Decarbonization Potential in Sectors: Facility and Fuel Impacts (2010-2023)

https://github.com/Marina777D/Du_Whitehead_ENV872_EDE_Finalproject

Daniel Whitehead and Yufan Du

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Rationale and Research Questions

With current global temperature rise accelerating towards dangerously high levels, there is a significant threat to meeting the targets established by the Paris Climate Accords. A main target for this agreement was to limit global temperature to a 2.0° increase. According to the International Energy Agency, the United States and China together accounted for 45% of global fuel combustion emissions. (IEA). With the US being such a large contributor to climate change, a major goal of climate scientists is to find ways to reduce US GHG emissions. For this analysis, we chose to look at EPA-provided emission data from 2010-2023. The main purpose of this analysis is to gain insight on which industries demonstrate the greatest potential for significant emissions reductions, and to better understand what role do facility and fuel characteristics play in driving this change over the past decade?

Industry sector data, greenhouse gas emission data, rated heat capacity data, and geospatial data will all be used to identify relationships and areas for improvement in the US. Additionally, most of our research questions are based on the most recent data, from 2023; however, time series analysis takes into account the full range of our data. Our central research questions set to examine how certain industry sectors should be limited in their production to limit the levels of greenhouse gas (especially carbon dioxide) emissions.

Dataset Information

The dataset utilized in this analysis is sourced from the Greenhouse Gas Reporting Program (GHGRP), a program administered by the Environmental Protection Agency (EPA) under congressional mandate. The GHGRP is the only comprehensive dataset that provides facility-level greenhouse gas (GHG) emissions data from major industrial sources across the United States. With over a decade of reporting (2010–2023) for most sectors, it offers critical insights into industrial emissions, including variations across industries, geographic regions, and time, down to the sector and facility levels. The dataset includes detailed variables necessary for analyzing emissions trends and decarbonization progress across sectors. Key data points include: Facility Information: Facility type, location, and rated heat capacity. Emissions Data: Greenhouse gas type (e.g., CO , CH , N O), emission quantities, and fuel type. Sector-Specific Details: Sector and subcategories (e.g., electricity generation, cement production). The dataset also provides temporal data that enables longitudinal analysis, revealing trends in emissions reductions and variability across geographic regions and industry types. The table below summarizes the structure of the dataset, including key variables, units, and their ranges or central tendencies:

Table 1: Table 1: Summary of Dataset Structure

Variable	Description	Unit
Facility Type	Type of facility (e.g., power plant, refinery)	Categorical
Location	Facility location (state and region)	Categorical
Rated Heat Capacity	Facility's energy production capacity	Million BTUs
GHG Type	Type of greenhouse gas (e.g., CO , CH , N O)	Categorical
Emissions	Total emissions by facility	Metric tons CO e
Fuel Type	Type of fuel used (e.g., coal, natural gas, biomass)	Categorical
Year	Reporting year	Year

Data Cleaning

We used two main datasets, as well as a couple of shapefiles of the US. For the downloaded datasets, the main issue we encountered was that some facilities included multiple industry sector types. This made it difficult to group our data, so we decided to take the most significant sector (the first sector listed for each facility) and base our findings from that. Missing data values were excluded, and year/date format was checked to ensure the time series analysis would run smoothly. For the shapefile, we excluded all areas East of 50°West longitude, as the focus was on the US. After these initial steps were taken, we had confidence in the organization of our data and were ready for analysis.

Downloaded datasets included date/time and mean discharge (cfs) columns. After the date column was properly classified as a date, unnecessary columns were removed from the data frame. Next, the date column was separated out to filter for years 1990-2021 and to filter for hurricane months (June-October). The dataset was then saved into the processed folder for each of the research locations. Missing data values were then filled using a linear interpolation and then daily averages of discharge were created in a new, clean column of daily means. After all fo these steps were taken the data was considered to be wrangled and was then ready for initial visualizations.

Exploratory Analysis

Our analysis focuses on assessing the performance of various sectors in decarbonization efforts, particularly their progress in reducing greenhouse gas (GHG) emissions. To facilitate this analysis, it is essential to first clarify the sector classifications within the dataset. Table 1 provides an overview of the Greenhouse Gas Reporting Program (GHGRP) sector classifications, grouping industrial activities into distinct categories such as Power Plants, Refineries, Chemicals, Fluorinated Chemicals, Waste, Metals, Minerals, Pulp & Paper, and Petroleum & Natural Gas Systems. Each sector is further broken down into specific subcategories, detailing the types of facilities and processes contributing to emissions, such as electricity generation under Power Plants or cement production under Minerals. This classification provides the foundation for understanding emission trends and evaluating decarbonization progress across sectors.

Table 2: Table 2: Classification of sectors under the Greenhouse Gas Reporting Program (GHGRP).

Sector	Subcategories
Power Plants	Electricity Generation
Refineries	Petroleum Refineries
Chemicals	Adipic Acid Production
Chemicals	Ammonia Manufacturing
Chemicals	Hydrogen Production
Chemicals	Nitric Acid Production
Chemicals	Phosphoric Acid Production
Chemicals	Petrochemical Production
Chemicals	Silicon Carbide Production
Chemicals	Titanium Dioxide Production
Chemicals	Other Chemicals Production
Fluorinated Chemicals	Fluorinated Gas Production
Fluorinated Chemicals	HCFC-22 Production/HFC-23 Destruction
Waste	Municipal Landfills
Waste	Industrial Waste Landfills
Waste	Industrial Wastewater Treatment
Waste	Solid Waste Combustion
Metals	Aluminum Production
Metals	Ferroalloy Production
Metals	Iron & Steel Production
Metals	Lead Production
Metals	Zinc Production
Metals	Magnesium Production
Metals	Other Metals Production
Minerals	Cement Production
Minerals	Glass Production
Minerals	Lime Manufacturing
Minerals	Soda Ash Manufacturing
Minerals	Other Minerals Production
Pulp & Paper	Chemical Pulp & Paper
Pulp & Paper	Other Paper Producers
Petroleum & Natural Gas Systems – Direct Emissions	Onshore Production
Petroleum & Natural Gas Systems – Direct Emissions	Offshore Production

Petroleum & Natural Gas Systems – Direct Emissions	Gathering and Boosting
Petroleum & Natural Gas Systems – Direct Emissions	Natural Gas Processing
Petroleum & Natural Gas Systems – Direct Emissions	Natural Gas Transmission Compression
Petroleum & Natural Gas Systems – Direct Emissions	Natural Gas Transmission Pipelines
Petroleum & Natural Gas Systems – Direct Emissions	Natural Gas Distribution
Petroleum & Natural Gas Systems – Direct Emissions	Underground Natural Gas Storage
Petroleum & Natural Gas Systems – Direct Emissions	Liquefied Natural Gas Storage
Petroleum & Natural Gas Systems – Direct Emissions	Liquefied Natural Gas Import/Export
Petroleum & Natural Gas Systems – Direct Emissions	Other Petroleum and Natural Gas Systems

The table 3 provides an overview of the distribution of reporting facilities across various industry sectors in the 2023 Greenhouse Gas Reporting Program (GHGRP) dataset. To create this summary, the industry sectors associated with each facility were split into individual categories and grouped for analysis. The number of reporters in each sector was then calculated, highlighting the contribution of different industries to overall emissions reporting. This breakdown offers valuable insights into the sectors with the most active reporting and provides a foundation for further sector-specific analysis of emissions trends and decarbonization progress.

Table 3: Table 3: Summary of Number of Reporters by Industry Sector

Industry Sector	Number of Reports
	8916
Chemicals	462
Coal-based Liquid Fuel Supply	1
Import and Export of Equipment Containing Fluorintaed GHGs	8
Industrial Gas Suppliers	21
Injection of CO2	26
Metals	295
Minerals	385
Natural Gas and Natural Gas Liquids Suppliers	96
Other	1251
Petroleum Product Suppliers	124
Petroleum and Natural Gas Systems	1305
Power Plants	1320
Pulp and Paper	208
Refineries	133
Suppliers of CO2	121
Waste	1453

The bar chart (figure 1) illustrates the distribution of emissions by gas type. The chart highlights the dominant contributions of carbon dioxide (CO), with methane (CH) and nitrous oxide (N O) playing significant roles as well. This visualization emphasizes the need for sector-specific strategies to address each type of GHG.

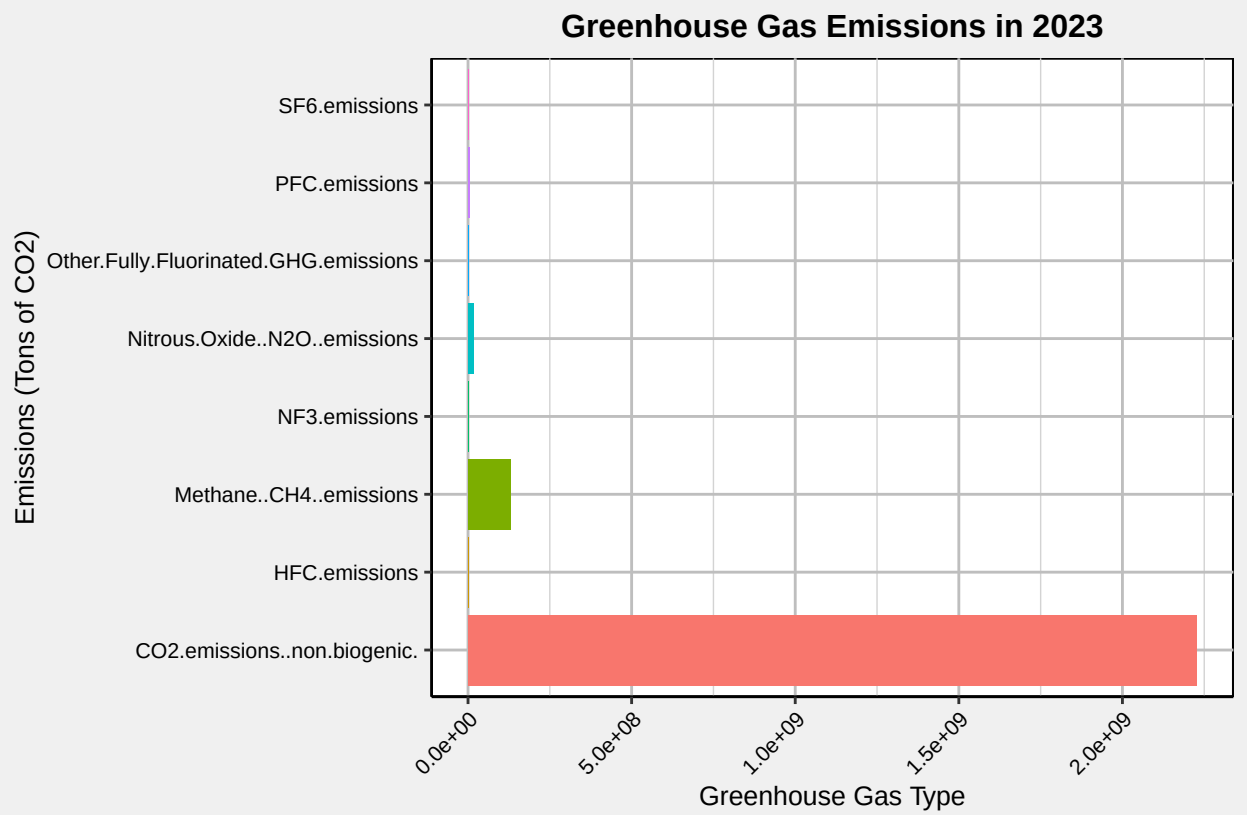

Figure 1: Distribution of greenhouse gas emissions by gas type in 2023

Analysis

Question 1: Which industries demonstrate the greatest change for significant emissions reductions over the past decade?

2023 Average CO2 Emissions by Industry Sector

The "Figure 2: Average 2023 CO2 Emissions by Sector" bar chart displays the values of average carbon dioxide emissions by industry sector. The chart shows the high emission contributions from coal-based liquid fuel suppliers, refineries, and petroleum product suppliers, while comparing the different levels of emission rate down to the sectors of low emission (ex: industrial gas suppliers and distribution of equipment containing fluorinated chemicals). This visualization highlights the necessity of sector-specific strategies to decrease carbon dioxide emissions.

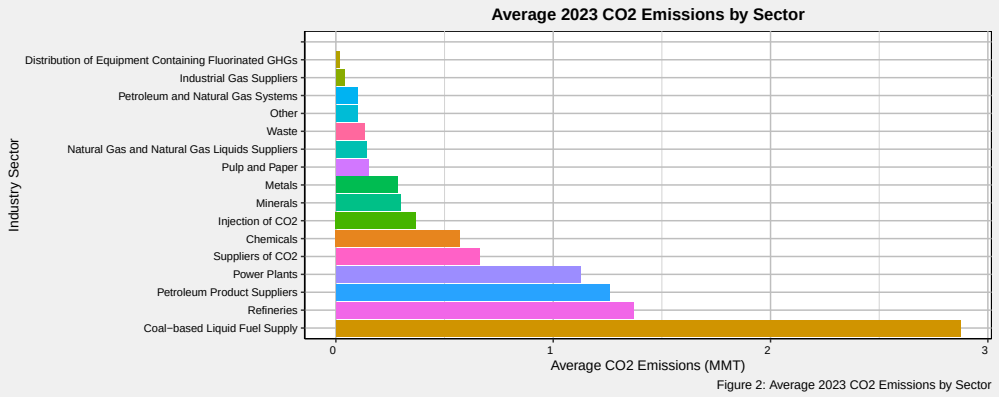

Figure 2: Average 2023 CO2 Emissions by Sector

2010-2023 Average CO2 Emissions by Industry Sector

The emission trend 2010-2023 is shown in figure 3. Most industry stays stable but the refinery goes higher and higher. For sources reporting to the GHGRP, emissions decreased 4.4% from 2022 to 2023. Between 2011 and 2023, GHGRP-reported direct emissions (e.g. excluding suppliers) decreased 22.3%. This decline is primarily caused by the decline in reported emissions from power plants, which decreased 33.8% over the same period.

Question 2: Which U.S. states have the greatest potential for reducing their carbon footprint?

2023 Total CO2 Emissions by Industry Sector and State

The "Figure 4: Total 2023 CO2 Emissions by State and Industry Sector" bar chart visualizes the values of total carbon dioxide emissions by state and industry sector contribution. The chart displays the states with the highest emissions, such as Texas (with over 500 million metric tonnes (MMT)) and Lousiana. State governments should consider their rank in terms of emission contribution, and the states with higher emissions should look to reduce their current levels. This display supports the need for state governments and their industries to find methods of reducing emissions. Additionally, it shows the large contribution of power plants to the total emissions, as power plants make up a large percentage of emission output.

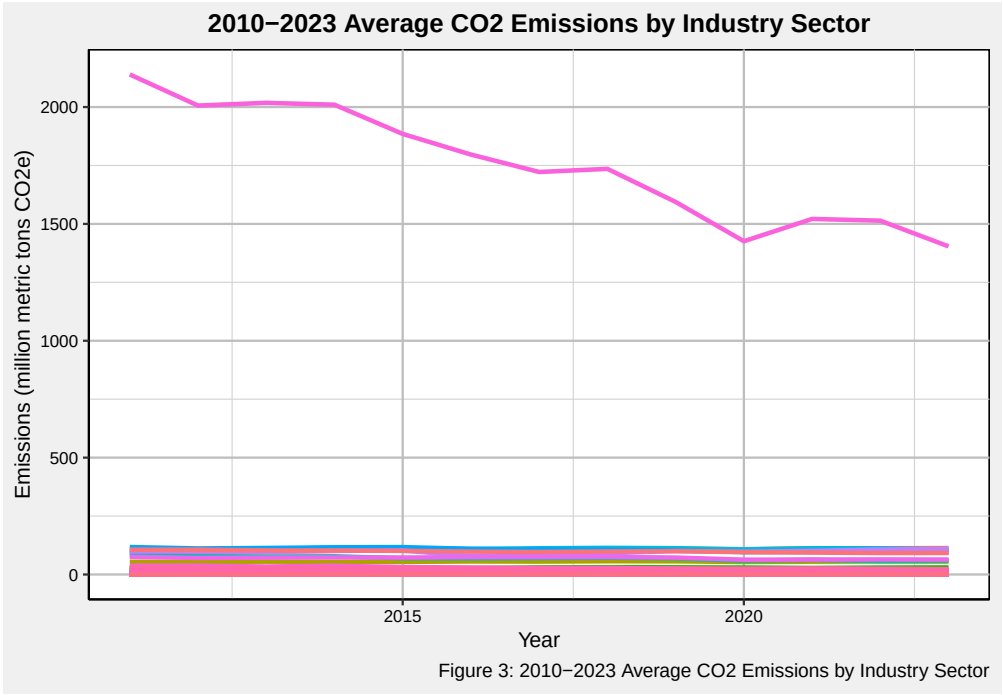

Figure 3: 2010-2023 Average CO2 Emissions by Industry Sector

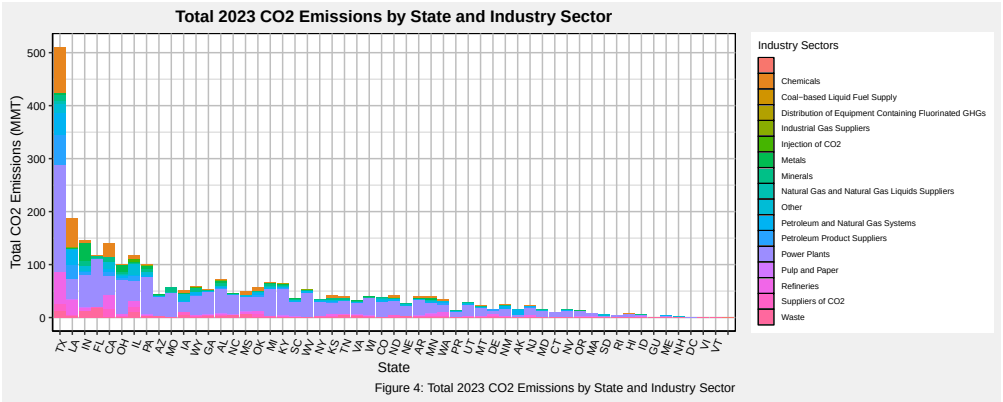

Figure 4: Total 2023 CO2 Emissions by State and Industry Sector

2023 CO2 Emissions by State

The "Figure 5: Map of CO2 emissions from direct emitters across the United States" bar chart visualizes the values of total carbon dioxide emissions (in metric tonnes) by spatial lcoation in the US. The map displays a scale of low to high emissions from individual facilities. Portions of the map that are mostly covered in light blue means that there are many facilities that contribute relatively low to medium carbon dioxide emissions, while areas with large dark circles indicates the presence of facilities with significant emissions. It is also interesting to mention that although Alaska possesses the highest area of land, it has a substantially lower output of emissions than the second largest state, Texas. State governments should consider their spatial emission contribution, and the states with higher emissions should look to reduce their current levels. Additionally, for clarification purposes, non-biogenic refers to the carbon that has not been absorbed by living organisms. Both carbon emission scale are based on the non-biogenic values.

```
## Reading layer `cb_2018_us_nation_20m' from data source
##   `/home/guest/EDE_FinalProject/code/Raw/cb_2018_us_nation_20m.shp'
##   using driver `ESRI Shapefile'
## Simple feature collection with 1 feature and 3 fields
## Geometry type: MULTIPOLYGON
## Dimension:     XY
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## Geodetic CRS:  NAD83
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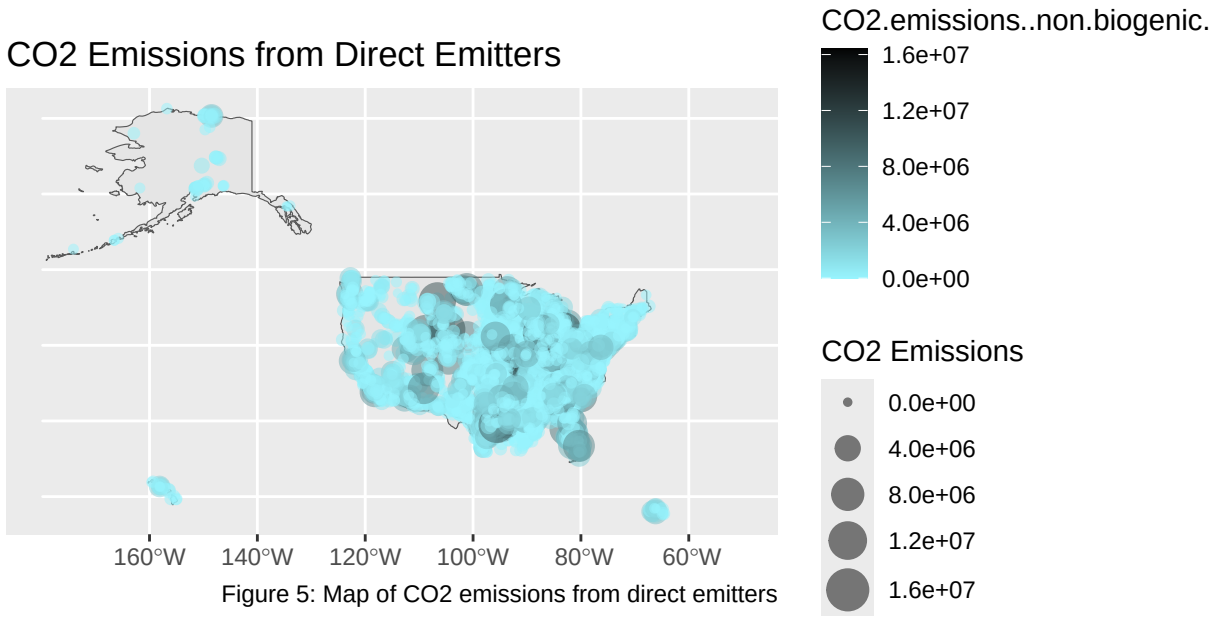

Figure 5: Map of CO2 emissions from direct emitters

Figure 5: Map of CO2 emissions from direct emitters across the United States

2023 Direct Emission Facilities by State

The "Figure 6: Number of Unique Facilities by State (2023)" bar chart visualizes the number of facilities in each state that directly emit carbon dioxide. Texas, Louisiana and California possess the highest numbers of facilities, with Texas having over 700. Vermont is accredited with the lowest number of facilities, and this low facility count is one of the reasons why Vermont also has the lowest carbon dioxide emissions output. The values in this chart could be interesting metrics to analyze when the US or individual states look to decrease their contributions to emission output and climate change.

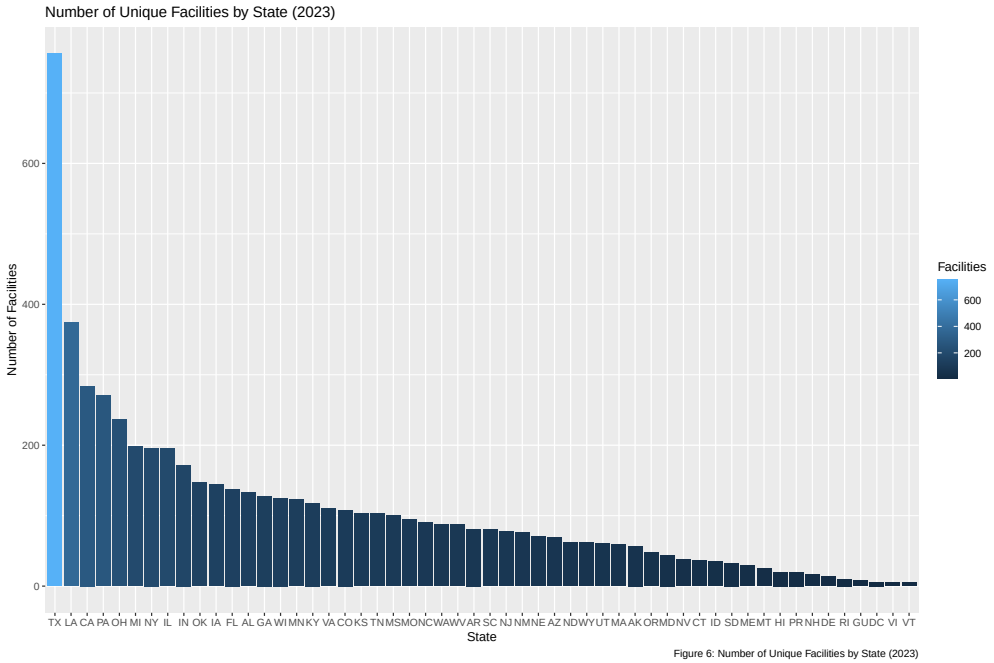

Figure 6: Number of Unique Facilities by State (2023)

Question 3: What role do facility and fuel characteristics play in driving this change over the past decade?

Facility Emission Analysis

The GHGRP provides a robust dataset that can be used to determine the number of facilities at various emissions levels in many industry sectors. Figure 7 shows the emission ranges in 2023. The number on the bar shows the amount of facilities in that range. Most of reporting facilities had emissions less than 250,000 metric tons CO2e. In 2023, the 633 largest-emitting facilities—those emitting more than one million metric tons CO2e—accounted for approximately 1.71 billion metric tons of CO2e. These high-emitting facilities are mainly power plants, but they also include facilities in all other direct emitter sectors.

Fuel Type Emission Analysis

Figure 8 illustrates the emissions of methane (CH4) and nitrous oxide (N2O) across various fuel types, measured in metric tons of CO2 equivalent (mt CO2e). Coal exhibits the highest emissions

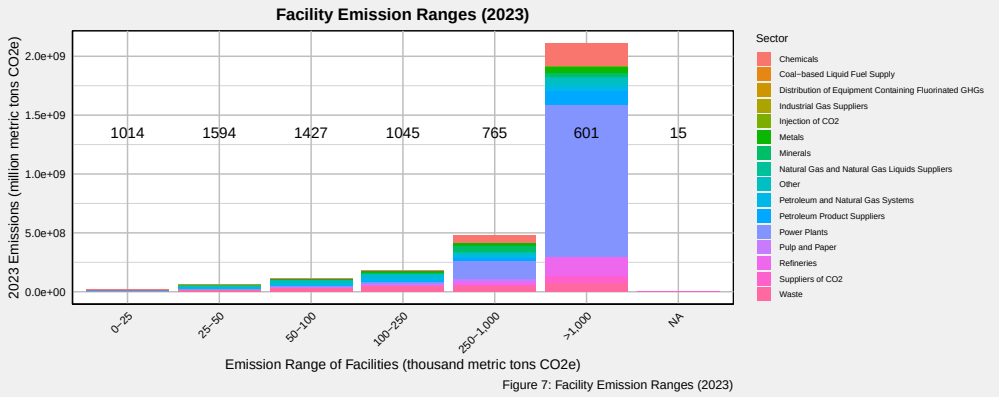

Figure 7: Facility Emission Ranges (2023)

for both CH4 and N2O, with methane emissions being notably dominant. Other fuel types, such as petroleum products and solid byproducts, have significantly lower emissions in comparison, while natural gas shows relatively minimal emissions in both categories.

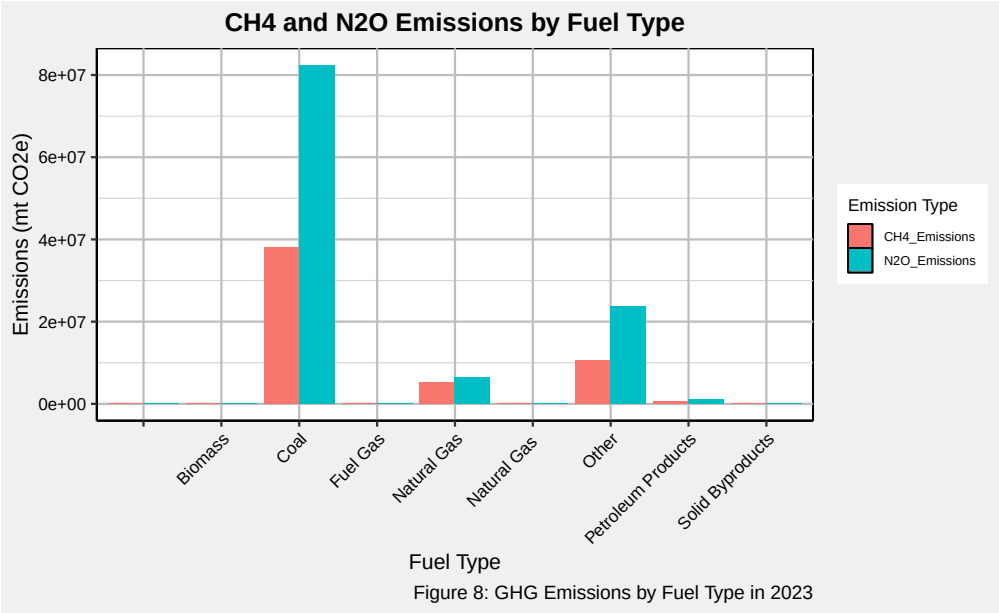

Figure 8: GHG Emissions by Fuel Type in 2023

Question 4: What are the demographic distributions of rated heat capacities across U.S. states and territories?

2023 Average Rated Heat Capacity by State

The "Figure 10: Average Rated Heat Capacity by State (2023)" bar chart visualizes the average rated heat capacity for facilities in each state or territory. Puerto Rico and Hawaii possess the highest average rated heat capacities, while Washington D.C. and Rhode Island have the lowest average capacities. This data is needed to better understand why smaller states with smaller

counts of facilities could have higher carbon dioxide emissions. A key question of this report was to find how rated heat capacity and carbon emissions relate. This chart gives us a better understanding of how facility sizes and outputs compare.

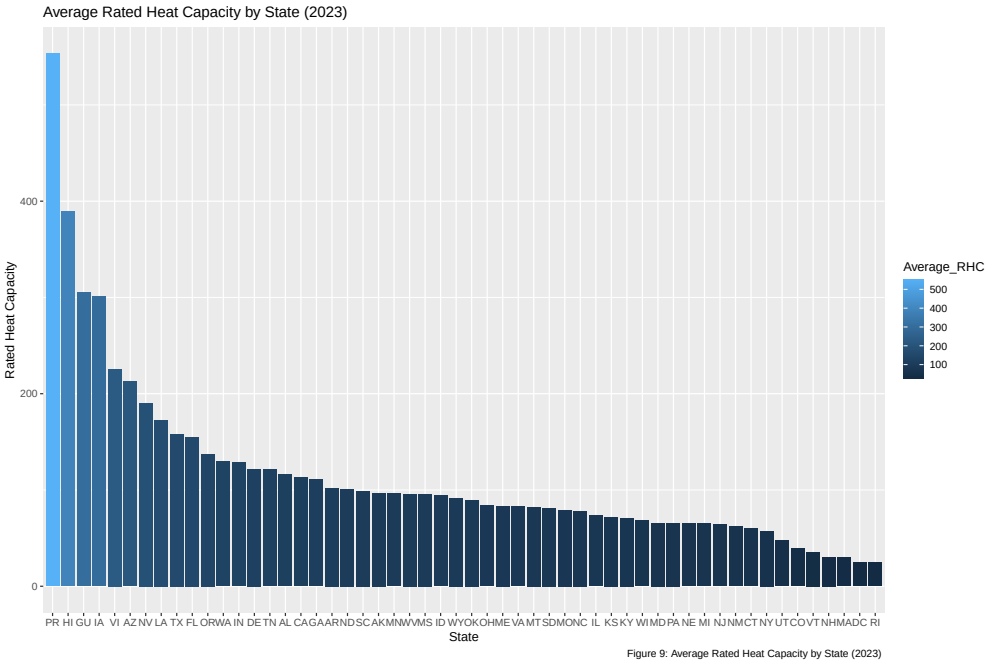

Figure 9: Average Rated Heat Capacity by State (2023)

2023 Total Rated Heat Capacity by State

The "Figure 11:Total Rated Heat Capacity by State (2023)" bar chart visualizes the total rated heat capacity for facilities in each state. Similarly to the facility number chart, Texas and Louisiana possess the highest rated heat capacities. This is also significant in determining how rated heat capacity and carbon dioxide emissions relate, as Texas and Louisiana also have the highest emissions outputs. This data could be used for energy agencies when examining how US states and territories could look to decrease their contributions to emission output and climate change.

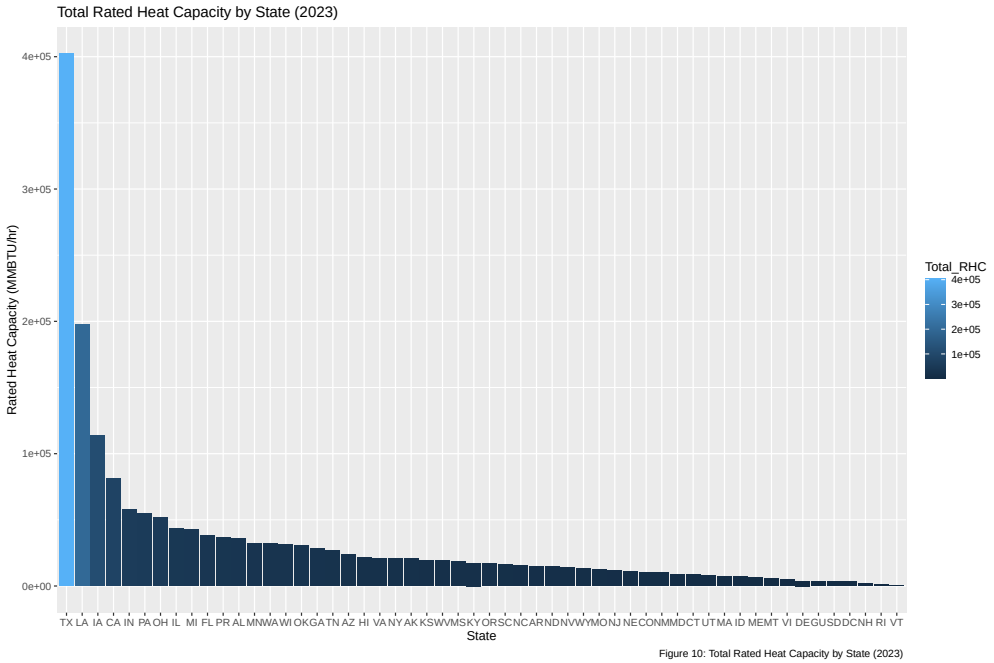

Figure 10: Total Rated Heat Capacity by State (2023)

Summary and Conclusions

Question 1: Which industries demonstrate the greatest change for significant emissions reductions over the past decade?

The analysis of greenhouse gas emissions from 2010 to 2023 reveals significant trends and insights into the sources and drivers of emissions. While most industry sectors maintained stable emissions over this period, the refinery sector experienced a consistent increase. Overall, GHGRP-reported direct emissions decreased by 22.3% between 2011 and 2023, with a notable 4.4% decline from 2022 to 2023. This reduction is largely driven by a 33.8% decline in emissions from power plants, which remain the largest contributors among high-emitting facilities.

Question 2: Which U.S. states have the greatest potential for reducing their carbon footprint?

From examination of US state (and territory) carbon dioxide emissions by sector, it is possible to determine the areas with the greatest opportunity for reduction. The data shows that Texas (with over 500 million metric tonnes (MMT)) has the highest contribution to national carbon emissions. State governments for larger contributors such as Texas, Louisiana, Indiana, and California have the most potential in creating policies to reduce their carbon footprints. Additionally, it shows the large contribution of power plants to the total emissions, as power plants make up a large percentage of emission output in most of the states and territories displayed in the data.

Question 3: What role do facility and fuel characteristics play in driving this change over the past decade?

Facility-level data highlights the disproportionate impact of a small subset of facilities. In 2023, the 633 largest emitters, primarily power plants, accounted for 1.71 billion metric tons of CO2e, underscoring the importance of targeting these high-emitting sources in mitigation strategies.

Fuel type analysis further illustrates coal's significant role in greenhouse gas emissions, particularly for methane (CH4) and nitrous oxide (N2O). These findings emphasize the need for tailored approaches that address both facility and fuel characteristics. Transitioning to cleaner fuels like natural gas and reducing emissions from coal-intensive industries will be critical in driving further reductions in greenhouse gas emissions over the next decade.

Question 4: Does size of a facility play a role in carbon emissions? How are rated heat capacities distributed across U.S. states and territories?

According to data from the EPA, the areas with the highest total rated heat capacities align similarly to those with the highest total emissions and highest number of facilities. Texas, and a distant second, Louisiana both rank highly in terms of rated heat capacity, and this corresponds with their respective facility counts and emissions. However, while one may assume that larger states will have larger facilities, this is not always the case, as data shows that smaller states with smaller counts of facilities can have higher average capacities. This data shows which states have room for reduction in terms of rated heat capacity, as downsizing and transitioning to renewable energy facilities could play a major role in meeting the goals of the Paris Climate Agreement.

Conclusion: In conclusion, this analysis from 2010 to 2023 reveals a 22.3% reduction in overall greenhouse gas emissions, primarily driven by declines in power plant emissions. However, industries like refineries have seen continued emissions growth, highlighting the need for targeted reductions in high-emitting sectors. States like Texas and Louisiana, which contribute significantly to national emissions, offer substantial opportunities for carbon footprint reduction, particularly through policy changes focused on power plants. Facility size and fuel type are key factors in emissions, with the largest emitters concentrated in power plants. Addressing these facilities and shifting to renewable energy could significantly support achieving climate goals like the Paris Agreement. In summary, reducing emissions will require specific strategies at the industry, state, and facility levels, with a focus on high-emitting sectors and cleaner energy sources.

References

[1] "Greenhouse Gas Emissions from Energy Data Explorer – Data Tools." IEA, 2 Aug. 2024, www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer.

[2] "GHGRP 2023 Overview Profile." EPA, October 2024, www.epa.gov/system/files/documents/2024-10/ghgrp-2023-overview-profile.pdf.