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CRADLE-TO-GATE LIFE CYCLE ANALYSIS BASELINE FOR UNITED STATES COAL MINING AND DELIVERY

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Disclaimer

Ashley Cutshaw[1,2]*: Methodology, Formal Analysis, Writing – Original Draft/Review & Editing;* ***Derrick Carlson***[1,2]*: Methodology, Formal Analysis, Data Curation, Writing – Original Draft/Review & Editing, Supervision;* ***Megan Henriksen***[1,2]*: Methodology, Formal Analysis;* ***Michelle Krynock***[1]*: Conceptualization, Methodology, Writing – Review & Editing, Supervision, Project Administration, Funding Acquisition;* ***Matthew Jamieson***[1*]*: Conceptualization, Methodology, Writing – Review & Editing, Supervision, Project Administration, Funding Acquisition;* ***Robert James III***[1*]*: Supervision, Project Administration, Funding Acquisition*

[1]National Energy Technology Laboratory (NETL) support contractor
[2]NETL
*Corresponding contact: Matthew.Jamieson.netl.doe.gov

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ACRONYMS AND ABBREVIATIONS

AP	Acidification potential
AR6	Sixth Assessment Report
ASCC	Alaska Interconnection
B	Bituminous
Btu	British thermal unit
CA	Central Appalachia
CFCs	Chlorofluorocarbons
CFC-11e	Trichlorofluoromethane equivalent
CH_4	Methane
CI	Central Interior
CMM	Coal mine methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DOE	Department of Energy
ECHO	Enforcement and Compliance History Online
EIA	Energy Information Administration
EP	Eutrophication potential
EPA	Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas, Inc.
FERC	Federal Energy Regulatory Commission
FRCC	Florida Reliability Coordinating Council
GHG	Greenhouse gas
GHGRP	Greenhouse Gas Reporting Protocol
GL	Gulf Lignite
GWP	Global warming potential
IB	Illinois Basin
ID	Identification number
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg	Kilogram
km	Kilometer
L	Lignite
lb	Pound
LCA	Life cycle analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MISO	Midcontinent ISO
MRO	Midwest Reliability Organization
MSHA	Mine Safety and Health Administration
N/A	Not applicable
N_2O	Nitrous oxide
NA	Northern Appalachia
Ne	Nitrogen equivalent
NEI	National Emissions Inventory
NERC	North American Electric Reliability Corporation
NETL	National Energy Technology Laboratory
NH3NO2	Nitromethane
NOx	Oxides of nitrogen
NPCC	Northeast Power Coordinating Council
NPDES	National Pollution Discharge Elimination System
O_3e	Ozone equivalent
PJM	PJM Interconnection
PM	Particulate matter
$PM_{2.5}$	Particles 2.5 microns or smaller
$PM_{2.5}e$	$PM_{2.5}$ equivalent
ppm	Parts per million
PRB	Powder River Basin
RFC	ReliabilityFirst
RM	Rocky Mountain
S	Subbituminous or surface
SA	Southern Appalachia
SERC	SERC Reliability Corporation
SF_6	Sulfur hexafluoride
SO_2e	Sulfur dioxide equivalent
SPP	Southwest Power Pool, Inc.
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts

U	Underground
U.S.	United States
UP	Unit process
USGS	United States Geological Survey
VOC	Volatile organic compound
WECC	Western Electricity Coordinating Council
WNW	West/Northwest
yr	Year

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EXECUTIVE SUMMARY

Despite declines in coal production and the retirement of coal power plants over the past decade, coal remains an integral part of energy production in the United States (U.S.). In 2022, coal was used to generate 19.5 percent of U.S. electricity [1]. Despite its historical and current importance, there is limited environmental life cycle inventory data for regional coal mining and transport operations available to support life cycle analysis (LCA). This study represents a comprehensive, regional cradle-to-gate LCA of coal mining and transportation activities in the United States.

The goal of this study is to highlight the environmental impacts from upstream coal production to its delivery at a power plant. This study is meant to characterize different coal basins, coal types, and mine types used to produce electric power in the North American Electric Reliability Corporation (NERC) regions in the United States using a functional unit of 1 kg of coal. The boundary of this study includes underground or surface extraction, water use at the mine, ventilation, coal handling, coal cleaning, mine tailing disposal, and transportation via conveyer belt, truck, ocean vessel, barge, and train.

This analysis examines various combinations of coal basins, coal types, mine types, and NERC regions (**Exhibit ES-1**) to produce 22 basin-coal type-mine type scenarios and 55 basin-coal type-mine type-NERC region scenarios. In addition, results for various disaggregated and aggregated scenarios are determined. Maps of the coal basins and NERC regions listed in **Exhibit ES-1** can be seen in **Exhibit ES-2**. Life cycle inventories representing the 22 basin-coal type-mine type scenarios and each transportation mode are included as supplemental materials with reference flows of 1 kg of coal and 1 kg*km, respectively. These data can be used to develop a custom inventory that is suited to a specific user or power plant. The results of this study should not be used to inform decisions about the preferability of one coal compared to another. The cradle-to-gate profiles should be put into the context of a service to society (e.g., electricity production, carbon fiber production) to determine relative preferabilities.

Exhibit ES-1. Complete list of U.S. coal basins, coal types, mine types, and NERC regions, and their respective abbreviations

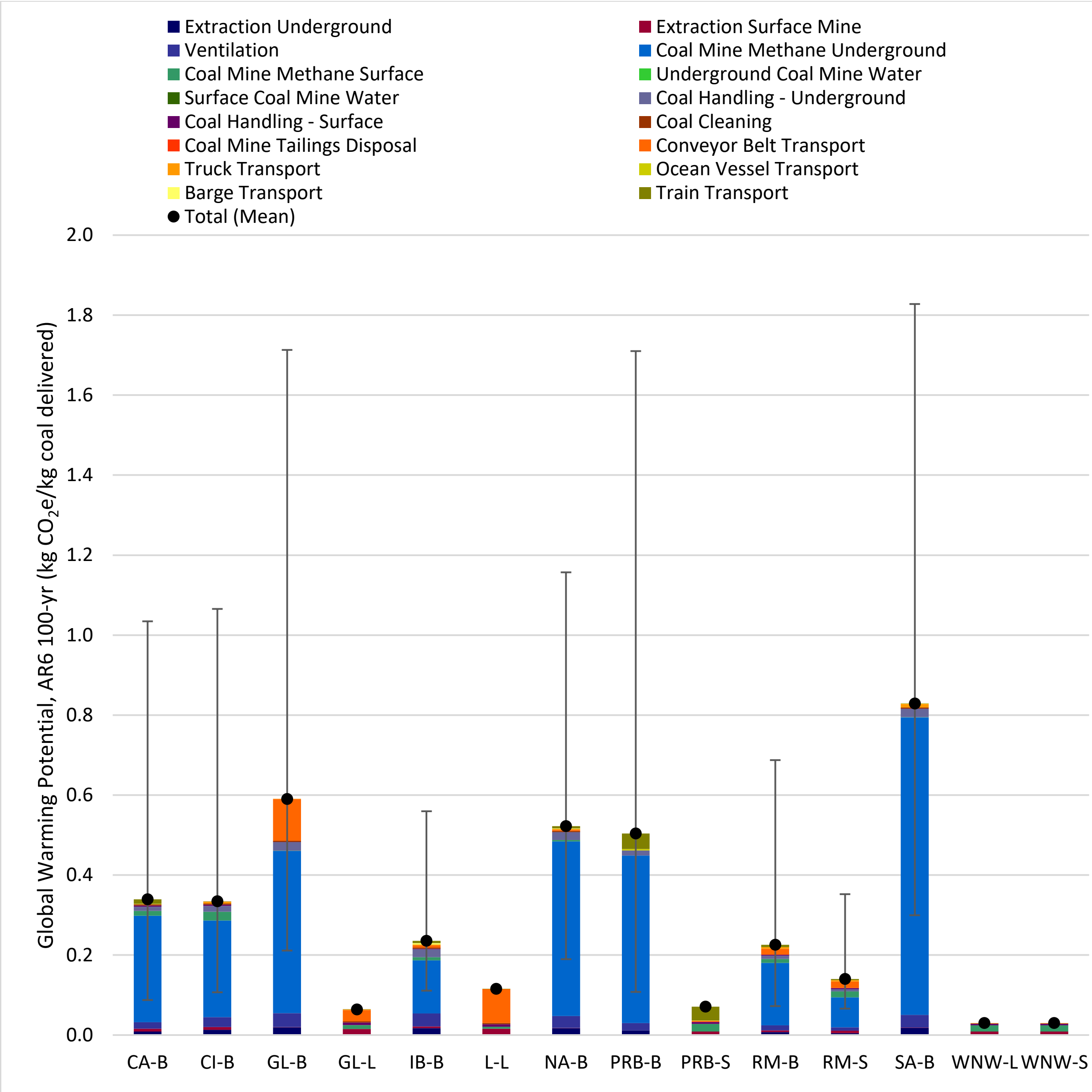
Name	Abbreviation
Coal Basin	
Central Appalachia	CA
Central Interior	CI
Gulf Lignite	GL
Illinois Basin	IB
Lignite	L
Northern Appalachia	NA
Powder River Basin	PRB
Rocky Mountain	RM

Name	Abbreviation
Southern Appalachia	SA
West/Northwest	WNW
Coal Type	
Bituminous	B
Subbituminous	S
Lignite	L
Mine Type	
Surface	S
Underground	U
NERC Region	
Alaska Interconnection	ASCC
Electric Reliability Council of Texas, Inc.	ERCOT
Florida Reliability Coordinating Council	FRCC
Midwest Reliability Organization	MRO
Northeast Power Coordinating Council	NPCC
Reliability First Corporation	RFC
SERC Reliability Corporation	SERC
Southwest Power Pool, Inc.	SPP
Western Electricity Coordinating Council	WECC

This LCA uses the Environmental Protection Agency's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) version 2.1 to assess the impacts of the identified scenarios. TRACI impact categories include acidification potential, eutrophication potential, global warming potential (GWP), ozone depletion potential, particulate matter formation potential, and photochemical smog formation potential. In addition to the impact categories in TRACI, the water consumption is evaluated using National Energy Technology Laboratory (NETL) methods.

Exhibit ES-2 shows the GWP impacts for the 14 unique basin-coal type scenarios, representing mass-weighted averages of the full 55 scenarios, when run using 1,000 iterations in a Monte Carlo simulation. Underground coal mine methane (CMM) is a notable source of GWP impacts, causing basins with high production from underground mines to have relatively higher impacts. The West/Northwest basin did not have any operational underground mines in 2016, which played a key role in its low GWP. In addition to high impacts, the uncertainty in underground CMM, when aggregated at the basin-level, results in 5^{th} and 95^{th} percentile GWP values that vary significantly from the mean.

Exhibit ES-2. Global warming potential (AR6, 100-yr) impacts for all basin-coal type scenarios



Note: Totals are equal to the mean and error bars are equal to the 5th and 95th percentile.

Ultimately, these results indicate that there is significant uncertainty across basins and coal types. Scenarios consisting of unique basin-coal type combinations are useful in illustrating how different coal types from the same basin and (conversely) how the same coal type from different basins can have vastly different impact results. It should be noted that these results represent an aggregated impact, and do not represent a life cycle result. Contributions resulting from different mine types cannot be discerned from this level of aggregation. The cradle-to-gate impact assessment results for the 55 basin-coal type-extraction-NERC region scenarios provide insights into the effects of specific combinations of scenario parameters without aggregation.

An important consideration when interpreting the results of this study is that the coal delivered by each scenario is not functionally equivalent. For example, different coal types have different qualities and, thus, not all coal types are suitable for a specific power plant. While switching basin sourcing may seem like a path toward reducing environmental impacts, it is important to consider variations in both coal specifications and production capacity, which could result in potential tradeoffs in power plant operations. Thus, it is critical that the dynamic operation of a power plant be considered in any sourcing decisions. This study provides a foundation for future work in this research space.

Modest improvements in the upstream portion of the life cycle, such as those resulting from changes in coal specifications or transportation, can yield measurable improvements in the full life cycle result through power generation. While CMM emissions are the dominating contributor to GWP impacts, a parameter like transportation is a significant contributor to acidification and ozone depletion impacts. Reductions in emissions transportation or switching to modes of transportation with lower emissions can result in a significant decrease in the overall life cycle impacts downstream. It is also worth noting that any potential reduction would be more dramatic for facilities that use considerable amounts of coal.

The results of this study can be used at various scales to represent coal supply chain emissions. This study builds upon NETL's work to evaluate emissions upstream of power generation, which previously only considered Illinois Basin and Powder River Basin coals. Additionally, the scope of environmental impacts has been expanded to provide for a more robust assessment for the current study and for future work. Ultimately, the work conducted here builds the foundation for evaluation of supply chain impacts associated with spatially differentiated coal delivery to power generation.

1 Introduction

Despite recent declines in coal production and the retirement of coal power plants, coal remains an integral part of energy production in the United States (U.S.). In 2022, coal was used to generate 19.5 percent of U.S. electricity [1]. Despite its continued significance, there is limited life cycle inventory (LCI) data available for regional coal operations. Detailed LCI data for coal extraction and transportation is critical to understanding the environmental impacts of the emissions that occur upstream of power generation. This becomes increasingly critical as there is a demand for reduction in greenhouse gas (GHG) emissions and a continued reliance on coal as a power source for U.S. electricity.

Several parameters must be considered when evaluating the environmental impacts of coal extraction and transportation. Namely, the coal basin, coal type, mine type, and location of downstream power generation. Hitachi Energy's Velocity Suite provides data on discrete coal basins and supporting geographical information [2]. The Velocity Suite database identifies ten coal basins: Central Appalachia, Central Interior, Gulf Lignite, Illinois Basin, Lignite, Northern Appalachia, Powder River Basin, Rocky Mountain, Southern Appalachia, and West/Northwest. From these basins, bituminous, subbituminous, and lignite coal types can be extracted using surface or underground methods. It should be noted that not all coal types are extracted from both mine types. Although the end destination of transported coal is a specific power plant, more broadly, coal is delivered to a regulatory authority region. The North American Electric Reliability Corporation (NERC) had nine electricity producing regions within the United States as of 2018: Alaska Interconnection (ASCC), Northeast Power Coordinating Council (NPCC), Reliability First (RFC), SERC Reliability Corporation (SERC), Florida Reliability Coordinating Council (FRCC), Midwest Reliability Organization (MRO), Southwest Power Pool, Inc. (SPP), Electric Reliability Council of Texas, Inc. (ERCOT), and Western Electricity Coordinating Council (WECC) [3]. Altogether, these coal-basin, coal-type, and mine-type parameters, in combination with the NERC regions, create the various scenarios that are examined in this life cycle analysis (LCA) study.

The goal of this study is to evaluate the environmental impacts from coal mining and delivery to a power plant for the year 2016. This is achieved using the National Energy Technology Laboratory's (NETL) Coal Baseline Model, hereafter referred to as the Coal Baseline Model, which was developed specifically for this study. This study characterizes different coal basins, coal types, and mine types used to produce electric power in NERC regions in the United States using a functional unit of 1 kg of coal delivered. The various scenario parameters examined in this LCA, and the function of the Coal Baseline Model, provide the flexibility to produce various aggregated results in addition to results for a specific basin-coal type-mine type-NERC region scenario. The key assumptions, data sources, and model sensitivities used in the Coal Baseline Model to determine the life cycle impact assessment (LCIA) results are documented in this report. Areas of uncertainty in the analysis are highlighted along with areas of potential improvement in data collection and environmental characterization.

This analysis expands upon previous LCA studies of coal power generation technologies performed by NETL [4, 5]. The results generated in this study may be used in conjunction with

NETL's power generation LCA reports to provide a complete life cycle perspective for coal-based power in the United States.

Beyond presenting the impact assessment results, this report also provides inventory data for the 22 basin-coal type-mine type scenarios, with a reference flow of 1 kg of coal extracted, and the delivery of coal using different modes of transportation, with a reference flow of 1 kg of coal transported.

2 Goal and Scope

The LCA was conducted according to International Organization for Standardization (ISO) 14040 and ISO 14044 standards [6, 7]. The goal of the LCA is to determine the environmental impacts of coal extraction and transportation to a power plant using the parameters outlined above to generate unique scenarios. Considering the goal of the LCA is to characterize the environmental impacts of extraction through delivery of coal to a power plant, the cradle-to-gate system boundary includes all material and energy consumption. **Exhibit 2-1** shows a comprehensive list of the coal basins, coal types, mine types, and NERC regions examined in this LCA, and their respective abbreviations. The abbreviations are used throughout this report to refer to disaggregated and aggregated scenarios. For example, the basin-coal type-mine type scenario code for the Illinois Basin, bituminous coal, and an underground mine would be IB-B-U.

Exhibit 2-1. Complete list of coal basins, coal types, mine types, and NERC regions, and their respective abbreviations

Name	Abbreviation
Coal Basin	
Central Appalachia	CA
Central Interior	CI
Gulf Lignite	GL
Illinois Basin	IB
Lignite	L
Northern Appalachia	NA
Powder River Basin	PRB
Rocky Mountain	RM
Southern Appalachia	SA
West/Northwest	WNW
Coal Type	
Bituminous	B
Subbituminous	S
Lignite	L
Mine Type	
Surface	S
Underground	U
NERC Region	
Alaska Interconnection	ASCC
Electric Reliability Council of Texas, Inc.	ERCOT

Name	Abbreviation
Florida Reliability Coordinating Council	FRCC
Midwest Reliability Organization	MRO
Northeast Power Coordinating Council	NPCC
Reliability First Corporation	RFC
SERC Reliability Corporation	SERC
Southwest Power Pool, Inc.	SPP
Western Electricity Coordinating Council	WECC

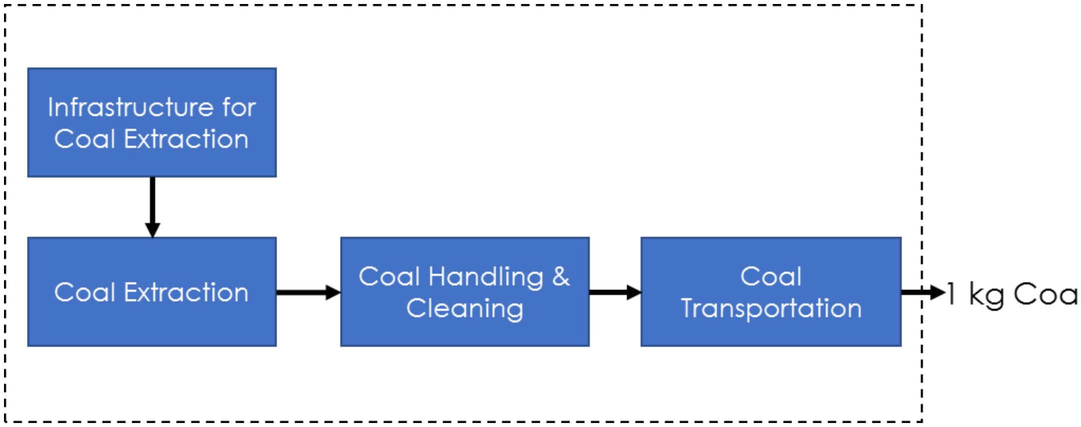
This LCA is conducted using the Coal Baseline Model, which was developed specifically for this study, and is available in both Excel and openLCA formats. All results presented in this report represent outputs from the Excel version of the model. Although both models contain identical information, Excel provides the utility to aggregate data and results for the purpose of this study.

2.1 Functional Unit and System Boundary

The LCA framework requires specification of a functional unit to normalize the LCI and LCIA results, and to establish a basis of comparison for comparative LCA. The functional unit for this LCA is 1 kg of coal delivered to a power plant. For the sake of analysis, some of the results presented in this report are aggregated into basin-coal type and NERC region-coal type scenarios. It is important to note that even in these scenarios, the functional unit of 1 kg of coal delivered is maintained.

As noted above, and to ensure consistency with the defined functional unit, this LCA has a cradle-to-gate system boundary. **Exhibit 2-2** displays a simplified flow diagram to illustrate the system boundary of this LCA. "Infrastructure for Coal Extraction" includes the construction of infrastructure required to extract coal, such as mine construction. "Coal Extraction" includes all operation activities needed to extract coal and "Coal Handling & Cleaning" includes the activities required to process extracted coal before its transported. Finally, "Coal Transportation" includes construction required for a mode of transportation and the transport necessary to move coal from a mine to its destination.

Exhibit 2-2. High-level overview of the life cycle stages included in the LCA system boundary



2.2 Representativeness

This LCA uses data gathered from a variety of sources, each of which represents a temporal period, geographic location, and state of technology. Since the results of this LCA are the combination of those sources, the temporal, geographic, and regional representativeness of the results must be determined.

2.2.1 Temporal

To determine the temporal representativeness of this LCA, the data vintage for the coal supply chain, transportation, and associated infrastructure was examined. The results generated in this study best represent the year 2016. Though some data included in this LCA pre-dates 2016 (**Exhibit 2-3**), it was determined to be the latest or highest quality data available. A study period of 30 years was used to apportion one-time burdens, such as mine, ship, and coal cleaning facility construction, to the functional unit.

Exhibit 2-3. Temporal representation of various unit processes included in the model

Unit Process	Data Year
Surface Mining	2011
Underground Mining	2014
Coal Mine Methane	2016
Surface Mine Water Consumption	2010
Underground Mine Water Consumption	2010
Coal Handling	1998–2002
Coal Cleaning	1995/2002
Mine Tailings Disposal	2000–2009
Coal Transportation	2016
Ventilation	1998–2002

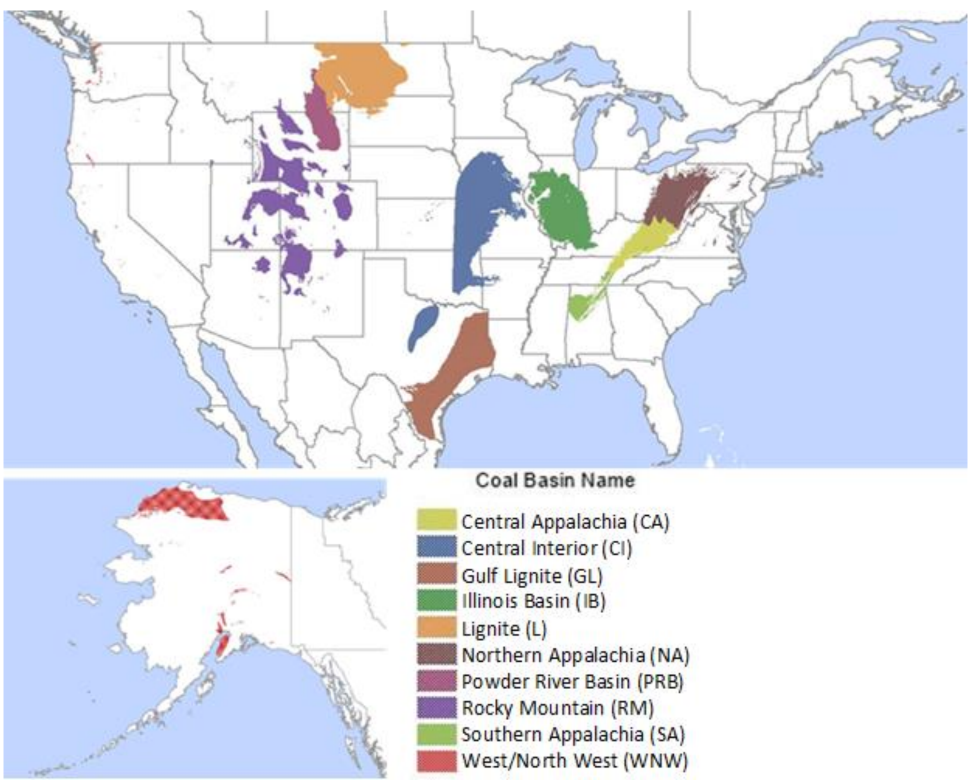
2.2.2 Technological

The coal delivered at the end of each discrete scenario is representative of a coal type and a mine type. The coal types include bituminous, subbituminous, and lignite; the mine types are surface and underground. In addition to these parameters, handling, cleaning, and transportation technologies varied throughout the scenarios evaluated and are represented by individual unit processes. The representativeness of these parameters and processes is explained in further detail in **Section 3. Life Cycle Inventory.**

2.2.3 Geographical

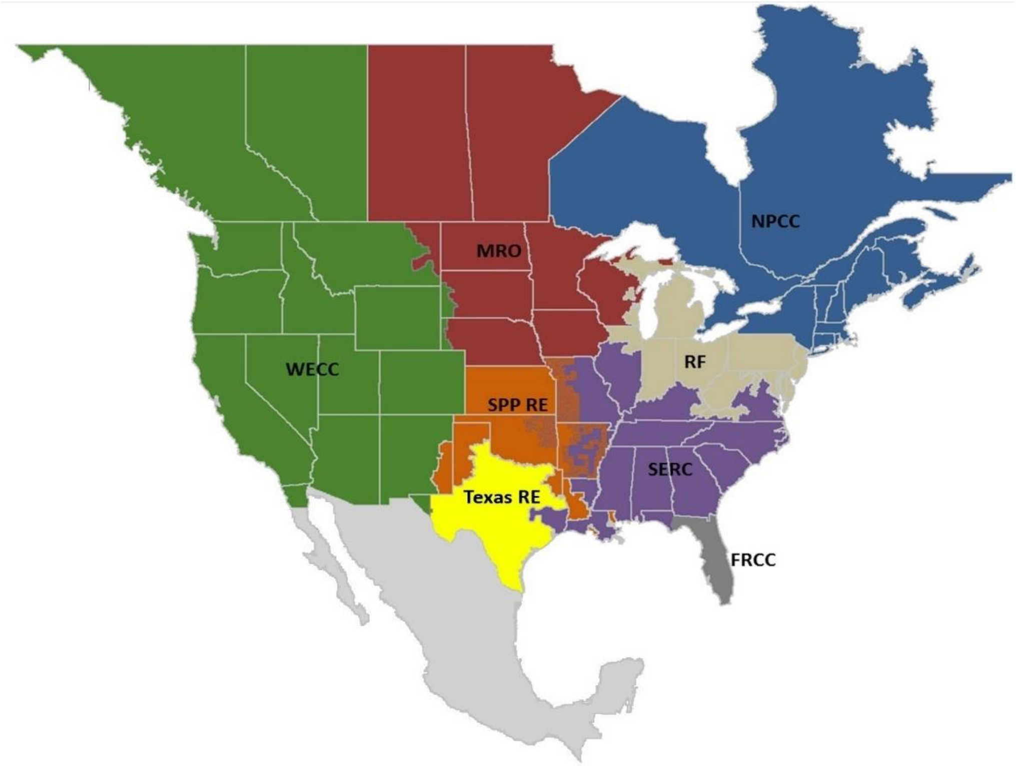
The ten coal basins identified in Hitachi Energy's Velocity Suite define the geographical representativeness of coal extraction (**Exhibit 2-4)** [2]. Additionally, transportation distances were extracted from Velocity Suite to model the impacts of coal transportation from a mine to a power plant. More broadly, transportation is modeled as delivery of coal from a basin to a specific NERC region. A map of the NERC regions in 2018 is provided in **Exhibit 2-5** [3]. ASCC (not shown on the map), NPCC, RFC (RF on the map), SERC, FRCC, MRO, SPP (SPP RE on the map), ERCOT (Texas RE on the map), and WECC make up the nine NERC regions in this LCA. While the Canadian portions of the NERC regions are shown on the map, this LCA does not include any coal delivered outside of the United States.

Exhibit 2-4. Coal basins in the United States used in this LCA



Source: Hitachi Energy [2]

Exhibit 2-5. Map of the NERC regions in North America as of 2018



Used with permission from NERC [3]

Exhibit 2-6 establishes the scenario codes used to describe the basin-coal type aggregations in this LCA. These scenarios highlight the fact that not all coal types are mined from each basin. For example, the Central Interior basin only produces bituminous coal and, thus, only has one basin-coal type scenario. **Exhibit 2-7** and **Exhibit 2-8** detail the flow of coal from a basin-coal type scenario to the relevant NERC regions. **Exhibit 2-7** shows the flow of coal relative to the total production of a specific coal type from each basin and **Exhibit 2-8** shows the flow of coal relative to the total U.S. coal production.

Exhibit 2-6. Basin-coal type scenario codes

Basin-Coal Type Scenario	Basin	Coal Type
CA-B	Central Appalachia	Bituminous
CI-B	Central Interior	Bituminous
GL-L	Gulf Lignite	Lignite
GL-B	Gulf Lignite	Bituminous
IB-B	Illinois Basin	Bituminous
L-L	Lignite	Lignite
NA-B	Northern Appalachia	Bituminous
PRB-S	Powder River Basin	Subbituminous

Basin-Coal Type Scenario	Basin	Coal Type
PRB-B	Powder River Basin	Bituminous
RM-B	Rocky Mountain	Bituminous
RM-S	Rocky Mountain	Subbituminous
SA-B	Southern Appalachia	Bituminous
WNW-L	West/Northwest	Lignite
WNW-S	West/Northwest	Subbituminous

Exhibit 2-7. Flow of coal from each basin-coal type scenario to a NERC region relative to the total production of a coal type from each basin

Basin-Coal Type Scenario	ASCC	ERCOT	FRCC	MRO	NPCC	RFC	SERC	SPP	WECC
CA-B			0.50%		1.54%	29.1%	68.9%		
CI-B								100%	
GL-B								100%	
GL-L		76.6%					7.17%	16.3%	
IB-B			3.39%	0.18%		63.9%	31.2%	1.24%	
L-L				100%					
NA-B			7.86%	0.16%	0.30%	86.1%	5.60%		
PRB-B						100%			
PRB-S		10.9%		18.0%		14.6%	26.7%	15.5%	14.4%
RM-B			3.71%	0.57%		3.98%	2.45%		89.3%
RM-S									100%
SA-B							100%		
WNW-L	100%								
WNW-S									100%

Note: Rows sum to 100%.

Exhibit 2-8. Flow of coal from each basin-coal type scenario to a NERC region relative to the total production of coal from the United States

Basin-Coal Type Scenario	ASCC	ERCOT	FRCC	MRO	NPCC	RFC	SERC	SPP	WECC
CA-B			0.02%		0.05%	0.94%	2.22%		
CI-B								0.06%	
GL-B									
GL-L		7.40%					0.69%	1.57%	
IB-B			0.17%	0.01%		3.13%	1.53%	0.06%	

Basin-Coal Type Scenario	ASCC	ERCOT	FRCC	MRO	NPCC	RFC	SERC	SPP	WECC
L-L				5.01%					
NA-B			0.11%			1.25%	0.08%		
PRB-B						0.03%			
PRB-S		7.50%		12.40%		10.09%	18.44%	10.67%	9.97%
RM-B			0.13%	0.02%		0.14%	0.08%		3.04%
RM-S									3.11%
SA-B							0.02%		
WNW-L	0.03%								
WNW-S									0.01%

Note: Table sums to 100%.

2.3 Impact Assessment

This LCA uses a modified version of the Environmental Protection Agency's (EPA) Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 method for calculating impact assessment results [8]. TRACI implements midpoint metrics that describe impacts at a point between the emission and ultimate damage to the environment. For example, emission of chlorofluorocarbons (CFCs) leads to midpoint ozone depletion impacts, and ultimately allows for higher ultraviolet B radiation from the sun and increases the rate of human skin cancer. Midpoint impact assessment methods like TRACI do not evaluate the ultimate damage caused by emissions. The following is a list of the impact categories included in this LCA.

Global warming potential (AR6, 100-yr) is the average increase in the temperature of the Earth's surface and lower atmosphere. Global warming can occur as a result of increased emissions of GHGs [9]. NETL modified TRACI to include updated global warming potential (GWP) factors from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) [10]. GWP characterization factors are available for 100-year and 20-year time frames. All GHG results in this LCA are expressed as 100-yr GWPs unless specified otherwise. Reporting units are kg carbon dioxide equivalent (CO_2e). **Exhibit 2-9** shows the IPCC AR6, 100-yr GWP characterization factors for four key GHGs. The characterization factors for methane (CH_4) represent fossil methane.

Exhibit 2-9. IPCC AR6 global warming potential characterization factors

Emission	20-year (kg CO_2e/kg)	100-year (kg CO_2e/kg)
CO_2	1	1
CH_4	82.5	29.8
N_2O	273	273
SF_6	18200	24300

Acidification potential is the increased concentration of hydrogen ions in a local environment. This can be from the direct addition of acids or by indirect chemical reactions from the addition of substances such as ammonia [8]. Reporting units are kg sulfur dioxide equivalent (SO_2e).

Eutrophication potential is the "enrichment of an aquatic ecosystem with nutrients (nitrogen, phosphorus) that accelerate biological productivity (growth of algae and weeds) and an undesirable accumulation of algal biomass." [11] Reporting units are kg nitrogen equivalent (Ne).

Photochemical smog formation potential is the increased concentration ground-level ozone, formed by the reaction of nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the presence of sunlight [8]. Reporting units are kg trichlorofluoromethane equivalent (CFC-11e).

Ozone depletion potential is the deterioration of ozone within the stratosphere by chemicals such as CFCs. Stratospheric ozone provides protection for people, crops, and other plant life from radiation [8]. Reporting units are kg ozone equivalent (O_3e).

Particulate matter formation potential is the increased concentration of "a mixture of solid particles and liquid droplets found in the air" that are smaller than 10 microns in diameter [12]. These small diameter particles can enter deep inside the lungs and cause many serious health problems. Almost all particulate matter (PM)-related health impacts are caused by particles 2.5 microns or smaller ($PM_{2.5}$) [13]. Reporting units are kg $PM_{2.5}$ equivalent ($PM_{2.5}$e).

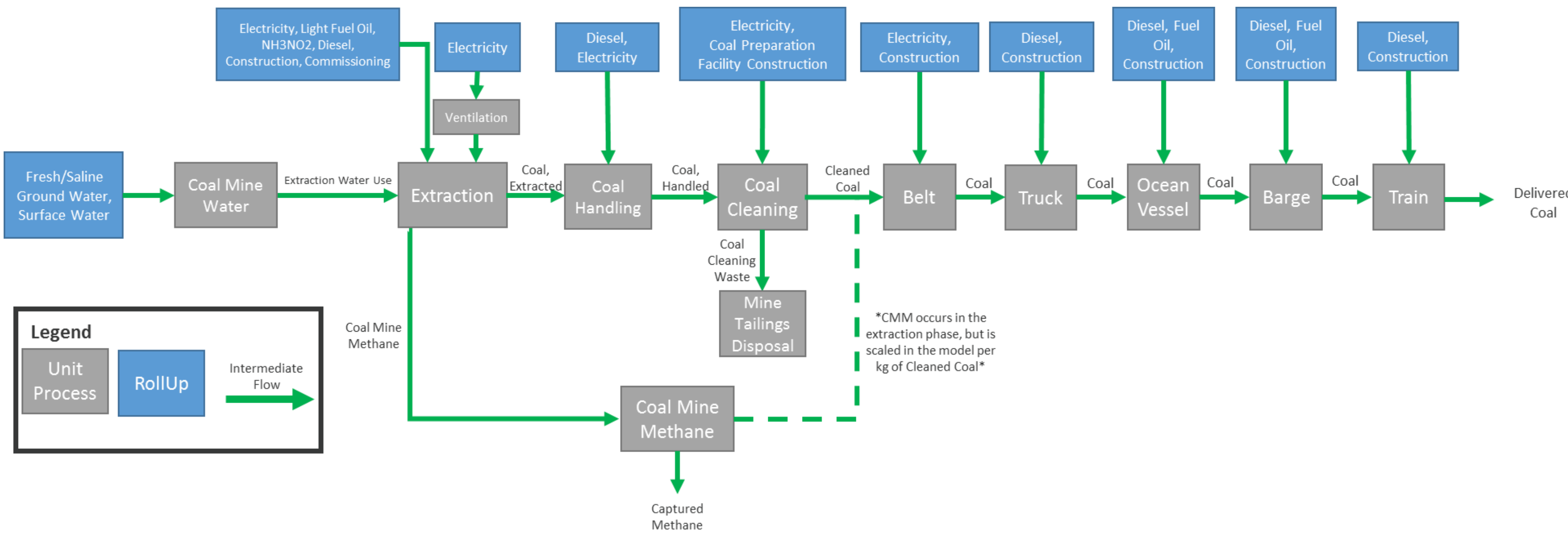
2.4 Uncertainty Analysis

The LCIA results presented in this report are generated using the Excel version of the Coal Baseline Model. The Excel model was developed to run a Monte Carlo simulation, or a series of simulations for several scenarios, to generate the life cycle impact results. Parameter-level uncertainty is included where the data was available. Most of the parameters with uncertainty are parametrically varied in a triangular distribution, with the peak set as the average value of the dataset between the minimum and maximum values. A notable exception to this are the parameters associated with the underground coal mine methane (CMM), which is not well modeled with a triangular distribution. The uncertainty associated with underground CMM and the distribution used to model this unit process are discussed in further detail in **Section 3.2 Coal Mine Methane**. It is important to note that there are instances within the model where a parameters minimum and maximum values are equal to the average, and there is no uncertainty attached to the parameter. The uncertainty associated with relevant parameters is represented in exhibits throughout this report with error bars equal to the 5^{th} and 95^{th} percentiles of the simulated results. Moving forward, additional uncertainty should be included in the Coal Baseline Model as data are updated and new data become available.

3 LIFE CYCLE INVENTORY

The primary unit processes (UPs) used in the model are based on publicly available processes developed by NETL and published in NETL's Unit Process Library [14]. Secondary UPs, such as production of steel and concrete for construction, are based on vetted, third-party industry data. A flow diagram, shown in **Exhibit 3-1**, shows the processes, process roll-ups (flattened models of upstream supply chains, e.g., electricity), and intermediate flows in the model, and illustrates how they are integrated. Parameter values for the various UPs within the model are obtained from a variety of sources, which are discussed in this section.

Exhibit 3-1. Flow diagram of unit processes and intermediate flows within the Coal Baseline Model



3.1 Coal Characteristics and Production

The physical characteristics of the coal used in this study, based on the basin and the coal type, can be seen in **Exhibit 3-2** [2]. Rather than aggregating to national average characteristics for coal, individual mine data were averaged to a basin-coal type scenario. This is done because different coals have different properties, including, but not limited to energy content. It is important to note that the coal delivered at the end of each scenario in this study is not functionally equivalent to all other scenarios. Differences in coal qualities justify the investigation of multiple scenarios, as two coals may not be interchangeable for a specific power plant. The coal properties in **Exhibit 3-2** can be used to determine the functional equivalence between scenarios, or the lack thereof.

Exhibit 3-2. Coal characteristics by basin-coal type scenario

Basin	Coal Type	Heating Value (Btu/lb)	Sulfur (%)	Ash (%)	Mercury (ppm)
Central Appalachia	Bituminous	1.24E+04	1.08%	7.43%	1.12E-01
Central Interior	Bituminous	1.03E+04	1.17%	8.22%	1.06E-01
Gulf Lignite	Bituminous	1.03E+04	1.39%	8.24%	N/A
	Lignite	6.46E+03	1.37%	6.93%	1.00E-01
Illinois Basin	Bituminous	1.15E+04	1.11%	7.32%	1.20E-01
Lignite	Lignite	6.75E+03	1.03%	8.77%	3.20E+00
Northern Appalachia	Bituminous	1.22E+04	1.13%	7.36%	1.17E-01
Powder River Basin	Bituminous	1.03E+04	0.47%	5.57%	N/A
	Subbituminous	8.76E+03	1.22%	7.79%	1.56E-01
Rocky Mountain	Bituminous	1.10E+04	0.99%	10.95%	1.16E-01
	Subbituminous	9.28E+03	0.94%	8.39%	1.22E-01
Southern Appalachia	Bituminous	1.23E+04	0.99%	6.66%	1.03E-01
West/Northwest	Lignite	7.19E+03	0.99%	7.61%	N/A
	Subbituminous	7.85E+03	1.12%	5.76%	7.30E-02
Total U.S. Bituminous	Bituminous	1.20E+04	1.11%	7.47%	1.16E-01
Total U.S. Subbituminous	Subbituminous	8.76E+03	1.21%	7.76%	1.55E-01
Total U.S. Lignite	Lignite	6.62E+03	1.22%	7.63%	1.18E+00

* Total U.S. Bituminous, Total U.S. Subbituminous, and Total U.S. Lignite rely on production-weighted averages for sulfur, ash, and mercury content. Production values for these three rows are sums of production in each basin.

For this study, coal production data from the Energy Information Administration (EIA) was compiled for the 2016 production year [15]. When 2016 data were not available, the most recent production data were used. The EIA data are at mine level and include the supplying coal basin as well as other production data for the mine. Similar to the coal characteristics, individual mine data were aggregated to basin-coal type scenarios. **Exhibit 3-3** shows a summary of the production data for 2016 by basin and coal type [15].

Exhibit 3-3. Coal production by basin-coal type scenario

Basin	Coal Type	Quantity (Short Tons)	Percent of Coal Type Production	Percent of Total Production
Central Appalachia	Bituminous	2.81E+04	12.09%	4.51%
Central Interior	Bituminous	6.62E+02	0.28%	0.11%
Gulf Lignite	Bituminous	1.27E+02	0.05%	0.02%
	Lignite	4.26E+04	65.73%	6.83%
Illinois Basin	Bituminous	8.73E+04	37.55%	14.01%
Lignite	Lignite	2.21E+04	34.08%	3.54%
Northern Appalachia	Bituminous	8.31E+04	35.73%	13.33%
Powder River Basin	Bituminous	1.44E+02	0.06%	0.02%
	Subbituminous	3.04E+05	93.36%	48.82%
Rocky Mountain	Bituminous	3.11E+04	13.40%	5.00%
	Subbituminous	2.16E+04	9.30%	3.47%
Southern Appalachia	Bituminous	1.94E+03	0.83%	0.31%
West/Northwest	Lignite	1.24E+02	0.19%	0.02%
	Subbituminous	2.54E+01	0.01%	0.004%
Total Bituminous		2.32E+05	100%	37.31%
Total Lignite		6.48E+04	100%	10.39%
Total Subbituminous		3.26E+05	100%	52.30%

3.2 Coal Mine Methane

In-ground coal and its surrounding rock strata contain gaseous CH_4 that is released during mining and post-mining activities, which is referred to as CMM [16]. NETL calculates CMM based on the sum of five activities that are regulated by specific entities: ventilation air CH_4 (Mine Safety and Health Administration [MSHA]), active mine drainage/degasification systems (EPA), post mining emissions (EPA), abandoned mine emissions (EPA), and nonproducing mine emissions (MSHA). The full procedure is used to determine CMM is documented in a previously published NETL report [4, 17].

In underground mining, CMM must be removed from the mine for health and safety reasons, and is typically vented out using fans. However, in some cases, operators drill wells into the coal seam to extract CMM before mining operations to reduce the CH_4 concentration when mining begins. This CH_4 usually exists at a high enough concentration to be recovered as an intermediate product or to be flared. The benefits of oxidizing or using the CH_4 are to prevent the inadvertent accumulation of CH_4, which poses a safety risk at the mine, and to reduce the

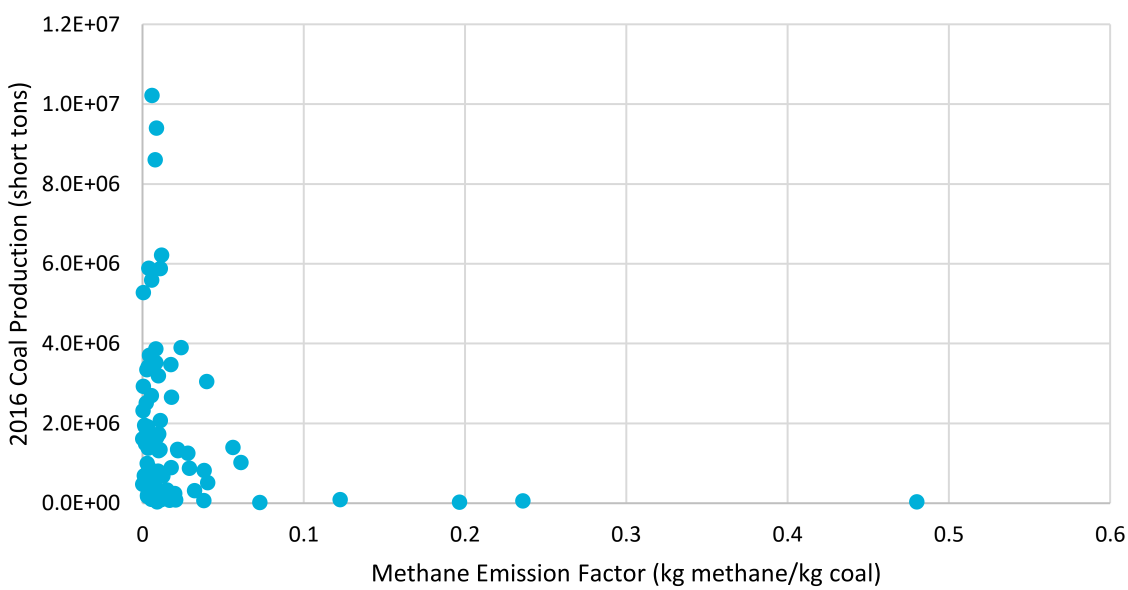
GWP impact of the mine by converting the CH_4 to carbon dioxide (CO_2), which has a lower GWP impact per unit mass than CH_4.

CH_4 emissions attributed to post-mining activities are difficult to assess. Post-mining emissions occur in the form of CH_4 desorption during coal transportation and storage. EPA estimates that post-mining emissions represent 25–40 percent of average in situ content, and a value of 32.5 percent can be used for analysis [18]. CH_4 emissions from abandoned underground mines were estimated using an EPA study that estimates net underground abandoned coal mine emissions by region for the year 2002 [19]. These estimates are considered “net” emissions, as they are adjusted for CH_4 recovery. Within the Illinois Basin, abandoned CMM emissions were proportioned to the three states within the basin using a 2008 EPA report with an inventory of abandoned mines [20].

Despite providing various data on CMM, EPA does not provide estimates at the sub-basin-level. Thus, the EPA Greenhouse Gas Reporting Program (GHGRP) was leveraged to determine representative basin-level CMM emissions for the 2016 production year [21]. Mine-level CMM emissions are matched to each coal basin to compile basin-level CH_4 emissions. Production-weighted CMM emission factors for each coal basin are calculated by dividing the total CH_4 emissions in each basin by the total production reported by EIA. Notably, CMM emission data were incomplete for Central Interior, Powder River Basin, Gulf Lignite, and Lignite coal basins.

CMM is a key parameter in the Coal Baseline Model with the respect to uncertainty and GWP impacts. During model development it was determined that underground CMM is not well modeled with a triangular distribution. The underground CMM data contain outliers that push the maximum value much higher than the minimum and average values. This results in a skewed distribution (**Exhibit 3-4**) that drives the simulated mean value much higher than the expected production-weighted average parameter value. Ultimately, these inflated simulated means lead to incorrect LCIA results that, in some cases, may be several orders of magnitude higher than results produced with the expected mean.

Exhibit 3-4. Distribution of methane emissions factors and coal production by mine in 2016



It should be noted that the four data points that exceed 0.1 kg CH_4 per kg of coal produced are from coal mines have very low production: the E4-1 mine in Perry, KY; Bowie No. 2 Mine in Delta, CO; Carlisle Mine in Sullivan, IN; and Pond Creek No. 1 Mine in McDowell, WV. The Bowie No. 2 Mine closed in February of 2016, which means that 2016 production data were based on less than two months of activity, while CMM emissions were recorded for the entire calendar year. This mine will not appear in 2017 data; however, this does raise the question of how abandoned CMM emissions should be handled in the future. Bowie No. 2 will continue to emit CH_4 in 2017 and, unless the mine reopens for production, it will have no production. Ultimately, this would result in an infinite CMM emissions factor if it were to appear in the data. This analysis addresses abandoned CMM through a top-down estimate at the coal basin level; however, future work may benefit from bottom-up measurements of abandoned mines.

Positively skewed distributions, like the distribution shown in **Exhibit 3-4** have high, albeit infrequent, values that affect the overall mean of the distributions. These values cannot be treated as outliers and excluded from the data set, which would require an arbitrary decision on where to truncate the long tail of the skewed distribution. Thus, a lognormal distribution was applied to CMM parameters. U.S. average parameter values were calculated and applied for those basins with incomplete CMM emission data. Where representative data were unavailable, no geometric standard deviation was determined, and no distribution was applied. For instance, only one data point was available for each CMM parameter for the West/Northwest coal basin. Thus, each parameter was represented by one value and no distribution was used during Monte Carlo simulation.

3.3 Coal Extraction

Coal can be mined from surface and underground mines depending on the type of coal formation. In this study, coal extraction from surface and underground mines is modeled separately. Surface coal mine extraction and underground coal mine extraction UPs from NETL's Unit Process Library were updated for this study to represent the year 2016 [22, 23]. Irrespective of the method of mining, extracting coal requires electricity and diesel for operations, and explosives for blasting coal. Energy inputs for extracting coal were based on an estimate made by the Department of Energy for coal mining [24, 25]. Explosives demand for blasting was adopted from Stump [26]. Electricity input for mining operations in this study was modeled using the Grid Mix Explorer UP representing U.S. average grid power consumed in the year 2014 [27]. Life cycle profile of diesel is modeled using NETL's petroleum baseline model [28].

3.3.1 Surface Coal Mine Extraction

Surface coal mine extraction is modeled using NETL data on coal extraction for the years 1989–2011 [22]. The UP encompasses overburden removal, coal extraction, and reclamation as mining stages. A strip ratio from any mine can be applied to scale the impacts of the overburden removal scenario. The strip ratio is used as a scalar in the model to adjust the impact of the energy consumption of mining equipment and use of explosives when there is more or less overburden to remove than the reference mine. Surface mines in this study were assumed to have a strip ratio of 5:1 [29]. For energy calculations, the mining equipment was separated into electrically powered equipment and diesel-powered equipment. For all calculations, the equipment was separated into mining stage: overburden removal, coal extraction, and mine reclamation.

3.3.2 Underground Coal Mine Extraction

Underground coal mine extraction is modeled using data on extraction using the longwall mining method for the years 1989–2011 [23, 30]. This UP was updated with revised emissions and emission factors for the purposes of this study. The emission factors for PM_{10} and $PM_{2.5}$ were updated using National Emissions Inventory (NEI) data from EPA and coal production data from EIA for the year 2014 [15, 31]. First, EIA coal mines were mapped by facility or operator name to those in the NEI data. Once mapped, the mine-level PM emissions from NEI data were filtered to only consider emissions from coal extraction. The PM emission factors from individual coal mines were calculated by normalizing the emissions with the corresponding annual coal production. County-level PM emission factors were computed by taking a weighted average of emissions of individual coal mines within a county. Finally, emission factors for a coal basin were similarly calculated using the emission factors of each county within a basin. In addition to PM updates, the VOC emissions from underground coal mining were updated by re-normalizing the VOC emissions with coal production by type for 2016 [15].

3.4 Coal Mine Water Consumption

Water is used during coal mining to cool the machinery, to prevent coal ignition, and for dust control [32, 33]. Separate UPs were used in this study for surface and underground coal mine water consumption to capture the differences in operations. The UPs contain water withdrawals during mining operations and emissions present in water discharged from mines. Both UPs represent updates to the surface and underground coal mine water processes available from NETL's Unit Process Library [34, 35].

Data from the United States Geological Survey (USGS), EPA, and EIA were used to update the water use and emission factors in the UPs [36-38]. Specifically, water consumption was updated using county-level water withdrawals data (representative of the year 2010) from the USGS [36]. The USGS data does not allocate water withdrawals by mining material (coal, metals, clay, etc.); therefore, the withdrawals associated with coal mining had to be determined using EIA data. First, the water withdrawal from a county containing a coal mine was determined by mapping the state and county of the respective mine to the county in the USGS data [38]. Water consumed by the coal mine was then computed by multiplying the county-level water withdrawal by the ratio of coal produced from corresponding type of coal mines within that county [2]. This process was repeated for all mines in all coal basins. Finally, the calculated water withdrawals were divided by coal production from corresponding mines to normalize the water consumption to 1 kg of coal produced.

The effluent water discharges and emissions from coal extraction were updated using data from the EPA Enforcement and Compliance History Online (ECHO) database [37]. Coal mines from the EIA coal production data were first mapped by facility or operator name with those in the ECHO database to obtain National Pollution Discharge Elimination System (NPDES) identification numbers (IDs). These IDs were queried to obtain mine-level water discharges and emissions from the ECHO database. The mine-level water parameters were normalized to the corresponding coal production to obtain water-quality emission factors.

3.5 Coal Handling and Cleaning

The surface and underground coal handling UPs used in this study are available from NETL's Unit Process Library [39, 40]. These processes represent the energy required to move coal about the mine site by trucks, conveyor belts, load haul dumper machines, bulldozers, and front-end loaders. The data in these UPs comes from estimates in the "Energy and Environmental Profile of the U.S. Mining Industry" [24]. This source is also used to determine the energy used in coal cleaning in a separate UP.

The coal cleaning UP used in this LCA represents a modified version of the process available from NETL's Unit Process Library [41]. Coal cleaning represents the processes on the mine site required to separate coal from rock, dirt, clay, and other materials. In addition to energy use, the coal cleaning process includes an estimate of waste and criteria air pollutants. The waste estimates are calculated using an example of a realistic coal cleaning process, while the criteria air pollutants are based on EPA AP-42 emission factors for coal cleaning [42, 43]. Updates to previous modeling rely on EIA data representing fractions of coal that were cleaned by region for the year 1983 [44]. Considering the age of the data, a sensitivity check was completed to determine the effect of coal cleaning on LCIA results. These calculations show that the most extreme variation in coal cleaning (all coal cleaned and no coal cleaned) results in, at most, a 5 percent change in impact. Thus, significant changes in the portion of coal that is cleaned will not result in significant differences in the LCIA results. **Exhibit 3-5** shows the percent of coal cleaned for each coal basin. For those coal basins that did not have sufficient coal cleaning data, the U.S. average coal cleaning was assumed.

Exhibit 3-5. Coal cleaning by region

Coal Basin	Percent of Coal Cleaned
Central Appalachia	73%
Central Interior	83%
Gulf Lignite	75.5%
Illinois Basin	75.5%
Lignite	75.5%
Northern Appalachia	70%
Powder River Basin	0%*
Rocky Mountain	0%*
Southern Appalachia	79%
West/Northwest	0%*
U.S. Average	75.5%

*Coal washing in the Western coal-producing states, except for the interior states, is not extensive (AK, IA, KS, MO, OK).

3.6 Coal Transportation

Coal transportation in this study was modeled via train, truck, conveyor belt, barge, and ocean/lake vessel. Train, truck, barge, and ocean/lake vessel transportation UPs were sourced from NETL's Unit Process Library [45-48]. Conveyor belt transportation was modeled using electricity consumption and travel distance sourced from the underground coal extraction UP [23, 45-48]. The NETL diesel combustion UP was used for both diesel combustion and as a proxy for light fuel oil combustion, which is consistent with previous NETL modeling [49]. In total, 35 unique scenarios, including the U.S. average scenario, were developed for coal transportation. Each unique scenario is represented by a specific combination of a coal basin and a NERC region, and a mixture of the various modes of transportation.

Coal transportation receipts from Velocity Suite for 2016, which sources data from Form EIA-923, were used to develop transportation parameters. The parameters describe the average transportation mode and distance traveled from a mine in a specific basin to a power plant in a NERC region for a kg of coal [2]. Each entry in the database is based on a specific origination point within the basin and a specific destination point within the NERC region. Thus, these transportation parameters represent the average trip a unit of coal takes between a specific mine and specific power plant, not simply the distance between a central point in the basin and a central point in the NERC region. A U.S. average scenario was created using the complete set of transaction receipts and the same calculation method described above. It is important to note that transportation distances are dependent on basin and NERC region only, and do not change with differences in coal type or mine type. A summary of the transportation scenarios and parameters are shown in **Exhibit A-1**.

3.7 Electricity Grid

Basin-level electricity providers for the year 2016 were determined using relevant Federal Energy Regulatory Commission (FERC) Regional Transmission Organizations and Independent System Operators [50]. For basins that clearly lie within one FERC region, it was assumed that 100 percent of electricity was sourced from that region. For coal basins that cross FERC region boundaries, it was assumed that an equal share of electricity was sourced from the FERC regions where the basin resides. The U.S. average electricity was assumed to be provided in equal shares from all relevant FERC regions. **Exhibit 3-6** shows the percent of electricity provided by a FERC region to each coal basin.

Exhibit 3-6. Electricity providing FERC regions by basin

Coal Basin	ERCOT	MISO	Northwest	PJM	Southeast	Southwest	SPP
Central Appalachia	0%	0%	0%	100%	0%	0%	0%
Central Interior	0%	50%	0%	0%	0%	0%	50%
Gulf Lignite	100%	0%	0%	0%	0%	0%	0%
Illinois Basin	0%	100%	0%	0%	0%	0%	0%
Lignite	0%	50%	0%	0%	0%	0%	50%
Northern Appalachia	0%	0%	0%	100%	0%	0%	0%
Powder River Basin	0%	0%	100%	0%	0%	0%	0%
Rocky Mountain	0%	0%	50%	0%	0%	50%	0%
Southern Appalachia	0%	0%	0%	0%	100%	0%	0%
West/Northwest	0%	0%	100%	0%	0%	0%	0%
U.S. Average	14%	14%	14%	14%	14%	14%	14%

4 Life Cycle Impact Assessment Results

The cradle-to-gate boundary of this LCA includes mining, cleaning, and transportation of coal, with a final output of 1 kg of coal delivered to a power plant. The results presented in this section represent outputs from a Monte Carlo simulation with 1,000 iterations. All result totals represent the simulated mean and error bars are equal to the 5th and 95th percentile results. Using the TRACI 2.1 impact assessment method, impacts were calculated for 55 basin-coal type-mine type-NERC region scenarios. **Exhibit B-1** shows a summary of the scenario parameters and codes for all 55 scenarios. The results from all scenarios can be compared and analyzed to evaluate differences between specific cases or the impacts of a specific case. However, aggregating these results may be useful to evaluate the environmental impacts of high-level scenarios, like all coal of a specific type from a specific basin. This study examines several aggregation levels: basin-coal type-mine type, basin-coal type, and NERC region-coal type. The mass of coal in each disaggregated scenario is used to determine the total coal in each aggregated scenario and the percent contribution the disaggregated scenario represents. Together, the aggregated scenarios represent mass-weighted averages of the 55 unique scenarios.

4.1 Basin-Coal Type-Mine Type-NERC Region

Drawing conclusions from the impact assessment results of the 55 basin-coal type-mine type-NERC region scenarios is a difficult task. The coal delivered at the end of each scenario is not functionally equivalent to all other scenarios; thus, the results of one basin-coal type-mine type-NERC region scenario cannot reasonably be compared to another. Although this study does include the physical characteristics of the coal analyzed, it does not include any metrics beyond the heating value. Therefore, the true functional equivalence between scenarios cannot be determined in this study. However, the disaggregated basin-coal type-mine type-NERC region scenarios can be helpful in making comparisons between single variables or different upstream coal being delivered to the same NERC region to look for environmental tradeoffs.

For example, if a power plant in the RFC NERC region wanted to determine the environmental impacts of coal being delivered to the region, there are eight basin-coal type-mine type scenarios that deliver coal to RFC. The impact assessment results for these scenarios can be examined to determine what basin-coal type-mine type-NERC region scenarios cause the lowest environmental impacts. **Exhibit 4-1** and **Exhibit 4-2** show contribution analyses for GWP and particulate matter formation potential impact results for Central Appalachia bituminous underground coal to RFC (CA-B-U-RFC) and Powder River Basin subbituminous surface coal to RFC (PRB-S-S-RFC) scenarios.

Exhibit 4-1. Global warming potential (AR6, 100-yr) impacts for CA-B-U-RFC and PRB-S-S-RFC scenarios

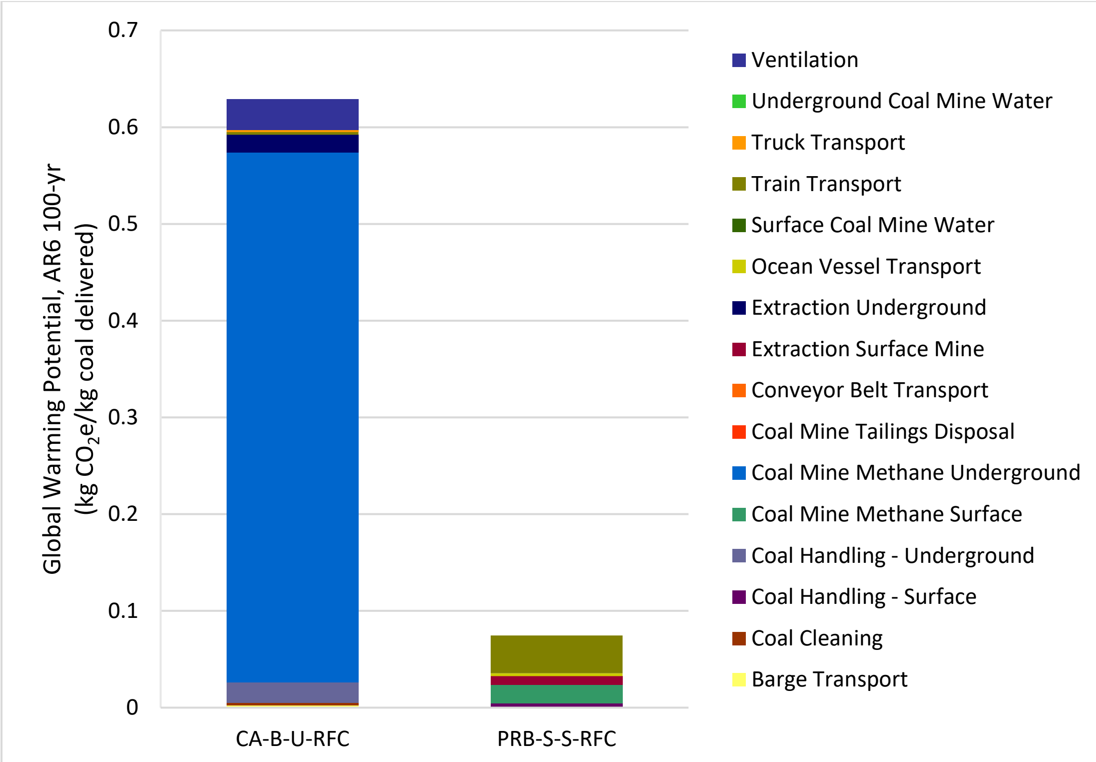


Exhibit 4-2. Particulate matter formation potential impacts for CA-B-U-RFC and PRB-S-S-RFC scenarios

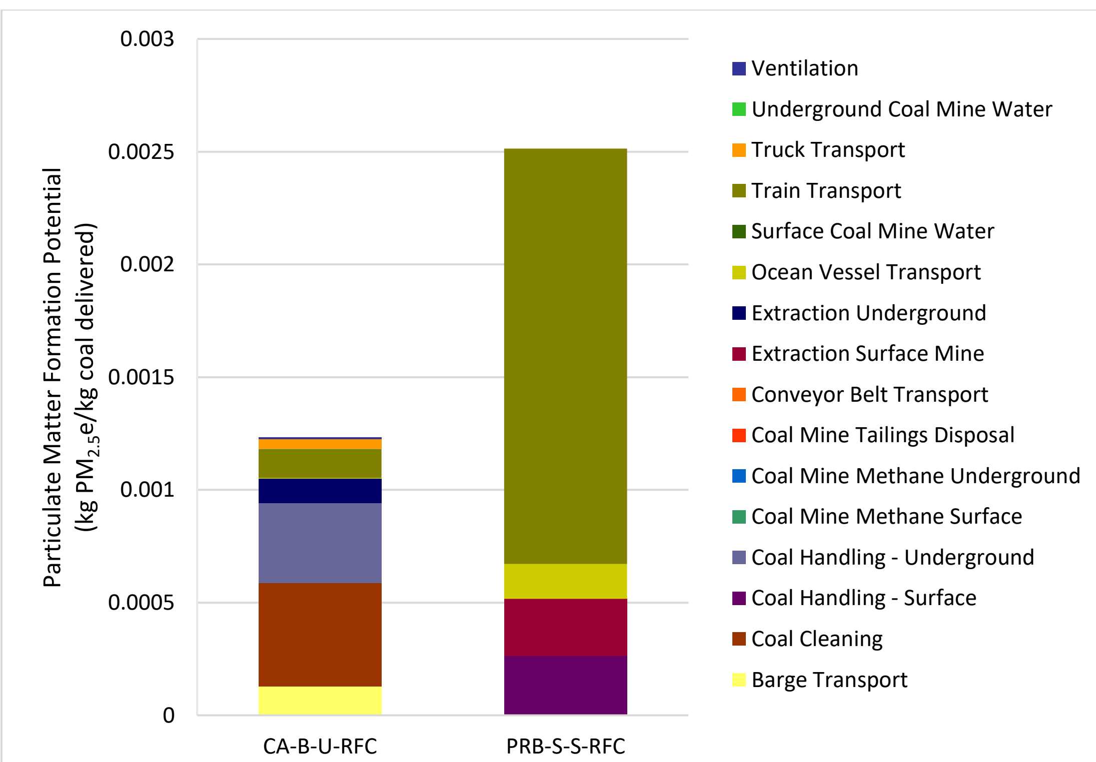


Exhibit 4-1 highlights the significance of CMM for underground mines. Underground CMM results in significant GWP impacts for the CA-B-U-RFC scenario when compared to PRB-S-S-RFC. While surface CMM does contribute to the GWP impact of PRB-S-S-RFC, it is considerably smaller than the contribution from underground CMM. Train transportation is a major contributor to the GWP impact of PRB-S-S-RFC and this impact is significantly larger than for CA-B-U-RFC. This is the result of a considerable difference in distance that extracted coal must travel by train from Central Appalachia basin (82.5 miles) and Powder River Basin (1,180 miles) to reach the RFC region (**Exhibit A-1**). This illustrates the importance of transportation distance when selecting a basin to source coal from for a power plant. This is highlighted further in **Exhibit 4-2**, which indicates that the transportation of coal from PRB to RFC has a significant effect on particulate matter formation potential impacts. While the contributions from coal extraction and handling are higher for CA-B-U-RFC than for PRB-S-S-RFC, the increased train transportation distance and resulting impacts cause PRB-S-S-RFC to have a higher overall particulate matter formation potential impact.

If a power plant was faced with choosing between these two, there is a tradeoff between CA-B-U-RFC and PRB-S-S-RFC scenarios. It is important to note that while tradeoffs between impact categories exist, there are other drivers not modeled here such as economics, existing technology capabilities, coal-quality specifications, and geographical coal availability that would inform such a decision. The coal delivered by each scenario examined here will have varying characteristics and will not be suitable to all power plants. Therefore, while this study can be useful for a NERC region to determine the environmental impacts of different basin-coal type-mine type scenarios, it is unlikely that these conclusions alone will be used to choose one basin-coal type-mine type scenario over another.

4.2 Basin-Coal Type-Mine Type

The 22 unique basin-coal type-mine type scenarios are useful to examine the impacts of extracted coal regardless of the destination of delivery. Although these scenarios do not differentiate based on NERC region, the impacts from transportation to the relevant NERC regions is included in the results presented. For example, Central Appalachia bituminous coal from an underground mine (CA-B-U) can be delivered to FRCC, MRO, NPCC, RFC, and SERC regions. Thus, the impact results for CA-B-U represent mass-weighted averages of the five CA-B-U-NERC region scenarios. In addition to the associated Coal Baseline Model, life cycle inventories representing the 22 basin-coal type-mine type scenarios and each transportation mode have been included as supplemental materials to this report.

Exhibit 4-3 and **Exhibit 4-4** show the GWP and acidification potential impact results, respectively. Notably, the error bars in **Exhibit 4-3** for GWP are significant for all underground mine scenarios. This is due to the uncertainty in underground CMM, which is the largest contributor to GWP. This same level of uncertainty is not present in surface CMM, which is reflected in the relatively small error bars. The GWP results for the disaggregated scenarios also showed large error bars and a significant contribution to GWP from CMM for underground mines. This outcome can be seen in all GWP results in this report, regardless of the level of aggregation.

While CMM is a major contributor to GWP, it makes no contribution to impact categories like acidification potential. The largest contributions to acidification potential come from train transport, both underground and surface coal handling, and surface mining (**Exhibit 4-4**). Diesel combustion during train transportation, and upstream diesel extraction and processing, result in significant contributions to acidification potential impacts. The scenarios that do not rely on trains to transport coal, or for which the distance traveled by train is minimal, have little to no contribution from train transport. Contributions from coal handling and surface extraction are also the result of diesel combustion, in addition to upstream impacts from electricity consumption. Overall, the WNW-L-S and WNW-S-S scenarios have the lowest GWP and acidification potential impacts. A summary of the TRACI impact assessment results for all basin-coal type-mine type scenarios can be seen in **Exhibit C-1**.

Exhibit 4-3. Global warming potential (AR6, 100-yr) impacts for all basin-coal type-mine type scenarios

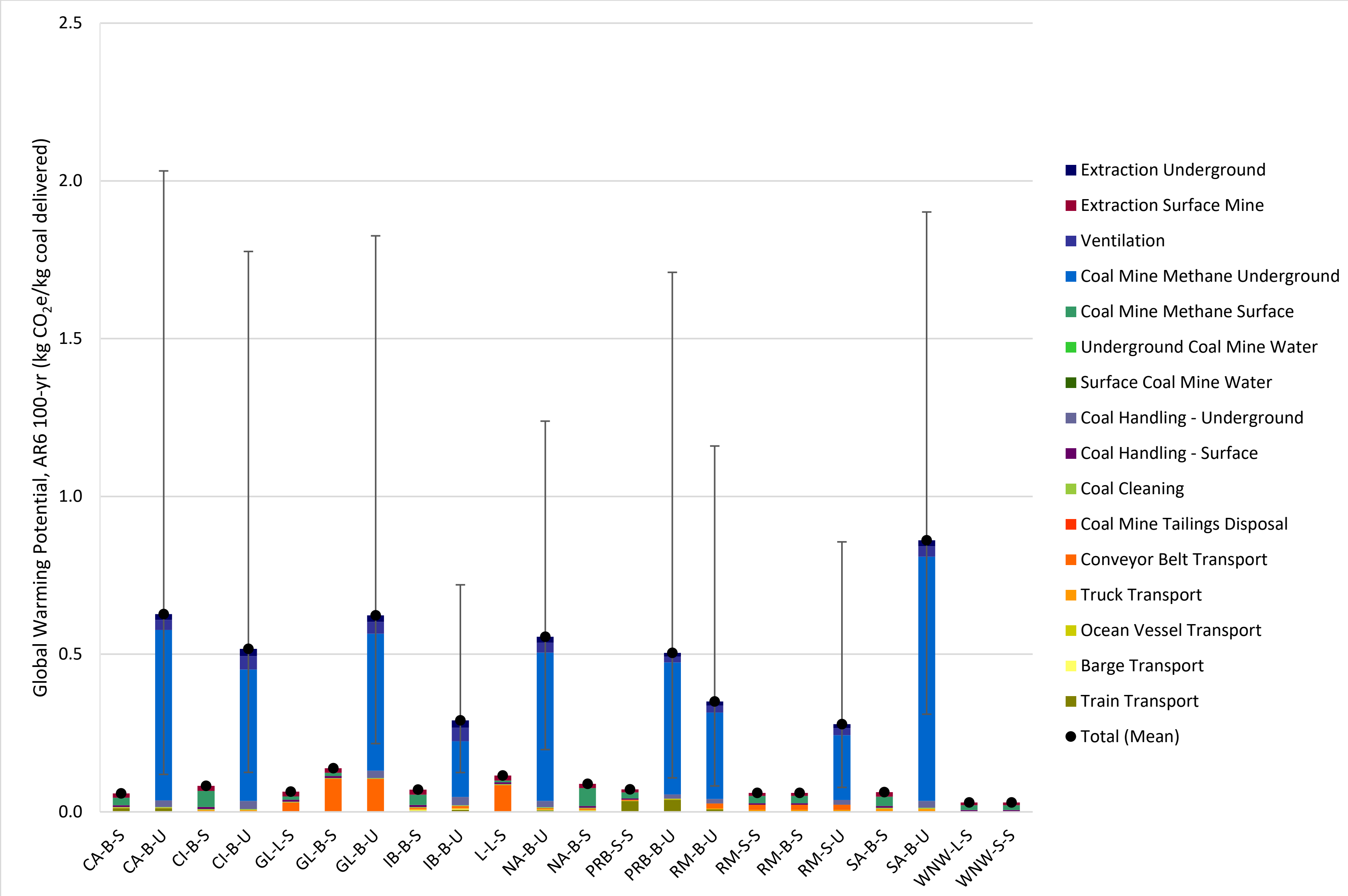
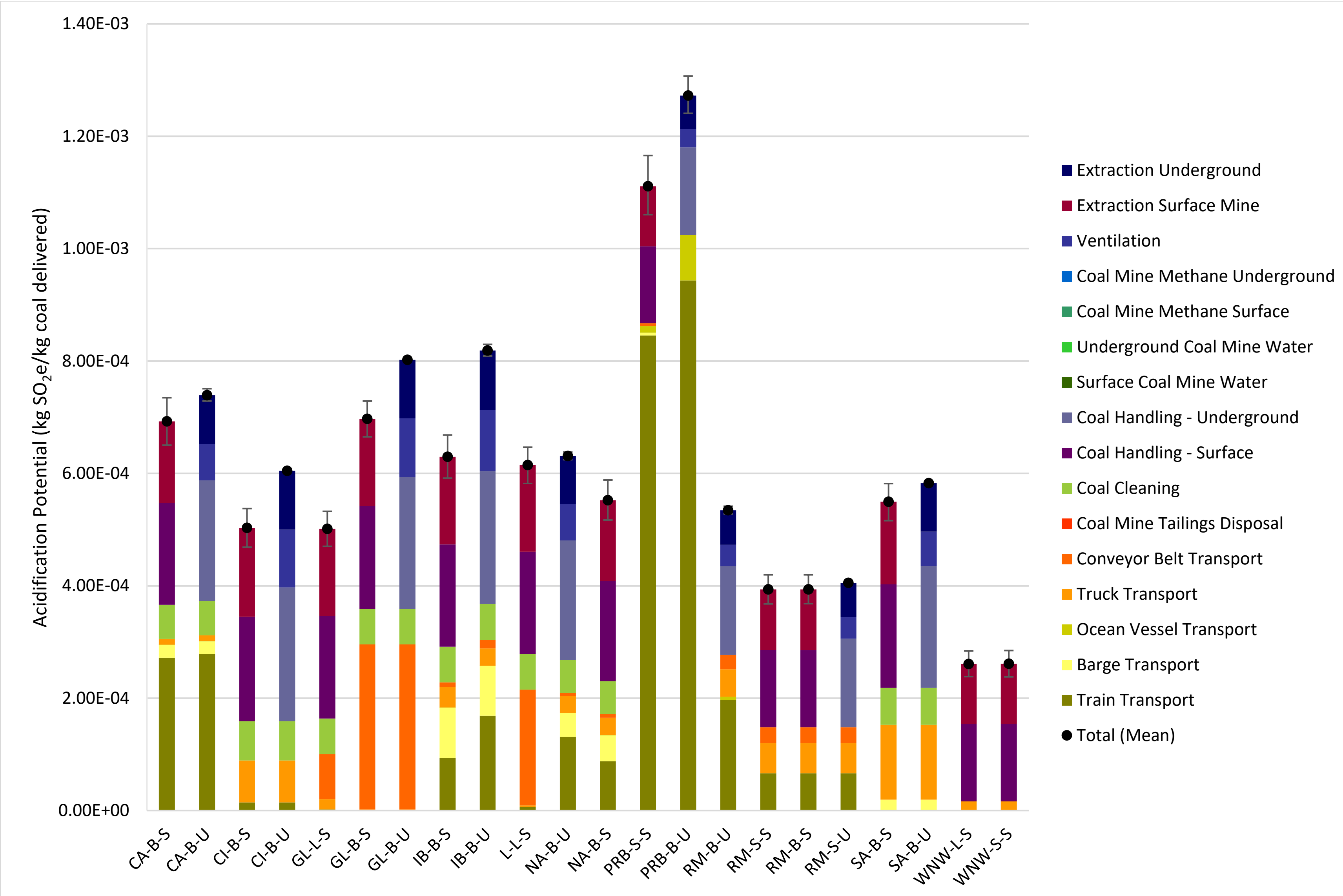


Exhibit 4-4. Acidification potential impacts for all basin-coal type-mine type scenarios



4.3 Basin-Coal Type

The 14 basin-coal type scenarios are useful in illustrating how different coal types from the same basin, and the same coal type from different basins, may result in vastly different life cycle impact results. The heat map in **Exhibit 4-5** shows the percent difference in the impact values for all basin-coal type scenarios relative to the production-weighted U.S. average. A color gradient is applied to each impact category to represent basin-coal type scenarios and values that are furthest from the production-weighted average. Values highlighted in shades of green are lower than the U.S. average, with the darkest green showing the basin-coal type scenario with the lowest environmental impact for a category. Values highlighted in shades of red are higher than the U.S. average, with the darkest red showing the basin-coal type scenario with the highest environmental impact for a category. The results of this heat map may be helpful to see the relative impacts of a specific basin-coal type scenario across categories or the relative impacts of all basin-coal type scenarios for one category.

When looking at individual impact categories, most basin-coal type scenarios have GWP and ozone depletion potential impacts that are higher than the production-weighted U.S. average and impacts in the remaining categories that are lower than the U.S. average. Alternatively, looking at individual basin-coal type scenarios, both PRB-B and PRB-S scenarios have impacts that are significantly higher than the production-weighted average. Notably, the SA-B scenario has a GWP impact that is over four times higher than the average, and both WNW scenarios have the lowest impacts compared to the U.S. average. It is important to reiterate that these percentages are relative to a production-weighted average; this may be reflected in the values for basin-type scenarios that produce large amounts of coal, like PRB-S.

Basin-coal type scenario results were also examined using contribution analysis. This type of analysis is particularly useful when looking at aggregated results. For example, although there is no distinction between underground and surface mines within the scenario, the contributions from different mine types can be identified using contribution analysis. **Exhibit 4-6** shows photochemical smog formation potential impacts for all 14 scenarios. Train transportation is a notable contributor for basin-coal type scenarios with significant train transport distances, such as CA-B, PRB-B, and PRB-S. This is likely due to the emissions of NOx during train transport, which have a high characterization factor for photochemical smog formation potential. Other transportation modes, such as conveyor belt, barge, and truck, have a notable effect on the photochemical smog formation potential impacts. Coal handling, both surface and underground, also make large contributions to the overall impact. While the photochemical smog formation potential impacts come from a variety of sources, **Exhibit 4-7** shows that GWP impacts are largely from underground CMM. This outcome, in addition to large error bars caused by uncertainty in underground CMM, has been consistent throughout all LCIA results in this study regardless of the level of aggregation. Like photochemical smog formation potential, train and conveyor belt transport are notable contributors to GWP impacts. A summary of the TRACI impact assessment results for all basin-coal type scenarios can be seen in **Exhibit C-2**.

Exhibit 4-5. Heat map of percent difference in impact values relative to the production-weighted U.S. average for basin-coal type scenarios

Basin-Type	Acidification Potential (kg SO_2e)	Eutrophication Potential (kg Ne)	Global Warming Potential, AR6 100-yr (kg CO_2e)	Ozone Depletion Potential (kg CFC-11e)	Particulate Matter Formation Potential (kg $PM_{2.5}e$)	Photochemical Smog Formation Potential (kg O_3e)	Water Consumption (NETL) (kg)
CA-B	83%	146%	188%	84%	94%	79%	24%
CI-B	65%	55%	185%	200%	73%	59%	33%
GL-B	92%	76%	327%	394%	57%	93%	108%
GL-L	58%	51%	35%	86%	70%	55%	19%
IB-B	89%	78%	131%	257%	88%	83%	9%
L-L	71%	120%	64%	372%	69%	63%	153%
NA-B	72%	64%	289%	147%	76%	67%	37%
PRB-B	147%	144%	279%	111%	136%	153%	20%
PRB-S	129%	126%	39%	23%	127%	133%	174%
RM-B	55%	53%	125%	123%	46%	58%	12%
RM-S	46%	45%	78%	103%	40%	49%	9%
SA-B	67%	61%	460%	125%	73%	66%	32%
WNW-L	30%	30%	17%	13%	32%	32%	5%
WNW-S	30%	30%	17%	13%	32%	32%	5%

Values higher than the U.S. average (darkest red shows the basin-coal type scenario with the highest environmental impact for a category)

Values lower than the U.S. average (darkest green shows the basin-coal type scenario with the lowest environmental impact for a category)

Exhibit 4-6. Photochemical smog formation potential impacts for all basin-coal type scenarios

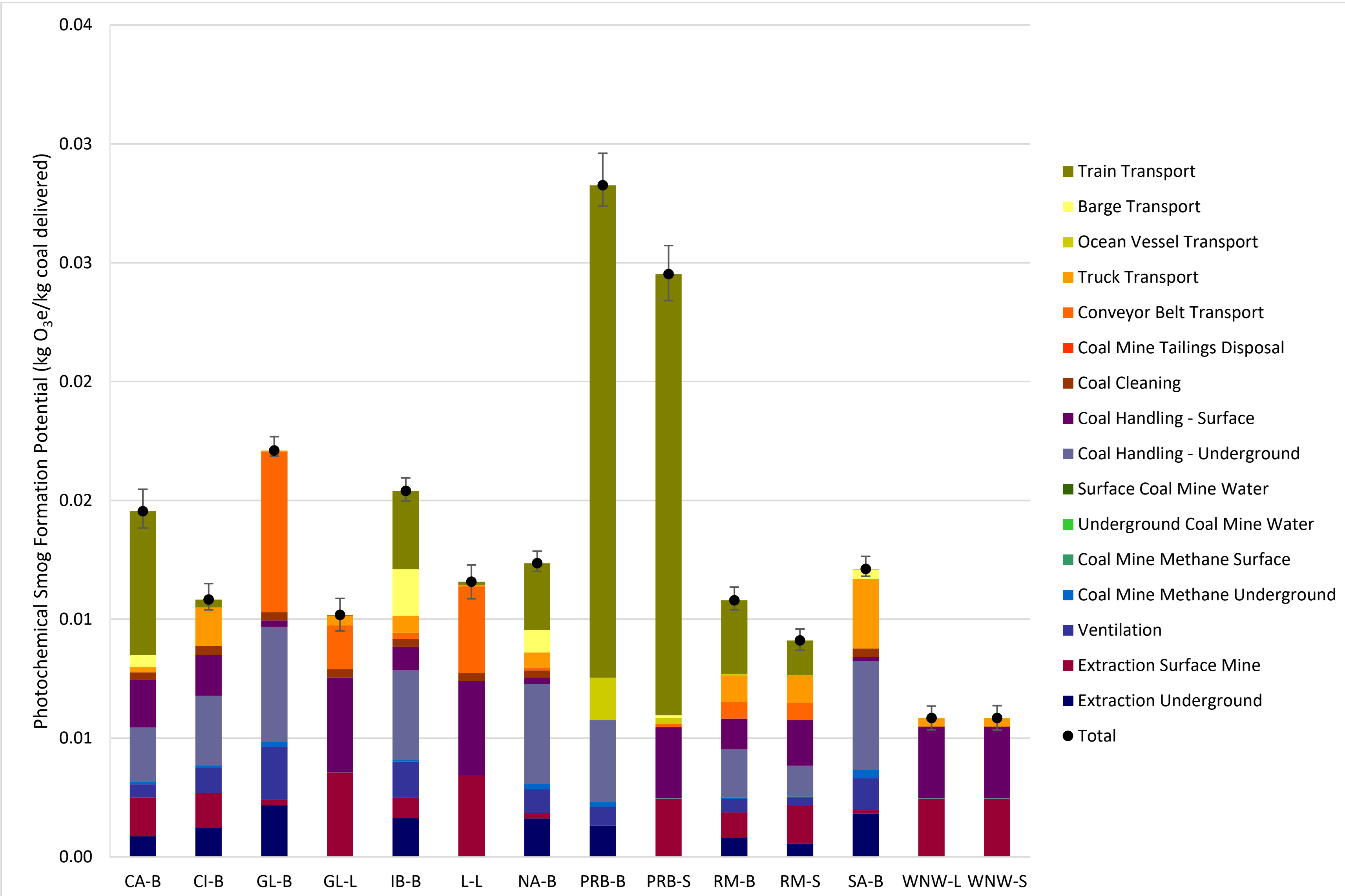
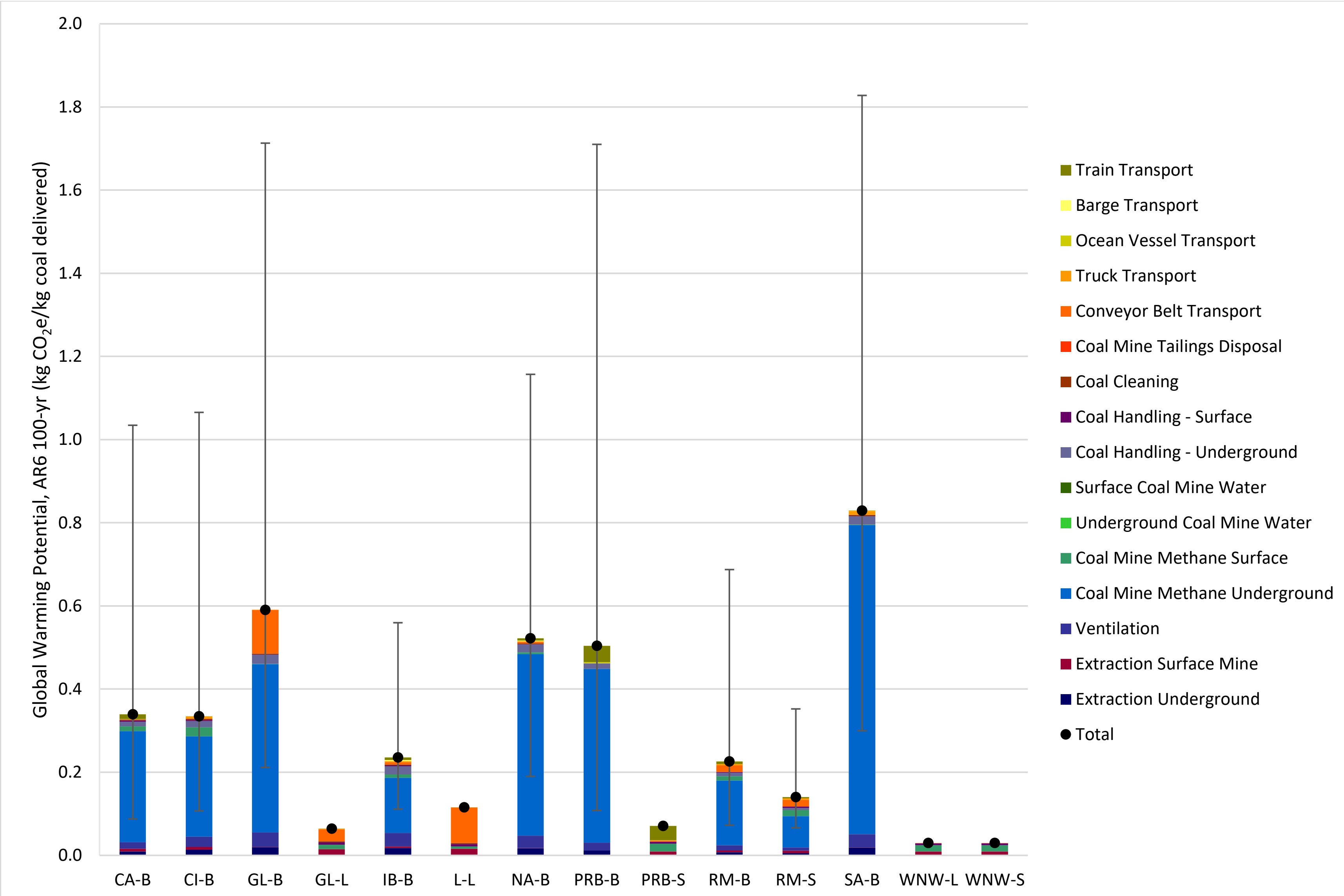


Exhibit 4-7. Global warming potential (AR6, 100-yr) impacts for all basin-coal type scenarios



4.4 NERC Region-Coal Type

Comparing the 18 NERC region-coal type scenarios is useful for power plants to characterize the environmental impacts of a single coal type being delivered to a NERC region. A summary of the TRACI impact assessment results for all NERC region-coal type scenarios can be seen in **Exhibit C-3**. **Exhibit 4-8** highlights, once again, the substantial contribution to GWP impacts from underground CMM. In particular, the scenarios with bituminous coal have much higher GWP impacts than other coal types due to the contribution from underground CMM. This result may seem to indicate that all bituminous coal is extracted from underground mines, resulting in emissions of underground CMM. However, bituminous coal is extracted from surface mines for some NERC region-coal type scenarios, but the mine type has been aggregated and, because the CMM emissions from surface mines are not significant, there is no notable contribution from surface CMM.

A similar finding can be interpreted from **Exhibit 4-9**, which shows water consumption impacts for all NERC region-coal type scenarios. Notably, the scenarios with subbituminous coal have significantly higher water consumption when compared to nearly all other coal types. The exception is the MRO-L scenario, which also has significantly higher water consumption compared to other NERC region-coal type scenarios. This is due to the large contributions from surface mine water use. In general, these aggregated results may not be of much use to those NERC regions that only have one type of coal delivered, like FRCC. However, regions like RFC and SERC that have multiple coal types delivered may use these results to compare the impacts of different coal types. Aggregating based on NERC region may be important for characterizing coal-based power production for a region and identifying opportunities to reduce environmental impacts in the upstream supply chain. This information may be of particular importance for future, cradle-to-grave LCA studies that include power generation, transmission, and distribution. Previous NETL studies may be leveraged to obtain cradle-to-grave LCIA results [5, 30].

Exhibit 4-8. Global warming potential (AR6, 100-yr) impacts for all NERC region-coal type scenarios

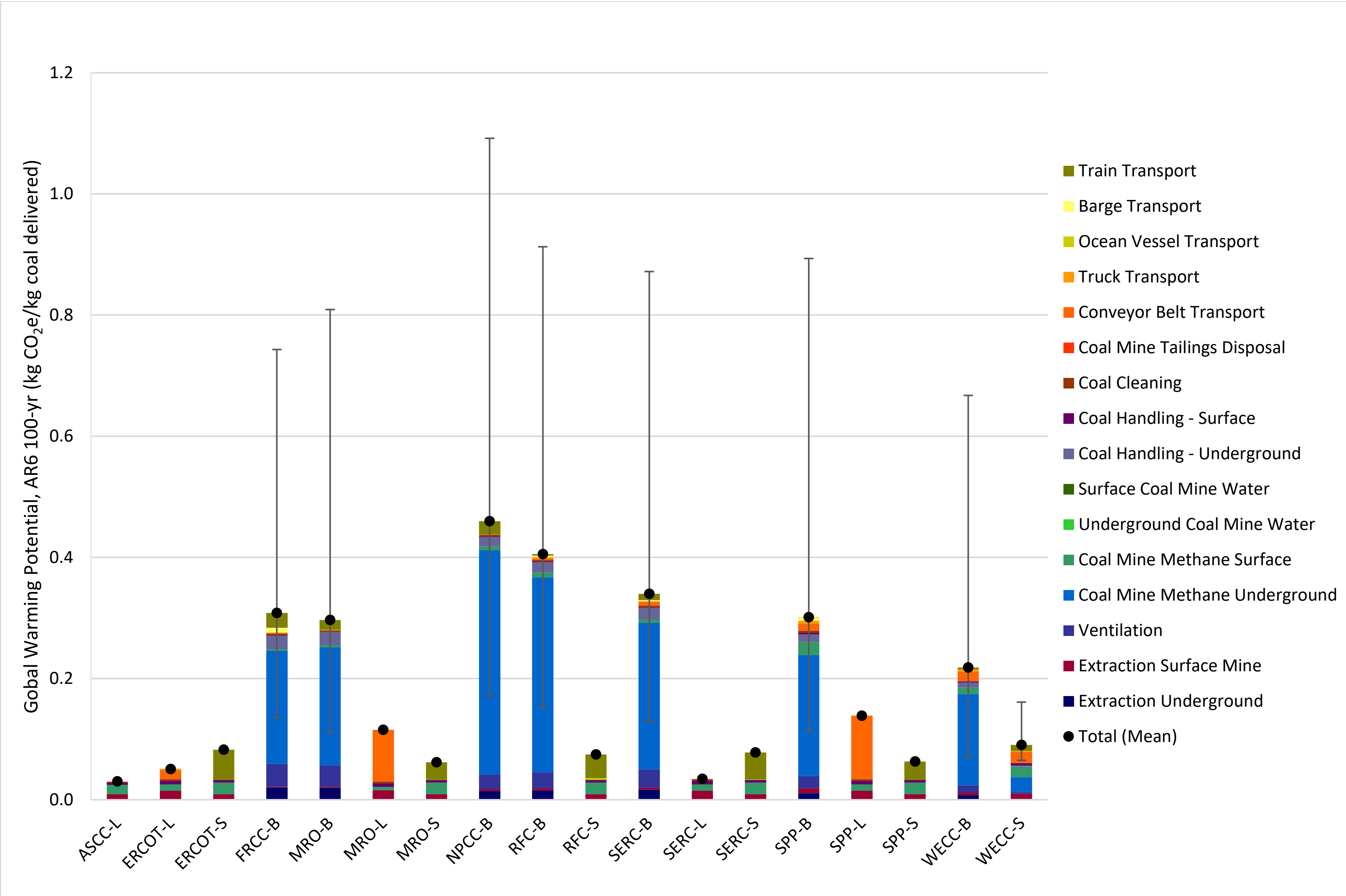
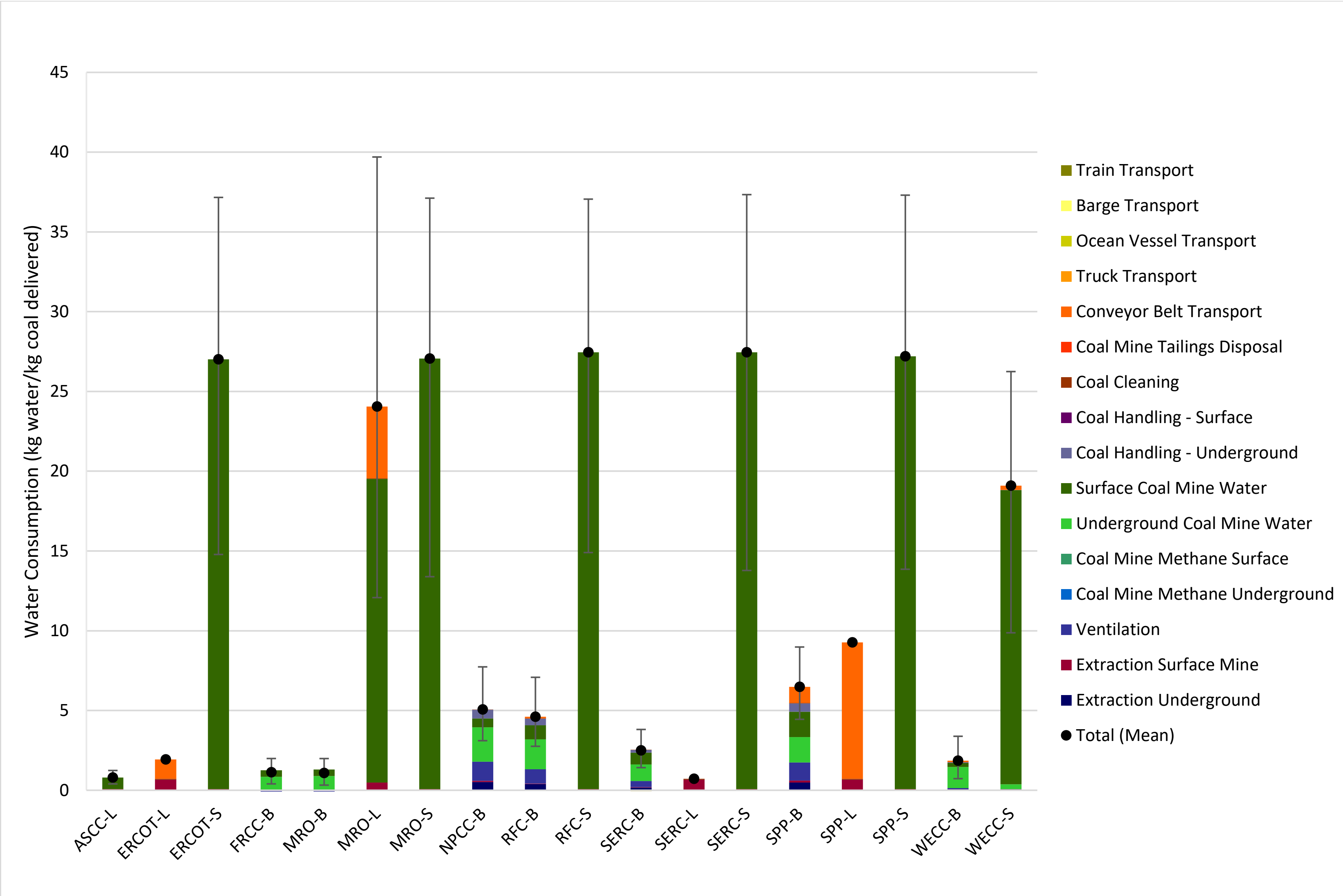


Exhibit 4-9. Water consumption impacts for all NERC region-coal type scenarios



5 CONCLUSIONS

Cradle-to-gate impact assessment results were calculated for 55 unique scenarios using a modified version of EPA's TRACI 2.1 impact assessment method. Each scenario is based on a unique combination of a coal basin, coal type, mine type, and a NERC region to which the coal is delivered. The results presented in this report represent results from individual scenarios and results from aggregation of the 55 scenarios. In addition, LCIs representing the 22 basin-coal type-extraction type scenarios and each transportation mode have been included as supplemental materials to this report and can be used to develop custom scenarios that are suited to a specific power plant. The different levels of aggregation examined in this study were used to highlight the various uses of this LCA and the difference, or similarity, between interpretation of the results depending on the level of aggregation. Altogether, the results of this study can be used at various scales to more accurately represent coal supply chain emissions.

Overall, PRB scenarios had the highest environmental impacts and WNW scenarios had the lowest. These outcomes are due to a combination of drivers. PRB produces nearly half of all coal in the United States; thus, when calculating results using mass-weighted averages, PRB will be a significant contributor. In addition, the transportation distances from PRB to different NERC regions are much higher than for other basins. On the other hand, the WNW produces significantly less coal overall and the transportation distances to NERC regions are orders of magnitude smaller than those for PRB. The results of this LCA also highlight the variability and uncertainty across basins, coal types, mine types, and NERC regions, regardless of the level of aggregation. Underground CMM, which is the most significant driver of GWP impacts, has significant associated uncertainty from basin-to-basin and by coal type. Water consumption practices vary depending on the mine type and coal type. Transportation distances from basin to NERC region are a notable source of variability between scenarios, leading to significant differences in transportation-related impacts in several categories.

Another important consideration regarding variability is the coal characteristics of different coal types and coal from different basins. When interpreting the LCIA results of this study, it is important to consider the coal delivered at the end of each scenario is not functionally equivalent. Different coal types, and the same coal type from different basins, have different qualities. A power plant is designed to operate effectively with a specific type of coal and would, therefore, not be able to select one coal type over another based on the environmental impacts alone. This makes the dynamic operation of a power plant a critical consideration for decisions regarding coal sourcing.

5.1 FUTURE WORK

There are several opportunities to enhance this study in future work, such as performing a cradle-to-grave LCA, and including additional years. This analysis does not include any physical coal properties besides heating value and the boundary of this analysis ends at delivery of coal to a power plant. Due to the variation in heating value, 1 kg of coal delivered from a specific scenario may not necessarily supply the same power as 1 kg of coal delivered from another scenario. For example, CA bituminous coal has a significantly higher heating value than PRB subbituminous coal, therefore 1 kg of CA bituminous coal will generate more power than 1 kg of PRB subbituminous coal and the two provide a different function downstream of delivery to the plant. Thus, true functional equivalence between scenarios was not established in this study. Extending the system boundary to include power generation, transmission, and distribution will result in a change in the functional unit from 1 kg of coal delivered to 1 unit (i.e., MWh) of power distributed. This would ensure functional equivalence when making comparisons between different coal delivery scenarios. In addition, a cradle-to-grave system boundary provides the context to determine whether the impacts evaluated here are significant in the context of the full life cycle. Interpreting the cradle-to-gate results of this study is useful for characterizing coal extraction and transportation, and for identifying opportunities to reduce environmental impacts in the upstream supply chain. However, this study cannot be used to identify whether a significant reduction in acidification potential impacts for a basin-coal type-mine type-NERC region scenario will be significant when considering a cradle-to-grave boundary.

Future work can leverage updated data to provide analysis for additional years. Extending the temporal representativeness of this LCA beyond 2016 would provide a collection of data and impact assessment results across multiple years, and could be used to examine trends and provide a more comprehensive evaluation of coal mining and delivery in the U.S. This broadened temporal scope could be accompanied by less aggregation of results, which would resolve the uncertainty associated with aggregating individual scenarios. Future work may also include updates to background data, such as the transportation related unit processes. While the transportation mixes represent the same year as coal production, the unit processes used to determine transportation impacts may provide more accurate results if they were updated to reflect current technologies. These opportunities for future work will result in a more robust analysis of the environmental impacts of coal mining and delivery in the U.S.

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APPENDIX A: TRANSPORTATION SCENARIOS AND PARAMETERS

Exhibit A-1. Coal transportation scenarios, modes, and distances

Basin	NERC Region	Transportation Mode (miles)					
		Belt	Truck	Barge	Ocean Vessel	Train	*Total*
Central Appalachia	FRCC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.11E+03	*1.11E+03*
	MRO	0.00E+00	0.00E+00	0.00E+00	3.07E+02	5.60E+02	*8.67E+02*
	NPCC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.85E+02	*8.85E+02*
	RFC	0.00E+00	5.75E+00	1.04E+02	2.73E+00	8.25E+01	*1.95E+02*
	SERC	0.00E+00	1.21E+00	7.51E+00	0.00E+00	4.32E+02	*4.41E+02*
Central Interior	SPP	0.00E+00	1.82E+01	0.00E+00	0.00E+00	1.84E+01	*3.66E+01*
Gulf Lignite	ERCOT	6.36E-01	5.69E+00	0.00E+00	0.00E+00	3.57E+00	*9.89E+00*
	SERC	0.00E+00	5.00E-01	0.00E+00	0.00E+00	0.00E+00	*5.00E-01*
	SPP	4.45E+00	5.29E-01	0.00E+00	0.00E+00	0.00E+00	*4.98E+00*
Illinois Basin	FRCC	0.00E+00	7.33E+00	3.65E+02	1.52E+00	6.21E+02	*9.96E+02*
	MRO	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.43E+02	*3.43E+02*
	RFC	0.00E+00	1.02E+01	1.36E+02	1.15E-01	4.80E+01	*1.94E+02*
	SERC	3.84E-01	6.31E+00	9.30E+01	0.00E+00	2.08E+02	*3.07E+02*
	SPP	0.00E+00	1.42E+01	8.78E+02	0.00E+00	2.78E+01	*9.20E+02*
Lignite	MRO	3.25E+00	7.50E-01	0.00E+00	0.00E+00	7.34E+00	*1.13E+01*
Northern Appalachia	FRCC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.39E+03	*1.39E+03*
	MRO	0.00E+00	0.00E+00	0.00E+00	1.65E+02	6.95E+02	*8.60E+02*
	NPCC	0.00E+00	1.83E+00	0.00E+00	0.00E+00	5.53E+02	*5.55E+02*
	RFC	1.67E-01	7.54E+00	7.51E+01	1.69E+00	7.87E+01	*1.63E+02*
	SERC	0.00E+00	6.09E+00	2.25E+01	0.00E+00	5.50E+02	*5.79E+02*
Powder River Basin	ERCOT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.52E+03	*1.52E+03*
	MRO	0.00E+00	0.00E+00	8.90E+00	6.95E-02	8.76E+02	*8.85E+02*
	RFC	0.00E+00	0.00E+00	0.00E+00	2.12E+02	1.18E+03	*1.39E+03*
	SERC	0.00E+00	0.00E+00	2.18E+01	0.00E+00	1.36E+03	*1.38E+03*
	SPP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.27E+02	*9.27E+02*
	WECC	1.28E+00	0.00E+00	0.00E+00	0.00E+00	3.98E+02	*3.99E+02*
Rocky Mountain	FRCC	0.00E+00	0.00E+00	0.00E+00	4.37E+02	1.99E+03	*2.43E+03*
	MRO	0.00E+00	0.00E+00	0.00E+00	3.44E+02	1.30E+03	*1.64E+03*
	RFC	0.00E+00	0.00E+00	1.14E-01	0.00E+00	1.79E+03	*1.79E+03*
	SERC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.03E+03	*2.03E+03*
	WECC	8.73E-01	1.31E+01	0.00E+00	0.00E+00	8.33E+01	*9.73E+01*
Southern Appalachia	SERC	0.00E+00	3.26E+01	2.82E+01	0.00E+00	1.35E+00	*6.21E+01*
West/Northwest	ASCC	0.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	*4.00E+00*
	WECC	0.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	*4.00E+00*
U.S. Average	U.S. Average	3.98E-01	3.78E+00	3.51E+01	4.21E+01	5.77E+02	*6.59E+02*

Appendix B: Scenario Codes and Parameters

Exhibit B-1. Summary of 55 basin-coal type-extraction-NERC region scenarios

Scenario Code	Basin	Coal Type	Mine Type	NERC Region
CA-B-S-FRCC	Central Appalachia	Bituminous	Surface	FRCC
CA-B-U-FRCC	Central Appalachia	Bituminous	Underground	FRCC
CA-B-S-MRO	Central Appalachia	Bituminous	Surface	MRO
CA-B-U-MRO	Central Appalachia	Bituminous	Underground	MRO
CA-B-S-NPCC	Central Appalachia	Bituminous	Surface	NPCC
CA-B-U-NPCC	Central Appalachia	Bituminous	Underground	NPCC
CA-B-S-RFC	Central Appalachia	Bituminous	Surface	RFC
CA-B-U-RFC	Central Appalachia	Bituminous	Underground	RFC
CA-B-S-SERC	Central Appalachia	Bituminous	Surface	SERC
CA-B-U-SERC	Central Appalachia	Bituminous	Underground	SERC
CI-B-S-SPP	Central Interior	Bituminous	Surface	SPP
CI-B-U-SPP	Central Interior	Bituminous	Underground	SPP
GL-B-S-SPP	Gulf Lignite	Bituminous	Surface	SPP
GL-B-U-SPP	Gulf Lignite	Bituminous	Underground	SPP
GL-L-S-ERCOT	Gulf Lignite	Lignite	Surface	ERCOT
GL-L-S-SERC	Gulf Lignite	Lignite	Surface	SERC
GL-L-S-SPP	Gulf Lignite	Lignite	Surface	SPP
IB-B-S-FRCC	Illinois Basin	Bituminous	Surface	FRCC
IB-B-U-FRCC	Illinois Basin	Bituminous	Underground	FRCC
IB-B-S-MRO	Illinois Basin	Bituminous	Surface	MRO
IB-B-U-MRO	Illinois Basin	Bituminous	Underground	MRO
IB-B-S-RFC	Illinois Basin	Bituminous	Surface	RFC
IB-B-U-RFC	Illinois Basin	Bituminous	Underground	RFC
IB-B-S-SERC	Illinois Basin	Bituminous	Surface	SERC
IB-B-U-SERC	Illinois Basin	Bituminous	Underground	SERC
IB-B-S-SPP	Illinois Basin	Bituminous	Surface	SPP
IB-B-U-SPP	Illinois Basin	Bituminous	Underground	SPP
L-L-S-MRO	Lignite	Lignite	Surface	MRO
NA-B-U-FRCC	Northern Appalachia	Bituminous	Underground	FRCC
NA-B-S-MRO	Northern Appalachia	Bituminous	Surface	MRO

Scenario Code	Basin	Coal Type	Mine Type	NERC Region
NA-B-S-NPCC	Northern Appalachia	Bituminous	Surface	NPCC
NA-B-U-NPCC	Northern Appalachia	Bituminous	Underground	NPCC
NA-B-S-RFC	Northern Appalachia	Bituminous	Surface	RFC
NA-B-U-RFC	Northern Appalachia	Bituminous	Underground	RFC
NA-B-S-SERC	Northern Appalachia	Bituminous	Surface	SERC
NA-B-U-SERC	Northern Appalachia	Bituminous	Underground	SERC
PRB-S-S-ERCOT	Powder River Basin	Subbituminous	Surface	ERCOT
PRB-S-S-MRO	Powder River Basin	Subbituminous	Surface	MRO
PRB-B-U-RFC	Powder River Basin	Bituminous	Underground	RFC
PRB-S-S-RFC	Powder River Basin	Subbituminous	Surface	RFC
PRB-S-S-SERC	Powder River Basin	Subbituminous	Surface	SERC
PRB-S-S-SPP	Powder River Basin	Subbituminous	Surface	SPP
PRB-S-S-WECC	Powder River Basin	Subbituminous	Surface	WECC
RM-B-U-FRCC	Rocky Mountain	Bituminous	Underground	FRCC
RM-B-U-MRO	Rocky Mountain	Bituminous	Underground	MRO
RM-B-U-RFC	Rocky Mountain	Bituminous	Underground	RFC
RM-B-U-SERC	Rocky Mountain	Bituminous	Underground	SERC
RM-S-S-WECC	Rocky Mountain	Subbituminous	Surface	WECC
RM-B-S-WECC	Rocky Mountain	Bituminous	Surface	WECC
RM-B-U-WECC	Rocky Mountain	Bituminous	Underground	WECC
RM-S-U-WECC	Rocky Mountain	Subbituminous	Underground	WECC
SA-B-S-SERC	Southern Appalachia	Bituminous	Surface	SERC
SA-B-U-SERC	Southern Appalachia	Bituminous	Underground	SERC
WNW-L-S-ASCC	West/Northwest	Lignite	Surface	ASCC
WNW-S-S-WECC	West/Northwest	Subbituminous	Surface	WECC

APPENDIX C: TRACI IMPACT ASSESSMENT RESULTS

Exhibit C-1. Summary of TRACI impact assessment results for basin-coal type-mine type scenarios

Scenario Code	Acidification Potential (kg SO_2e)	Eutrophication Potential (kg Ne)	Global Warming Potential, AR6 100-yr (kg CO_2e)	Ozone Depletion Potential (kg CFC-11e)	Particulate Matter Formation Potential (kg $PM_{2.5}e$)	Photochemical Smog Formation Potential (kg O_3e)	Water Consumption (NETL) (kg)
CA-B-S	6.93E-04	1.13E-04	5.87E-02	1.96E-10	1.73E-03	1.42E-02	2.68E+00
CA-B-U	7.39E-04	4.09E-05	6.27E-01	1.56E-09	1.54E-03	1.48E-02	4.95E+00
CI-B-S	5.03E-04	2.76E-05	8.29E-02	4.06E-10	1.39E-03	9.94E-03	1.66E+00
CI-B-U	6.05E-04	3.06E-05	5.17E-01	3.27E-09	1.18E-03	1.15E-02	7.70E+00
GL-L-S	5.01E-04	2.69E-05	6.39E-02	8.82E-10	1.20E-03	1.02E-02	3.04E+00
GL-B-S	6.97E-04	3.63E-05	1.39E-01	2.69E-09	1.19E-03	1.47E-02	9.26E+00
GL-B-U	8.02E-04	4.05E-05	6.23E-01	4.16E-09	9.74E-04	1.73E-02	1.75E+01
IB-B-S	6.30E-04	3.53E-05	7.05E-02	5.12E-10	1.58E-03	1.28E-02	5.12E+00
IB-B-U	8.19E-04	4.36E-05	2.90E-01	3.36E-09	1.51E-03	1.63E-02	1.76E-01
L-L-S	6.15E-04	6.37E-05	1.15E-01	3.83E-09	1.19E-03	1.16E-02	2.41E+01
NA-B-U	6.31E-04	3.44E-05	5.55E-01	1.61E-09	1.30E-03	1.25E-02	6.03E+00
NA-B-S	5.52E-04	3.11E-05	8.90E-02	2.73E-10	1.43E-03	1.12E-02	3.49E+00
PRB-S-S	1.11E-03	6.69E-05	7.11E-02	2.34E-10	2.20E-03	2.45E-02	2.73E+01
PRB-B-U	1.27E-03	7.61E-05	5.04E-01	1.14E-09	2.35E-03	2.83E-02	3.12E+00
RM-B-U	5.34E-04	3.18E-05	3.50E-01	1.73E-09	8.43E-04	1.22E-02	2.82E+00
RM-S-S	3.94E-04	2.36E-05	6.05E-02	6.47E-10	7.51E-04	8.89E-03	7.11E-01
RM-B-S	3.93E-04	2.36E-05	6.05E-02	6.47E-10	7.50E-04	8.88E-03	6.98E-01
RM-S-U	4.05E-04	2.40E-05	2.78E-01	1.77E-09	5.86E-04	9.49E-03	2.83E+00
SA-B-S	5.50E-04	3.09E-05	6.23E-02	1.68E-10	1.48E-03	1.11E-02	1.69E+00
SA-B-U	5.83E-04	3.26E-05	8.61E-01	1.34E-09	1.26E-03	1.22E-02	5.23E+00
WNW-L-S	2.61E-04	1.57E-05	3.01E-02	1.34E-10	5.49E-04	5.84E-03	7.94E-01
WNW-S-S	2.61E-04	1.57E-05	3.01E-02	1.34E-10	5.49E-04	5.85E-03	7.91E-01

Exhibit C-2. Summary of TRACI impact assessment results for basin-coal type scenarios

Scenario Code	Acidification Potential (kg SO_2e)	Eutrophication Potential (kg Ne)	Global Warming Potential, AR6 100-yr (kg CO_2e)	Ozone Depletion Potential (kg CFC-11e)	Particulate Matter Formation Potential (kg $PM_{2.5}e$)	Photochemical Smog Formation Potential (kg O_3e)	Water Consumption (NETL) (kg)
CA-B	7.16E-04	7.74E-05	3.39E-01	8.68E-10	1.64E-03	1.45E-02	3.80E+00
CI-B	5.62E-04	2.93E-05	3.35E-01	2.07E-09	1.27E-03	1.08E-02	5.16E+00
GL-B	7.95E-04	4.03E-05	5.90E-01	4.06E-09	9.88E-04	1.71E-02	1.70E+01
GL-L	5.01E-04	2.69E-05	6.39E-02	8.82E-10	1.20E-03	1.02E-02	3.04E+00
IB-B	7.72E-04	4.15E-05	2.36E-01	2.65E-09	1.53E-03	1.54E-02	1.40E+00
L-L	6.15E-04	6.37E-05	1.15E-01	3.83E-09	1.19E-03	1.16E-02	2.41E+01
NA-B	6.25E-04	3.41E-05	5.22E-01	1.52E-09	1.31E-03	1.24E-02	5.85E+00
PRB-B	1.27E-03	7.61E-05	5.04E-01	1.14E-09	2.35E-03	2.83E-02	3.12E+00
PRB-S	1.11E-03	6.69E-05	7.11E-02	2.34E-10	2.20E-03	2.45E-02	2.73E+01
RM-B	4.74E-04	2.83E-05	2.26E-01	1.26E-09	8.03E-04	1.08E-02	1.90E+00
RM-S	3.98E-04	2.38E-05	1.40E-01	1.06E-09	6.91E-04	9.11E-03	1.49E+00
SA-B	5.81E-04	3.26E-05	8.29E-01	1.29E-09	1.27E-03	1.21E-02	5.09E+00
WNW-L	2.61E-04	1.57E-05	3.01E-02	1.34E-10	5.49E-04	5.84E-03	7.94E-01
WNW-S	2.61E-04	1.57E-05	3.01E-02	1.34E-10	5.49E-04	5.85E-03	7.91E-01

Exhibit C-3. Summary of TRACI impact assessment results for NERC region-coal type scenarios

Scenario Code	Acidification Potential (kg SO_2e)	Eutrophication Potential (kg Ne)	Global Warming Potential, AR6 100-yr (kg CO_2e)	Ozone Depletion Potential (kg CFC-11e)	Particulate Matter Formation Potential (kg $PM_{2.5}e$)	Photochemical Smog Formation Potential (kg O_3e)	Water Consumption (NETL) (kg)
ASCC-L	2.61E-04	1.57E-05	3.01E-02	1.34E-10	5.49E-04	5.84E-03	7.94E-01
ERCOT-L	4.69E-04	2.54E-05	5.08E-02	5.63E-10	1.21E-03	9.44E-03	1.93E+00
ERCOT-S	1.46E-03	8.78E-05	8.28E-02	1.45E-10	2.89E-03	3.21E-02	2.70E+01
FRCC-B	1.32E-03	7.54E-05	3.08E-01	2.69E-09	2.56E-03	2.76E-02	1.13E+00
MRO-B	8.84E-04	4.89E-05	2.97E-01	2.58E-09	1.70E-03	1.81E-02	1.08E+00
MRO-L	6.15E-04	6.37E-05	1.15E-01	3.83E-09	1.19E-03	1.16E-02	2.41E+01
MRO-S	9.50E-04	5.72E-05	6.18E-02	1.40E-10	1.90E-03	2.10E-02	2.71E+01
NPCC-B	9.45E-04	6.95E-05	4.60E-01	1.23E-09	2.00E-03	1.95E-02	5.06E+00
RFC-B	5.95E-04	3.49E-05	4.05E-01	1.61E-09	1.27E-03	1.17E-02	4.61E+00
RFC-S	1.27E-03	7.64E-05	7.45E-02	1.43E-10	2.51E-03	2.80E-02	2.75E+01
SERC-B	7.92E-04	5.24E-05	3.40E-01	2.25E-09	1.60E-03	1.59E-02	2.50E+00
SERC-L	4.03E-04	2.19E-05	3.43E-02	2.08E-10	1.16E-03	7.95E-03	7.13E-01
SERC-S	1.34E-03	8.10E-05	7.81E-02	1.44E-10	2.67E-03	2.96E-02	2.74E+01
SPP-B	7.19E-04	3.89E-05	3.01E-01	1.90E-09	1.53E-03	1.45E-02	6.48E+00
SPP-L	6.97E-04	3.63E-05	1.39E-01	2.69E-09	1.19E-03	1.47E-02	9.26E+00
SPP-S	9.84E-04	5.93E-05	6.33E-02	1.40E-10	1.96E-03	2.17E-02	2.72E+01
WECC-B	4.00E-04	2.38E-05	2.18E-01	1.26E-09	6.61E-04	9.17E-03	1.86E+00
WECC-S	5.31E-04	3.16E-05	9.03E-02	8.73E-10	9.90E-04	1.19E-02	1.91E+01

APPENDIX D: LIFE CYCLE INVENTORIES

In addition to the Excel and openLCA Coal Baseline Models, life cycle inventories (LCIs) for the 22 basin-coal type-mine type scenarios and each transportation mode have been included as supplemental materials to this report. The openLCA version of the model was used to generate an inventory for each scenario and mode of transportation with reference flows of 1 kg of processed coal and 1 kg*km transport, respectively. The transportation modes and distances provided in the LCI file can be used to replicate scenarios evaluated in this study, or the user can create a custom transportation profile. The selected modes and distances are used to normalize the provided inventory, with a reference flow of 1 kg*km transport, to 1 kg of coal transported. Together, the coal and transportation inventories can be used to develop custom scenarios that are suited to a specific user or power plant.

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