Enhanced Modeling of GHG Emissions and Mitigation in NEMS

Component Design Report

Prepared by:

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Disclaimer

Executive Summary

The Biden Administration has established a goal of net-zero greenhouse gas (GHG) emissions by 2050. Developing policies to implement net-zero initiatives can be challenging because sources of GHG emissions are numerous and widely distributed throughout the U.S. economy. The U.S. Environmental Protection Agency (EPA) broadly categorizes all GHG emissions and removals into five sectors: energy; industry; agriculture; waste; and land use, land-use change, and forestry (LULUCF). The combined total of emissions and removals from the first four sectors (excluding LULUCF) is referred to as "gross GHG emissions", whereas the total from all five sectors is termed "net GHG emissions". The EPA additionally defines seven types of GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) (the last four types being collectively referred to as fluorinated gases). Policy requirements are therefore demanding that all GHGs be considered for their potential investments to achieve these reductions amidst the complexity and heterogenous nature of those industries and emissions.

The National Energy Modeling System (NEMS) is an energy-economic model of U.S. energy markets that is accepted as a standard for evaluating the effects of energy policy. NEMS is developed and maintained by the Energy Information Administration (EIA) and is used to produce the EIA's Annual Energy Outlook (AEO). NEMS projects future flows of energy from production to consumption across several connected modules that represent different segments of the U.S. energy market. Its position as an energy-economic model makes NEMS a promising option for modeling GHGs; furthermore, EIA has done extensive work in the past to enable NEMS to model U.S. CO_2 emissions from the combustion of fossil fuels as energy and some types of engineering processes that mitigate CO_2. However, the absence of non-CO_2 GHGs, as well as most CO_2 emissions outside of the energy sector, prevent NEMS from fully modeling net-zero GHG scenarios.

The Office of Fossil Energy and Carbon Management (FECM), together with OnLocation, has developed a custom version of NEMS, "FECM-NEMS", that includes additional representation of energy- and industry-sector GHG emissions and mitigation options beyond those represented in EIA NEMS. Compared with GHG emissions published by the EPA in their *Inventory of U.S. GHG Emissions and Sinks: 1990-2021*, FECM-NEMS endogenously represents 81% of gross U.S. GHG emissions; however, the remaining 19%, as well as LULUCF-sector emissions and removals, are still required to properly model net-zero GHG scenarios, which requires an accounting of all GHGs. Considering recent technological advances to mitigate CO_2 and non-CO_2 emissions, the Office of Carbon Management (OCM) within FECM has tasked OnLocation with creating this component design report (CDR) to address the gap in GHG representation. This report describes how FECM-NEMS could incorporate missing GHG emissions (including LULUCF-sector emissions and removals) and engineered processes for GHG mitigation.

From the 81% of GHG emissions that FECM-NEMS already represents, a vast majority – 78% of gross emissions – are from the energy sector, including CO_2 emissions from fossil fuel combustion, CO_2

emissions from non-energy use of fuels, and CH_4 from natural gas systems[1]. The remaining emissions included in FECM-NEMS represent industrial-sector process emissions, such as non-combustion CO_2 emitted during steel, cement, and lime production. The missing 19% of gross emissions disproportionately include non-CO_2 GHGs and non-energy-sector CO_2 emissions. The general strategy proposed in this CDR to incorporate missing emissions is to link relevant FECM-NEMS quantities to corresponding emissions factors. The options presented for each emissions category consider the quantity of missing emissions and the category's similarity to existing structures within FECM-NEMS.

FECM-NEMS has extensive technologies for mitigating CO_2 from fossil fuel combustion and some industrial sources. However, there are no mitigation options for non-CO_2 GHGs in FECM-NEMS. Sectors without mitigation potential in FECM-NEMS account for 25% of gross emissions (this value is larger than the 19% of gross emissions missing from FECM-NEMS because of sectors where emissions are modeled but mitigations are not). This CDR recommends two primary options for most sectors to incorporate missing mitigation into FECM-NEMS: marginal abatement cost (MAC) curves and explicit mitigation technologies. The former option refers to a simplified, numerical representation of the cost of mitigating GHG emissions, which is applied to relevant emissions factors to represent reduced GHG emissions. The MAC curve approach is best suited for smaller emissions categories or categories whose emissions processes are not modeled explicitly in FECM-NEMS. The latter option describes sets of technological choices, with varying costs and mitigation potential, that FECM-NEMS can select from when constructing new energy, industrial, or agricultural capacity (or when retrofitting existing capacity). The explicit technologies option has many benefits but requires extensive modeling detail to implement and is better suited for emissions categories whose emissions processes are explicitly modeled in FECM-NEMS. Applying MAC and endogenous technology approaches throughout FECM-NEMS would enable mitigation potential in sectors representing 9% and 7% of gross emissions, respectively, bringing sectors without mitigation potential in FECM-NEMS down to 9% of gross emissions.

The remaining 9% of gross emissions lacking mitigation potential are exclusive to the agricultural and LULUCF sectors and could be modeled by linking FECM-NEMS with a suitable external model that already has a detailed representation of GHGs. This third option (rather than using a MAC or endogenous technology approach) is most relevant to agricultural activity and LULUCF, which are significant sources of GHG emissions and removals but are not modeled in detail by FECM-NEMS. FECM-NEMS already handles some agricultural and LULUCF quantities through connections to a modified version of the Policy Analysis System Model (POLYSYS); enhancing the existing POLYSYS framework or linking another model would allow FECM-NEMS to model agricultural and LULUCF-sector GHGs in greater detail. The complexity of linking an external model makes this option less realistic for the energy and industry sectors, which are already modeled in detail by FECM-NEMS.

FECM-NEMS is composed of several interconnected modules that represent different sections of the U.S. energy system, with four energy supply modules, four energy demand modules, three energy conversion

[1] "Non-energy use of fuels" is an emissions category in the EPA GHG Inventory that includes CO_2 emitted from feedstocks, asphalt, lubricants, waxes, and other fossil-derived products. "Natural gas systems" is another category that represents process emissions of CO_2 and CH_4 throughout the natural gas supply chain.

modules, and three supporting modules. The modifications suggested in this CDR affect most of these modules, given the distributed nature of GHG emissions throughout the U.S. economy. The recommended modifications are organized by economic sector, using categories based on the EPA GHG inventory report. Energy- and industry-sector emissions are divided into narrower groups because of their closer connections to FECM-NEMS. For each sector, options of varying complexity are proposed to incorporate missing GHG emissions and mitigation based on emissions factors, MAC curves, technologies, and model linkages. The goals of the modifications described in this CDR are not to solely add as many missing GHG emissions into FECM-NEMS as possible, but to do so in a way that enables enough options for endogenous, policy-responsive GHG mitigation that FECM-NEMS can properly model net-zero GHG scenarios.

The appendices of this CDR include a discussion on model implementation and a summary of the discussion and feedback from the Workshop on Non-Energy CO_2 GHG Emissions and Mitigation in NEMS.

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

AEO	Annual Energy Outlook
AGR	Acid gas removal
AR5	Fifth Assessment Report from the IPCC
BECCS	Bioenergy with carbon capture and storage
BOF	Basic oxygen furnace
CCRD	CO_2 Capture Retrofit Database
CCS	Carbon capture and storage
CDR	Component Design Report
CFC	Chlorofluorocarbons
CGE	Computable general equilibrium
CH_4	Methane
CMM	Coal Market Module
CO_2	Carbon Dioxide
CO_2 eq.	CO_2 equivalent units
CTUS	Carbon transport, utilization, and storage
DAC	Direct air capture
EAF	Electric arc furnace
EIA	Energy Information Administration
EMM	Electricity Market Module
EOR	Enhanced oil recovery
EPA	Environmental Protection Agency
FARM	Future Agricultural Resources Model
FASOM-GHG	Forest and Agricultural Sector Optimization Model Greenhouse Gas Version
FECM	Fossil Energy and Carbon Management
GCAM	Global Change Analysis Model
GDP	Gross domestic product
GHG	Greenhouse gas
GHGRP	Greenhouse gas reporting program
GLOBIOM	Global Biosphere Management Model
GTAP	Global Trade Analysis Project
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFCF	Chlorodifluoromethane
HFO	Hydrofluoroolefin
HMM	Hydrogen Market Module
IDM	Industrial Demand Module
IPCC	Intergovernmental Panel on Climate Change
LFMM	Liquid Fuels Market Module
LULUCF	Land use, land-use change, and forestry

MAC	Marginal abatement cost
MAM	Macroeconomic activity module
MECS	Manufacturing Energy Consumption Survey
MMT	Million metric tonnes
MSHA	Mine Safety and Health Administration
N_2	Nitrogen
N_2O	Nitrous Oxide
NAICS	North American Industrial Classification System
NEMS	National Energy Modeling System
NETL	National Energy Technology Laboratory
NF_3	Nitrogen Trifluoride
NGMM	Natural Gas Market Module
OCM	Office of Carbon Management
OGSM	Oil and Gas Supply Module
PFC	Perfluorocarbon
POLYSYS	Policy Analysis System Model
REAP	Regional Environment and Agriculture Programming Model
RFM	Renewables Fuel Module
SF_6	Sulfur Hexafluoride
SGM	Second Generation Model
SMR	Steam methane reforming
tonne	Metric tonne (1,000 kilograms)
U.S.	United States
VAM	Ventilation air methane
WiNDC	Wisconsin National Data Consortium

1. Introduction and Background

The Biden Administration has set a goal of net-zero greenhouse gas (GHG) emissions by 2050 to be achieved via a combination of reductions and removals. Policy in support of this goal must be designed with a consideration for all GHG emissions and mitigation pathways.

While GHG emissions are closely associated with the energy sector, the National Energy Modeling System (NEMS), a standard tool for evaluating U.S. energy policy, does not model all types and sources of GHGs and is therefore incapable of comprehensive net-zero GHG modeling without exogenous assumptions. Developed by the Energy Information Administration (EIA), NEMS is an energy-economic model of U.S. energy markets that is used in the creation of the Annual Energy Outlook (AEO), the most recent version having been released in early 2023 (AEO23-NEMS). AEO23-NEMS includes a detailed representation of carbon dioxide (CO_2) emissions from fossil fuel combustion and use as feedstocks, as well as some methods for CO_2 mitigation, but is missing most non-CO_2 GHGs, as well as most non-combustion CO_2. Altogether, AEO23-NEMS models approximately 78% of gross GHG emissions.

The Office of Carbon Management (OCM) within the of Fossil Energy and Carbon Management (FECM) worked with OnLocation to develop an enhanced version of NEMS (FECM-NEMS) with expanded representation of CO_2 mitigation technologies and some non-CO_2 GHG emissions, covering 81% of gross GHG emissions. However, missing emissions in FECM-NEMS, the majority of which are non-CO_2 GHGs, still account for 19% of total U.S. gross emissions. Many mitigation options and sinks – including removals in the land use, land-use change, and forestry (LULUCF) sector – are also not modeled in FECM-NEMS, leaving 25% of gross emissions (as well as LULUCF removals) without a mitigation pathway. FECM-NEMS should be expanded to include the missing emissions and sinks for it to properly model net-zero scenarios. Non-CO_2 GHG emissions are important for net-zero modeling because they "buy time" for advancements in CO_2 mitigation, enabling trade-offs between near-term actions, hard-to-abate sectors, and carbon removal. Furthermore, endogenizing these missing emissions and sinks would allow them to respond dynamically to the changing energy systems in FECM-NEMS, keeping them consistent with other emissions and processes throughout the model.

OCM has tasked OnLocation with writing this component design report (CDR) to evaluate the current state of GHG emissions and mitigations within FECM-NEMS and recommend how missing emissions and mitigation options could be best implemented. Section 2 summarizes existing emissions and mitigation options in FECM-NEMS, identifies gaps that need to be addressed, and explains the main approach for enhancing GHG representation via emissions factors, marginal abatement cost (MAC) curves, and mitigation technologies. Section 3 describes all emissions by economic sector and makes specific recommendations for how additional GHGs could be represented. Section 4 gives final conclusions and recommendations. In the appendices, section 5 describes a recommended method to implement the non-CO_2 enhancements into FECM-NEMS, section 6 summarizes presentations from the *Workshop on Non-Energy CO_2 GHG Emissions and Mitigations in NEMS*, and section 7 contains tabulated emissions data.

2. Review of Existing Representation of U.S. GHG Emissions and Mitigations in FECM-NEMS

2.1. Defining and Categorizing GHG Emissions

The *Inventory of U.S. GHG Emissions and Sinks: 1990-2021*[2] is the most recent edition of an annual report by the Environmental Protection Agency (EPA) that provides a comprehensive breakdown of U.S. GHG emissions and removals by economic sector. The EPA GHG inventory gives estimates of emissions from seven GHGs: CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). HFCs and PFCs represent groups of individual molecules with similar structures and warming properties that are often combined for reporting purposes. Together with SF_6 and NF_3, the latter four GHG types are known as fluorinated gases.

Emissions of each type of GHG are reported in units of million metric tonnes (MMT) of CO_2 equivalent (CO_2 eq.), where one MMT CO_2 eq. represents a quantity of GHG that would generate the same atmospheric warming effect as one MMT of CO_2. The warming effect of a certain mass of GHG divided by the warming effect caused by an identical mass of CO_2 equals the GHG's global warming potential (GWP). The CO_2 equivalent emissions of a given amount of GHG released to the atmosphere are therefore the product of the GHG's GWP and mass.

The GWP of a GHG depends on several factors, including molecular weight, chemical bonding, adsorption wavelength, and lifetime in the atmosphere. Because GHGs break down in the atmosphere at different rates, affecting their contribution to atmospheric warming over time, GWP is defined with respect to a reference timeframe. GWP values vary from one for CO_2 (by definition) to 23,500 for SF_6 (the highest of any recognized GHG). Emissions values reported throughout this CDR are based on the EPA GHG inventory, which itself uses 100-year GWP values from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report[3] (AR5). Table 2.1 lists 100-year GWPs and emissions from each GHG type in MMT CO_2 eq. in the U.S. The majority of weighted emissions (79.4% of gross) are CO_2, particularly from fossil fuel combustion (73.2% of gross), but non-CO_2 emissions (20.6% of gross) and land use removals are also significant sources of GHG flows.

[2] EPA (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. U.S. Environmental Protection Agency, EPA 430-R-23-002. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

[3] Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Table 2.1. U.S. GHG Emissions in 2021, by Gas

Emissions Category	100-year GWP (from AR5, 2013)[3]	MMT CO_2 eq.[4]	% of Gross Emissions
CO_2 (Fossil fuel combustion)	1	4,639	73.2%
CO_2 (Other)	1	393	6.2%
CH_4	28	727	11.5%
N_2O	265	393	6.2%
Fluorinated gases	116-23,500	187	2.9%
All GHG, gross emissions[5]		**6,340**	**100%**
Land use, land-use change, and forestry[6]		-754	
All GHG, net emissions		**5,586**	

The EPA inventory also groups GHG emissions by the following sectors: energy, industrial processes and product use (referred to throughout this CDR as simply "industry"), agriculture, waste, and LULUCF. Emissions that come from the combustion of fossil fuels as part of an industrial, agricultural, or waste process are classified as energy-sector emissions. The non-energy sectors represent GHG emissions from sector-specific leakages, chemical reactions, and other non-combustion processes. Most emissions (82.0% of gross) fall within the energy sector, especially emissions caused by the combustion of fossil fuels. The remaining 18.0% of gross emissions are broadly distributed amongst the other sectors. Emissions by sector are listed in Table 2.2.

Table 2.2. U.S. GHG Emissions in 2021, by EPA GHG Inventory Sector. Emissions from the combustion of fossil fuels in service of industrial, agricultural, or waste processes are classified as energy-sector emissions.

Emissions Category	MMT CO_2 eq.[4]	% of Gross Emissions
Energy (CO_2 from fossil fuel combustion)	4,639	73.2%
Energy (Other)	558	8.8%
Industry	376	5.9%
Agriculture	598	9.4%
Waste	169	2.7%
All GHG, gross emissions[5]	**6,340**	**100%**
Land use, land-use change, and forestry[6]	-754	
All GHG, net emissions	**5,586**	

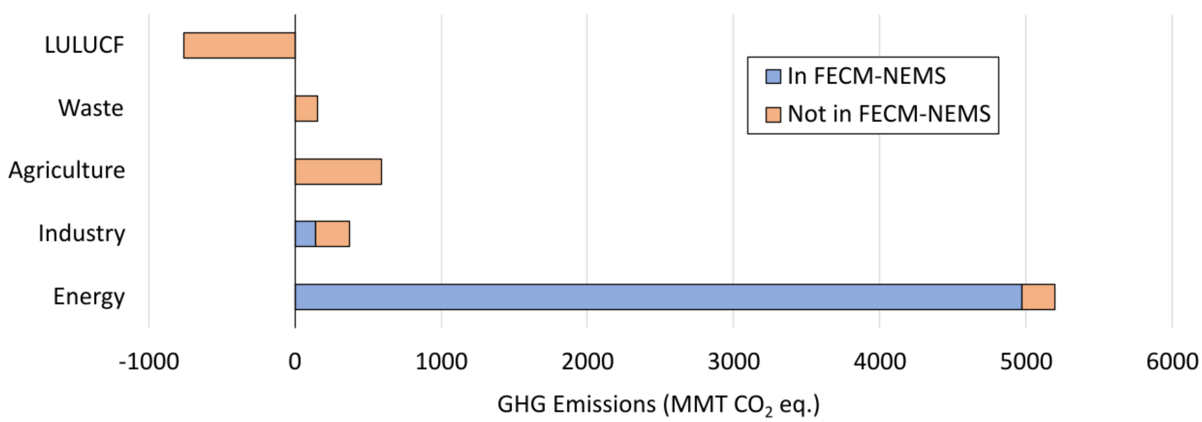
[4] U.S. emissions or removals from 2022 in units of million metric tonnes of CO_2 equivalent (100-year time horizon)
[5] Excluding LULUCF-sector emissions (78 MMT CO_2 eq.)
[6] Combined sum of all LULUCF-sector emissions and removals

2.2. Inclusions and Gaps of GHG Emissions in FECM-NEMS

FECM-NEMS is an integrated model with several modules and submodules that represent different parts of the U.S. energy system. There are fourteen modules in total: four supply modules, where energy flows are created; three conversion modules, where energy can change from one form to another; four demand modules, where energy flows are consumed; and three additional modules that serve supporting roles. Activities that generate GHG emissions – especially those in the energy sector – are widely distributed throughout the fourteen modules. Non-energy sector emissions have additional connections to various modules and submodules. NEMS modules are organized by economic sector – residential, commercial, industrial, transportation, etc. – and while the EPA reports high-level emissions results for similar economic sectors, they report far more emissions detail for what they call “inventory sectors.” There is a complicated mapping from economic sectors to inventory sectors, so for the sake of simplicity, the EPA inventory sectors and subsectors are used throughout this CDR.

Figure 2.1 displays the emissions and gaps in FECM-NEMS from each of the five main sectors identified in the EPA GHG Inventory, using the inventory values reported for U.S. GHG emissions in 2021. Emissions are divided into two categories: “In FECM-NEMS”, and “Not in FECM-NEMS”. This determination is made by comparing the existing structure and emissions reporting of FECM-NEMS against the EPA GHG inventory. For each GHG, if the emissions calculated for a given category in FECM-NEMS are close (within a few percent) to the inventory values, the category is considered to be “in FECM-NEMS”; the FECM-NEMS value need not exactly equal the EPA inventory value for this comparison because of modeling differences. The representation of some emissions sources marked as “In FECM-NEMS” could nevertheless be Improved; any improvements to existing emissions modeling are discussed in Section 3.

Figure 2.1. Emissions and gaps in FECM-NEMS by EPA GHG Inventory sector. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels in service of industrial, agricultural, or waste processes are classified as energy-sector emissions.

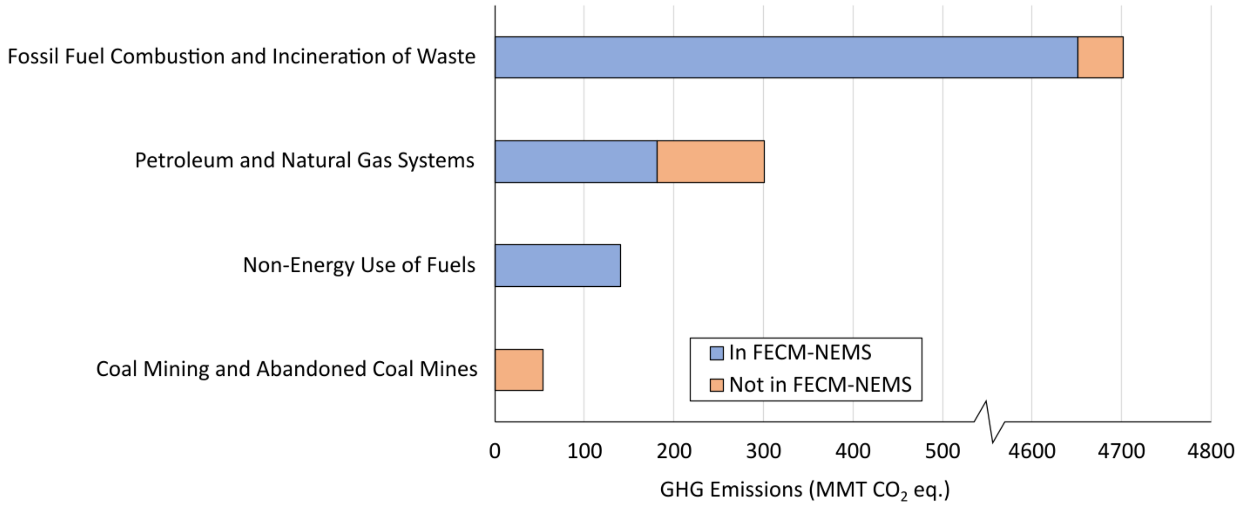


The energy sector has the highest total emissions at 5197 MMT CO_2 eq., of which 4973 MMT CO_2 eq. are currently represented by FECM-NEMS. GHG emissions from industry also have some representation in FECM-NEMS, with 140 MMT CO_2 eq. of the 376 MMT CO_2 eq. total currently tracked by the model.

Emissions from the remaining agriculture, waste, and LULUCF sectors are not currently modeled in FECM-NEMS. As a result, out of a total of 6340 MMT CO_2 eq. gross emissions (excluding LULUCF), FECM-NEMS currently represents 5114 MMT CO_2 eq. (81% of gross emissions).

Figure 2.2 plots U.S. GHG emissions in 2021 from the energy sector in greater detail. The values underlying Figure 2.2 are listed in Table 7.1 in the appendices.

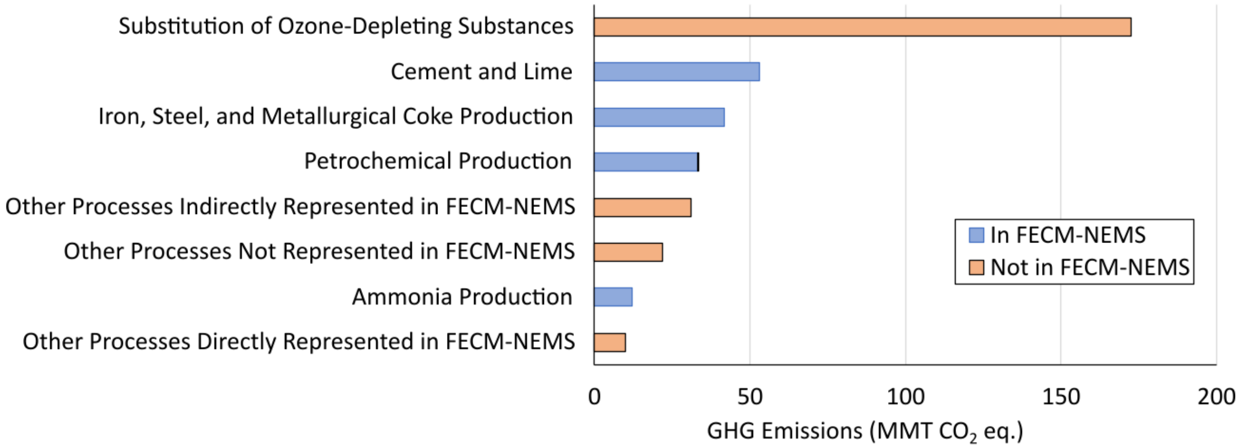
Figure 2.2. Energy-Sector GHG emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory.



The above plot disaggregates energy-sector emissions into groups of subsectors based on the EPA GHG inventory. The largest group, *Fossil Fuel Combustion and Incineration of Waste*, includes emissions of CO_2, CH_4, and N_2O from stationary and mobile combustion sources, and represents a majority of all U.S. GHG emissions. This grouping combines two subsectors from the EPA GHG inventory: *Fossil Fuel Combustion* (both stationary production and mobile combustion) and *Incineration Waste*. FECM-NEMS currently models the CO_2 emissions from this group (4652 MMT CO_2 eq.) but does not model CH_4 and N_2O emissions (51 MMT CO_2 eq.). The second-largest category, *Petroleum and Natural Gas Systems*, includes CO_2 and CH_4 emissions from the *Petroleum Systems*, *Natural Gas Systems,* and *Abandoned Oil and Gas Wells* subsectors of the EPA GHG inventory. FECM-NEMS models CH_4 emitted from the natural gas supply chain in the Natural Gas Market Module (NGMM), representing 181 MMT CO_2 eq. of the 301 MMT CO_2 eq. emissions in this group. *Non-Energy Use of Fuels* refers to the CO_2 emitted over the lifetime of petroleum products, such as lubricants or waxes. FECM-NEMS represents all 140 MMT CO_2 eq from this category. *Coal Mining and Abandoned Coal Mines* emit 43 MMT CO_2 eq. of combined CO_2 and CH_4, neither of which FECM-NEMS tracks. This group includes the EPA GHG inventory subsectors *Coal Mining* and *Abandoned Underground Coal Mines*. The specific emission sources are described in greater detail in their respective subsections within Section 3.1.

Figure 2.3 plots 2021 U.S. GHG emissions for the industry sector, divided into subsectors based on the EPA GHG inventory. Values underlying this figure are listed in Table 7.2 in the appendices.

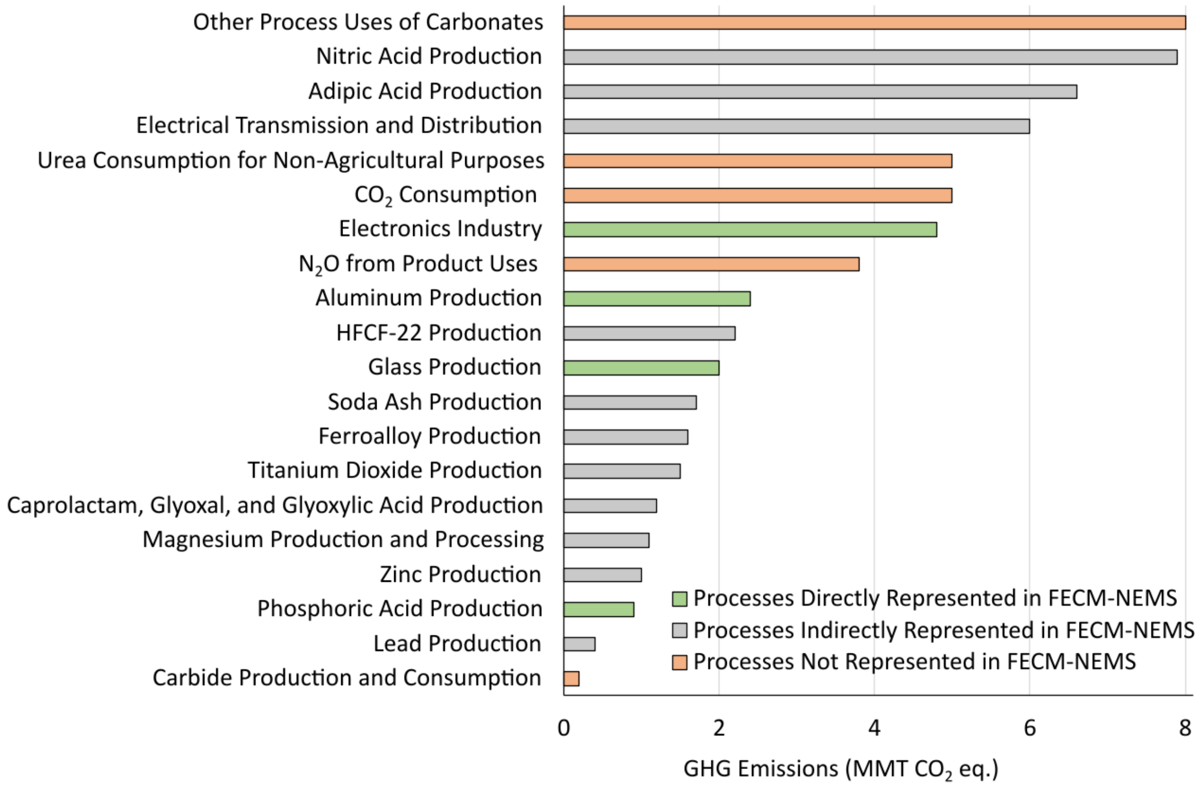
Figure 2.3. Industry-sector GHG emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels are not counted in this sector.



The largest emissions category in the industry sector comes from HFCs used as substitutes for ozone-depleting chlorofluorocarbons (CFCs) that began to be phased out in the late 1980's. This category emitted 173 MMT CO_2 eq. in 2021, none of which is modeled in FECM-NEMS. Another four subsectors describe different production processes that emit GHGs: iron, steel, and metallurgical coke; cement and lime; petrochemicals; and ammonia. FECM-NEMS attempts to model nearly all the emissions from these four categories, except for small amounts of CH_4 from petrochemical production.

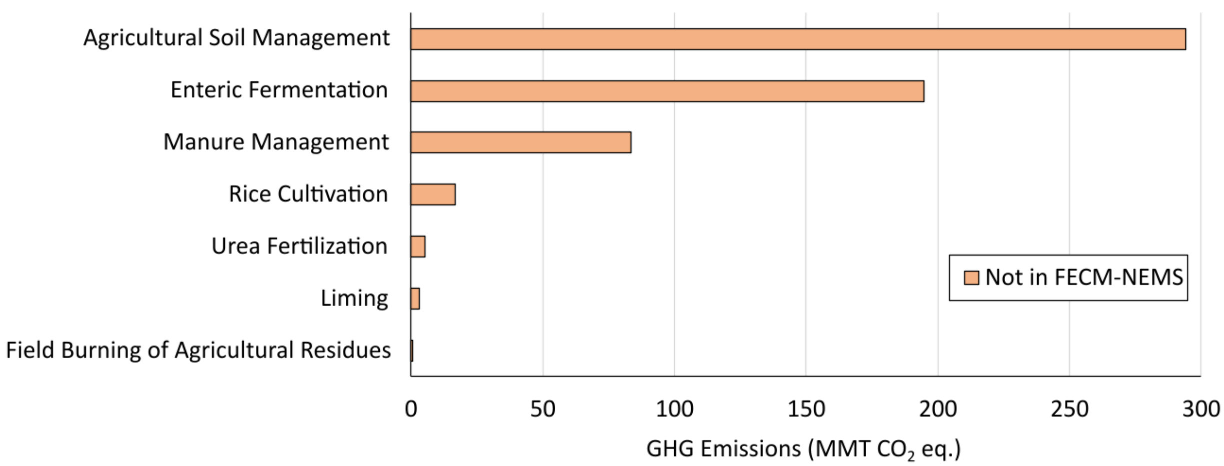
The remaining three groups represent the sum of industrial-sector emissions sources where FECM-NEMS does not track GHG emissions. The largest of the three, *Other Processes Indirectly Represented in FECM-NEMS*, describes processes that are not explicitly modeled in FECM-NEMS but are included indirectly as part of a macroeconomic or other process. These include the production of nitric acid, adipic acid, chlorodifluoromethane (HFCF-22), soda ash, ferroalloy, titanium dioxide, caprolactam, glyoxal, glyoxylic acid, magnesium, zinc, and lead. This group accounts for a total of 31 MMT CO_2 eq. of emissions. The second group, *Other Processes Not Represented in FECM-NEMS*, represents emissions from assorted activities that are not modeled in FECM-NEMS. The various subgroups within *Other Processes Not Represented in FECM-NEMS* – *Other Process Uses of Carbonates*, *Urea Consumption for Non-Agricultural Purposes*, *CO_2 Consumption*, *N_2O from Product Uses*, and *Carbide Production and Consumption* – are not tied to a specific module or process in FECM-NEMS. This category accounts for 22 MMT CO_2 eq. of emissions. The smallest group, *Other Processes Represented in FECM-NEMS*, represents the remaining emissions associated with activities that are already modeled by FECM-NEMS. This category includes the production of electronics, aluminum, glass, and phosphoric acid, altogether accounting for 10 MMT CO_2 eq. of emissions. Figure 2.4 plots emissions from these categories in greater detail, and Table 7.3 in the appendix lists the emissions values from each category.

Figure 2.4. Other industry-sector emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels are not counted in this sector.



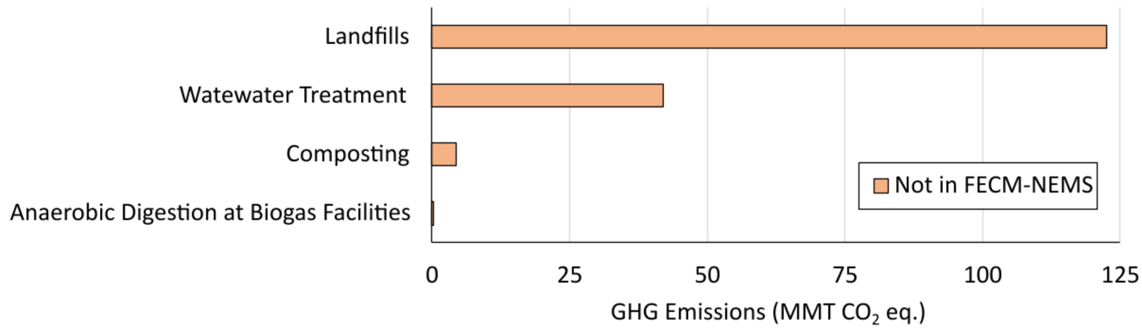
Figures 2.5, 2.6, and 2.7 plot GHG emissions from the agricultural, waste, and LULUCF sectors, respectively. Corresponding values are listed in Tables 7.4, 7.5, and 7.6 of the appendices. FECM-NEMS does not endogenously track any GHG emissions from these three sectors.

Figure 2.5. Agriculture-sector emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels are not counted in this sector.



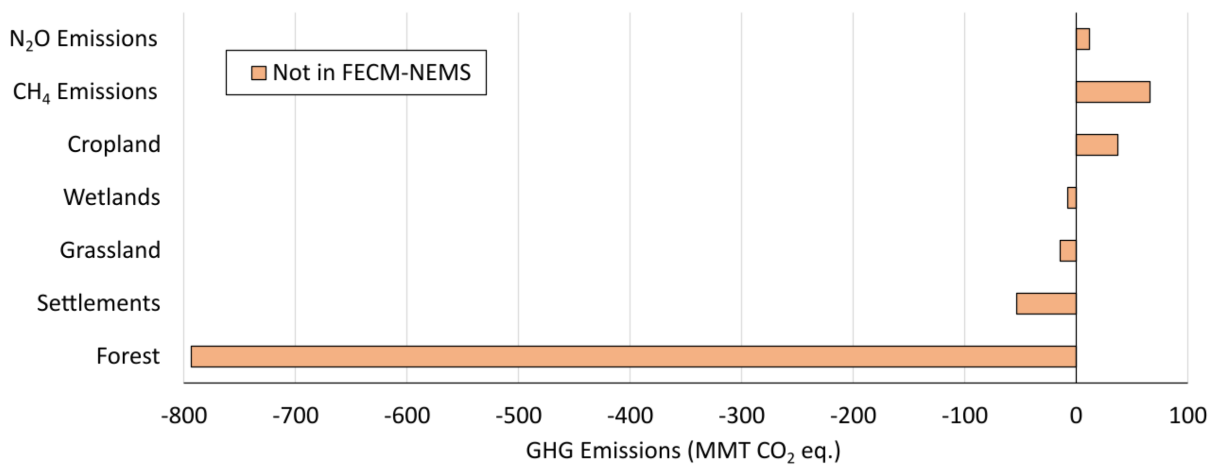
Agricultural Soil Management, which includes the use of organic and synthetic fertilizers, is the largest group of agricultural-sector emissions and is the largest overall source of N_2O emissions (294 MMT CO_2 eq.). *Enteric Fermentation* refers to CH_4 formed by livestock during digestion, and accounts for 195 MMT CO_2 eq. Management of manure from livestock additionally releases CH_4 and N_2O (83 MMT CO_2 eq.). The final four categories – *Rice Cultivation*, *Urea Fertilization*, *Liming*, and *Field Burning of Agricultural Residues* – are relatively smaller for the U.S., totaling to 26 MMT CO_2 eq. None of the agricultural-sector emissions are currently modeled in FECM-NEMS.

Figure 2.6. Other waste-sector emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels are not counted in this sector.



The largest source of waste-sector emissions is CH_4 leakage from *Landfills* (123 MMT CO_2 eq.), followed by emissions of CH_4 and N_2O from *Wastewater Treatment* (42 MMT CO_2 eq.), CH_4 and N_2O from *Composting* (4 MMT CO_2 eq.), and a small amount of CH_4 from *Anaerobic Digestion at Biogas Facilities* (0.2 MMT CO_2 eq.). FECM-NEMS does not currently model any emissions from this sector.

Figure 2.7. LULUCF-sector emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory.



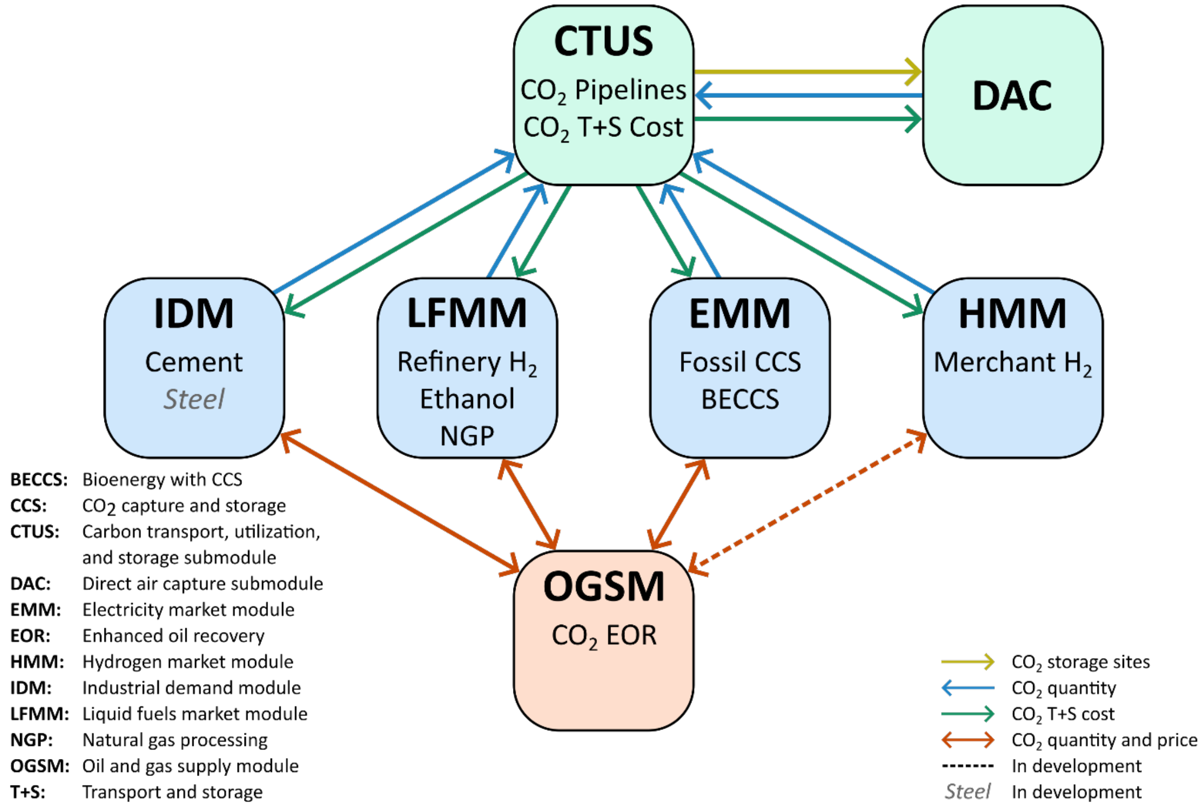
While the LULUCF sector does have its own emissions of CH_4 and N_2O, these are small relative to LULUCF-sector total carbon removals. Emissions plotted for the five land categories – *Cropland, Wetlands, Grassland, Settlements,* and *Forest* – represent the flow of CO_2 between the atmosphere and land over one year, measured as a net change in carbon inventory associated with each land type. In the case of cropland, changes in carbon inventories cause CO_2 to transfer from land to the atmosphere, represented as positive emissions (38 MMT CO_2 eq.). However, the LULUCF sector is dominated by carbon removals in forests (-794 MMT CO_2 eq.), where each year vast quantities of CO_2 transfer from the atmosphere and are sequestered as biomass. FECM-NEMS does not represent any LULUCF-sector emissions or removals.

2.3. Inclusions and Gaps of GHG Mitigations in FECM-NEMS

FECM-NEMS has several options to mitigate CO_2 emissions from different sources using carbon capture and storage (CCS), many of which are not represented in other versions of NEMS. In total, sectors with mitigation options currently modeled in FECM-NEMS represent approximately 75% of gross GHG emissions, leaving sectors totaling 25% of gross emissions (as well as LULUCF removals) with no mitigation pathway.

In response to a policy incentive (such as cap-and-trade or a carbon price or tax credits), CO_2 can be captured and sequestered from the following anthropogenic sources: cement production, steel production, hydrogen production in refineries, ethanol production, natural gas processing, fossil fuel combustion at power plants, coal/bioenergy retrofits with CCS (BECCS), and direct air capture (DAC). The latter two technologies, BECCS and DAC, enable the model to represent CO_2 removals. The Carbon Transport, Utilization, and Storage (CTUS) submodule in FECM-NEMS organizes the flow of CO_2 from its capture at an industrial or energy source to storage or utilization sites, which can either be hydrocarbon reservoirs for enhanced oil recovery (EOR) or saline aquifers. Figure 2.8 illustrates the pathways that CO_2 can take in FECM-NEMS.

Figure 2.8. CO_2 mitigation pathways in FECM-NEMS



CO_2 is captured at an anthropogenic source from one of the following modules: the Industrial Demand Module (IDM), the Liquid Fuels Market Module (LFMM), the Electricity Market Module (EMM), the Hydrogen Market Module (HMM), and the DAC submodule. This CO_2 is either sold to the Oil and Gas Supply Module (OGSM) for an EOR project or sent to a saline aquifer. The CTUS submodule projects the pipeline infrastructure and CO_2 transportation and saline storage costs. The linkage between the OGSM and HMM for EOR and the addition of a dedicated bioenergy with CCS are currently being developed, and CCS from steel is not currently connected to the CTUS submodule. Work is underway to expand these mitigation options.

OGSM also has the capability to purchase CO_2 for the EOR market directly from various sectors based on static supply curves, calculated using data from an older version of the National Energy Technology Laboratory (NETL) CO_2 Capture Retrofit Database (CCRD); the most recent version of the CCRD is available on the NETL website[7]. These exogenous supply curves at one time covered the power sector and specific industrial sectors: ethanol, hydrogen in refineries, natural gas processing, cement, and ammonia. Because endogenous CCS capability was added to most of the CO_2 sources (apart from ammonia), these exogenous curves are no longer used in the OGSM module. However, ammonia is still

[7] Hughes, S., Zoelle, A., Woods, M., Henry, S., Homsy, S., Pidaparti, S., Kuehn, N., Hoffman, H., Forrest, K., Fout, T., Summers, W.M., Herron, S., & Grol, E. (2022). Industrial CO2 Capture Retrofit Database (IND CCRD) [Data set]. Pittsburgh, PA: National Energy Technology Laboratory, U.S. Department of Energy. https://www.netl.doe.gov/energy-analysis/details?id=a9f14d58-52d3-4a06-85cc-33d5cba5c895

connected to the EOR market as an exogenous source of CO_2 without a direct connection to the industrial module. Potential pathways of connecting CCS from ammonia facilities to the industrial module, as is done for cement facilities, will be discussed in Section 3.2.1.

Aside from the CCS methods listed above, FECM-NEMS has many options to mitigate CO_2 emissions through energy efficiency and fuel switching in the demand and conversion sectors of the economy. The largest mitigation response to carbon pricing is generally the transition of electricity generation towards greater use of renewables and other low-carbon sources.

2.4. Modeling GHG Emissions Gaps in FECM-NEMS

Missing GHG emissions can be incorporated into FECM-NEMS in three main steps: first, by identifying a part of the model that is correlated to emissions generation in a benchmark or base year (FECM-NEMS quantity); second, by developing a conversion factor that converts the quantity into the appropriate amount of GHG emissions (emissions factor); and thirdly, to implement ways for the emissions factor to change over time in response to existing trends or changes in energy policy (mitigation). Because GWP values are updated occasionally in response to new research and reporting, all GHG emissions should be calculated individually in units of mass and converted to CO_2 equivalents as a final reporting step. The conversion to CO_2-equivalent units could be adjusted by the user by modifying GWP values in an input file.

For some emissions sources, there is a direct quantity available in FECM-NEMS from which emissions can be calculated, such as units of production or an energy consumption value. In certain sectors, enough detail is available in FECM-NEMS to develop highly regional emissions estimates, which is the preferred choice where possible. However, for emissions sources not explicitly modeled in FECM-NEMS, emissions estimates may need to rely on aggregated macroeconomic quantities, such as industrial gross output. FECM-NEMS performs macroeconomic calculations in the macroeconomic activity module (MAM) across various submodules. First, a national model (IHS Markit) generates multiple outputs including GDP and its components, price and productivity measures, income, employment, and inflation. The outputs from the national model are then fed into industrial and regional models. An important set of values calculated by the industrial model is the revenue for all 58 industrial sectors considered by FECM-NEMS, organized by the North American Industry Classification System (NAICS) category[8]. These outputs represent the real value of shipments from each sector and are ultimately transferred to the IDM, from which they could be used as quantities to pair with the appropriate emissions factor. For emissions sources with no direct or indirect modeling in FECM-NEMS that do not correspond to a specific industrial sector in the MAM, GDP itself could be used to calculate emissions. Greater detail about MAM is available in EIA's published documentation[9].

[8] https://www.naics.com/, official NAICS website, retrieved May 2023.
[9] EIA (2022). Model Documentation Report: Macroeconomic Activity Module of the National Energy Modeling System: Model Documentation 2022. U.S. Energy Information Agency. https://www.eia.gov/outlooks/aeo/nems/documentation/macroeconomic/pdf/MAM_2022.pdf

Approaches to estimating FECM-NEMS quantities and emissions factors are considered below over the five key inventory sectors: energy, industry, waste, agriculture, and land use (agriculture and land use are grouped together). Mitigation options are discussed in Section 2.5.

2.4.1. Energy system drivers

Emissions in the energy system are driven by various activities, which can be characterized by their inputs (e.g., fuel consumed by a particular technology) or outputs (e.g., fuel or service produced by a particular technology). Emissions information is technology specific. As a result, different technologies that produce the same output can have different emissions per unit of activity. Most GHGs can be estimated based on specific emission factors tied to activities or drivers in a particular system (analogous to how methane emissions in natural gas systems are currently estimated in FECM-NEMS).

2.4.2. Industrial drivers

Industrial-sector emissions are broadly divided into three groups: (1) emissions sources whose underlying industrial activities are represented directly in FECM-NEMS; (2) sources whose underlying activity is represented indirectly; (3) sources that are not represented at all. In the first group, emissions can be calculated by using a production or energy consumption variable directly associated with the emissions source (e.g., leveraging quantities of aluminum produced to estimate process emissions from aluminum production). In some cases, FECM-NEMS has already calculated GHG emissions from these sources. In the second group, emissions can be calculated from more broadly aggregated variables, such as macroeconomic shipments or revenue (e.g., using the macroeconomic activity of the inorganic chemicals industry as a basis for estimating emissions from titanium dioxide production). In the third group, the emissions source lacks any presence in FECM-NEMS, and emissions need to be calculated from broad variables that cover the entire economy (e.g., using GDP as a baseline quantity to roughly estimate emissions from carbide production).

Some industrial emissions sources have other connections to quantities in FECM-NEMS. Fluorinated GHGs are emitted in the industrial inventory sector, including HFC134a from cooling systems (air conditioners). Some gases could be linked to activities or drivers in FECM-NEMS, e.g., SF_6 emissions from electric transformers could scale with electricity consumption or generation. For many of the industry related GHGs, it may be necessary to adjust emissions factors over time for emissions projections to 2050 to reflect a continuation of current trends.

2.4.3. Waste drivers

Although it represents a significant amount of GHG emissions as a group, the waste sector has few connections to activities in FECM-NEMS. As a result, emissions from the waste sector need to be calculated using broad, economy-wide parameters such as population and GDP. As discussed above, these variables are available as part of the MAM.

2.4.4. Agriculture and land-use drivers

The most relevant quantities to use as agricultural or LULUCF drivers in FECM-NEMS come from the POLYSYS model, an agricultural model that operates within FECM-NEMS. The Policy Analysis Systems Model (POLYSYS) was developed at the University of Tennessee and Oak Ridge National Laboratory for projecting land-use changes. A modified form of POLYSYS is currently used by FECM-NEMS to model biomass supply and prices, including agricultural energy crops and residues as well as food crops for use in bioenergy combustion and biofuels conversion, although a majority of the features of the original POLYSYS model are not available. Further integration between the two models would make POLYSYS-specific drivers – including land inventories, crop yields, and forestry – available to FECM-NEMS for calculating agricultural- and LULUCF-sector emissions and removals. Another option explored in more detail below would be to link FECM-NEMS with a different model that already calculates emissions and mitigation endogenously and relying on the drivers and emissions passed from that model.

2.5. Modeling GHG Mitigation

In energy system and economic models, there are three main approaches for including GHG mitigation. The first is a traditional endogenous approach similar to mitigation of fossil energy CO_2 emissions that incorporates abatement technologies directly into models for each emission source. Mitigation technologies are defined by their cost and performance characteristics for a number of existing and future abatement systems and processes, e.g., reducing natural gas leaks and hence methane emissions from natural gas pipelines or capturing methane from underground coal mines.

The second approach is to use exogenous marginal abatement cost curves (MAC curves) that estimate the potential for emissions mitigation as a function of increasing costs, normally defined as $ per ton of CO_2 equivalent. The MAC curves can be mapped to FECM-NEMS sector and sub-sector and technologies from the EPA's 2019 report on non-CO_2 greenhouse gas mitigation[10]. The MAC curves provided by the EPA report cover the largest sources of GHG emissions, but MAC curves are not available for the smallest emissions sources; these curves would need to be sourced from public research, reports from foreign government agencies, or neglected altogether given their low overall abatement potential. Extra care would need to be made to ensure to adjust MAC curves as mitigation actions are employed throughout the model over time to avoid the double counting of mitigation methods; that is, a mitigation option in a 2035 MAC curve that last 15 years would not be available in 2040. The complexity in adjusting MAC curves and risk of double counting make the endogenous approach the preferred method where sufficient detail exists in the model. The curves would need to be updated from time to time as the EPA updates their estimations; changes to curves could be streamlined into a single input.

The third approach is to develop links between FECM-NEMS and an external model that already includes emissions estimates and mitigation opportunities. The model linkage could initially be based on critical price and quantity changes in energy and economic drivers and on GHG policy stringency and mitigation costs where a few iterations between the models would be needed to arrive at a new equilibrium. A more robust model linkage could be accomplished by incorporating a reduced form of a secondary model into FECM-NEMS to account for key non-energy sector dynamics. This approach is especially

[10] EPA (2019). Global Non-CO2 Greenhouse Gas Emission Projections & Mitigation: 2015-2050. U.S. Environmental Protection Agency, EPA 430-R-19-010. https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-non-co2-greenhouse-gas-emission-projections.

promising for modeling emissions, mitigations, and removals in the agricultural and LULUCF sectors, as discussed in a later Section 3.4.3.

3. Recommendations for Model Enhancement in FECM-NEMS

This section reviews each inventory sector in the EPA GHG inventory and discusses how missing emissions and mitigation options could be incorporated into FECM-NEMS. The recommendations given throughout this section are summarized in Table 3.1. The first column lists the major emitting categories from each individual GHG, the second column identifies the type of variables to which emissions factors could be applied, and the third column gives the approach suggested to add GHG mitigation into FECM-NEMS.

Table 3.1. Summary of recommendations for modeling emission and mitigation in FECM-NEMS, by GHG and source

GHG AND SOURCE	Emission Estimates Quantity	Mitigation Approach[11]
CO_2		
Energy: Fossil fuel combustion	Already modeled	Already modeled
Energy: Petroleum and natural gas systems	Oil and gas production and processing quantities	Endogenous technologies
Energy: Non-energy use of fuels	Already modeled	MAC
Energy: Coal mining	Coal production and processing quantities	Endogenous technologies
Industry: Cement, ammonia	Already modeled	Already modeled
Industry: Iron and steel, petrochemicals	Already modeled	Endogenous technologies
Industry: Smaller sources, process directly represented in FECM-NEMS (aluminum, glass, phosphoric acid)	Industry activity energy consumption	MAC
Industry: Smaller sources, process indirectly represented in FECM-NEMS (soda ash, titanium dioxide, nitric acid, ferroalloys, zinc, lead)	Industry activity macroeconomic shipments or revenue	MAC
Industry: Smaller sources, process not represented in FECM-NEMS (urea consumption, carbides, carbonates, CO_2 consumption)	Population or GDP	MAC
Agriculture and LULUCF: changes to carbon stocks (deforestation, biomass burning), urea fertilization, liming	POLYSYS production quantities and land inventories	POLYSYS or model linkage
CH_4		
Energy: Fossil fuel combustion	Fossil fuel combustion	MAC
Energy: Petroleum and natural gas systems	Oil and gas production and processing quantities	Endogenous technologies[12]
Energy: Coal mining	Coal production and processing quantities	Endogenous technologies[12]
Industry: Petrochemicals, other	Petrochemical production quantities	N/A[13]

[11] MAC curves will be used as indicated when sufficient data is available.
[12] Mitigation data is available in the 2019 EPA report on non-CO_2 GHG mitigation (see footnote 10)
[13] Industrial CH_4 process emissions from the petrochemical sector are not a viable target for mitigation. The sum of industrial-sector CH_4 emissions is less than 0.5 MMT CO_2 eq. and can be neglected as a mitigation target.

Agriculture and LULUCF: rice cultivation, enteric fermentation, manure management, agricultural residues, LULUCF emissions	POLYSYS production quantities and land inventories	POLYSYS or model linkage
Waste: landfills, wastewater treatment, and other waste-sector emissions	Population or GDP	MAC[12]
N_2O		
Energy: Fossil fuel combustion	Fossil fuel consumption	MAC
Industry: Smaller sources, process directly represented in FECM-NEMS (electronics)	Industry activity energy consumption	MAC
Industry: Smaller sources, process indirectly represented in FECM-NEMS (nitric acid, adipic acid, caprolactam, glyoxal, glyoxylic acid)	Industry activity macroeconomic shipments or revenue	MAC[12]
Industry: Smaller sources, process not represented in FECM-NEMS (N_2O from product use)	Population or GDP	MAC
Agriculture and LULUCF: agricultural soil management, manure management, agricultural residues, LULUCF emissions	POLYSYS production quantities and land inventories	POLYSYS or model linkage
Waste: wastewater treatment and other waste-sector emissions	Population or GDP	MAC[12]
HFCs		
Industry: Substitution of ozone depleting substances	Total building floorspace industry production macro	MAC[12]
Industry: Smaller sources, process directly represented in FECM-NEMS (electronics)	Industry activity energy consumption	MAC[12]
Industry: Smaller sources, process indirectly represented in FECM-NEMS (HCFC-22, magnesium)	Industry activity macroeconomic shipments or revenue	MAC[12]
PFCs		
Industry: Smaller sources, process directly represented in FECM-NEMS (electronics, aluminum)	Industry activity energy consumption	MAC[12]
SF_6		
Industry: Smaller sources, process directly represented in FECM-NEMS (electronics)	Industry activity energy consumption	MAC[12]
Industry: Smaller sources, process indirectly represented in FECM-NEMS (electrical transmission and distribution, magnesium)	Electrical capacity, industry activity macroeconomic shipments or revenue	MAC[12]
NF_3		
Industry: Smaller sources, process directly represented in FECM-NEMS (electronics)	Industry activity energy consumption	MAC[12]

3.1. Energy-Sector GHGs

Most U.S. GHG emissions come from the energy inventory sector, with a significant portion being CO_2 emitted during fossil fuel combustion. The energy-sector categories described in the EPA GHG inventory have been aggregated into four main groups for this section: *Fossil Fuel Combustion and Incineration of*

Waste, Petroleum and Natural Gas Systems and Abandoned Wells, Non-Energy Use of Fuels, and *Coal Mining and Abandoned Underground Coal Mines*.

3.1.1. Fossil fuel combustion and incineration of waste

CO_2, CH_4, and N_2O are emitted during the combustion of fossil fuels and waste. These emissions occur from combustion for industrial, residential, and commercial activities (stationary production), as well as transportation (mobile combustion). Table 3.2 lists GHG emissions caused by combustion, using data from the EPA GHG inventory. Smaller subcategories have been aggregated together to simplify the table.

Table 3.2. Emissions from fossil fuel combustion and incineration of waste, by subcategory

Emissions Subcategory	GHG	2021 U.S. GHG Emissions (MMT CO_2 eq.)
Stationary Production	CO_2	2,858
Mobile Combustion	CO_2	1,757
Incineration of Waste	CO_2	13
Stationary Production – Residential	CH_4	5
Stationary Production – Other	CH_4	4
Mobile Combustion – Total	CH_4	3
Stationary Production – Electric Power	N_2O	19
Stationary Production – Other	N_2O	3
Mobile Combustion – Gasoline On-road	N_2O	6
Mobile Combustion – Non-road	N_2O	7
Mobile Combustion – Other	N_2O	3
Incineration of Waste	N_2O	0.4
Total		**4,702**
Total: CH_4 and N_2O only		**51**

Stationary Production

Stationary Production represents GHGs emitted during fuel combustion from non-mobile sources (e.g., power plants). CO_2 emissions are by far the largest category and are significant across all sectors. FECM-NEMS models all CO_2 emissions from stationary combustion sources. The largest emitting subcategory of CH_4 is *Stationary Production – Residential*, driven primarily by wood combustion. N_2O from stationary combustion is emitted primarily at coal-fired power plants, as represented by the *Stationary Production – Electric Power*. The remaining CH_4 and N_2O emissions are distributed across the other economic sectors and are often caused by wood combustion.

Mobile Combustion

The *Mobile Combustion* subcategories represent GHGs released from combustion in vehicles. CO_2 from mobile combustion is a major emissions source and is already modeled in FECM-NEMS. Mobile CH_4 emissions occur in small quantities in a wide variety of vehicles, usually because of incomplete combustion. Mobile N_2O emissions are larger, especially in *Gasoline On-road* and *Non-road*. N_2O is sometimes emitted during catalytic control of other pollutants (such as CH_4), which caused N_2O

emissions from vehicles to increase throughout the 1990's. However, N_2O has quickly declined thanks to improved control technologies.

Incineration of Waste

The final category, *Incineration of Waste*, represents non-biogenic CO_2 (biogenic CO_2 is assumed to be net-zero with regards to emissions) and a small amount of N_2O emitted at municipal solid waste facilities. FECM-NEMS calculates the CO_2 from these facilities but neglects the N_2O.

Recommendations for Modeling Emissions

GHG emissions from combustion depend on the chemical composition of the fuel, efficiency of the combustion reaction, and pollution controls. CO_2 from *Fossil Fuel Combustion and Incineration of Waste* are already well represented throughout FECM-NEMS, which uses emissions factors published in the CO_2 chapter of the AEO assumptions document[14]. As a result, there are no specific changes to modeling CO_2 emissions from combustion recommended in this report.

Estimating emissions of CH_4 and N_2O from combustion sources is relatively straightforward given the existing framework for estimating CO_2 emissions in FECM-NEMS. CH_4 and N_2O emissions from combustion could be calculated similar to how CO_2 emissions are already calculated in FECM-NEMS – by multiplying the quantity of fuel with an emissions factor at the point of combustion. The emissions factor would consider the fuel content, combustion technology, and combustion reaction conditions. The EPA GHG inventory uses a list of emissions factors[15] developed by the IPCC and could be included into FECM-NEMS as an input file.

CH_4 and N_2O emissions factors can be based on technology-specific values derived from NETL baseline studies[16] and the CCRD[7]. The EPA GHG Inventory can be used to benchmark overall emissions estimates. Emissions factors could be designed with consideration for existing trends in technology; for example, they should have a mechanism to decrease over time to represent the replacement of older vehicles with newer and more efficient ones but increase over time at coal plants to recognize aging infrastructure.

Recommendations for Modeling Mitigations

FECM-NEMS has multiple methods to mitigate emissions from CO_2 combustion using CCS. Existing mitigation options are discussed in greater detail in Section 2.3. While not available in FECM-NEMS currently, CCS could be expanded to include waste incineration, which thanks to the partially biogenic origin of waste would represent net-negative CO_2 emissions.

[14] EIA (2023). Assumptions to the Annual Energy Outlook 2023: Energy-Related Carbon Dioxide. U.S. Energy Information Agency. https://www.eia.gov/outlooks/aeo/assumptions/.

[15] EPA (2023). Annexes to the Inventory of U.S. Greenhouse Gas Emissions and Sinks, EPA 430-R-19-010. https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-non-co2-greenhouse-gas-emission-projections.

[16] The NETL baseline studies are a collection of technical reports that asses the cost and performance of various fossil fuel combustion technologies, available at https://netl.doe.gov/node/7512.

Although CH_4 and N_2O emissions are significant as a group, they are dispersed among various smaller sources, making mitigation with technology options difficult to implement. MAC curves would be a better choice for this category. The EPA does not provide MAC curves for CH_4 and N_2O from combustion and similar data is not easily available, so a literature review will be required to determine a suitable estimate.

One consideration for modeling emissions mitigation from fossil fuel combustion is that technological improvements that increase combustion efficiency and reduce emissions may affect emissions of CO_2, CH_4, and N_2O simultaneously. FECM-NEMS already contains mechanisms to improve the efficiency of combustion process (such as via learning curves). As a result, existing mechanisms in FECM-NEMS that improve combustion efficiency will be evaluated to ensure that emissions are appropriately mitigated for all gases with a consideration for relevant linkages.

3.1.2. Petroleum and natural gas systems and abandoned wells

The oil and gas supply chain emits CO_2 and CH_4 via flaring, leakage, venting, and other activities. Table 3.3 displays emissions from petroleum and natural gas systems by subcategory. Smaller subcategories have been aggregated together to simplify the table.

Table 3.3. Emissions from natural gas systems and abandoned gas wells, by subcategory

Emissions Subcategory	GHG	2021 U.S. GHG Emissions (MMT CO_2 eq.)
Exploration – Oil	CO_2	0.5
Production – Oil	CO_2	20
Production – Gas	CO_2	9
Processing - Gas	CO_2	26
Other	CO_2	5
Exploration – Oil	CH_4	0.2
Production – Oil	CH_4	49
Exploration – Gas[17]	CH_4	0.2
Production – Gas[17]	CH_4	94
Processing – Gas[17]	CH_4	14
Transmission and Storage – Gas[17]	CH_4	45
Distribution and Post-Meter – Gas[17]	CH_4	28
Abandoned Oil and Gas Wells	CH_4	8
Other	CH_4	1
Total		301

FECM-NEMS does not estimate CO_2 emissions from the oil and gas supply chain, except for natural gas combustion to move gas through the pipeline system, nor does it estimate CH_4 emissions from the oil supply chain; only CH_4 emissions from the natural gas system are currently represented. The EPA classifies CO_2 emissions from the combustion of pipeline fuel under fossil fuel combustion, so they are not represented in the above table. CH_4 emissions from gas wells are calculated using two emissions

[17] Emissions are already estimated in FECM-NEMS

factors: one regional emissions factor applied to natural gas production quantities, and another national average emissions factor applied to natural gas transport flows. However, given the detailed representation of oil and gas in FECM-NEMS in the OGSM, NGMM, and LFMM, there are opportunities to expand the current emissions estimate into a more detailed calculation that includes CO_2 and CH_4 for both oil and gas wells.

Exploration

The *Exploration* category refers to GHG emissions that occur during drilling, well testing, and completions, and consists of CO_2 and CH_4 emitted during leaks, venting, or flaring. Most emissions come from well completions in hydraulically fractured formations. *Exploration* makes up a relatively small share of overall emissions and has been declining in recent years. FECM-NEMS contains sufficient detail about oil and gas operations (including project investment decisions and drilling activity) to extract quantities to which emissions factors can be applied.

Production

The *Production* category represents GHG emissions from oil and gas wells through leaks, venting, and flaring. CO_2 emissions from production come almost completely from gas flaring (the intentional combustion of surplus CH_4 into a gas with lower GWP), an activity not represented by FECM-NEMS. CH_4 emissions occur during flaring because of incomplete combustion, but also arise from leakage and venting from production equipment (including pneumatics, pumps, and compressors) and produced water. There are two potential methods to model the missing CO_2 and CH_4 emissions and mitigation. A simplified method to estimate these emissions would be to combine oil and gas production quantities within FECM-NEMS with their corresponding emissions factors for CO_2 and CH_4 emissions, similar to how CH_4 emissions from natural gas systems are already calculated (emissions from exploration, specifically, are small and can be combined with emissions from production). This approach would pair well with a MAC-curve approach for GHG mitigation, discussed in the next section. A more complex representation of GHG emissions from exploration and production would use technology-specific emissions factors applied to different stages of the production process, including an endogenous representation of gas flaring. This approach would be more suitable for mitigation with technology options.

Processing

Processing – Gas refers to emissions of CO_2 and CH_4 that are released when natural gas is treated to prepare it for pipeline transport. CO_2 is removed from the natural gas stream through acid gas removal (AGR) processes and is typically vented to the atmosphere. CH_4 is emitted from compressors during processing. While CH_4 emissions are currently accounted for in FECM-NEMS as part of an average emissions factor applied to natural gas production, there is enough detail in the NGMM to apply a specific emissions factor to the processing stage.

Transmission and Storage

Transmission and Storage – Gas represents CH_4 emissions due to leaks and venting during transport and storage (mainly from compressors and pneumatic systems). Transmission and storage processes are both modeled in detail by FECM-NEMS, and emissions from transmission are already estimated using a single national average emissions factor applied to natural gas pipeline flows. This emissions factor could be applied to intra- and inter-state pipeline flows, taking advantage of the detailed pipeline network modeled by FECM-NEMS (pipeline distance is an important driver of emissions). Storage as a process could be separated with its own emissions factor applied to stored gas volumes. There are existing variables that represent natural gas consumption as fuel during natural gas transport and storage; these areas would be logical places to incorporate the emissions factors. Energy used for compression could be disaggregated to improve modeling of compression-specific emissions and mitigation, given the large volume of emissions from compressors during transmission and storage.

Distribution and Post-Meter

Distribution and Post-Meter – Gas represents CH_4 emissions at the end of the natural gas supply chain, caused by leaks during the last step of transport to consumers and leakage at the point of consumption (this category does not include emissions from natural gas combustion). These emissions could be separated from their existing representation in FECM-NEMS into a separate category, using specific, regionalized emissions factors for leakage during the distribution and post-meter stages. These emissions factors could be applied to natural gas consumption volumes, analogous to how the *PIP_DIST* variable (natural gas consumption during flow through distribution pipelines) is used.

Abandoned Oil and Gas Wells

Abandoned Oil and Gas Wells accounts for CH_4 emitted over time from abandoned (and often older) oil and gas wells. Wells that were not plugged at the end of production continue to emit methane and trace volumes of CO_2 to the atmosphere. The emissions from this category depend on the number of abandoned wells and the fraction of abandoned wells that are plugged (a mitigation option to prevent further emissions). Because FECM-NEMS models drilling activity and well / field retirements, emissions from abandoned wells could be estimated via an emissions factor applied to a population of abandoned, unplugged wells which includes a historic baseline population and changes in response to drilling activity. Mitigation could be accomplished with a MAC curve that reflects the cost of well plugging.

The emissions in the *Other* categories represent emissions from crude oil refining, CO_2 leakage that occurs after natural gas processing, and other smaller sources. These emissions could be ignored or combined with other emissions categories (such as *Transmission and Storage*) using an averaged emissions factor. Petroleum and natural gas systems additionally emit trace amounts of N_2O (<0.01 MMT CO_2 eq.), which are neglected here.

Recommendations for Modeling Emissions

The EPA GHG inventory provides thorough estimates of CO_2 and CH_4 emissions throughout the petroleum and natural gas supply chains (including abandoned oil and gas wells), the most recent report covering emissions through 2021. Any work conducted to incorporate missing emissions into FECM-NEMS should benchmark results for years covered by the most recent EPA GHG inventory against the inventory values. Emissions factors used for emissions modeling in FECM-NEMS should consider changes over time in response to factors such as degradation of methane transport infrastructure (which would increase emissions factors) and process improvements (which would reduce emissions factors). The rate of process improvements would in turn respond to the carbon price as a form of mitigation.

The scale and measurement of CH_4 emissions is an evolving issue, and the scientific consensus has shifted in recent years with advancements in methane leakage detection. One challenge with modeling CH_4 emissions from petroleum and natural gas systems, in particular, is enabling the model to be adaptable to changes in emissions factors driven not by technology, but by an improved understanding of methane leakage pathways. In addition to default values benchmarked to the EPA GHG inventory, methane leakage emissions factors should be structured such that users can easily modify the values to run sensitivity cases (for example, by selecting a higher emissions factor to reflect a case where methane emissions are greater than estimated). Mitigation options, discussed in the section below, should be implemented in a way that is consistent with adjustable emissions factors. Regionalizing these values where appropriate data exists will help improve emissions estimates and allow for localized methane leakage sensitivities.

Recommendations for Modeling Mitigations

Mitigation with Technology Options

Given the extensive detail of oil and gas systems in FECM-NEMS, modeling mitigation with individual technologies is a viable option. Various pieces of equipment throughout the oil and gas supply chain emit CO_2 and CH_4, including compressors, pneumatic devices, pumps, and pipelines. The EPA identifies the several technology-based mitigation options in their report on non-CO_2 GHG emissions mitigation[10] including improved inspection and maintenance, vapor recovery units for oil storage tanks, replacing pneumatic devices, and installing catalytic converters to gas engines and turbines. These options broadly affect the entire oil and gas supply chain and enable GHG mitigation from the *Exploration, Production*, *Processing – Gas*, *Transportation and Storage,* and *Distribution and Post-Meter* categories. Estimates of technology costs are reported in the National Energy Technology Laboratory's (NETL's) *Industry Partnerships & Their Role in Reducing Natural Gas Supply Chain Greenhouse Gas*[18].

The mitigation of CO_2 from the *Processing – Gas* category already exists in FECM-NEMS in the form of CO_2 capture facilities for AGR. Currently, CO_2 from AGR is not connected to specific emissions from the natural gas supply chain, but rather draws on CO_2 capture opportunities and costs as reported in NETL's industrial CCRD. While the CO_2 captured changes over time in response to policies in the model, the underlying CO_2 emissions themselves are not tracked. The AGR process in FECM-NEMS should be connected to specific natural gas flows with reporting of any CO_2 emissions to properly represent mitigation.

The main method for mitigating emissions from *Abandoned Oil and Gas Wells* is through well plugging, which dramatically reduces emissions rates. Well plugging could be implemented as an option for both existing abandoned wells and newly retired wells.

Mitigation with MAC Curves

For a simpler option, mitigation from oil and gas systems could be estimated using MAC curves. The EPA has developed MAC curves for U.S. CH_4 mitigation from petroleum and natural gas systems in their

[18] Rai, Srijana, Littlefield, James, Roman-White, Selina, Zaimes, George G., Cooney, Gregory, & Skone, Timothy J. *Industry Partnerships & Their Role In Reducing Natural Gas Supply Chain Greenhouse Gas Emissions – Phase 2. United States*. https://doi.org/10.2172/1647225

Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation, 2015-2050. These MAC curves could be converted into a percentage basis (representing the fraction of emissions mitigated) and multiplied with emissions factors as a function of a policy-driven carbon price.

Recommendations

Petroleum and natural gas systems are modeled in extensive detail in FECM-NEMS through the OGSM, NGMM, and LFMM. Given the existing modeling infrastructure, GHG mitigation with technology options is an excellent choice for this category. Oil and gas supply chains are currently modeled in FECM-NEMS from beginning to end, with representation of individual wells and fields, pipeline infrastructure, processing, gas storage, and consumption across multiple demand modules. In addition, there are several explicit technologies (improved pneumatics and compressors, well plugging, etc.) designed for mitigating CO_2 and CH_4 in oil and gas systems, with detailed estimates of cost and mitigation potential available[10,18]. Because modeling mitigations with technology options is considered the most thorough and accurate approach, it would make sense to do so in FECM-NEMS.

Modeling mitigations with MAC curves is another valid choice for this category and would require less time and effort to implement. However, their reliance on numerical averages means that MAC curves do not capture mitigations with as much detail as would be possible with a technology-based approach.

3.1.3. Non-energy use of fuels

In addition to combustion, fossil fuels are used for a variety of non-combustion purposes, both from their own use as products and as feedstocks to other products. Fossil fuels used in these ways can still emit CO_2 to the atmosphere, either during a manufacturing step or throughout their lifetime. All fossil fuels contain some number of carbon atoms that have potential to be released as CO_2 over their lifetime. Across all non-energy uses, the EPA estimates in their GHG inventory report that 38% of the carbon is ultimately emitted as CO_2 (excluding CO_2 emitted during the incineration of waste, which is counted separately). These emissions are listed in Table 3.4. While not all non-energy uses of fuels are represented explicitly in FECM-NEMS, all emissions from this category are represented on an aggregate basis.

Table 3.4. Emissions from non-energy use of fuels, by subcategory

Emissions Subcategory	GHG	2021 U.S. GHG Emissions (MMT CO_2 eq.)
Feedstocks	CO_2	113
Asphalt	CO_2	0.3
Lubricants	CO_2	16
Waxes	CO_2	0.4
Other	CO_2	11
Total	CO_2	**140**

Emissions accounting from non-energy use of fuels is complicated, with a risk of double counting. For reporting purposes, the EPA GHG inventory includes emissions from *Non-Energy Uses of Fuels* as their own section in the energy sector, distinct from *Petrochemical Production* and *Incineration of Waste.* As a result, CO_2 emissions during end-of-life combustion/incineration of fossil fuels or fossil fuel-related products, as well as emissions from the production of specific petrochemicals (acrylonitrile, carbon black, ethylene, ethylene dichloride, ethylene oxide, and methanol), are not listed in Table 3.4. Uses of fossil fuels for chemical reduction (for example, metallurgical coal for iron and steel production) are also tracked separately in the industry sector.

In Table 3.4, the *Feedstocks* group includes emissions from fossil fuels used as feedstocks to produce plastics, rubber, synthetic fibers, and other products. The *Asphalt* group represents emissions from the production and usage of asphalt (the EPA estimates only 0.4% of carbon in asphalt is released to the atmosphere as CO_2). Fossil fuels are additionally used as lubricants and waxes, which both emit some CO_2. The *Other* category includes emissions from non-energy use of industrial coking coal, distillate fuel oil, petroleum coke, and other miscellaneous products.

FECM-NEMS models emissions from *Non-Energy Use of Fuels* (as well as other non-energy uses of fossil fuels that are reported in different EPA GHG inventory sections) by multiplying fuel quantities with an emissions factor, itself a product of a CO_2 coefficient and a combustion fraction. FECM-NEMS does not have explicit representations of every single non-energy activity that emits GHGs from fossil fuels; however, the scope of FECM-NEMS does include all fossil fuels as an aggregate. As a result, by multiplying aggregated fuel quantities with the appropriate emissions factors, FECM-NEMS models all emissions from this category at an aggregated level. Another possible enhancement would be to represent emissions from these emissions over the lifetimes of the products, where appropriate, rather than at the time of their creation as is currently done.

Recommendations for Modeling Emissions

Because FECM-NEMS already models emissions from *Non-Energy Use of Fuels*, there are no changes required to comprehensively cover these emissions. The existing emissions in FECM-NEMS could be enhanced by disaggregating the fuel quantities – emissions factor pairs into more detailed non-energy processes. Because the emission rates over product lifetimes may vary significantly by product time, attempting to incorporate that additional level of detail is not recommended.

Recommendations for Modeling Mitigations

Non-Energy Use of Fuels contains emissions from a variety of small, different processes. Given the complexity, emissions mitigation of this kind would best be represented with MAC curves. However, MAC curves are not readily available for this category, which includes some emissions sources that are a function of the carbon content of fuels and are therefore intrinsically difficult to mitigate. As a result, it is recommended that mitigation from this category be represented by reduction in the demand for various products made from fossil-fuels in response to a rising carbon price, or by replacement with new processes that produce similar items with less or no fossil fuels (e.g., bioplastics).

3.1.4. Coal mining and abandoned underground coal mines

CO_2 and CH_4 occur naturally in coal mines and are released into the atmosphere during and after mining activity. Table 3.5 displays GHG emissions from coal mining and abandoned underground coal mines.

Table 3.5. Emissions from coal mining and abandoned underground coal mines

Emissions Subcategory	GHG	2021 U.S. GHG Emissions (MMT CO_2 eq.)
Underground Mining	CO_2	2
Surface Mining	CO_2	0.3
Underground Mining	CH_4	33
Surface Mining	CH_4	6
Post-Mining – Underground	CH_4	5
Post-Mining - Surface	CH_4	1
Abandoned Underground Coal Mines	CH_4	6
Total		**53**

Underground Mining

Underground Mining represents the majority of emissions from this section. As mines are developed, CO_2 and CH_4 that were originally locked away are liberated to the atmosphere. Gases are ventilated from the mine intentionally to reduce concentrations of CO_2 and CH_4 inside the mine to safer levels during operations. The quantity of emissions depends on the chemical composition of the coal, a parameter that varies regionally. Deeper coal tends to be richer in CH_4, which partly explains why emissions from underground mines are larger than those from surface mines. Some mines include capture systems to isolate and repurpose fugitive CH_4; these systems capture 18 MMT CO_2 eq. of CH_4, which together with the 51 MMT CO_2 eq. total of CH_4 liberated in underground mines gives a net emission of 33 MMT CO_2 eq. FECM-NEMS models coal supply and production by region, composition (coal rank) and mine type (underground or surface). The coal supply curves could be combined with emissions factors to estimate emissions of CO_2 and CH_4.

Surface Mining

Surface Mining represents emissions released from surface coal mines. Unlike underground mines, CH_4 capture is not a realistic option for surface mines. Because FECM-NEMS tracks quantities of coal from surface and underground mines separately, emissions from surface mines could be calculated with emissions factors using a similar approach to emissions from underground mines.

Post-Mining

The *Post-Mining* categories refer to the CH_4 released during the transportation and processing of mined coal. These emissions could be modeled using emissions factors on production volumes. The EPA provides separate estimates of post-mining emissions from underground and surface mines.

Abandoned Underground Coal Mines

The *Abandoned Underground Coal Mines* category represents continued emissions from abandoned mines. Similar to *Abandoned Oil and Gas Wells* from Section 3.1.2, CH_4 can leak from abandoned mines at a near constant rate over time. The leakage can be mitigated with mine flooding (a natural process) or CH_4 capture. Emissions from abandoned mines could be estimated in FECM-NEMS by applying an emissions factor to decreases in coal supply as coal is phased out (a numerical representation of coal mine retirements). Emissions from these recently retired mines can then be added to a baseline leakage rate.

Recommendations for Modeling Emissions

Process emissions from coal mining are estimated in the EPA's GHG inventory, which itself draws data from their Greenhouse Gas Reporting Program (GHGRP) and from the U.S. Mine Safety and Health Administration (MSHA). Emissions factors throughout the coal mining subsector should be indexed to the most current emissions estimates (2021). Emissions estimates could be disaggregated by leveraging previous work by the NETL to model emissions from coal mining at a regional level[19]. Emissions factors can be chosen to reflect changes over time, such as decreases in the emissions rate from abandoned mines due to natural mine flooding or increases associated with reduced efficiency from aging methane capture units. As coal mining activity decreases in the U.S, a process should be implemented to represent mine retirements and corresponding increases to GHG emissions from the *Abandoned Underground Coal Mines* category. An estimate of mine retirements could be calculated from decreases in coal supply and demand over time.

Recommendations for Modeling Mitigation

Mitigation with Technology Options

Although coal mining activities emit fewer GHGs than petroleum and natural gas systems, they are still a significant source of missing GHGs in FECM-NEMS. Additionally, coal processes are modeled in detail in the Coal Market Module (CMM), and specific technologies to mitigate coal are well described in literature. Given these factors, emissions mitigation from coal mining activities could be represented effectively with technology options.

There are two main techniques to mitigate emissions from coal mining: ventilation air methane (VAM) oxidation, and degasification. The former technology refers to the capture and oxidation of low-concentration CH_4 from active or abandoned underground mines, which converts emissions from high-GWP CH_4 into low-GWP CO_2. Most mitigatable emissions from coal mining can be achieved with VAM oxidation. The latter technology, degasification, involves drilling to remove concentrated CH_4 which can be sold or combusted on-site for energy. Degasification can occur before, during, or after mining. The technology options should be implemented in a way that represents all VAM oxidation units that currently exist in the first modeling year.

Mitigation with MAC Curves

Emissions mitigation from coal mining could alternatively be modeled using MAC curves. Although MAC curves are only a numerical representation of mitigation and lack the specific detail of technology options, MAC curves require less data and are easier to implement. Coal mining supply in the CMM is calculated from a supply curve, which is itself a numerical representation - as a result, MAC curves pair well with the existing representation of coal in FECM-NEMS. The EPA provides national MAC curves for coal mining in their report on non-CO_2 GHG mitigation[10].

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[19] Carlson, Derrick R., Krynock, Michelle, Roman-White, Selina, Cooney, Greg, and Skone, Timothy J. Modeling the Life Cycle Impacts of U.S. Coal Mining at a Regional Level - ISSST2018. United States: N. p., 2023.

Recommendations

The coal mining sector is one of the few categories of missing emissions that are significant in number, described in detail in FECM-NEMS, and studied extensively in public reports. Emissions from coal mines are likely to remain significant over time with the emissions burden shifting from active to abandoned mines as mines close in response to net-zero initiatives. Furthermore, there are only two significant technologies considered for mitigating emissions: VAM oxidation and degasification. As a result, technology options are a good choice for modeling mitigation. Mitigation with MAC curves would be another valid strategy and would be easier to implement. However, given that technology options are the ideal approach to modeling mitigation thanks to their detail, it is recommended that they be employed for coal mining.

3.2. Industrial-Sector GHGs

The industrial sector representation in AEO is described below in an extract from the IDM documentation[20]:

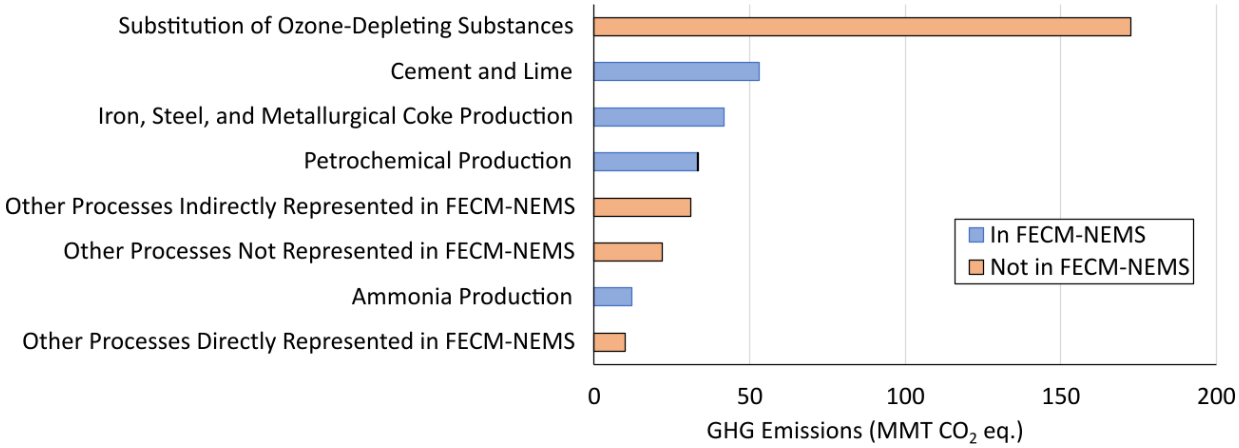
"Each industry is associated with one or more NAICS codes. (NAICS is the North American Industrial Classification System.) The IDM classifies these industries into three general groups: energy-intensive manufacturing industries, non-energy-intensive manufacturing industries, and non-manufacturing industries. There are eight energy-intensive manufacturing industries, of which seven are modeled in the IDM: food products; paper and allied products; bulk chemicals; glass and glass products; cement and lime; iron and steel; and aluminum. Also within the manufacturing group are eight non-energy-intensive manufacturing industries: metal-based durables, consisting of fabricated metals; machinery; computers and electronics; electrical equipment and appliances; transportation equipment; wood products; plastic and rubber products; and the balance of manufacturing."

As of AEO23, and in FECM-NEMS based on AEO22, the data associated with fuel consumption are based on the 2018 Manufacturing Energy Consumption Survey (MECS)[21]. The survey is consistent with NAICS[8] categories last updated in 2017 and are mentioned in the following sections wherever applicable. As seen in the Figure 3.1 below the largest source of non-combustion related GHG emissions in the industrial sector is from HFCs used as substitutes for ozone-depleting CFCs that that began to be phased out in the late 1980's in industrial and residential/commercial refrigeration. These are mainly due to leakages of these HFCs from product use; HFCs have high GWP potential and therefore small quantities may still lead to high CO_2 equivalent emissions. The next biggest industries are the energy intensive industries of cement & lime, iron & steel, petrochemicals, and ammonia, all of which have process emissions of 60 MMT or less. The industrial sector has many small subsectors, so the remaining emissions come from a long tail of these sectors but still add up to more than 60 MMT total emissions.

[20] EIA (2022). Model Documentation Report: Industrial Demand Module of the National Energy Modeling System. U.S. Energy Information Agency.
https://www.eia.gov/outlooks/aeo/nems/documentation/industrial/pdf/IDM_2022.pdf

[21] EIA MECS 2018, retrieved May 2023.

Figure 3.1. Industry-sector GHG emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels are not counted in this sector.



3.2.1. Industrial sources with significant emissions fully represented in FECM-NEMS

The following sources are well represented in FECM-NEMS either directly with a high level of detail as in the case of cement & lime and iron & steel industries, or indirectly as part of an aggregated group as is the case with petrochemical and ammonia production.

Sources represented in Energy Intensive Manufacturing

These sources have a detailed representation of their process steps in the industrial model and add up to about 94.9 MMT of emissions.

Cement (NAICS: 327310) and lime (NAICS: 327410) production

The model representation of the cement industry includes technology options and fuel choices for the process steps of grinding mills, kilns producing clinker for cement and finished grinding. It also includes a fixed representation of additives to clinker to make the final cement product. As a result, most of the non-energy emissions from this industry are well represented in the model. These emissions are largely CO_2 and add up to approximately 41.3 MMT in 2021. For the cement industry, FECM-NEMS already includes the decarbonization options of CCS, fuel switching and increases in clinker additives using data available in the 2022 NETL CCRD[7]. For the lime industry, the kiln process step is similarly represented with fuel choice and technology options. The emissions from this industry add up to 11.9 MMT. However, only non-energy emissions that are captured from cement are currently reported explicitly in FECM-NEMS. Non-energy emissions from cement and lime are calculated but not directly reported. Instead, they are added to a continuously growing 'other sectors' process emissions curve along with a legacy calculation for cement.

Iron (NAICS: 331110), steel (NAICS: 3312*), and metallurgical coke (NAICS: 324199) production

The industrial model representation includes technology options and fuel choices for the process steps of metallurgical coke production, iron production using direct reduction for basic oxygen furnaces (BOF) and electric arc furnaces (EAF), steel making in blast furnaces and BOF/EAF, and steel product making in casting, hot roll, and cold roll processes. As a result, most of the non-energy emissions from this industry are well represented in the model as part of total emissions from this industry. They are largely CO_2 emissions and add up to about 41.7 MMT. Modeling mitigation through CCS retrofits and fuel/technology switching is therefore easy to implement and is currently being explored as part of FECM-NEMS development.

Sources represented in Bulk Chemicals

Petrochemical production

Production of organic petrochemicals (NAICS: 325110) such as ethylene, ethylene dichloride, ethylene oxide and methanol result in CO_2 emissions, while resins (NAICS: 3252*) made from petrochemicals such as acrylonitrile result in small amounts of CH_4 emissions. The entire petrochemicals sector adds up to about 33.6 MMT of emissions. All non-energy emissions from this category, except for the small amount of methane, are represented in the industrial model as part of total emissions from the bulk chemicals sector. There are no direct pathways for mitigation in the model which mainly involve capture of the CO_2 emissions, but they may be inferred through activity in the petrochemicals sector.

Sources represented in Bulk Chemicals: Agricultural

Ammonia production (NAICS: 325311)

Emissions from ammonia, which are mainly CO_2 emissions of about 12.2 MMT, are reported through natural gas consumption for the steam methane reforming (SMR) process used to make hydrogen for ammonia, but not directly reported. However, they can be inferred based on available data in the 2022 NETL CCRD, which includes a complete list of ammonia sites and their capacity. This database also provides an opportunity to model mitigation of CO_2 emissions from ammonia by evaluating each site for potential CCS retrofits. Another new feature developed for FECM-NEMS recently is the HMM which allows for substitution of onsite hydrogen with potentially clean merchant hydrogen, either from SMRs with CCS or from electrolyzers using renewable electricity.

Recommendations for improving the modeling of mitigation

In addition to the existing options in the model for GHG mitigation across the above sectors, the emissions factors can be reviewed and modified if necessary to include GHG mitigation as a result of improvements in process efficiency. Increases in certain types of efficiency can lead to a reduction of process emissions because fewer inputs are required to achieve the same outputs. Many processes in FECM-NEMS have efficiency improvements built-in, typically following learning curves that represent technological advances. These improvements may be implemented as a function of time, or in response to specific incentives. As a result, existing methods in FECM-NEMS that act to improve process efficiency could be assessed or edited to verify that they adequately represent the potential for GHG mitigation.

3.2.2. Industrial sectors with significant emissions not represented in FECM-NEMS

Substitution of ozone depleting substances (NAICS: 325120)

As mentioned earlier, the HFCs replacing CFCs are the biggest sources of industrial GHGs, adding up to 172.5 MMT total. The most common HFCs are R-32 (difluoromethane), R-410a and R-134a (tetrafluoroethane), replacing the CFC R-12 (freon). CFCs and HFCs are included under the inorganic chemicals section under bulk chemicals. However, their emissions, which are primarily fluorinated gases, are not represented in the model. Their mitigation is mainly through substitution with hydrofluoroolefins (HFOs), for example by R-1234yf (an HFO), and potentially by other common chemicals like propane, isobutane, ammonia, and CO_2. Although the emissions of these substances occur at their end use application, particularly in residential and commercial sectors, their mitigation has previously been targeted at the production source.

Recommendations for modeling emissions

Since there is not a good representation of these processes in the industrial model and their production depends on end use sector demand, the emissions due to their production are better tracked through overall economic activity in the MAM and targeted quantities related to air conditioning and floor space in the residential and commercial modules.

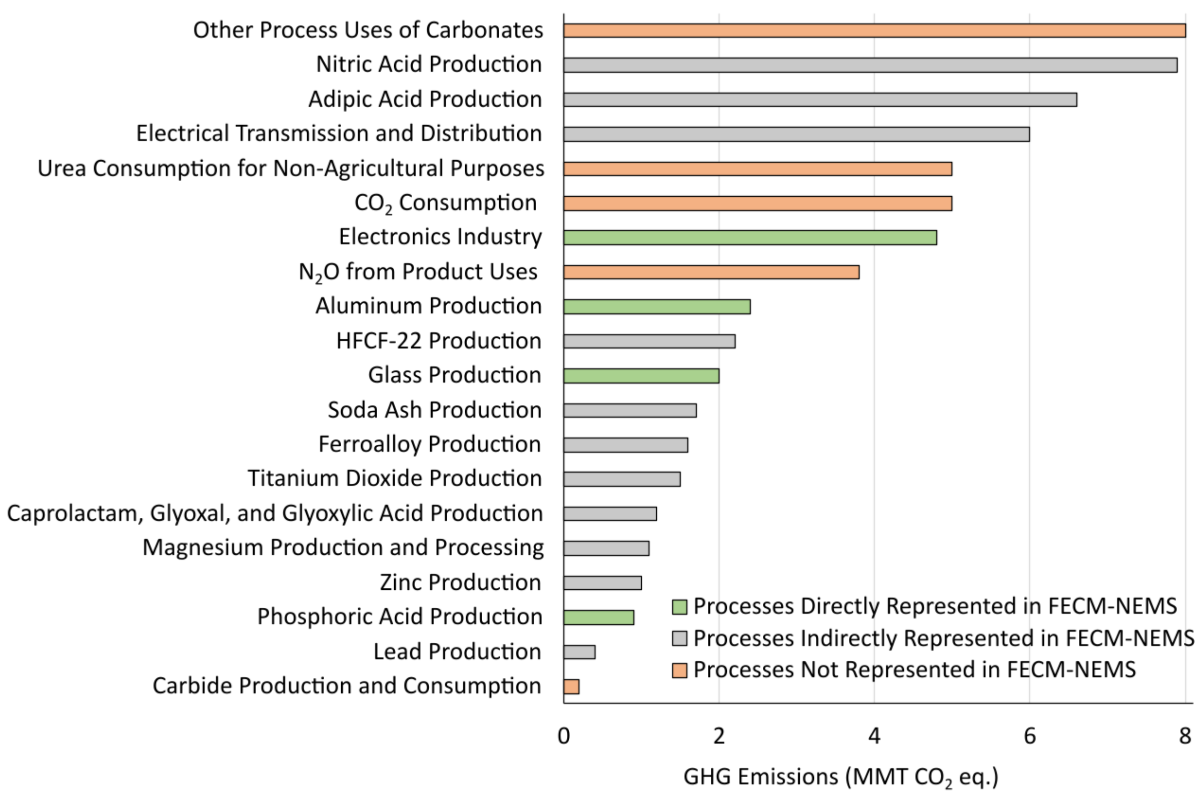
Recommendations for modeling mitigation of emissions

Due to the lack of representation in the model, the mitigation of emissions can be linked to mitigation in the overall economy and MAC curves. The EPA has calculated MAC curves for *Substitution of Ozone Depleting Substances* in their non-CO_2 mitigations report.

3.2.3. Other smaller sources of emissions

These other sources of emissions have individual small contributions (<10 MMT) as seen in the Figure 3.2 below but add up to a significant total of approximately about 63.3 MMT.

Figure 3.2. Other industry-sector emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels are not counted in this sector.



Assorted sources with related processes directly represented in FECM-NEMS

The following sources are represented in the FECM-NEMS industrial model in detail, or at least mentioned explicitly as part of a broader sector. The MECS 2018 survey reports fuel consumption for some of these in detail and links them to their NAICS code. Together they account for 10.1 MMT of reported emissions.

Sources represented in Energy Intensive Manufacturing

The following sources have a detailed representation of their process steps in the industrial model and add up to about 4.4 MMT of emissions.

Aluminum production (NAICS: 331313)

The industrial model has a detailed representation of aluminum manufacturing and includes primary production from bauxite ore and secondary production using recycled aluminum. Non-energy emissions, which are about 2.4 MMT, are not reported although they can be tied to fuel consumption, and mainly include CO_2 related emissions which account for two-thirds of the total, the rest being from fluorinated gases.

Glass production

The industrial model has a detailed representation of glass manufacturing that includes flat, blown, and container glass (NAICS: 3272*), plus fiberglass (NAICS: 327993). Emissions are reported through fuel consumption which is primarily electricity and natural gas. The non-energy emissions are not reported and add up to 2.0 MMT. These can be directly correlated to the energy related emissions.

Sources represented in Bulk Chemicals: Agricultural

Phosphoric acid production (NAICS: 325312)

Most of the phosphoric acid produced is used for fertilizers and the industrial model includes it as part of bulk chemicals under agricultural chemicals. Production can be through a wet or dry process, releasing CO_2 emissions of about 0.9 MMT.

Sources represented in Metal-Based Durables in Non-Energy Intensive Manufacturing

Electronics industry (NAICS: 334)*

Electronics manufacturing is included as part of computers and electronics manufacturing. It accounts for 4.8 MMT of emissions, most of which are fluorinated gases.

Recommendations for modeling emissions

CO_2 emissions from energy use in the aluminum and glass industry are already modeled in FECM-NEMS and non-energy CO_2 can be correlated to energy use. The non-CO_2 emissions from aluminum can be tracked assuming their proportion of the total emissions stays the same in the future. Phosphoric acid production is part of agricultural chemicals in the bulk chemicals subsector of the industrial model, and its emissions can be tracked as a proportion of emissions from agricultural chemicals. For electronics manufacturing represented computers and electronics subsector of metal-based durables, the emissions can be tracked assuming the proportion of the total emissions in stays the same in the future.

Recommendations for modeling mitigation of emissions

Mitigation of CO_2 emissions for the aluminum and glass industry can be implemented since the process is detailed via process steps and technology options which allow for introduction of electrification and fuel. Mitigation of non-CO_2 emissions in aluminum can be correlated to mitigation of CO_2 through MAC curves. Mitigation of emissions in phosphoric acid production may be considered through MAC for agricultural chemicals. For electronics manufacturing, mitigation can be correlated to mitigation in the metal-based durables sector through MAC curves.

Assorted sources with related processes indirectly represented in FECM-NEMS

The following sources of emissions do not have an explicit representation in the industrial model but add up to 31.2 MMT of emissions. However, they are classified under specific NAICS codes, which helps us locate the sections in the industrial model that represent these emissions. Based on an understanding of their manufacture[22], some connections can be made with other industries represented in FECM-NEMS as well.

Sources represented in Bulk Chemicals: Organic (NAICS: 325199)

These sources add up to about 10 MMT of total emissions.

Adipic acid

Adipic acid is used to produce nylon and other polymers and is itself produced using nitric acid, releasing nitrous oxide (N_2O) as a byproduct, which is a majority of the reported emissions of 6.6 MMT. Mitigation can be through alternative methods of production that do not produce N_2O as a byproduct or catalytically convert it back to N_2 and O_2.

HFCF-22 (R-22) production

HFCF-22 is commonly known as R-22, a refrigerant HCFC (hydrochlorofluorocarbon) which is still produced in small quantities in the US[23] for feedstock use, but also may be present in older air conditioning units and can also be imported. The GHGs produced by the production of R22 are mainly fluorinated gases adding up to about 2.2 MMT of emissions.

Caprolactam, glyoxal, and glyoxylic acid production

These compounds are produced downstream of ammonia and nitric acid production and add up to about 1.2 MMT of emissions, mainly from caprolactam which is still produced in the US and consisting mostly of N_2O emissions.

Sources represented in Bulk Chemicals: Inorganic (NAICS: 325180)

These sources add up to about 3.2 MMT of total emissions.

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[22] Ullmann's Encyclopedia of Industrial Chemistry. Weinheim: Wiley-VCH. doi:10.1002/14356007.a17_293

[23] https://www.epa.gov/sites/default/files/2015-07/documents/phasing_out_hcfc_refrigerants_to_protect_the_ozone_layer.pdf

Soda ash

Soda ash (sodium carbonate) is produced by the Solvay process using ammonia, brine, limestone (or SMR produced CO_2) and releases net CO_2 emissions of about 1.7 MMT.

Titanium dioxide

Titanium dioxide is mainly used in pigments and paints and releases CO_2 emissions of about 1.5 MMT.

Sources represented in Bulk Chemicals: Agricultural

Nitric acid (NAICS: 325311)

Nitric acid is produced via the Ostwald process using Ammonia via a two-step process. The intermediate products of nitric oxide and nitrogen dioxide are accompanied by the byproduct nitrous oxide, which forms almost all of the reported emissions of about 7.9 MMT.

Sources represented in the power sector

Electrical transmission & distribution

Manufacture of electrical equipment is included as part of electrical equipment, appliances, and components manufacturing (NAICS: 335*) but does not include the emissions due to electrical transmissions and distribution. It also does not account for the emissions from transmission and distribution that are mainly fluorinated gases, about 6.0 MMT. These sources can instead be linked to the capacity and generation in the power sector, through the EMM in FECM-NEMS.

Sources represented in Iron and Steel

Ferroalloy production (NAICS: 331110)

Ferroalloys are various alloys of iron with a high proportion of other elements such as manganese, aluminum, or silicon. They are mostly produced in electric arc furnaces with a typical CO_2 release similar to that associated with steel production, about 1.6 MMT.

Sources represented in Balance of Manufacturing: Other Metals (NAICS: 331410)

These sources together produce about 2.5 MMT of emissions but are not categorized into any of the major categories in the industrial model. Instead, they are included as part of the balance of manufacturing which includes other smaller sectors.

Magnesium

Magnesium is produced using the Dow process, which is the electrolysis of fused magnesium chloride from brine and sea water and involves treatment with lime. Fluorinated gases form the majority of the related emissions for magnesium production, about 1.1 MMT.

Zinc

Zinc is produced similar to aluminum via a smelting process and produces CO_2 during the pyrometallurgy step. It is also energy intensive and produces about 1.0 MMT of emissions. Zinc is used primarily for galvanization of steel so its emissions can be linked to steel production. Mitigation options may involve CO_2 capture and/or technology switching.

Lead

Lead is produced in a coke-fired blast furnace similar to steel, produced primarily CO_2 emissions of about 0.4 MMT. It is used for lead acid batteries in cars and its emissions can potentially be linked to auto industry growth or decline of gas-powered vehicles. Mitigation options may involve CO_2 capture and/or technology switching.

Recommendations for modeling emissions

For sources represented in the organic/inorganic chemicals subsector of bulk chemicals, the emissions can be tracked assuming the proportion of the emissions in organic/inorganic chemicals, respectively, stays the same in the future. Nitric acid production is part of agricultural chemicals in the bulk chemicals subsector of the industrial model, and its emissions can be tracked as a proportion of emissions from agricultural chemicals. Ferroalloy production is indirectly represented as part of the iron and steel industry. For sources represented in the balance of manufacturing, the emissions can be tracked assuming the proportion of the emissions in the total balance of manufacturing stays the same in the future. As a result, it is directly linked to industrial activity reported by the macro module. For zinc manufacturing, a case can be made to link its production to steel production activity directly.

Recommendations for modeling mitigation of emissions

For sources represented in the organic chemicals subsector of bulk chemicals, mitigation can be correlated to mitigation in the organic chemicals sector through MAC curves either via alternative pathways for adipic acid or phaseout for HFCF-22. For sources represented in the inorganic chemicals subsector of bulk chemicals, mitigation can be correlated to mitigation in the inorganic chemicals sector via CO_2 capture considered through MAC curves. Mitigation of emissions in nitric acid production may be considered through MAC curves for agricultural chemicals. Mitigation of emissions in ferroalloy production can be linked to the mitigation in the iron and steel industry. For sources represented in the balance of manufacturing, mitigation can be correlated to mitigation in the overall industrial sector. However, for mitigation of emissions from zinc and lead that are primarily CO_2, capture and technology options may be considered through MAC curves. Smaller sources with insufficient mitigation data available can be neglected here.

Assorted sources with <u>no</u> related processes represented in FECM-NEMS

The following sources have no representation in the industrial model, not even indirectly, but add up to about 22 MMT of total emissions.

Urea for non-agricultural purposes

About 90% of the urea manufactured in the U.S. is used for agricultural purposes, and the associated emissions are categorized by the EPA as agricultural-sector emissions. The remaining 10% release industrial-sector emissions of about 5.0 MMT to the atmosphere when the urea molecules break down. Urea is used for a wide variety of non-agricultural purposes in the energy and industrial sectors that are not fully represented in FECM-NEMS.

Carbides

Carbides are molecules containing a carbon atom and a metal and are mainly used as abrasives. Carbide production generates emissions of about 0.2 MMT. Carbides are not represented in the industrial model.

Other sources

These include other process uses of carbonates, N_2O from product use and CO_2 consumption (NAICS: 325120) and add up to approximately 16.8 MMT of total emissions. The usage can be across many sectors and not exclusive to just the industrial sector.

Recommendations for modeling emissions

The reported emissions for electrical transmission and distribution can be linked directly to power sector capacity using an emissions factor. The reported emissions for the other sources can be linked directly to the overall economic growth using an emissions factor.

Recommendations for modeling mitigation of emissions

The mitigation of emissions from electrical transmission and distribution can be correlated to mitigation in the power sector and MAC curves developed by the EPA. The mitigation of the other emissions can similarly be correlated to mitigation in the overall economy. Some sources with sufficiently small emissions quantities and insufficient mitigation data available can be neglected.

3.2.4. Summary of industrial emissions sources and their mitigation

Table 3.6 below summarizes all the industrial sources listed in the EPA GHG inventory, with their NAICS codes (if used), reported GHG emissions, representation in FECM-NEMS, and mitigation pathways.

Table 3.6. Summary of industrial-sector emissions and mitigations

Source	NAICS code	GHG Emissions	Representation in FECM-NEMS	Potential Mitigation Pathway
Substitution of Ozone-Depleting Substances	325120	172.5	Part of inorganic chemicals in bulk chemicals	Phase out linked to MAC and economic activity
Iron, Steel, and Metallurgical Coke Production	331110, 3312*, 324199	41.7	Direct representation of process steps	Implement more granular data for CCS and technology switching opportunities
Cement Production	327310	41.3	Direct representation of process steps	No enhancements needed (CCS and fuel switching already present)
Petrochemical Production	325110	33.6	Represented by organic chemicals in bulk chemicals	CCS and technology switching linked to MAC

				and petrochemicals activity
Ammonia Production	325311	12.2	Part of agricultural chemicals in bulk chemicals	Utilize granular data for CCS retrofits, make explicit clean ammonia through HMM
Lime Production	327410	11.9	Direct representation of process steps	Explicit reporting of process emissions linked with MAC and lime industry activity
Other Process Uses of Carbonates	Various	8.0	No representation	Linked to economic activity
Nitric Acid Production	325311	7.9	Part of agricultural chemicals in bulk chemicals	Linked to MAC and agricultural chemicals activity
Adipic Acid Production	325199	6.6	Part of organic chemicals in bulk chemicals	Linked to MAC and organic chemicals activity
Electrical Transmission and Distribution	Various	6.0	No representation in industrial model, linked to electricity model	Linked to MAC and power sector capacity
CO_2 Consumption	Various	5.0	No representation	Linked to economic activity
Urea Consumption for Non-Agricultural Purposes	Various	5.0	No representation	Linked to economic activity
Electronics Industry	334*	4.8	Part of computers and electronics in metal-based durables	Linked to MAC and industrial activity
N_2O from Product Uses	Various	3.8	No representation	Linked to economic activity

Aluminum Production	331313	2.4	Direct representation of process steps	Linked to MAC and aluminum activity
HFCF-22 Production	325199	2.2	Part of organic chemicals in bulk chemicals	Linked to MAC and organic chemicals activity
Glass Production	3272*	2.0	Direct representation of process steps	Linked to MAC and glass activity
Soda Ash Production	325180	1.7	Part of inorganic chemicals in bulk chemicals	Linked to MAC and inorganic chemicals activity
Ferroalloy Production	331110	1.6	Part of steel production in iron & steel	Linked to mitigation in iron & steel industry
Titanium Dioxide Production	325180	1.5	Part of inorganic chemicals in bulk chemicals	Linked to MAC and inorganic chemicals activity
Caprolactam, Glyoxal, and Glyoxylic Acid Production	325199	1.2	Part of organic chemicals in bulk chemicals	Linked to MAC and organic chemicals activity
Magnesium Production and Processing	331410	1.1	Part of balance of manufacturing	Linked to industrial activity
Zinc Production	331410	1.0	Part of balance of manufacturing	Linked to steel activity and MAC
Phosphoric Acid Production	325312	0.9	Part of agricultural chemicals in bulk chemicals	Linked to MAC and industrial activity
Lead Production	331410	0.4	Part of balance of manufacturing	Linked to transportation activity and MAC
Carbide Production and Consumption	Various	0.2	No representation	Linked to economic activity

3.3. Waste-Sector GHGs

Waste management is a smaller but significant source of anthropogenic GHGs in the U.S., accounting for 169 MMT CO_2 eq. in 2021 (2.7% of gross emissions). FECM-NEMS has few connections to waste management activities and does not model any GHG emissions from this sector. Waste-sector emissions are reported as their own chapter in the EPA GHG inventory, divided into four categories: *Landfills*, *Wastewater Treatment*, *Composting*, and *Anaerobic Digestion at Biogas Facilities*. Emissions from these categories are listed in Table 3.7:

Table 3.7. Emissions from waste, by category

Emissions Subcategory	GHG	2021 U.S. GHG Emissions (MMT CO_2 eq.)
Landfills	CH_4	123
Wastewater Treatment	CH_4	21
Composting	CH_4	3
Anaerobic Digestion at Biogas Facilities	CH_4	0.2
Wastewater Treatment	N_2O	21
Composting	N_2O	2
Total		**169**

Landfills

Landfills represents CH_4 emitted from waste landfills, which store the majority of solid waste in the U.S. Organic components of waste decompose over time, releasing some CO_2 (from aerobic bacteria) and some CH_4 (caused by anaerobic and methanogenic bacteria). The CO_2 emitted from landfills is considered to be carbon-neutral and is accounted for as LULUCF-sector changes in carbon stocks. CH_4 emissions, however, occur from decomposition in the anaerobic conditions caused by modern landfill practices and are considered to be carbon-positive and anthropogenic. Many landfills – especially municipal solid waste facilities - have capture systems that collect emitted CH_4 as biogas. 202 MMT CO_2 eq. of CH_4 were recovered in this way in 2021 (the 123 MMT CO_2 eq. figure in Table 3.7 accounts for the captured CH_4). FECM-NEMS includes landfill gas in the Landfill Gas Submodule of the Renewable Fuels Module (RFM), and models landfill gas capacity as a function of GDP. However, FECM-NEMS does not track landfill emissions, nor does it have a complete representation of landfills in general.

Wastewater Treatment

Wastewater Treatment is another significant category that includes CH_4 and N_2O emissions. Like landfills, wastewater treatment involves the management of domestic or industrial aqueous waste that can expose organic material to anaerobic conditions that encourage decomposition into CH_4. Additionally, nitrogen-rich materials in wastewater can undergo various pathways to produce N_2O in similar quantities to CH_4. FECM-NEMS does not have any representation of wastewater treatment or the associated GHG emissions.

Composting

Composting is a technique for waste management designed to limit the exposure of organic material to anaerobic conditions and generates nutrient-rich compost as a product. Composting imitates the natural process of organic waste decomposition, and any CO_2 emitted is accounted for as carbon-neutral and part of changes in LULUCF-sector carbon stocks. Composting generates small amounts of CH_4 and N_2O as byproducts. FECM-NEMS does not model any composting activity, and emissions from composting are not tracked in FECM-NEMS.

Anaerobic Digestion at Biogas Facilities

The final category, *Anaerobic Digestion at Biogas Facilities*, refers to a small quantity of CH_4 emissions from biogas facilities and usage. Biogas refers to natural gas captured from anaerobic decomposition processes and is considered to be a form of carbon-neutral energy. However, there is a small amount of leakage and incomplete combustion from these systems that emit anthropogenic CH_4 to the atmosphere. FECM-NEMS does not model these emissions.

Recommendations for Modeling Emissions

Emissions from waste are challenging to incorporate into FECM-NEMS because the waste sector is not represented in detail. Emissions factors will need to be applied to broad economic variables with correlation to waste activities that FECM-NEMS does model, such as GDP or population. The model currently projects landfill gas capacity as a function of GDP. However, the EPA models most waste emissions in their GHG inventory as functions of population. Emissions factors throughout this sector should be fitted to these variables and benchmarked against emissions trends reported in the EPA GHG inventory, as well as data from the EPA's Landfill Methane Outreach Program.[24]

Waste emissions decreased from 1990-2010 because of widespread adoption of landfill gas capture facilities throughout the U.S. but have climbed in recent years and are expected to continue to grow because of population increases. However, waste emissions are a function of multiple other factors, such as consumer habits and the economy. The emissions factors could therefore be modified with time to reflect anticipated changes (i.e., an uptake in composting and decrease in landfills in response to carbon price incentives).

Recommendations for Modeling Mitigations

Given the lack of explicit modeling of the waste-sector in FECM-NEMS, any mitigation should be modeled using MAC curves. While an endogenous approach would be ideal, especially considering the size of the waste sector and importance of renewable natural gas to a decarbonized energy system, significant work would be needed to properly endogenize waste activities in FECM-NEMS in order to connect GHG mitigation back to the emissions source. The EPA has calculated MAC curves for the landfill and wastewater treatment facilities. Like the emissions factors for waste, these MAC curves would need to be applied to broad economic variables. The EPA mentions in their non-CO_2 mitigation report that mitigating CH_4 emissions from landfills is likely to be limited (only 8 MMT CO_2 eq. by 2030), given the already high adoption of landfill gas capture systems.

3.4. Agricultural and Land Use, Land-Use Change, and Forestry GHGs

After GHG emissions from the energy sector, total absolute changes, or fluxes, in GHG emissions from agriculture, land use, or forestry are the next largest source in the U.S. As the current version of FECM-NEMS does not account for any GHG changes from agricultural, land use, or forestry activities, accounting for emissions and mitigation of related gases will need to be done either exogenously via offline estimates or with a possible linkage to a sufficiently detailed agriculture and forestry model.

[24] The Landfill Methane Outreach Program can be found at: https://www.epa.gov/lmop

FECM-NEMS currently models agricultural activity using the Policy Analysis Systems Model (POLYSYS)[25], which was developed at the University of Tennessee and Oak Ridge National Laboratory for projecting land-use changes. POLYSYS is a partial equilibrium model of the U.S. agricultural sector, capable of estimating the competitive allocation of agricultural land between food crops for humans and livestock, pasture for grazing, energy crops, and the crop prices associated with changes in yield and management practices. POLYSYS projections are based on the United States Department of Agriculture (USDA) baseline[26], a set of projections and forecasts developed by USDA regarding the future trends and outlook for various agricultural commodities. The USDA baseline provides a comprehensive analysis of the supply and demand factors affecting the agricultural sector, including crop production, crop-to-waste conversion, livestock, trade, and prices. POLYSYS does not model agricultural or LULUCF-sector emissions and mitigation but contains a number of relevant drivers that could be leveraged to do so. A reduced version of POLYSYS runs within the RFM of FECM-NEMS (NEMS-POLYSYS) to produce endogenous biomass supply curves for agriculture residues and energy crops using the USDA projections. Additional descriptions of the POLYSYS and FECM-NEMS linkages on biomass supply are in a recent OnLocation report to FECM[27]. FECM-NEMS has no endogenous representation of LULUCF.

3.4.1. Agricultural sectors with significant emissions not represented in FECM-NEMS

Table 3.8 displays emissions from the agricultural sector. Although agriculture is a large source of GHG emissions, the sector is only weakly represented in FECM-NEMS, due to its energy focus, and none of the emissions in Table 3.8 (or mitigation) are counted.

Table 3.8. Emissions from agriculture

Emissions Subcategory	GHG	2021 U.S. GHG Emissions (MMT CO_2 eq.)
Urea Fertilization	CO_2	5
Liming	CO_2	3
Enteric Fermentation	CH_4	195
Manure Management	CH_4	66
Rice Cultivation	CH_4	17
Field Burning of Agricultural Residues	CH_4	0.5
Agricultural Soil Management	N_2O	294
Manure Management	N_2O	17
Field Burning of Agricultural Residues	N_2O	0.2
Total		**598**

Agricultural Soil Management

N_2O occurs naturally in soils from microbial activity on existing nitrogen. Nitrogen is a key nutrient for crop growth and is a major component of commercial fertilizers; several methods (e.g., synthetic fertilizers) exist to enhance the quantity nitrogen in the soil, which consequently increases N_2O in the

[25] For more information about POLYSYS, see: https://arec.tennessee.edu/wp-content/uploads/sites/17/2021/03/POLYSYS_documentation_1_overview.pdf

[26] USDA Agricultural Projections to 2030, Long-Term Projections Report, OCE-2021-1, February 2021.

[27] FECM-NEMS Biomass Supply and Demand

soil and leads to anthropogenic N_2O emissions. These can occur directly from activity in the soil, or indirectly as nitrogen-rich material is transported through runoff or volatilization and later emitted as N_2O.

Enteric Fermentation

In agricultural livestock, ruminant animals (cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 due to their digestive system where microbes ferment food consumed by the animal. This fermentation process, known as enteric fermentation, produces methane as a byproduct which is exhaled by the animal. Some non-ruminant livestock (swine, horses, and mules) produce small quantities of CH_4 in the large intestine. Although livestock also exhale CO_2, the carbon is assumed to come from photosynthesis in plants, making it net-zero.

Manure Management

Handling and processing of manure from livestock can lead to anthropogenic emissions of CH_4 and N_2O. The former gas is emitted during anaerobic decomposition from microbes, which is common in certain manure treatment systems (in particular, when manure is processed as a liquid). N_2O can be formed from nitrogen atoms from the manure through multiple direct and indirect processes. Emissions from this category are dominated by cattle, swine, and poultry. Because emissions depend on the type of treatment systems, non-emitting systems (including manure processed as a solid) can be used as a form of mitigation.

Rice Cultivation

Rice is usually cultivated in flooded fields that promote anaerobic conditions. Methanogenic bacteria in these environments produce CH_4, some of which escapes into the atmosphere. More than half of the CH_4 does not make it to the atmosphere and oxidizes into CO_2, which is treated as a net-zero emission that does not contribute to overall anthropogenic GHG emissions.

Urea Fertilization

Urea ($CO(NH_2)_2$) is commonly used as a fertilizer and breaks down to release CO_2. Urea is produced in a reaction that combines ammonia and CO_2. Ammonia is produced synthetically from nitrogen (derived from the air) and hydrogen (derived from hydrocarbons), the latter producing anthropogenic CO_2 as a byproduct. As a result, nearly all U.S.-produced urea is generated at the site of ammonia production, and therefore the CO_2 emissions associated with urea are anthropogenic and are intrinsically linked to emissions from ammonia production. While non-agricultural uses of urea are reported above in the industrial sector, the EPA lists its usage as a fertilizer under the agricultural sector.

Liming

Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are rocks containing minerals rich in carbonates (CO_3). The minerals dissolve when exposed to acid, releasing anthropogenic CO_2. Limestone and dolomite are applied to agricultural soils to reduce acidity. They have other uses in the industrial sector, reported above.

Field Burning of Agricultural Residues

Agricultural residues can be managed or disposed of in several ways, with one method being field burning. Although the CO_2 produced from this process is assumed to be net-zero, the combustion of agricultural residues produces small amounts of CH_4 and N_2O as a byproduct, which contribute to overall GHG emissions.

3.4.2. Land use, land-use change, and forestry emissions not represented in FECM-NEMS

Table 3.9 lists emissions and removals from the LULUCF sector. Although total land does not change, changes within each land type and shifts from one land type to another generate emissions and alter carbon inventories.

Table 3.9. Emissions and removals from land use, land-use change, and forestry

Emissions and Removals Subcategory[28]	2021 U.S. GHG Emissions (MMT CO_2 eq.)
Forest Land Remaining Forest Land	-671
Land Converted to Forest Land	-98
Cropland Remaining Cropland	-19
Land Converted to Cropland	57
Grassland Remaining Grassland	11
Land Converted to Grassland	-25
Wetlands Remaining Wetlands	42
Land Converted to Wetlands	0.6
Settlements Remaining Settlements	-133
Land Converted to Settlements	81
Total Removals of CO_2	-832
Total Emissions of CH_4	66
Total Emissions of N_2O	12
Total Net Emissions and Removals	**-754**

Forest Land

The *Forest Land* category includes areas of land (at some minimum size) with at least 10% live tree cover, not including forest areas that are completely surrounded by urban environments. Thirty-two percent of U.S. land area is estimated to be forest land, a total that relatively static (although the biomass density of existing forest land is increasing over time). The biomass in forests contains vast inventories of carbon sequestered from the atmosphere. *Forest Land* is divided by the EPA into two subcategories: *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. The former represents carbon removals thanks to the regeneration of forest land over the last 30 years and is expected to remain a large source of removals in the near term. It also includes non-CO_2 GHG emissions from forest fires and soils (the CO_2 is calculated as part of removals). The latter subcategory represents carbon removals associated with the conversion of other lands to forests.

[28] Subcategories represent net emission and removals in MMT CO_2 eq.

Cropland

Cropland refers to managed areas where crops are grown and represent 17% of U.S. area. Croplands hold smaller carbon inventories than forests, although woody crops and soil have the ability to store carbon. *Cropland Remaining Cropland* and *Land Converted to Cropland* track changes to carbon inventories, mostly from changes involving mineral and organic soils, and do not include any GHG emissions.

Grassland

The *Grassland* category refers to area with a plant cover dominated by grass and grass-like plants and are the largest land group by acreage at 39% of U.S. area. Grasslands are used as pasture and range lands. *Grassland Remaining Grassland* includes changes in the carbon inventory of mineral and organic soil, as well as small amounts of non-CO_2 emissions from grassfires. *Land Converted to Grassland* represents net-negative carbon removals from other land becoming grassland and has no GHG emissions.

Wetlands

Wetlands include all water-submerged land, as well as lakes and rivers. They are the smallest category by area (5%), except for "Other" lands (rock, ice) that do not appreciably contribute to GHG emissions or carbon removals. *Wetlands Remaining Wetlands* includes several subgroups of emissions and removals, with microbial CH_4 released from flooded lands (45 MMT CO_2 eq. in 2021) and changes in biomass carbon inventories (-9 MMT CO_2 eq. in 2021) being the most significant. *Land Converted to Wetlands* represents far smaller volumes of CH_4 emissions and carbon inventory change.

Settlements

The final land-use category, *Settlements*, represents land maintained and used for urban purposes (residential, industrial, commercial, roads, airports, etc.). Some of the land from *Settlements* include forested areas enclosed in urban space and parks. Settlements represent 5% of U.S. land area but have grown over the last 30 years and continue to expand. *Settlements Remaining Settlements* includes CO_2 flux into the atmosphere from organic soils, significant removals (-138 MMT CO_2 eq. in 2021) in the form of tree stocks, removals from organic material in landfills, and a small amount of N_2O emissions; *Land Converted to Settlements* is the large amount of carbon inventory loss associated with other lands becoming settlements.

3.4.3. Modeling emissions, removals, and mitigation from the agriculture, forestry, and land-use change

Recommendations for modeling emissions

There are few connections between FECM-NEMS and the agricultural and LULUCF sectors. Many of the quantities most applicable to these emissions and removals, such as the use of synthetic fertilizers or acreage of forest land, are not modeled endogenously in FECM-NEMS. A simple approach to modeling these emissions would therefore be to create emissions factors based on broad economic parameters, such as GDP, agricultural energy consumption, or population, with perhaps an adjustment based on usage of biomass energy crops. However, given the importance of the agricultural and LULUCF sectors to overall GHG accounting, better representations of emissions modeling could be explored. A more detailed approach would involve enhancing the representation of the existing NEMS-POLYSYS framework within FECM-NEMS and applying emissions factors to appropriate quantities from the expanded POLYSYS. Finally, the most complex approach to model emissions would be to link FECM-NEMS with an existing agricultural and land use model that already calculates emissions in detail. This third option is further explored in a section below.

Recommendations for modeling mitigation

Due to the lack of mitigation representation in POLYSYS, the mitigation of emissions can be linked to mitigation in the specific agricultural sub-sector using MAC curves. In their non-CO_2 mitigations report, the EPA provides MAC curves for *Agricultural Soil Management*, *Enteric Fermentation*, *Manure Management*, and *Rice Cultivation*. These MAC curves could be applied to quantities and emissions factors as part of an enhanced NEMS-POLYSYS framework. Other MAC curves could be sourced to represent LULUCF removals; these would need to be applied to land acreage values tracked by an enhanced NEMS-POLYSYS framework to prevent double-counting of land.

Recommendations for modeling linkages

A more robust and detailed representation of mitigation could be accomplished by linking FECM-NEMS with an agriculture, forestry and land use model that calculates technological mitigation options for those sectors. Options here could be to enhance the capability of the existing POLYSYS to expand the scope of its analysis by adding forestry and land use changes as well as all the related emissions and mitigation & sequestration options. Alternatively, an existing model that already takes a comprehensive modeling approach to all these sectors could be employed, for example the Forest and Agricultural Sector Optimization Model Greenhouse Gas Version (FASOM-GHG)[29]. The Future Agricultural Resources Model (FARM)[30] and Global Biosphere Management Model (GLOBIOM)[31] are other models that could be potentially linked with FECM-NEMS.

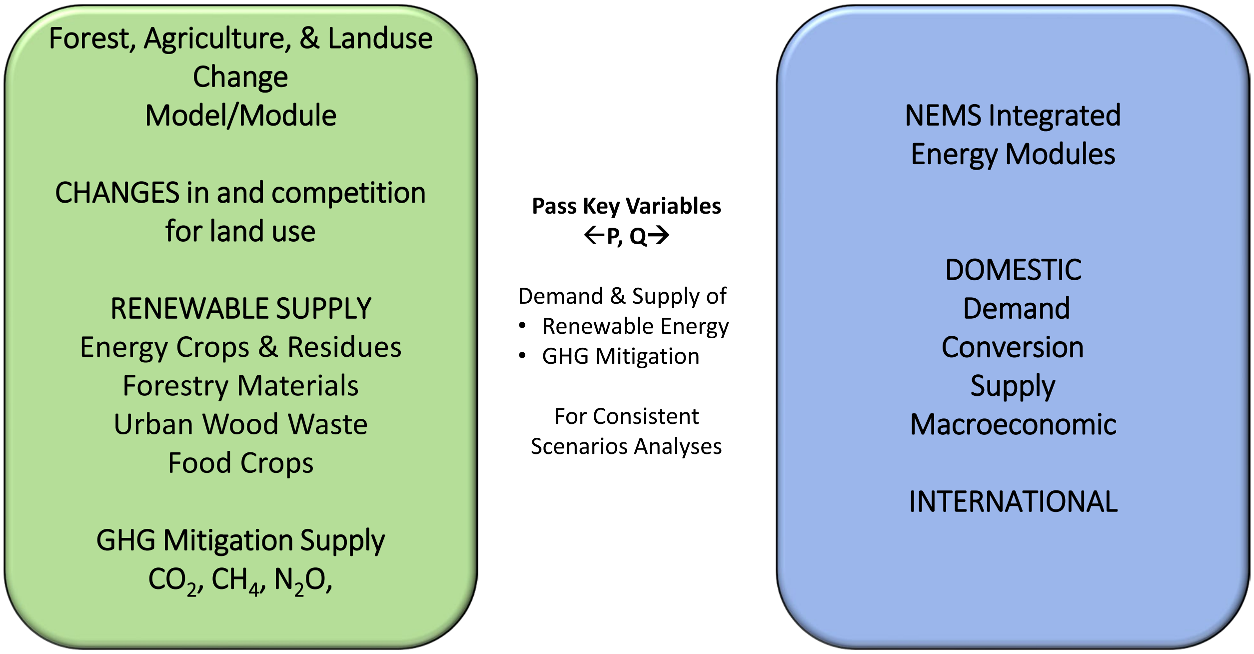
Once an appropriate model is identified, an approach can be developed to pass price and quantity data of the key variables between the energy modules in FECM-NEMS. These key variables would include bioenergy renewable supplies and GHG mitigation of methane (CH_4), nitrous oxide (N_2), and CO_2 fluxes (emission and sequestration) in both agriculture soil, forestry, and land use (see figure below).

[29] For more information about FASOM-GHG, see: https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=OAP&dirEntryId=82963

[30] More information about the FARM model is available at the following reference:
Sands, Ronald D., Carol A. Jones, and Elizabeth Marshall. Global Drivers of Agricultural Demand and Supply, ERR-174, U.S. Department of Agriculture, Economic Research Service, September 2014.

[31] For more information about GLOBIOM, see: https://iiasa.github.io/GLOBIOM/

Figure 3.3. Agriculture, forestry and land use model linkages



4. Conclusions

The Biden Administration has set a national goal of net-zero GHG emissions by 2050 to meet global climate initiatives. Policies in support of this goal must be developed and evaluated with consideration of both CO_2 emissions and non-CO_2 emissions. While FECM-NEMS models approximately 81% of U.S. GHG emissions, the remaining 19% of emissions, as well as LULUCF-sector removals, are not modeled. Additionally, sectors representing 25% of GHG emissions do not have a mitigation pathway in FECM-NEMS. The missing emissions and mitigation disproportionately include non-CO_2 GHGs and must be incorporated into FECM-NEMS for proper modeling of net-zero scenarios. The diverse and broadly distributed nature of the remaining emissions throughout the economy make them challenging to endogenously model. FECM-NEMS already represents U.S. energy-economic markets in extensive detail, however, and is consequently a promising candidate for comprehensive net-zero modeling with the right enhancements.

Throughout this CDR, strategies have been proposed to add missing emissions and mitigation options across all economic sectors. Emissions can be calculated by multiplying an appropriate quantity with an emissions factor. For sectors already well-represented by FECM-NEMS (energy and parts of industrial), the quantities proposed are more specific and detailed; for sectors less well-represented by FECM-NEMS (parts of industrial and waste), the quantities are based on more broad variables. For mitigation, two main approaches have been recommended: mitigation with technology options (most suitable for well-represented sectors) and mitigation with MAC curves (best for poorly represented sectors).

The agricultural and LULUCF sectors provide a unique challenge given their importance to overall GHG accounting but lack of connections to the energy sector, and thus, to FECM-NEMS. The existing NEMS-POLYSYS framework has some agricultural and land-use quantities that could be leveraged to model emissions and mitigation, but NEMS-POLYSYS would likely need substantial enhancements to properly incorporate all emissions and the available MAC curves. An option of linking FECM-NEMS with an existing agriculture and land-use model that already calculates emissions and mitigations would be a more complex but detailed way to model the agricultural and LULUCF sectors.

Table 4.1 summarizes the quantity of missing emissions and mitigation below, as well as the strategy and level of effort to implement missing mitigations. The level of effort estimates that MAC curves will be easier to implement, endogenous technologies will be more difficult, and model linkages will be the most challenging. Combining these strategies, this CDR gives a roadmap for next steps on filling existing gaps in emissions and mitigations and enabling FECM-NEMS to model net-zero scenarios. Next steps include compiling data on emissions factors and mitigation options and making modifications throughout FECM-NEMS to incorporate GHGs.

Table 4.1. Missing emissions and mitigation in FECM-NEMS

Sector and Category	Emissions not Modeled in FECM-NEMS[32]		Emissions from Categories without Mitigation Potential[32]		Mitigation Approach	Effort to Implement Mitigation
Energy - Total	**224**	**3.5%**	**519**	**8.4%**		
Fossil fuel combustion	51	0.8%	64	1.0%	MAC	Low
Petroleum and natural gas systems	119	1.9%	275	4.3%	Endogenous technologies	Medium
Non-energy use of fuels	0	0.0%	140	2.2%	MAC	Low
Coal mining	54	0.8%	53	0.8%	Endogenous technologies	Medium
Industry - Total	**236**	**3.7%**	**311**	**4.9%**		
Cement, ammonia	0	0.0%	0	0.0%	Already modeled	
Iron and steel, petrochemicals	0.4	0.0%	75	1.2%	Endogenous technologies	Medium
Substitution of ozone depleting substances	173	2.7%	173	2.7%	MAC	Low
Smaller sources, process directly represented in FECM-NEMS (aluminum, glass, phosphoric acid)	10	0.2%	10	0.2%	MAC	Low
Smaller sources, process indirectly represented in FECM-NEMS (soda ash, titanium dioxide, nitric acid, ferroalloys, zinc, lead)	31	0.5%	31	0.5%	MAC	Low
Smaller sources, process not represented in FECM-NEMS (urea consumption, carbides, carbonates, CO_2 consumption)	22	0.3%	22	0.3%	MAC	Low
Waste – Total	**169**	**2.7%**	**169**	**2.7%**	**MAC**	**Low**
Agriculture – Total	**598**	**9.4%**	**598**	**9.4%**	**POLYSYS or model linkage**	**High**
Gross Total[33]	**1227**	**19.3%**	**1610**	**25.4%**		
LULUCF – Total[34]	**-754**		**-754**		**POLYSYS or model linkage**	**High**
Net Total	**473**		**856**			

[32] U.S. emissions or removals from 2022 in units of million metric tonnes of CO_2 equivalent (100-year time horizon) or as a % of gross emissions
[33] Sum of missing emissions, excluding LULUCF-sector emissions (78 MMT CO_2 eq.)
[34] Combined sum of all LULUCF-sector emissions and removals

5. Appendix: Approach to Model Implementation

Gaps in the GHG emissions and mitigation coverage in FECM-NEMS are widely distributed across most of the fourteen modules. Emissions accounting, however, benefits from being performed in a central location. As a result, this CDR recommends that non-energy, non- CO_2 GHG emissions are calculated in their respective models and passed to the Emissions Policy Submodule (EPM) through the restart file. The EPM then performs all unit conversions with GWPs, accounting, and effects of CO_2 policy. This structure is similar to the existing framework used to calculate CO_2 emissions and removals in FECM-NEMS.

5.1. Existing Framework to Calculate CO_2 Emissions and Removals in FECM-NEMS

Under the existing structure in FECM-NEMS, CO_2 accounting and reporting is managed by the EPM, which is called by the integrating module. The general workflow used by FECM-NEMS to model price-induced mitigation of CO_2 emissions follows three steps:

A CO_2 price is determined by the EPM: An input to the EPM defines CO_2 emissions policies for each model year, either in the form of a CO_2 price ($/tonne CO_2) or a CO_2 cap (total emissions per year). In the latter case, the EPM establishes a price from the CO_2 cap by determining the price necessary to incentivize the level of CO_2 emissions reduction required by the CO_2 cap (this determination is refined over multiple iterations). Then, prices are sent directly or indirectly to the various CO_2-emitting modules via the restart file. For the case of fossil fuels, this CO_2 price is first added to fuel prices in the integrating module, increasing the prices of fossil energy that are seen by other modules. For most non-fossil process emissions, the carbon price is sent directly to various modules.

Using the adjusted fuel price, modules calculate their activity: CO_2-emitting activities throughout the model read the adjusted fuel prices from the restart file and use them in their economic evaluations. After the activities have been modeled, fuel consumption quantities are passed to the restart file, which the EPM later reads to calculate emissions. CO_2 prices are also read by modules to enable CO_2 capture, where CO_2 emissions can be captured for a tax credit equal to the CO_2 price that helps to offset the elevated fuel cost (in the case of fossil CCS), offset the avoided tax on process emissions, or generate revenue with negative emissions (in the case of DAC). CO_2 emissions and removals calculated in response to the CO_2 price are passed to the restart file.

Emissions are calculated in the EPM, aggregated, and a new CO_2 price is determined: At the end of each iteration, the EPM reads the consumption of each fuel and calculates the emissions from fossil fuels by combining relevant fuel quantities with emissions factors. The EPM then combines fossil emissions with any captured or process emissions from the restart file and aggregates all CO_2 emissions and removals occurring throughout FECM-NEMS into one total. FECM-NEMS aggregate emission totals are sent to the restart file. If the projection scenario was defined by a CO_2 cap, the EPM compares these emissions and removals values to the CO_2 cap and refines its CO_2 price. The process repeats in the next iteration, passing the new CO_2 price and adjusted fuel prices to the individual modules via the restart file.

Outputs in the FTAB are created from variables saved in the restart file. Variables containing CO_2 emissions, removals, and price are all written to the restart file as part of the above steps and are used by the FTAB for reporting purposes.

5.2. Modified Framework to Calculate Non-CO_2 Emissions and Mitigation

Non-CO_2 emissions can be calculated by making changes to the EPM and individual modules in an analogous manner to the process described above. Emissions policies can be sent as inputs to the EPM, which sends prices to the restart file to be read by various FECM-NEMS modules. Because most non-CO_2 GHG emissions are not tied to specific fuel consumption totals, adjusted fuel prices will not be needed for most of the proposed changes; rather, GHG prices can be sent directly to modules. These modules then use the prices to calculate emissions, which the EPM reads to update its prices. However, while the basic framework is similar, there are key differences to how non-CO_2 emissions are modeled thanks to the different GWP of each GHG.

CO_2 prices or caps are converted to GHG-specific units in the EPM: Each GHG has a different GWP that specifies its warming potential (relative to CO_2) for a given length of time. These GWPs are subject to change with updates in the scientific literature or differences in the modeled time-horizon. As a result, it is desirable to implement GWPs into the model in a way that is easy to update in the future. This can be done by introducing GWPs into the model through an input file to the EPM. GHG emissions should therefore be converted from the original gas to CO_2-equivalent units inside the EPM. To minimize changes when GWP values are updated, this conversion can be implemented as one of the last steps in emissions accounting, before calculating the new CO_2 price. The updated CO_2 price (reflecting the price of CO_2-equivalent emissions) can then be converted with GWPs back to GHG-specific prices before being sent to the individual modules, keeping all CO_2-equivalent variables inside the EPM.

Modules calculate their emissions and mitigation with GHG-specific quantities and prices: Throughout the various GHG-emitting modules, emissions factors and mitigation options can be applied to respond to the GHG-specific price ($/tonne GHG) and calculate GHG emissions in units of tonnes of gas. This calculation can be carried out separately for CO_2, CH_4, N_2O, and fluorinated gases. Fluorinated gases could be further split into HFCs, PFCs, SF_6, and NF_3. All GHG-emitting modules would read from a single input file that contains information about GHG-specific emissions factors and mitigation prices (whether using technology options or MAC curves). Although this CDR suggests using macroeconomic variables as quantities to calculate emissions from certain sources, the MAM can be avoided in this step, given its complexity; enough macroeconomic information is passed to the IDM to make the IDM an excellent choice for calculating macroeconomic-reliant emissions and mitigation. Emissions from the various modules would be sent separately for each gas to the restart file, without converting to CO_2-equivalent units.

Emissions are aggregated in the EPM and converted to CO_2 equivalent units for pricing and reporting: Once variables for tonnes of GHG emitted arrive at the EPM (through the restart file), they would be converted with GWPs into CO_2-equivalent units for the purpose of reporting emissions to the restart file and updating the CO_2 cap (if applicable). A net-zero GHG criteria requires that CO_2-equivalent emissions equal zero, and the CO_2 cap would be defined in CO_2-equivalent units to reflect this requirement.

Emissions from the different GHGs could be converted with GWPs and combined to calculate a CO_2-equivalent total, and this total would be used to satisfy the emissions cap. The emissions price that satisfies the cap would also be calculated again in CO_2-equivalent units and sent to the restart file for reporting. The price would also be converted from CO_2-equivalent units (\$/tonne CO_2 eq.) back into the respective GHGs (\$/tonne GHG) using the GWPs within the EPM, and these prices could be fed to each GHG-emitting module through the restart file to repeat and iterate the entire process.

The advantage of this approach is that changes to the GWP only affect calculations and inputs to the EPM and leave the remaining modules unchanged. This would allow GWPs to be easily updated in an input file without extensive changes to the model code.

6. Appendix: Summary of Notes from the *Workshop on Non-Energy CO_2 GHG Emissions and Mitigation in NEMS*

As technologies to mitigate CO_2 and non-CO_2 emissions have advanced significantly in recent years, there has been increased effort to expand how GHGs could be fully incorporated endogenously within NEMS and other energy-market models to assess net-zero initiatives and policies more adequately. On March 23, 2023, the OCM within the FECM held the *Workshop on Non-Energy CO_2 GHG Emissions and Mitigations in FECM-NEMS*. The workshop gathered experts in GHG accounting, modeling, and mitigation to share expertise across the wide range of GHG-related subjects and generate ideas for incorporating non-CO_2 GHGs into energy-market models. The workshop consisted of a mix of short presentations and a round-table discussion. Topics for discussion included methane emissions from energy systems, endogenizing emissions and removals from agriculture and land use, selecting appropriate model quantities and emissions factors, and developing mitigation options that allow GHG-emitting sectors to respond to changes in policy. This appendix summarizes the key points from each workshop speaker.

6.1. Session Summaries

6.1.1. Opening Comments

Non-CO_2 GHG emissions are important to consider when developing net-zero scenarios. A net-zero GHG target that encompasses non-CO_2 GHGs is very different from a net-zero CO_2 target. Many sources of non-CO_2 GHGs cannot be realistically mitigated and need to be balanced out with equivalent CO_2 removal pathways (either with technology or through the LULUCF sector). Balancing emissions and removals in a net-zero scenario is a complicated task, and it is important to understand how the energy system is evolving with time to predict future abatement opportunities.

A key focus of net-zero GHG modeling is to understand the tradeoffs involved in achieving net-zero emissions, such as the effect of net-zero policy on the price of beef. These tradeoffs are influenced by the pathway employed to achieve net-zero, which could emphasize emissions mitigation, CO_2 removal, or some combination of the two. FECM-NEMS currently achieves net-zero emissions by employing DAC to remove up to 3,000 MMT CO_2 per year. This value is higher than other models and may be unrealistically large. Incorporating missing non-CO_2 GHG emissions and removals into FECM-NEMS will help diversify its net-zero pathways and allow it to model net-zero scenarios without as strong a reliance on DAC.

6.1.2. Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021

The EPA published their *Inventory of U.S. GHG Emissions and Sinks: 1990-2021*[2] on April 15, 2023, providing the agency's catalogue of U.S. GHG emissions through 2021. Notable changes to this year's inventory were the switch from GWPs based on IPCC AR4 to values based on IPCC AR5 and an increased focus on industrial and agricultural processes. The updated GHG inventory report indicated a seven percent increase in national GHG emissions, caused by economic rebound from the pandemic. A follow-up inventory report for individual U.S. states is expected to be made available in the Fall of 2023 and cover emissions from 1990-2021 (the most current state-level inventory report publicly available covers

1990-2020). State-level emissions estimates use bottom-up (activity) data and state-level modeling for emissions and livestock.

The key takeaway of the EPA's inventory and similar efforts to catalogue emissions are the use of quantities and emissions factors, as well as mitigations, to predict emissions when direct data is scarce. The EPA publishes CSV data files and extensive supplementary material alongside the inventory reports, explaining their methods and sources in detail. This data provides a framework for similar emissions and mitigation calculations in FECM-NEMS.

6.1.3. Current Coverage of Greenhouse Gas Emissions and Mitigation in NEMS

With strong connections to energy systems, AEO23-NEMS contains detailed estimates of CO_2 emissions from fossil fuel combustion, covering 78% of gross GHG emissions specified in the EPA GHG Inventory. FECM-NEMS contains enhancements that expand the existing emissions coverage of AEO22-NEMS, primarily the addition of methane associated with natural gas production, and endogenously represents 81% of U.S. gross GHG emissions; however, a majority of remaining emissions, including some non-combustion CO_2 and almost all non-CO_2 GHGs, are not represented endogenously. FECM-NEMS also has multiple approaches to mitigate CO_2 from energy and industry sources, but other mitigation options – including LULUCF-sector removals – are missing. The gaps of emissions and mitigations in FECM-NEMS include parts of the energy and industry sectors and all of the agriculture, waste, and LULUCF sectors. Sources of missing emissions with strong connections to FECM-NEMS could be prioritized and incorporated in more detail. More weakly-connected sectors – for example, agriculture – would need a broader representation, or a linkage to an existing agricultural model. The specifics of emissions and mitigation modeling in FECM-NEMS are explained in greater detail in Section 2 of this CDR.

6.1.4. EPA Non-CO_2 Projections and Mitigation

While non-CO_2 GHGs can be thought of as equivalent to CO_2 emissions using GWP values, GWPs are in reality a simplification and the distinction between the two emission types is helpful from a policy perspective. Non-CO_2 mitigation can be thought of as "buying time" to achieve climate targets as CO_2 mitigation scales up. Approximately 1,300 MMT CO_2 eq. of non-CO_2 GHG mitigation is estimated by EPA (if that is the right source) to be available globally at no cost by 2030, and 34% of all non-CO_2 GHGs can be mitigated at some price. CH_4 has the greatest opportunity for mitigation of the non-CO_2 GHGs (particularly in the natural gas and waste sectors).

The EPA published a report in 2019 on non-CO_2 GHG mitigation titled *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation, 2015-2050*[10]. The report discusses mitigation approaches of several categories of non-CO_2 GHGs, including MAC curves for the U.S. and other countries, as well as estimates for technologies and costs available for mitigation. MAC curves use data from outreach programs to develop a bottom-up engineering cost analysis by region and sector that represents the equilibrium carbon price for a given total quantity of GHG mitigation. Technology-based mitigation combines assumptions of technology cost and effectiveness to give predictions of mitigation at different price points. MAC curves are simpler to use than technologies but suffer from the "vintaging" problem of carrying a curve from year to year in a model without double-counting emissions. There is demand for an updated version of the report, likely to be released sector-by-sector.

6.1.5. Modeling Land Use and Agriculture Emissions and Mitigation

Agricultural-sector and LULUCF-sector emissions are an important consideration for designing and evaluating net-zero policy. Agricultural-sector emissions, primarily N_2O and CH_4, total approximately 700 MMT CO_2 eq. per year and have slightly increased in the past three decades. LULUCF-sector emissions and removals were static in that timeframe and reach a net total of approximately -750 MMT CO_2 eq. per year. Mitigation pathways for agricultural- and LULUCF-sector emissions and removals vary by their technical difficulty and reversibility. There are three main modeling approaches proposed for agricultural and LULUCF-sector emissions modeling: 1) MAC curves (Forest and Agricultural Sector Optimizing Model – FASOM GHG; Second Generation Model – SGM), 2) modeling of management practices (Regional Environment and Agriculture Programming Model - REAP), and 3) modeling changes in carbon stocks (FARM). FARM, in particular, is a global-scale computable general equilibrium (CGE) model that assesses climate impacts on U.S. agriculture and the role of agriculture in achieving net-zero. There are several resources available for modeling agricultural- and LULUCF-sector emissions and removals, including EPA MAC curve estimates, the Global Trade Analysis Project (GTAP) for agricultural markets data, and the Wisconsin National Data Consortium (WiNDC) for energy, agricultural, and economic modeling.

Agricultural-sector emissions include non-CO_2 GHGs that can be partially mitigated but are difficult to fully eliminate. The excess emissions (as well as other hard-to-mitigate sectors) are compensated in most models by net-negative CO_2 strategies, which include land management and BECCS. An ideal representation of BECCS in FECM-NEMS would further endogenize the supply and demand of biomass and use specific land use and BECCS technologies to model removals.

6.1.6. GCAM Modeling of Non-CO_2

The Global Change Analysis Model (GCAM) is a global equilibrium model that integrates economic, energy, LULUCF, water, and climate systems. GCAM tracks emissions and mitigations from 16 different GHGs. GCAM is also linked to Hector, a climate model. Results from GCAM demonstrate the importance of modeling non-CO_2 GHGs in both net-zero GHG scenarios and net-zero CO_2 scenarios; while non-CO_2 GHGs are included in emissions targets set by the former scenario, they also tend to reduce in the latter scenario as a byproduct of decarbonization. Climate targets of 1.5 °C are difficult to achieve without considering non-CO_2 GHGs.

GCAM models mitigations using MAC curves. The abatement potential implied by MAC curves in GCAM increases over time to reflect technological advancements. The level of increase is specific to each emissions category to reflect how advanced the existing process already is (for refrigeration, there is room for significant technological advancements; for photovoltaics, the possible technological advancement is relatively small). MAC curves are additionally phased-in according to expert judgment to reflect the time needed for widespread adoption of mitigations and prevent abrupt changes to modeling parameters. While non-CO_2 GHGs can be partially mitigated, it is difficult to remove all non-CO_2 emissions. Unlike CO_2 emissions, non-CO_2 sources cannot be simply electrified. As a result, several countries require significant carbon dioxide removal to compensate for unavoidable non-CO_2 GHG emissions.

6.1.7. Closing Comments

Incorporating missing mitigations into FECM-NEMS is a key challenge for preparing the model to forecast net-zero scenarios. The decision between MAC curves or mitigation technologies depends on the quantity of emissions and connection of the emissions source to FECM-NEMS. While mitigation technologies are ideal, they are likely not appropriate for smaller emissions sources and for sources poorly connected to the existing model infrastructure. Oil and gas supply chains are an example of a subsector that should be represented with mitigation technologies (potentially by creating a submodule to handle renewable natural gas).

In its current state, FECM-NEMS achieves net-zero emissions through large volumes of DAC. The reliance on DAC is partly caused by a lack of options to mitigate emissions, and partly due to a lack of competitive methods for carbon dioxide removal. Most other models do not employ as much DAC to achieve net-zero, but rather use extensive BECCS, mitigations, or a balance of DAC, BECCS, and LULUCF removals. The goal of incorporating missing GHGs is to have FECM-NEMS model all emissions listed in the EPA GHG inventory, with sufficient mitigation and removal options to avoid an overreliance on DAC. The key takeaways from this exercise will be the trade-offs required to reach net-zero by 2050 (e.g., the price of beef under a high cost of carbon).

7. Appendix: Tables of Emissions and Gaps in FECM-NEMS, Based on the EPA GHG Inventory

Table 7.1. Energy-sector GHG emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory.

Emissions Category	Total Emissions (MMT CO_2 eq.)	Emissions from Categories Modeled in FECM-NEMS (MMT CO_2 eq.)	Emissions Not Modeled in FECM-NEMS (MMT CO_2 eq.)
Fossil Fuel Combustion and Incineration of Waste	4,702	4652	51
Petroleum and Natural Gas Systems	301	181	119
Non-Energy Use of Fuels	140	140	0
Coal Mining and Abandoned Coal Mines	54	0	54
Total Energy-Sector Emissions	**5197**	**4973**	**224**

Table 7.2. Industry-sector GHG emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels are not counted in this sector.

Emissions Category	Total Emissions (MMT CO_2 eq.)	Emissions from Categories Modeled in FECM-NEMS (MMT CO_2 eq.)	Emissions Not Modeled in FECM-NEMS (MMT CO_2 eq.)
Substitution of Ozone-Depleting Substances	173	0	173
Cement and Lime Production	53	53	0
Iron, Steel, and Metallurgical Coke Production	42	42	0
Petrochemical Production	34	33	0.4
Ammonia Production	12	12	0
Other Processes Not Represented in FECM-NEMS	22	0	22
Other Processes Indirectly Represented in FECM-NEMS	31	0	31
Other Processes Directly Represented in FECM-NEMS	10	0	10
Total Industry-Sector Emissions	**377**	**140**	**236**

Table 7.3. Other industry-sector GHG emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels are not counted in this sector.

Emissions Category	Total Emissions (MMT CO_2 eq.)
Other Process Uses of Carbonates	8
Nitric Acid Production	8
Adipic Acid Production	7
Electrical Transmission and Distribution	6
CO_2 Consumption	5
Urea Consumption for Non-Agricultural Purposes	5
Electronics Industry	5
N_2O from Product Uses	4
Aluminum Production	2
HFCF-22 Production	2
Glass Production	2
Soda Ash Production	2
Ferroalloy Production	2
Titanium Dioxide Production	2
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1
Magnesium Production and Processing	1
Zinc Production	1
Phosphoric Acid Production	0.9
Lead Production	0.4
Carbide Production and Consumption	0.2
Total Emissions from Other Industrial Processes	**63**

Table 7.4. Agriculture-sector GHG emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels are not counted in this sector.

Emissions Category	Total Emissions (MMT CO_2 eq.)
Agricultural Soil Management	294
Enteric Formation	195
Manure Management	83
Rice Cultivation	17
Urea Fertilization	5
Liming	3
Field Burning of Agricultural Residues	0.6
Total Agricultural-Sector Emissions	**598**

Table 7.5. Waste-sector GHG emissions and gaps in FECM-NEMS. Values represent annual emissions in the U.S. in 2021, from the EPA GHG Inventory. Emissions from the combustion of fossil fuels are not counted in this sector.

Emissions Category	Total Emissions (MMT CO_2 eq.)
Landfills	123
Wastewater Treatment	42
Composting	4
Anaerobic Digestion at Biogas Facilities	0.2
Total Waste-Sector Emissions	**169**

Table 7.6. LULUCF-sector GHG emissions, removals, and gaps in FECM-NEMS. Values represent annual emissions and removals in the U.S. in 2021, from the EPA GHG Inventory.

Emissions Category	Total Emissions (MMT CO_2 eq.)
Forest Land	-794
Settlements	-54
Grassland	-15
Wetlands	-8
Cropland	38
CH_4 Emissions Combined	66
N_2O Emissions Combined	12
Total LULUCF-Sector Net Emissions and Removals	**-754**