tg / million ton-km for HDVs).

***Future Year Emission Factors*:** Future year emission factors were taken directly from the MARKAL data for a given year and vintage and converted to the appropriate units. For example, the emission factor for a vehicle in 2025 is the factor given in MARKAL for a 2025 vintage in the year 2025.

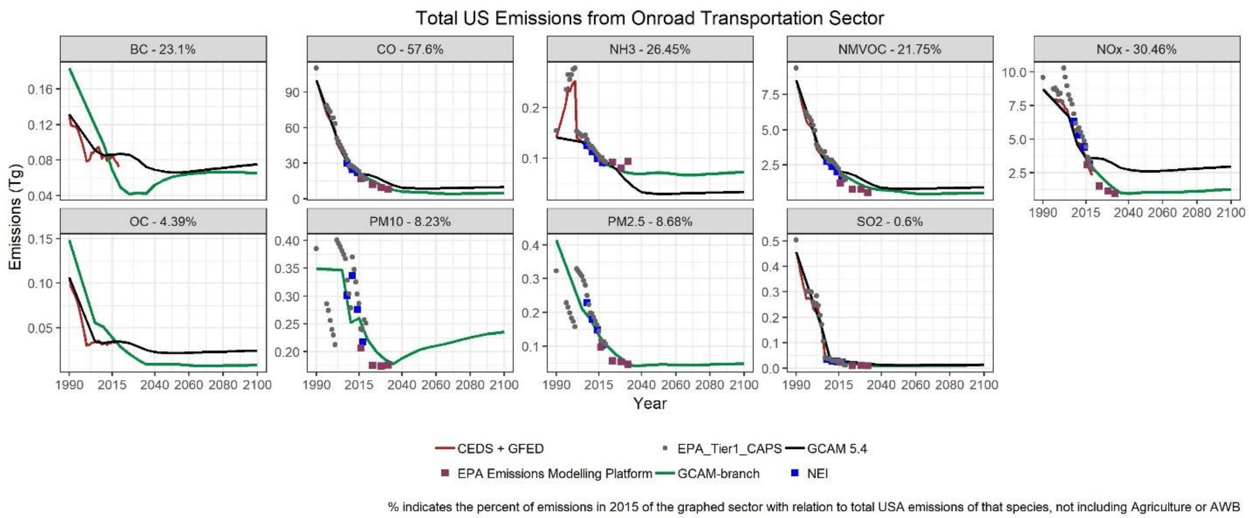
***Emission Factor Controls*:** We also need to take into account that as vehicles age, their relative emissions tend to increase. Also, however, vehicles are used less as they age, and older vehicles retire. These factors are taken into account as follows.

Current base year evolution: For the current base year, emission factors were given evolution rates over time according to a linear control function. A start year, end year, and final emission factor were required as inputs to the linear control function. For each vehicle vintage, technology, and pollutant, the start year was defined as the vehicle vintage year (last model base year), the end year as the sum of the start year and the technology's lifetime assumption for GCAM-USA, and the final emission factor was determined using a linear fit. An emission factor time series for each vehicle and fuel type was calculated as a sum product from the MARKAL weighted emission factors that captured the counteracting behaviors of older vintages retiring while new vintages aged. For example, as older vintages retire, the average emission factor in a given period would decrease, while as the remaining vehicles age, the average emission factor across the fleet for that aggregate base-year vintage would increase. We capture this behavior by taking the emission factors in a given period only for vintages that are less than or equal to the current base year vintage and using age fractions to compute a fleet-average emission factor for each future year as the base-year stock ages.

Future year degradation: For future vintages, we treat each vintage as one lump. Emission factors were given degradation rates over time according to a linear control function just like the current base year, but the values were taken directly from the MARKAL emission factor time series for each vintage and converted to GCAM’s preferred units.

Validation:

Figure 2.3 presents comparisons between CEDS + GFED from the GCAM data system, EPA 2016 v1 emissions modeling platform, the GCAM-formatted NEI input, GCAM 5.4, and GCAM-USA values from our branch for pollutant emissions.



2.4 Other Transportation Sector

The Other Transportation Sector includes GCAM trn_freight - Domestic Ship, trn_freight - Freight Rail, trn_pass - Passenger Rail, and trn_pass - Domestic Aviation.

Scripts: L176.nonghg_othertrn_USA.R, L276.nonghg_othertrn_USA.R

Overview: Emission factors for model base-years in this sector are generally calculated by dividing inventory emissions by state, sector, and stub-technology by GCAM fuel consumption (input-driver). Domestic shipping emission factors come from an exogenous source, described below.

Files Involved: One exogenous file is used in non-GHG other transportation emission factor processing. It is described further in the *Data Sources* section below.

- IMO_Shipping_EF.csv
    - Emission factors for domestic shipping

Data Sources:

GCAM-USA Data Sources

Base-year emission factors were calculated from the composite state, fuel, technology level emissions dataset described above. Emission factors for BC and OC were calculated using fractions of $PM_{2.5}$ as described in the methods section.

Emission Factor Data Sources: (gcam-usa/emissions):

- IMO_Shipping_EF.csv: National domestic shipping emission factors by pollutant and CEDS fuel, obtained from the Fourth International Maritime Organization's GHG Study 2020 (MEPC 75-7-15)

Methods:

Base Year Emission Factors:

Rail: NEI does not distinguish emissions from passenger and freight rail, so technology shares are calculated from GCAM calibrated fuel input to distribute emissions. Emission factors were then calculated based on the shared emissions data from the composite, scaled emissions data described in section 1 above, and calibrated fuel input from GCAM-USA, with the aim of having national emissions in GCAM in the base years' equal national emissions in CEDS. BC and OC emission factors were computed as fractions of $PM_{2.5}$ emissions, using the assumptions listed below in Table 2.4.1.

Domestic Aviation, International Aviation, and International Shipping: Receive a national emission factor that is assigned to every US state. To compute a national emission factor, emissions from NEI was aggregated nationally by tranSubsector, year, and pollutant, and calibrated fuel inputs from GCAM were aggregated nationally by tranSubsector and year. Emission factors were calculated from this nationally aggregated data. BC and OC emission factors were computed as fractions of $PM_{2.5}$ emissions, using the assumptions listed below in Table 2.4.1. PM_{10} EFs for International Shipping were computed as a ratio of $PM_{2.5}$ EFs, with the ratio calculated from the EPA US inventory modelling platform 2016v2.

In some cases, there were missing values for emission factors at the state/fuel level. In these cases, described under "Missing Values" in section 2.1, a national median emission factor was calculated from existing values and applied to the missing entries. The national median emission factor also replaced existing emission factors outside a threshold. This method is further described below.

Domestic Shipping: GCAM fuel consumption will not, in general, correspond with NEI values for domestic shipping, so these emission factors, for most species, were from a study by the International Maritime Organization (IMO). IMO provides emission factors for CO, NO_x, NMVOC, SO_x (interpreted as SO_2), PM (interpreted as PM_{10}), $PM_{2.5}$, and BC for three CEDS fuels (heavy_oil, diesel_oil, and natural_gas) for years 2012 through 2018. There is only one fuel for domestic shipping in GCAM (Liquids), so these emission factors were weighted to create "Liquids", assuming it is composed of 60% residual fuel and 40% diesel. 2012 emission factors were carried back to previous base years, 2015 was used for the current base year of 2015, and

2018 was carried to the future years. In the future, a different data source should be used for the historical years before 2015, as domestic shipping has changed notably in the last decade.

Table 2.4.1: Freight and Passenger Transportation BC and OC Fractions

Sector	tranSubsector	Fuel	Year	BC Fraction	OC Fraction	Source/Justification
trn_freight trn_freight trn_pass trn_pass	Freight Rail Domestic Ship Passenger Rail Domestic Aviation	Liquids	1990	0.4475	0.3366	Klimont et al; non-road transport - diesel
trn_freight trn_freight trn_pass trn_pass	Freight Rail Domestic Ship Passenger Rail Domestic Aviation	Liquids	2005	0.4338	0.3528	Klimont et al; non-road transport - diesel
trn_freight trn_freight trn_pass trn_pass	Freight Rail Domestic Ship Passenger Rail Domestic Aviation	Liquids	2010	0.4299	0.3566	Klimont et al; non-road transport - diesel
trn_aviation_intl	International Aviation	Liquids		0.7	0.2	Bond et al (Table 7); for Aviation fuel, aircraft
trn_shipping_intl	International Shipping	Liquids		0.66	0.21	Bond et al (Table 7); for Diesel and heavy oil, ships

Note: BC/OC fractions without a year associated with them are assumed constant in all years. 2010 values are carried forward to 2015, unless 2015 is specified.

Future Year Emission Factors:

Rail and Aviation: Emission factors from the current base year are carried forward to future years.

Shipping: Aside from SO_2, emission factors from the current base year are carried forward to future years. The diesel standard past 2012 is 15ppm sulfur, and as per US EPA 2009, Category 3 marine engines have a sulfur limit of 1,000ppm for marine fuels produced and/or sold for use within and emissions control area. This includes all domestic shipping, so a new emission factor for SO_2 is calculated based on these policy limits and applied to future years.

Validation:

Figure 2.4 presents comparisons between CEDS + GFED from the GCAM data system, EPA 2016 v1 emissions modeling platform, the GCAM-formatted NEI input, GCAM 5.4, and GCAM-USA values from our branch for pollutant emissions.

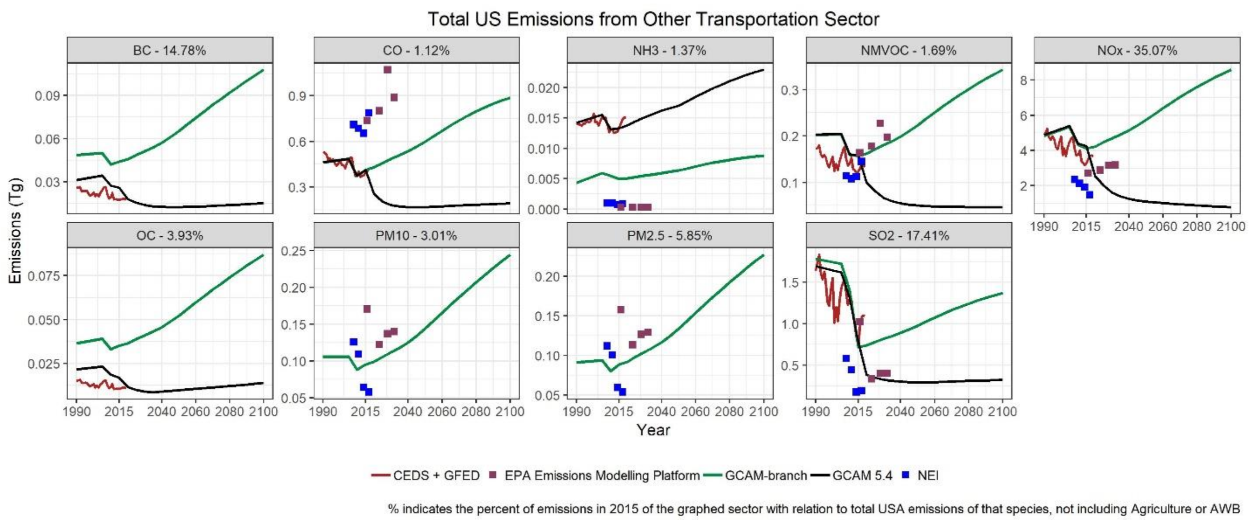


Figure 2.4: Note that emissions increase in future periods due to base year emission factors being carried forward, and there is a dip in 2010 due to the 2008 recession. In a future CMP, future period EFs will be updated.

2.5 Industrial Energy Sector

Scripts: L275.nonghg_indenergy_USA.R

Overview: Emission factors for model base-years in this sector are generally calculated by dividing inventory emissions by fuel, state, and sector by GCAM fuel consumption (input-driver).

Files Involved: One exogenous file is used in non-GHG industrial energy use emission factor processing. It is described further in the *Data Sources* section below.

- MARKAL_nonghg_indenergy_tech_coeff_USA_dhl.csv

- Industrial emission factors for future years

Data Sources:

GCAM-USA Data Sources

Base-year emission factors were calculated from the composite state, fuel, technology level emissions dataset described above. Emission factors for BC and OC were calculated using fractions of $PM_{2.5}$ as described in the methods section.

Emission Factor Data Sources: (gcam-usa/emissions):

- MARKAL_nonghg_indenergy_tech_coeff_USA_dhl.csv
  - Industrial emission factors for coal, gas, biomass, and refined liquids by US state for future years from MARKAL. This is assuming industrial sector vintaging is being used, which could lead to discontinuity if not. These values come from Dan Loughlin (EPA)'s calculations based on GREET 2014 and market shares estimated using the EPA US nine-region MARKAL database.

Methods:

***Base Year Emission Factors*:** The technology information in the industrial energy use sector has the same level of detail as the NEI data, so we calculate emission factors based on emissions data from the composite, scaled emissions data described in section 1 above and calibrated fuel input from GCAM-USA, with the aim of having national emissions in GCAM in the base years equal national emissions in CEDS. BC and OC emission factors were computed as fractions of $PM_{2.5}$ emissions, using the assumptions listed below in Table 2.5.1.

In some cases, there were missing values for emission factors at the state/fuel level. In these cases, described under “Missing Values” in section 2.1, a national median emission factor was calculated from existing values and applied to the missing entries. The national median emission factor also replaced existing emission factors outside a threshold. This method is further described below.

Table 2.5.1: Industrial Energy Use BC and OC Fractions

Sector	**Subsector**	**Fuel**	**Year**	**BC Fraction**	**OC Fraction**	**Source/Justification**
industrial energy use	coal	coal		0.200	0.04	Bond et al (Table 5); hard coal, stoker
industrial energy use	coal	coal cogen		0.006	0.00	Bond et al (Table 5); hard coal, pulverized
industrial energy use	gas	gas		0.060	0.50	Bond et al (Table 5); for all natural gas

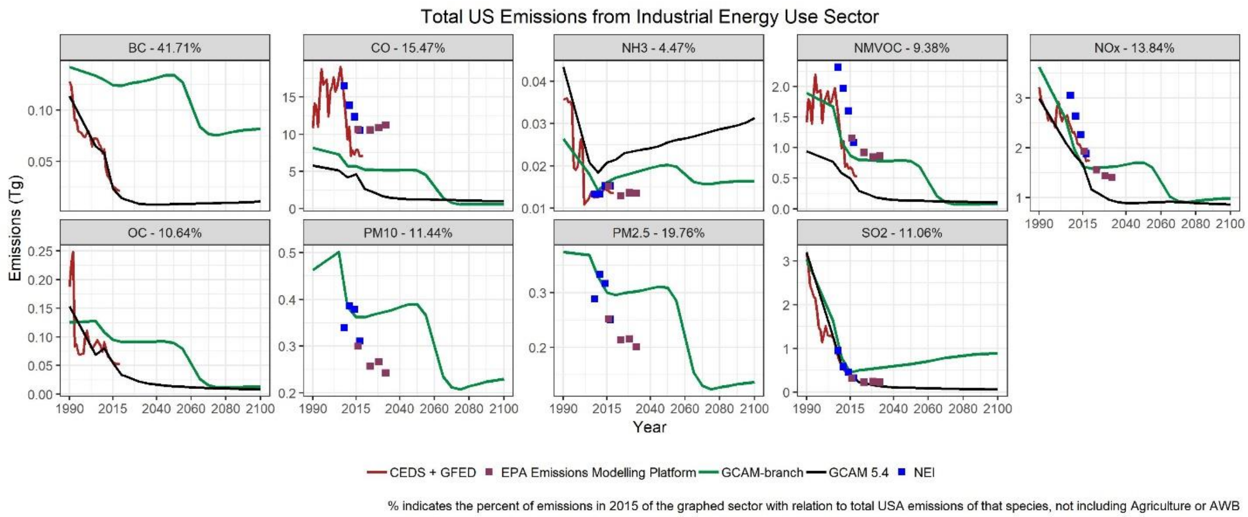
industrial energy use	gas	gas cogen		0.060	0.50	Bond et al (Table 5); for all natural gas
industrial energy use	refined liquids	refined liquids refined liquids cogen	1990	0.4475	0.3366	Klimont et al; non-road transport - diesel
industrial energy use	refined liquids	refined liquids refined liquids cogen	2005	0.4338	0.3528	Klimont et al; non-road transport - diesel
industrial energy use	refined liquids	refined liquids refined liquids cogen	2010	0.4299	0.3566	Klimont et al; non-road transport - diesel
industrial energy use	biomass	biomass biomass cogen	1990	0.4147	0.3133	Derived using ECLIPSE_V6b emissions data
industrial energy use	biomass	biomass biomass cogen	2005	0.4743	0.2798	Derived using ECLIPSE_V6b emissions data
industrial energy use	biomass	biomass biomass cogen	2010	0.4966	0.2667	Derived using ECLIPSE_V6b emissions data
industrial energy use	biomass	biomass biomass cogen	2015	0.5156	0.255	Derived using ECLIPSE_V6b emissions data

Note: BC/OC fractions without a year associated with them are assumed constant in all years. 2010 values are carried forward to 2015, unless 2015 is specified.

***Future Year Emission Factors*:** Future year emission factors out to 2050 were provided by Dan Loughlin from MARKAL for all industrial energy use technologies and pollutants with the exception of NH_3. Emission factors for model years after 2055 were assumed to be constant.

Validation:

Figure 2.5 presents comparisons between CEDS + GFED from the GCAM data system, EPA 2016 v1 emissions modeling platform, the GCAM-formatted NEI input, GCAM 5.4, and GCAM-USA values from our branch for pollutant emissions.



2.6 Industry and Urban Process Emission Sectors and Cement

Specifically, industry_processes, landfills, solvents, waste_incineration, wastewater treatment, and cement sectors.

Scripts: L277.nonghg_prc_USA.R

Overview: Emissions for model base-years in this sector come from the composite state, fuel, technology dataset described above.

Files Involved: There are no exogenous files is used in non-GHG industry and urban emissions processing.

Data Sources:

GCAM-USA Data Sources

Base-year input emissions for process and cement sectors were taken from the composite state, fuel, technology level emissions dataset described above.

Methods:

Base Year Emissions**:** For industry and urban processing and cement sectors, we use input emissions rather than emission factors. Emissions are taken directly from L170.NEI_1990_2017_GCAM_sectors and assigned to the appropriate GCAM sectors, supplysectors, subsectors, and technologies. BC and OC emissions were computed as fractions of $PM_{2.5}$ emissions, using the assumptions listed below in Table 2.6.1.

Table 2.6.1: Urban Processes BC and OC Fractions

Sector	**Subsector**	**Year**	**BC Fraction**	**OC Fraction**	**Source/Justification**
urban processes	waste_incineration		0.06426	0.52102	CEDS

Note: BC/OC fractions without a year associated with them are assumed constant in all years. 2010 values are carried forward to 2015, unless 2015 is specified.

Future Year Emissions: Not applicable.

Maximum Reduction and Steepness: For non-combustion emissions such as these, we don't really have a proper driver of, for example, waste disposed, so the GCAM driver is some combination of population and income driven. Because of this we have some generic controls to make sure emissions don't continuously grow into the future for these process sectors. Therefore, we adopt the USA level max reduction and steepness values for GDP controls for air pollutants for these sectors at the US state level. These parameters should be re-evaluated for any study for which these emissions are important.

Validation:

Figure 2.6 presents Industry Processes comparisons between CEDS + GFED from the GCAM data system, EPA 2016 v1 emissions modeling platform, the GCAM-formatted NEI input, GCAM 5.4, and GCAM-USA values from our branch for pollutant emissions.

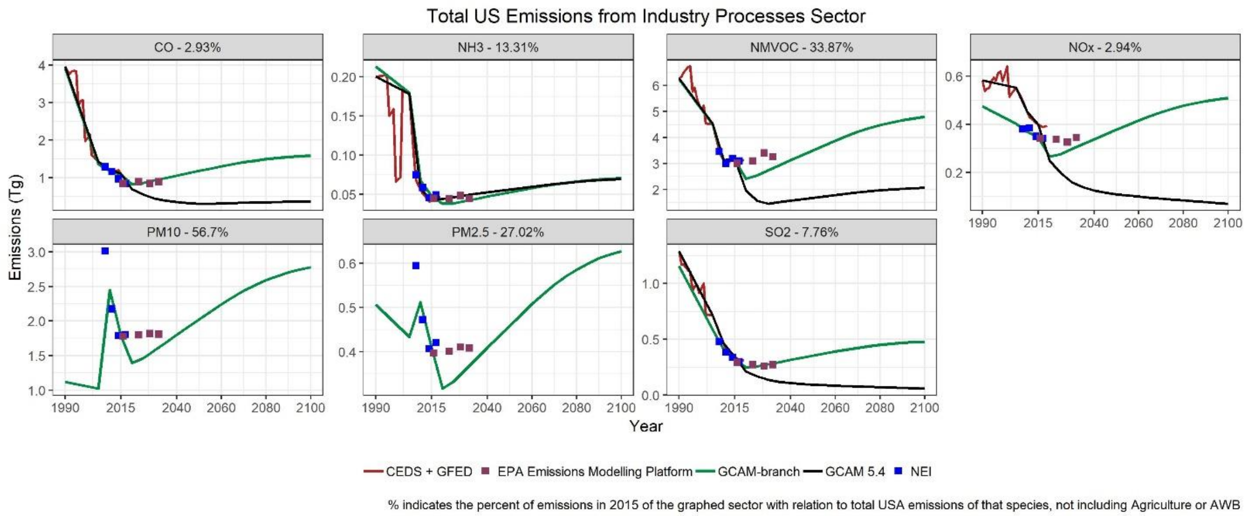


Figure 2.7 presents Urban Processes comparisons between CEDS + GFED from the GCAM data system, EPA 2016 v1 emissions modeling platform, the GCAM-formatted NEI input, GCAM 5.4, and GCAM-USA values from our branch for pollutant emissions.

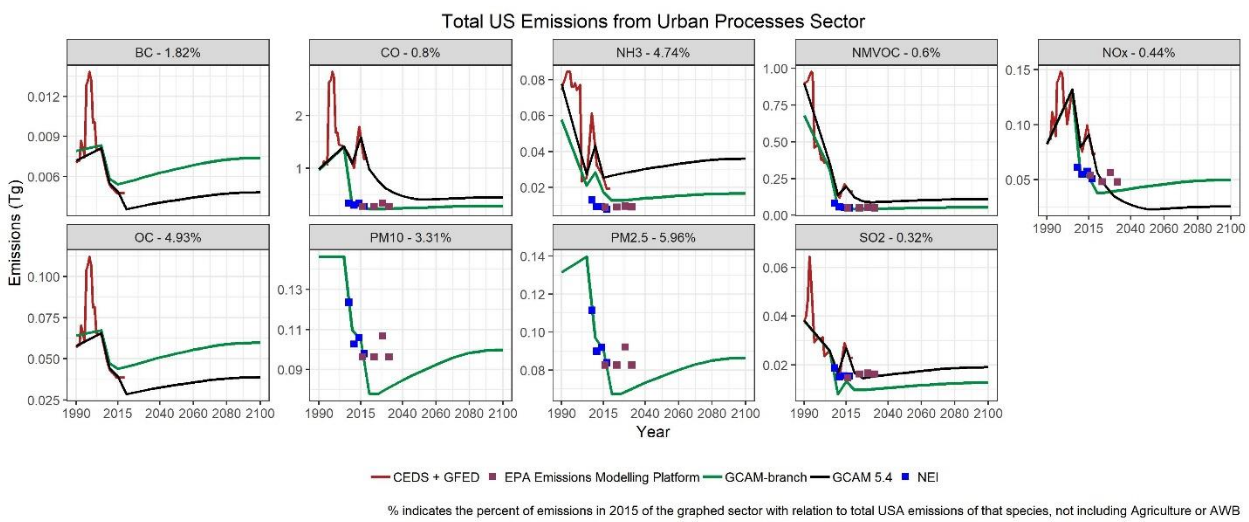
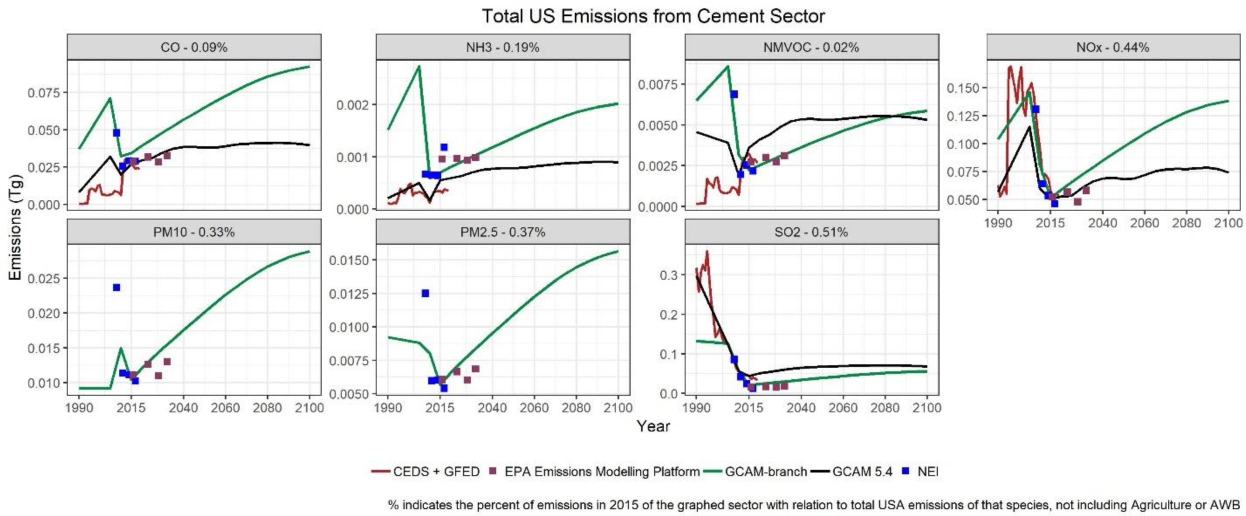


Figure 2.8 presents Cement comparisons between CEDS + GFED from the GCAM data system, EPA 2016 v1 emissions modeling platform, the GCAM-formatted NEI input, GCAM 5.4, and GCAM-USA values from our branch for pollutant emissions.



Future Development: In the future, cement emissions should be assigned to "process heat cement" and have emission factors. Most of the cement emissions being processed in these chunks are not actually process emissions, except for $PM_{2.5}$.

2.7 Refining Sector

Scripts: L273.nonghg_refinery_USA.R

Overview: Emissions for model base-years in this sector come from the composite state, fuel, technology dataset described above. Further development is needed for this sector to include all combustion emissions.

Files Involved: There are no exogenous files used in non-GHG refining emissions processing.

Data Sources:

GCAM-USA Data Sources

Base-year input emissions for refining sectors were taken from the composite state, fuel, technology level emissions dataset described above.

Methods:

***Base Year Emissions*:**

Natural Gas Production, Petroleum Production: We have aggregate natural gas production + distribution and petroleum production emissions at the state level from NEI, and energy consumption from GCAM at the USA level. Because resource production has vintaging in the base years, we replaced the oil_gas emissions from CEDS with those from NEI in module_emissions_L112.ceds_ghg_en_R_S_T_Y and kept the rest of the processing as is. Natural gas and petroleum production are assigned the same emissions factors in all_energy_emissions.xml.

Natural Gas Distribution: Currently aggregated with Natural Gas Production. Distribution is done at the grid region level, not state. If we want these emissions at a state level, we need to restructure and have a state level secondary sector.

Petroleum Distribution: This is done at the grid region level, not state. If we want these emissions at a state level, we need to restructure and have a state level secondary sector.

Petroleum Refining: We have petroleum refining emissions by state from NEI, so just assign these to the correct GCAM supplysectors, subsectors, and technologies.

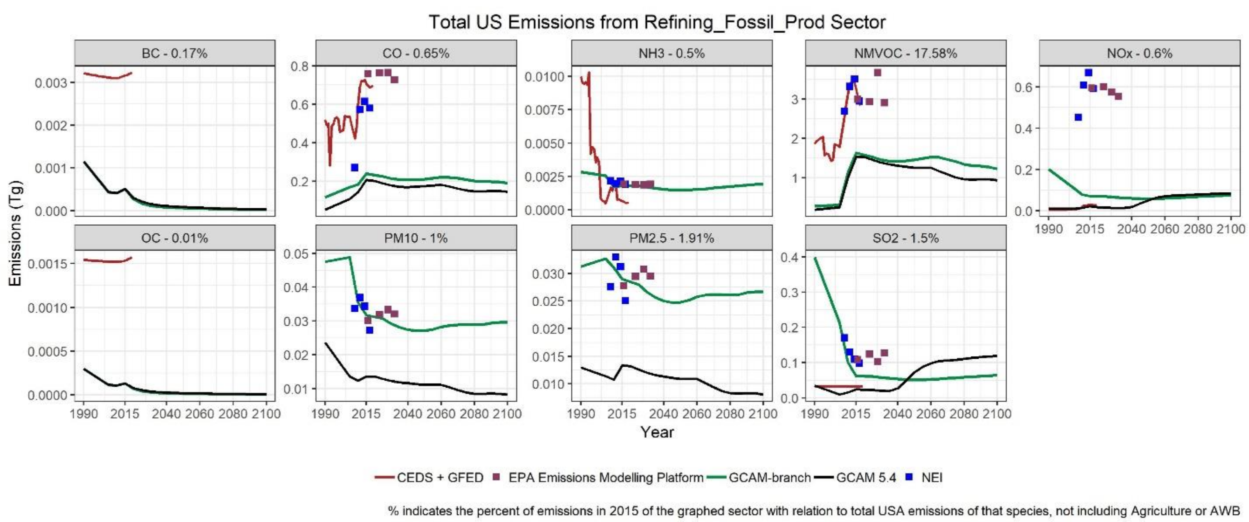
Ethanol Production: We have ethanol production emissions by state from NEI, so just assign these to the correct GCAM supplysectors, subsectors, and technologies.

Biodiesel Production: We have biodiesel production emissions by state from NEI, so just assign these to the correct GCAM supplysectors, subsectors, and technologies.

Future Year Emissions**:** Emissions are not assigned to the future years as this data is not available.

Validation:

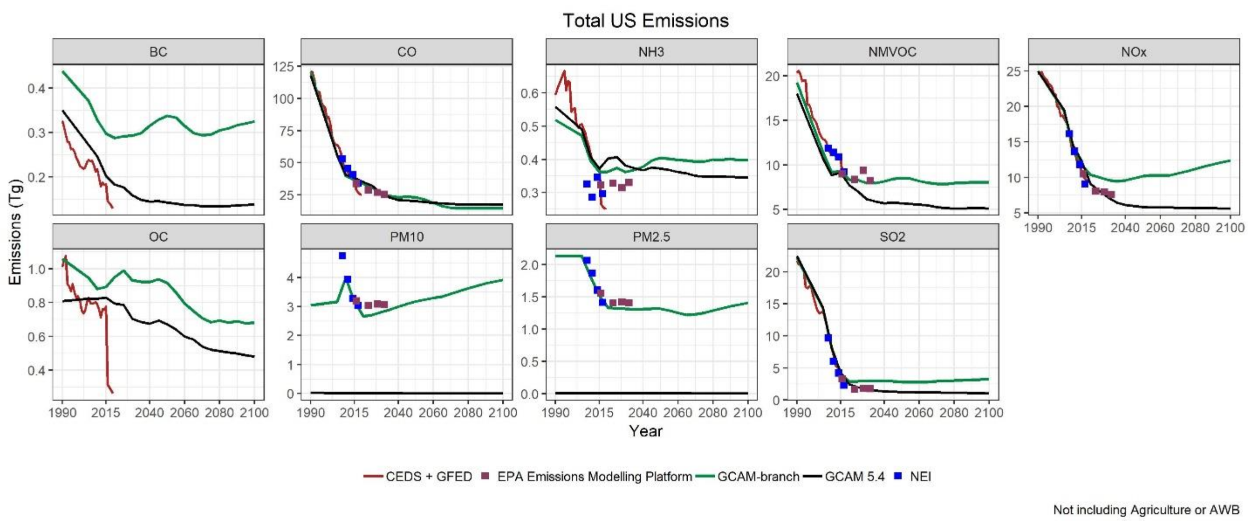
Figure 2.9 presents comparisons between CEDS + GFED from the GCAM data system, EPA 2016 v1 emissions modeling platform, the GCAM-formatted NEI input, GCAM 5.4, and GCAM-USA values from our branch for pollutant emissions.



Future Developments: In the future, for refining technologies not present in the historical data (cellulosic ethanol, etc.) we will get emission factors from GREET or some other source and use a new method (CMP #336) that allows users to drop files containing emission factors into a folder that is processed into the appropriate GCAM format.

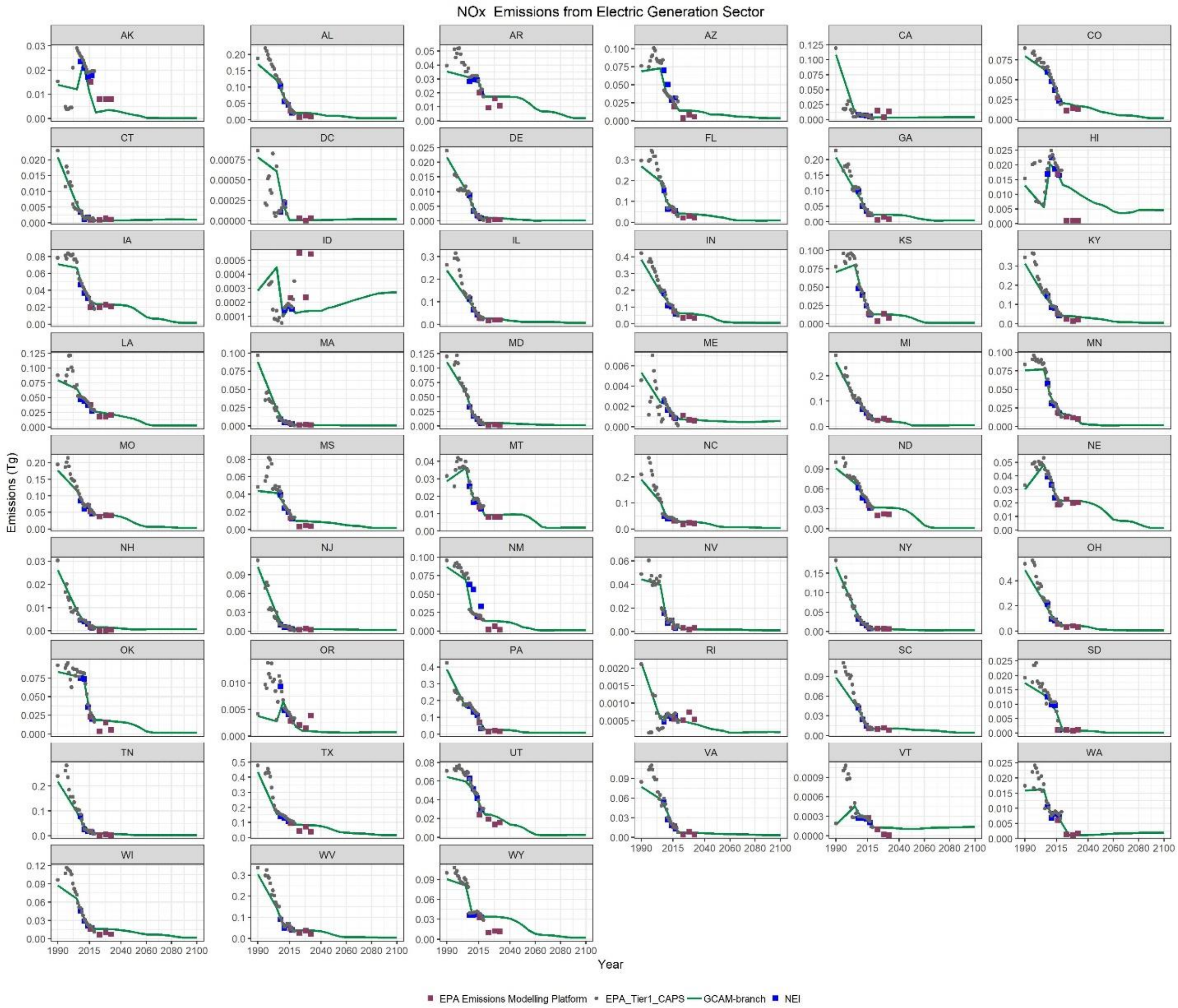
3. National Results

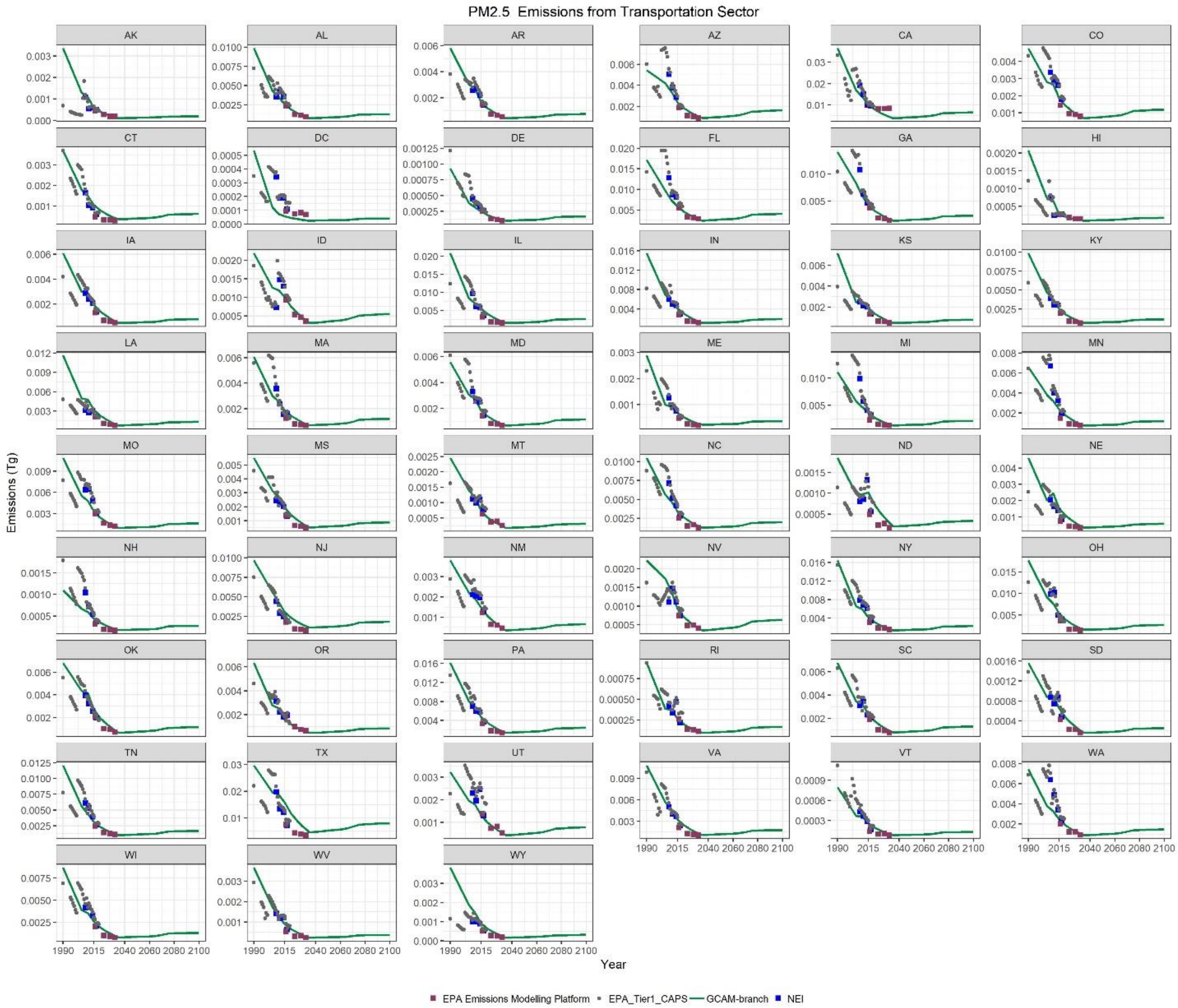
The results shown in Figure 3.1 are aggregate emissions totals for the USA by pollutant, not including Agriculture or Agriculture Waste Burning emissions. The comparison includes CEDS + GFED from the GCAM data system, EPA 2016 v1 emissions modeling platform, the GCAM-formatted NEI input, GCAM 5.4, and GCAM-USA values from our branch for pollutant emissions.



4. State Level Results

Figures 4.1 and 4.2 are examples of sectoral emissions by state and pollutant from EPA 2016 v1 emissions modeling platform, EPA Tier 1 CAPS, the GCAM-formatted NEI input, and GCAM-USA values from our branch for pollutant emissions. The datasets included vary by sector, and because the EPA modeling platform and NEI do not include BC or OC and these values are based on PM2.5, these pollutants are not included.


NOx Emissions from Electric Generation Sector
AK
AL
AR
AZ
CA
CO
CT
DC
DE
FL
GA
HI
IA
ID
IL
IN
KS
KY
LA
MA
MD
ME
MI
MN
MO
MS
MT
NC
ND
NE
NH
NJ
NM
NV
NY
OH
OK
OR
PA
RI
SC
SD
TN
TX
UT
VA
VT
WA
WI
WV
WY
Emissions (Tg)
Year
EPA Emissions Modelling Platform
EPA_Tier1_CAPS
GCAM-branch
NEI

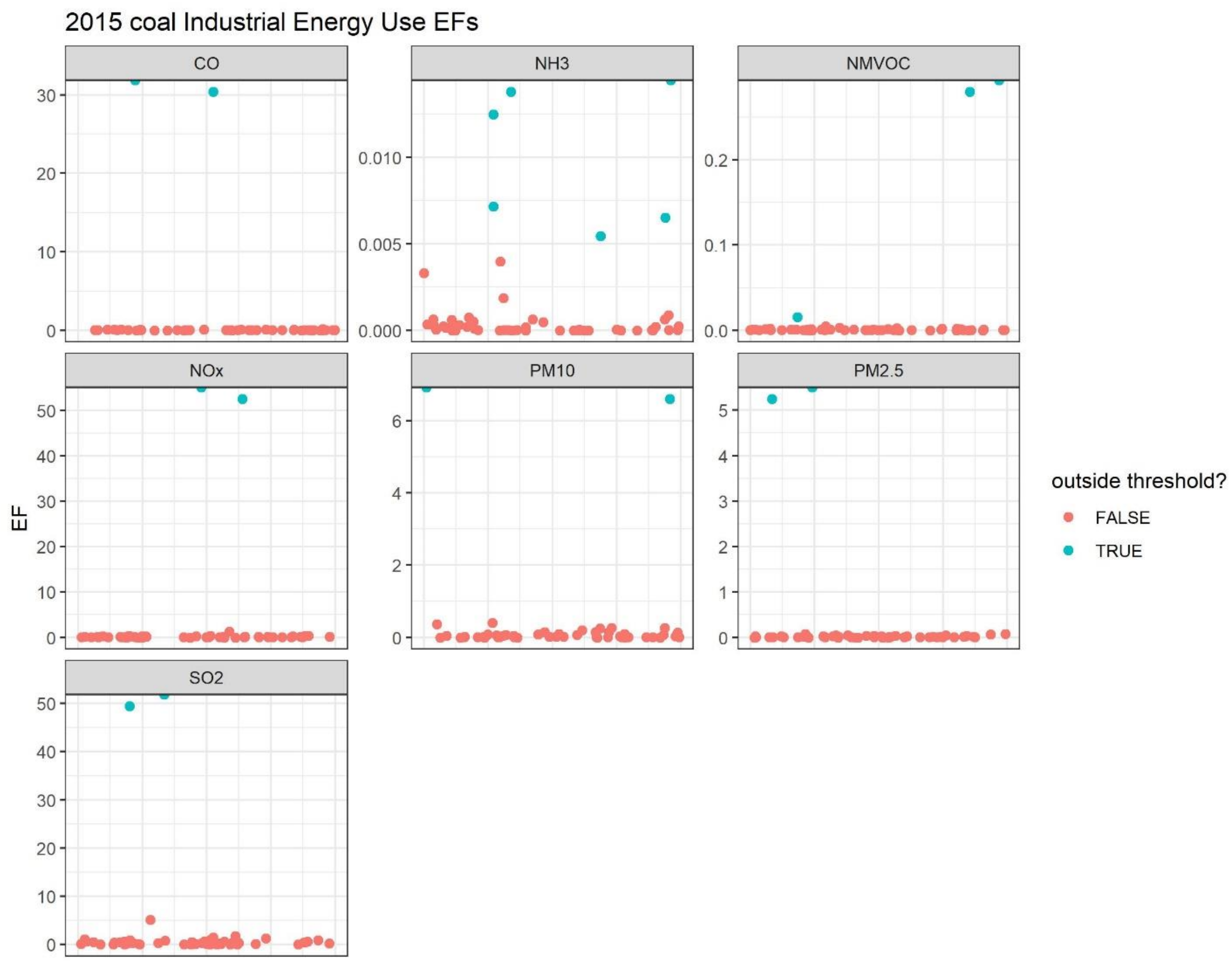


5. Additional Items

Emission Factor Thresholds Adjustment**:** Because, for many sectors, we estimate an implied emission factor by dividing emissions by fuel consumption (or other activity), inconsistencies between datasets can result in unrealistically large emission factors, which can skew results if those technologies become more important in the future. To ensure there are no unreasonable base year emission factors in sectors where emission factors are calibrated from NEI emissions and GCAM fuel consumption, a systematic approach was taken to replace values above a defined threshold with the national median for that specific supplysector / subsector / technology / pollutant. It was assumed that any emission factor greater than the national median * 20 was an unreasonable value, and was replaced with the respective national median.

One instance where this is executed is in electric generation in Hawaii. For example, Hawaii has a computed emission factor of 39.15 for coal-fueled NO_x emissions in 1990, due to large input emissions from NEI and low fuel consumption from GCAM. The national median for coal-NO_x in this sector in 1990 is 0.25, making Hawaii's emission factor over 7x the threshold of 0.25 *

20. So, Hawaii's emission factor was replaced with the respective national median. Figure 5.1 shows an example of this threshold being applied.



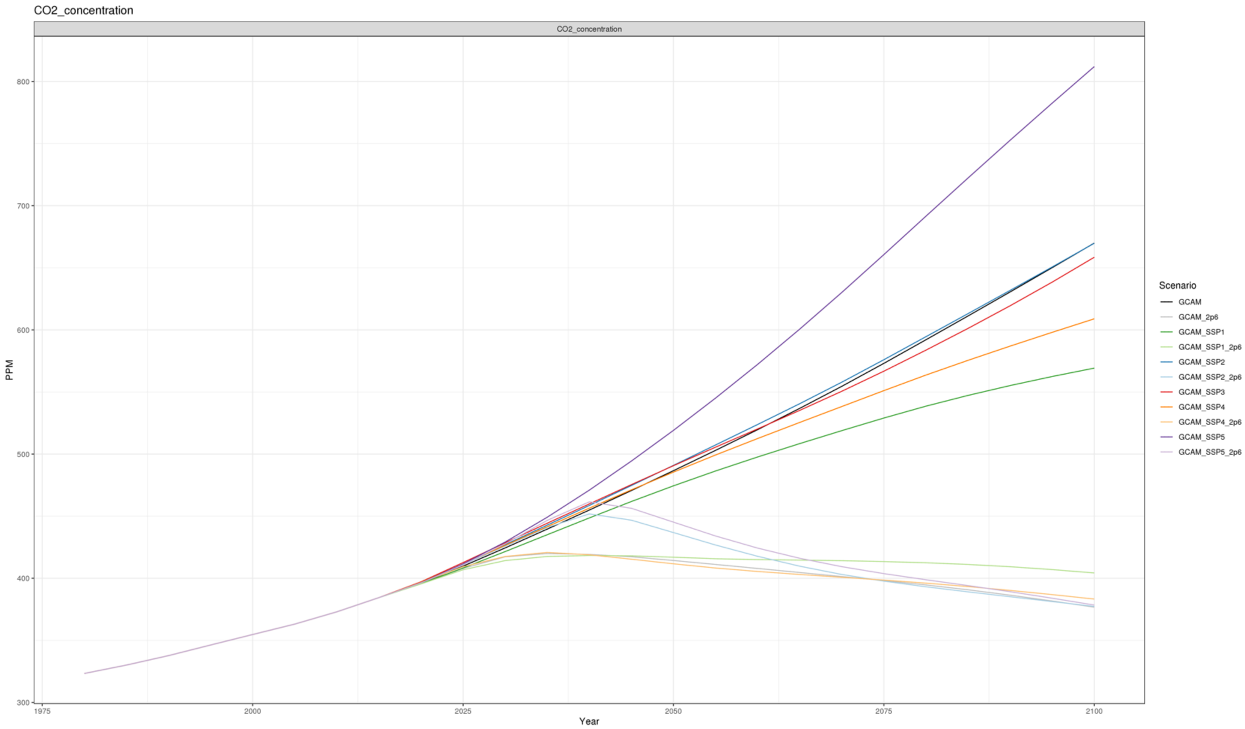
C++ Code Changes: In cvs/objects/emissions/include, linear_control.h and linear_control.cpp were added to. These additions allow the linear control object to reduce emissions based on a percentage reduction as an alternative to specifying the final emissions coefficient.

Core vs Branch Diagnostics:

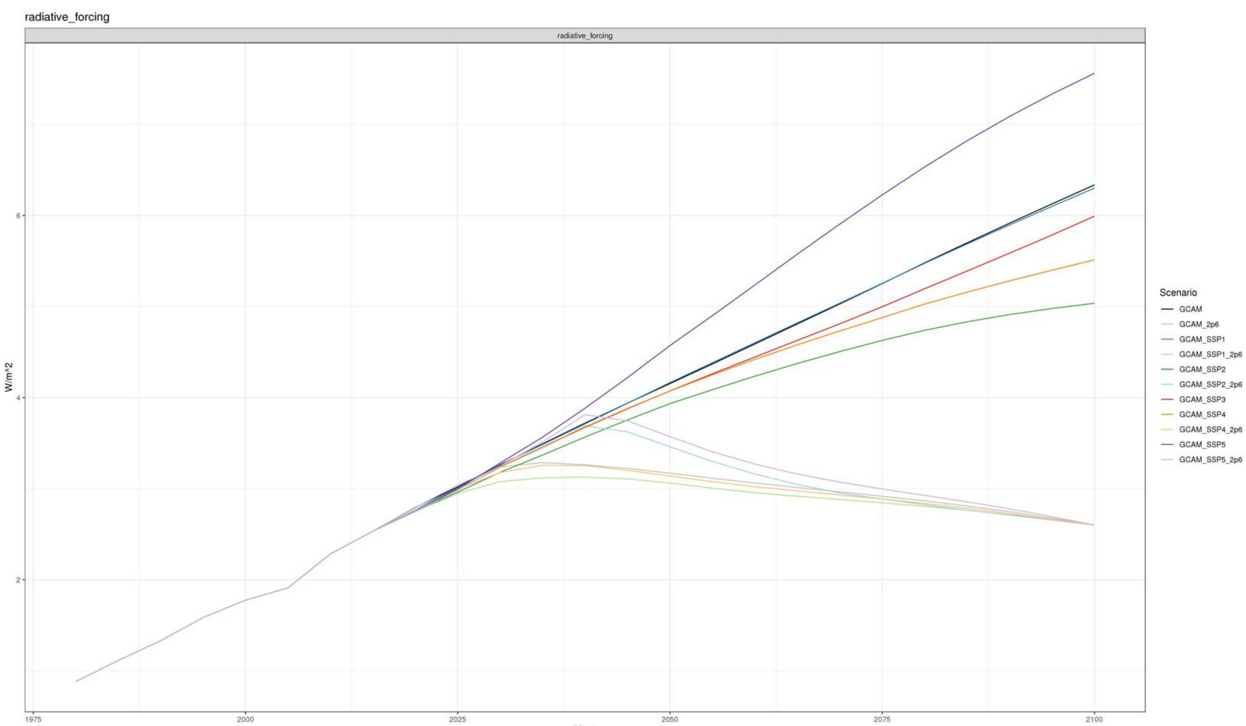
The results shown in Figures 5.2 - 5.8 are reference runs for this branch vs GCAM-core, and show that the C++ changes do not change the model results for two basic queries.

The results shown in Figure 5.10 compare a GCAM-USA reference run vs a GCAM-USA carbon tax run, showing the behavior of different pollutants in a policy scenario.

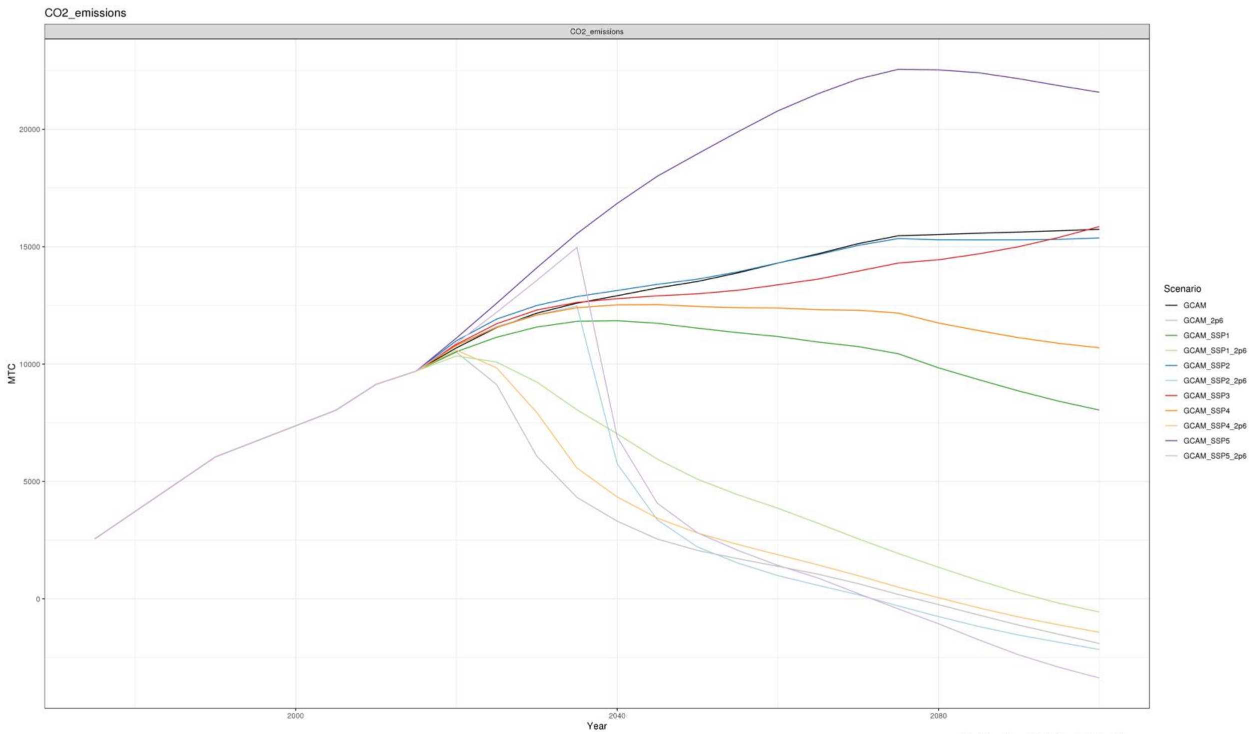
The results shown in Figure 5.11 compare a GCAM-USA reference run vs a GCAM-USA carbon tax run, showing the behavior of climate variables in each scenario.



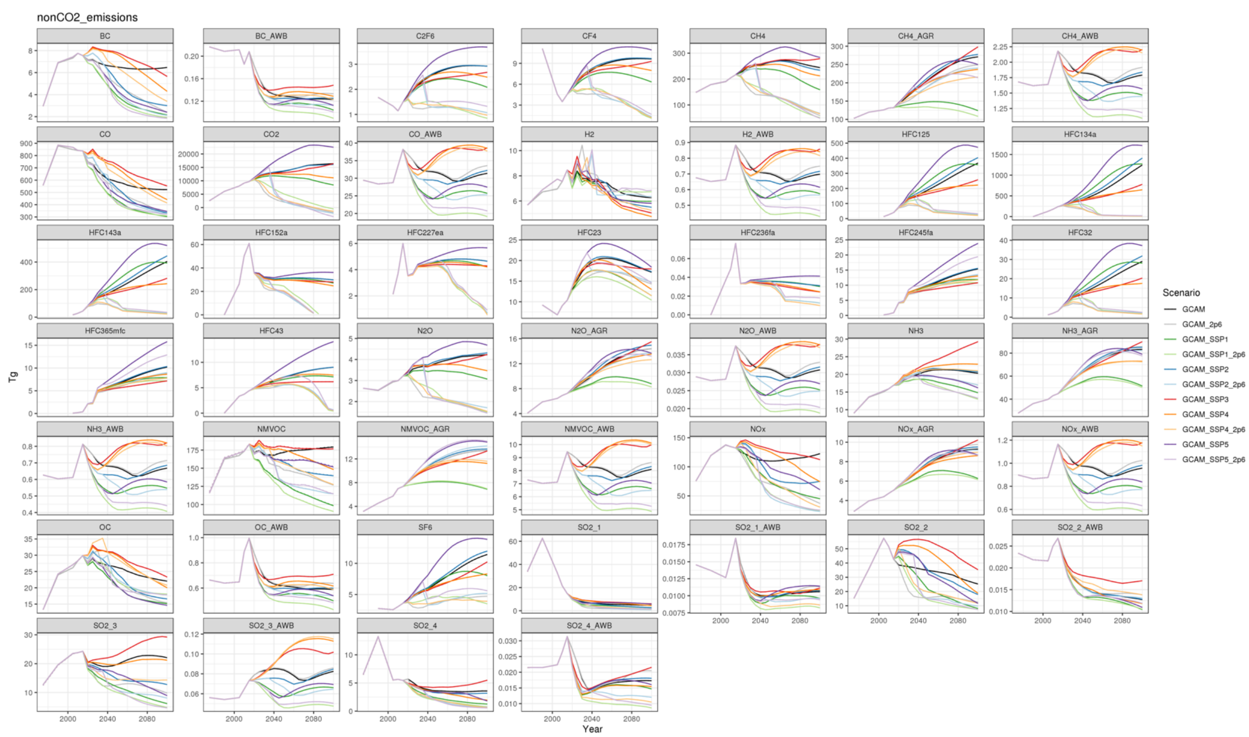
Dotted is Old. Solid is New.



Dotted is Old. Solid is New.

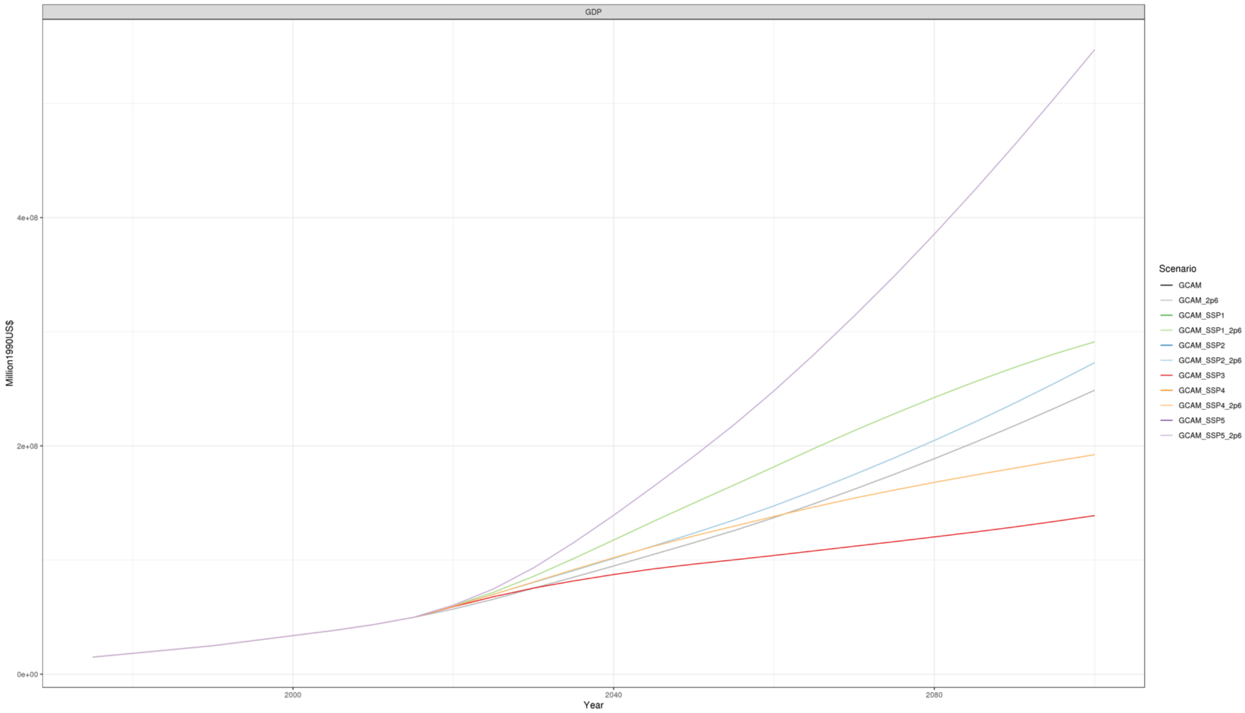


Dotted is Old. Solid is New.



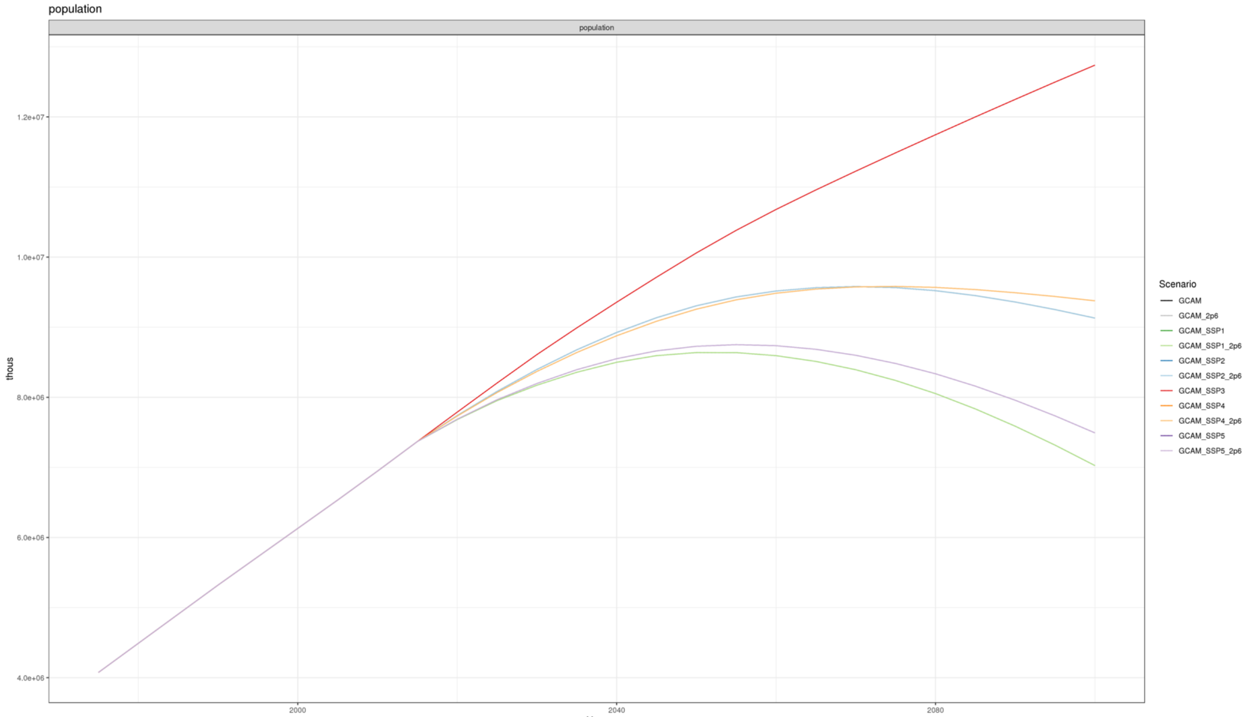
Dotted is Old. Solid is New.

GDP

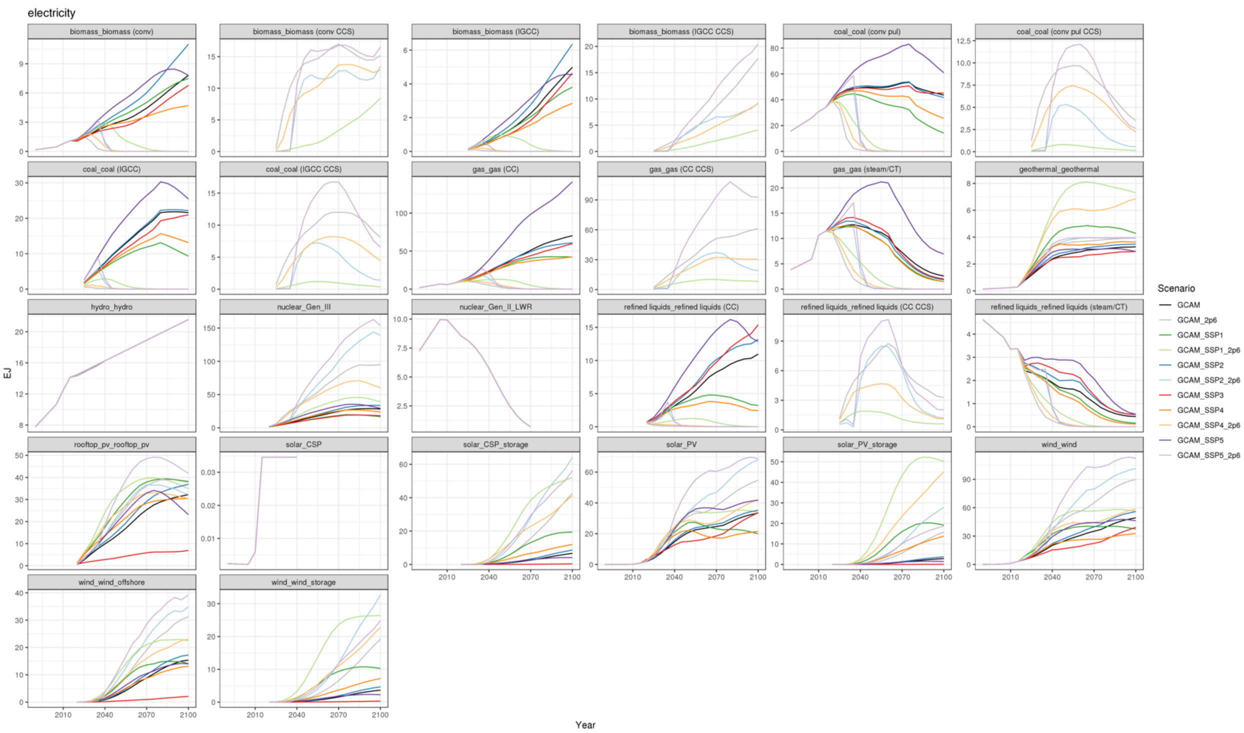


Dotted is Old. Solid is New.

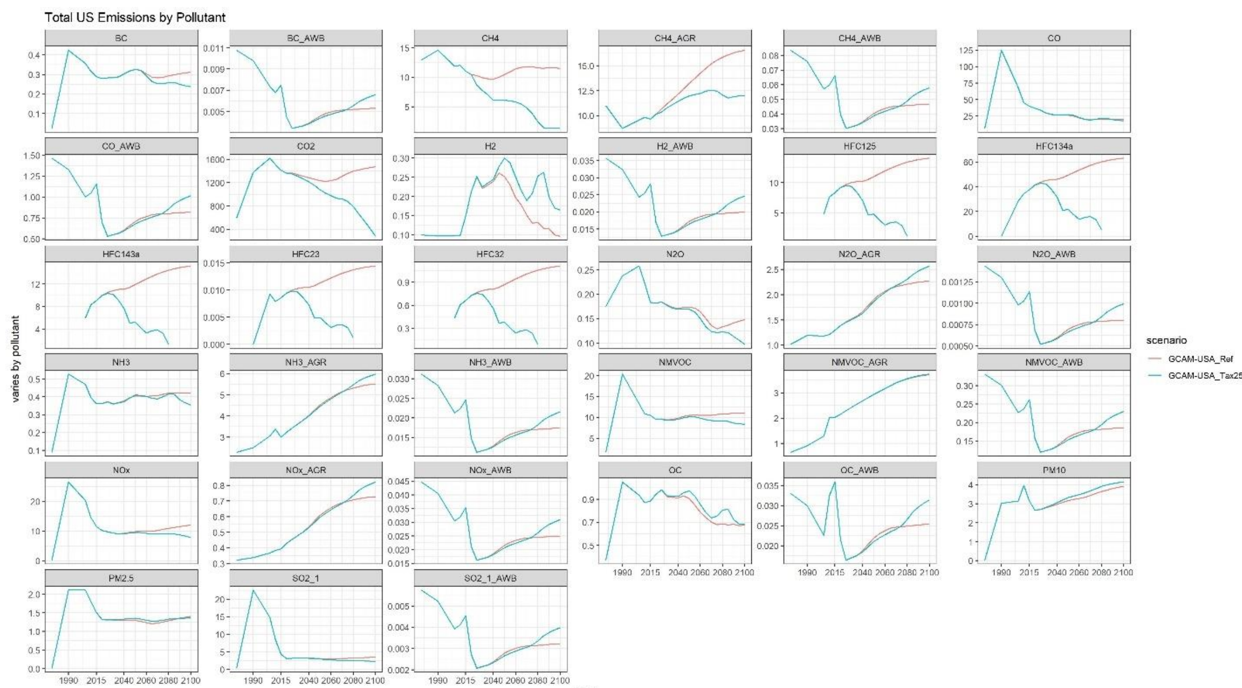
population

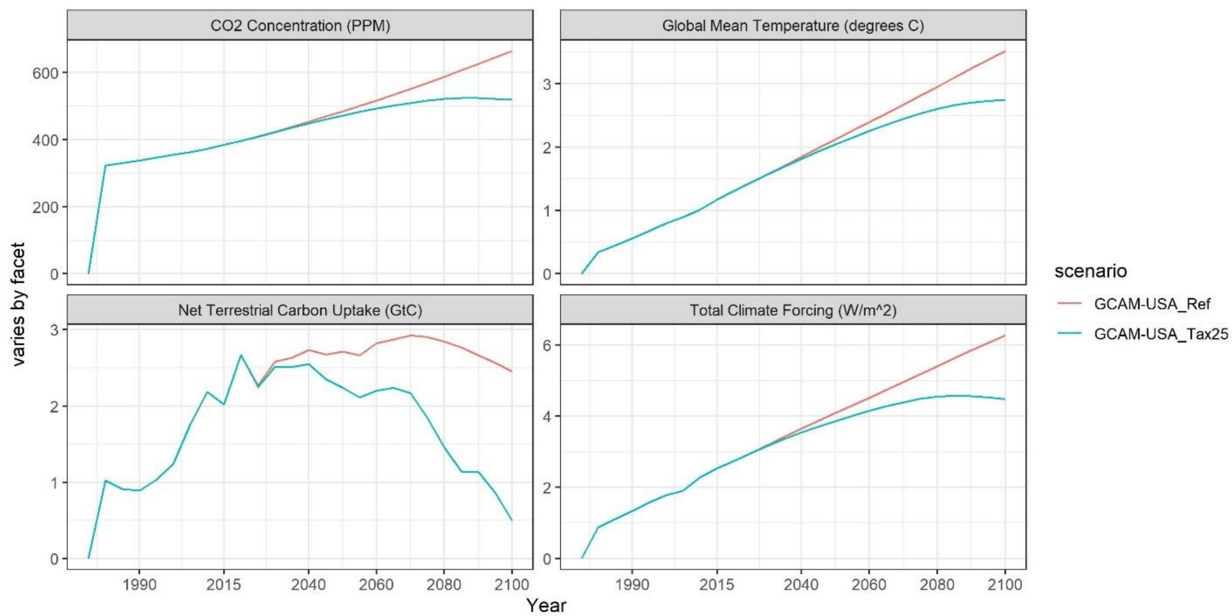


Dotted is Old. Solid is New.



Dotted is Old. Solid is New.





References:

Argonne National Laboratory. 2014. *GREET v1.2.0 11425*. For model information, please contact greet@anl.gov.

Argonne National Laboratory. 2014. Criteria air pollutant and greenhouse gas emission factors compiled by eastern research group for incorporation in GREET. Systems Assessment Group, Energy Systems Division.

Bento, Antonio M., Roth, Kevin D. and Zuo, Yiou. (2013). "Vehicle Lifetime Trends and Scrappage Behavior in the U.S. Used Car Market". Available at SSRN: https://ssrn.com/abstract=2262593 or http://dx.doi.org/10.2139/ssrn.2262593

Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.H. & Klimont, Z. (2004). A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research: Atmospheres (1984-2012), 109*(D14).

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., Schopp, W. (2017). Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics, 17*, pp.8681-8723.

Mishra, G.S., Kyle, P., Teter, J., Morrison, G., Yeh, S., and Kim, S. 2013. *Transportation Module of Global Change Assessment Model (GCAM): Model Documentation Version 1.0.* Institute of Transportation Studies, University of California at Davis; and Pacific Northwest National Laboratory. Report UCD-ITS-RR-13-05. June 2013.

Shi, W., Ou, Y., Smith, S.J., Ledna, C.M., Nolte, C.G., and Loughlin, D.H., 2017. Projecting state-level air pollutant emissions using an integrated assessment model: GCAM-USA. *Applied energy*, *208*, pp.511-521.

Task Force on Hemispheric Transport of Air Pollution (HTAP). (May 2015). "Residential Wood Combustion Modeled Contribution to PM2.5" Accessed on 13 January 2017, from http://www.htap.org/meetings/2015/2015_May_11-15/Powerpoint%20Presentations/Friday/Mason_Baker_EPAreswood_WSAQW2015_06may2015.pdf

U.S. Energy Information Administration. "Commercial Sector Key Indicators and Consumption." *Annual Energy Outlook 2017 with Projections to 2050.* U.S. Energy Information Administration, January 5, 2017.

U.S. Energy Information Administration. "Residential Sector Key Indicators and Consumption." *Annual Energy Outlook 2017 with Projections to 2050.* U.S. Energy Information Administration, January 5, 2017.

U.S. Energy Information Administration. 2014. *State Energy Data System.* Accessed 13 January 2017 from https://www.eia.gov/state/CEDS/CEDS-data-complete.cfm.

U.S. Environmental Protection Agency (EPA). 2016. Air emissions modeling: 2011 version 6.2 platform. Available at: https://www.epa.gov/air-emissions-modeling/2011-version-62-platform. Last accessed September 22, 2016.

U.S. Environmental Protection Agency (EPA). November 2013. "Chapter 3: Power System Operation Assumptions." *Documentation for EPA Base Case v.5.13 Using the Integrated Planning Model*. EPA # 450R13002. https://www.epa.gov/sites/production/files/2015-07/documents/chapter_3_power_system_operation_assumptions_0.pdf (Accessed 3 April 2017).

Wang, M. and Elgowainy, A. 2014. "Well-to-wheels GHG emissions of Natural Gas Use in Transportation: CNGVs, LNGVs, EVs, and FCVs." Argonne National Laboratory, Systems Assessment Section, Energy Systems Division. http://greet.es.anl.gov/files/EERE-LCA-NG.