# An Economic-based Approach to Tackle Climate Change:

*Emission Trading Systems as an environmental abatement policy in the U.S.*

**Mauricio Saettone Prado**

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**Abstract**

With the effects of climate change becoming increasingly evident and severe, on top of no global cooperation to reduce global warming, environmental policy within nations becomes an essential tool to prevent a major climate disaster. Today, economic development largely relies on fossil-fuel intensive activities that give rise to one of the most significant market failures, a negative externality from which the costs come in the form of the consequences of climate change. Having a range of policies to deal with the negative externality arising from Greenhouse Gas emissions, Emissions Trading Systems (ETS) stands as a highly effective environmental abatement policy to establish a pre-defined limit on emissions.

In this paper, data from the U.S. Energy Information Administration was analyzed using linear and multivariate regression calculations to investigate the relationship between Carbon Dioxide emissions and fossil fuel production (Crude Oil, Coal, and Natural Gas) in the largest fossil fuel producing U.S. states. Linear Regression results revealed a strong positive correlation between total carbon dioxide emissions and total production of crude oil and natural gas in the top ten U.S. states producing each of these fuels. Conversely, a weak negative correlation was found between total carbon dioxide emissions and total production of Coal in the top ten Coal producing U.S. states. This result is likely to be attributed to numerous variables not reflected by the data used (p.11). Multivariate regression results showed there is a definite difference in the response rate between Coal, Oil and Natural Gas, however, did not meet the arbitrary cut-off for statistical significance. Overall, introducing an ETS to the firms in the top ten Crude Oil, Coal, and natural gas producing U.S. states would result in a practical policy to correct the negative externality arising from the use of fossil fuels. In turn, the U.S. will have the opportunity to lead the decarbonization of the global economy as they benefit from increased levels of innovation, the development of low-carbon technologies, and effectively decouple fossil fuel-intensive activities from economic growth.

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## Introduction

As the effects of climate change become increasingly threatening and evident, there is still no sign of global cooperation to slow its rate down. Global greenhouse gas emissions are estimated to be roughly 51 billion tons of carbon dioxide equivalents (co2e) per year (Breakthrough Energy, n.d.), increasing about 40% since 1990. This is reflected in the rate of temperature increase worldwide, which has soared from 0.08 degrees Celsius per decade since 1880 to 0.18 degrees Celsius since 1981 (Sanchez-Lugo, 2020), increasing over two hundred percent.

The greenhouse effect is causing such phenomenon: a natural process that warm's the earth's surface. As solar radiation reaches the earth, some penetrate the atmosphere, whereas some are reflected into space. The energy that penetrates the ozone layer is absorbed by the land and oceans, heating the earth. This heat then radiates from the earth back into space. However, some of the heat is trapped by the greenhouse gases in the atmosphere, keeping planet earth warm to sustain life (Department of Agriculture, Water, and the Environment A.U., n.d.). The Problem arises as human anthropogenic activities such as the burning of fossil fuels and deforestation accelerate. The number of greenhouse gases released into the atmosphere increases, trapping extra heat and causing the earth's temperature to rise. This "enhancement" of the greenhouse effect can be mainly attributed to our dependence on fossil fuels.

Electricity has become an indispensable commodity both for our own lives (lighting, heating, cooling, refrigeration, medical purposes) and the development of the economy, such as the mechanization of industrial processes (increases an industry's efficiency and productive capacity). Over time, the price of electricity has decreased: found to be nearly 200 times more affordable in 2000 than in the year 1900 (Smil, 2017). This has been primarily due to the decrease in fossil fuel prices, as their extraction and conversion into energy became more cost-effective. Over and above, the United States government has also directed their policy towards maintaining fossil fuel prices relatively low since 1789, when protectionist measures were taken to impose a tariff on the sale of British Coal in the U.S. (Johnson, 2011). Similarly, when the corporate income tax was established in 1913, oil and gas producers were authorized to deduct expenses such as drilling costs, representing nearly 42 billion dollars in support of producers (Cone et al., 1980). Historical government data, reports, and documents reveal an annual average of nearly 5 billion dollars of aid in the form of subsidies to oil and gas producers during 1918-2009 (Pfund & Healey, 2011).

As a result, the burning of fossil fuels gives rise to a massive market failure. This is because the atmosphere, as a repository for greenhouse gas emissions, is an open-access resource. Therefore, it is rivalrous and non-excludable (there are no legal constraints on its use). Thus, anyone can emit any amount of greenhouse gases into the atmosphere. The most common outcome for open-access resources is overexploitation. In this case, the overuse of fossil fuels leads to excess emissions. According to the "Tragedy of the commons" theory, this is because, under the scenario where there is no global authority restricting the use of the atmosphere as a repository for greenhouse gases, firms and countries adopt a "use it or lose it" mentality, increasing the level of emissions worldwide to an excessive level (Tietenberg & Lewis, 2012). This is provoked by self-benefit-seeking decisions which ignore the effect of emissions on the global economy.

Additionally, a negative externality arises from the excessive use of fossil fuels. The burning of fossil fuels imposes an external cost on third parties not involved in the economic transaction. In this case, the external costs come in the form of climate change. Given that the whole world bears the by-products of climate change, the cost is incurred worldwide, detracting from global social welfare.

The effect of fossil fuel subsidies on the negative externality is the main factor to consider. These decrease fossil fuel prices and worsen the negative externality as the free-market equilibrium shifts further away from the suitable price level that reflects the additional external costs. Correspondingly, fossil fuels have become more accessible, so increased emissions arise from increased fossil fuel-consuming activities. Hence, the negative externality is magnified.

For instance, the NOAA's National Centers for Environmental Information (NCEI), in their 2020-Billion-dollar disaster report, reported that 22 different weather and climate disasters in the U.S cost the nation nearly $95 billion in damages (NOAA, 2020). Adding 2020's costs to the natural disasters that occurred in the U.S. since 1980, the cumulative cost adds up to more than $1.875 trillion (adjusted for inflation) (NOAA, 2020). The Ecological Threat Register (ETR) also revealed an increase of over 915% in worldwide disasters from 1960 to 2019. Thus, the cost is likely to continue growing exponentially as the frequency and severity of natural disasters increase because of rising temperatures.

Additionally, the cost of climate change varies across geographical regions (IPCC, 2001). Developing countries (LED's) are most likely to be greater affected by the impacts of climate change. This is due to the economic importance of climate-reliant sectors such as agriculture. Abrupt weather changes restricting the water supply or soil erosion would heavily affect the world's poor, from which 70% depend on natural resources (UNDP, 2015). Thereby, climate change causes a host of other problems that arise, such as malnutrition. So, climate change and poverty are inextricably linked. The World Bank estimates more than 130 million people could be pushed into poverty over the next 10-years, undoing a history of hard-won development gains (World Bank, 2021) that would increase economic inequality between and within countries.

As a result of this market failure, economists have referred to the external costs of greenhouse gas emissions as the "social cost of carbon," a measure of economic damage from the consequences borne worldwide expressed as the value (in dollars) of the total harm from emitting one ton of carbon dioxide into the atmosphere. This cost tends to vary widely among different countries. For instance, a survey made by the OECD found that countries including Canada, the US, France, UK, and Germany had an average price of $56 per ton of carbon dioxide in 2014, expected to rise to $115 by 2050 (OECD, 2015). After the Trump-administration set the social cost of carbon at a price varying between $1 and $8, the Biden administration has increased it to about $51 (Jean Chemnick, 2021).

Incorporating the social cost of carbon into the economic system is referred to as "pricing carbon." This can be done indirectly by setting a cap on total emissions or directly by adjusting the free-market price via a tax to reflect the social cost of carbon.

**Emission Trade Systems (ETS):** An ETS is also known as a cap-and-trade mechanism where a cap (limit) is set on emissions or fossil fuel production by the Government. Allowances (emission permits) equal to the number of emissions under the cap are provided to firms through free allocation or an auction. For emitters to comply with the regulation, they must hold a permit equal to their total emissions. The number of emission permits in the economy is limited and is reduced over time to reduce polluting emissions gradually. These are also tradeable among firms covered by the scheme. If a polluting firm violates the law or fails to have an emission permit to cover their total emissions, they are penalized with hefty fines.

**Carbon Tax:** A carbon price is set by defining a tax rate per ton of greenhouse gas emissions emitted. As costs of production rise, the tax's purpose is to provide incentives for producers and consumers to shift to more sustainable consumption and production by adopting new technologies to lower emissions and avoid the tax.

This paper will specifically focus on how an ETS can be incorporated into the U.S. fossil fuel industry to correct the negative externality arising from their use.

## Emission Trading Systems

Because the costs of immediately eliminating all greenhouse gas emissions would exceed the environmental benefits, it is necessary to provide the right policies to sustain the decarbonization of the economy. Abatement policies offer this support as they abate (reduce) pollution and environmental damage by providing incentives to divert society's current uses to reduce the detrimental effects of economic activity.

Therefore, as previously mentioned, an ETS combines a pre-defined limit on emissions with an incentive-based approach to assigning the abatement required to meet the legal limit established among firms.

The ability of an ETS to smoothen the transition to a low-carbon economy is primarily due to the flexibility it provides to firms. Individual firms are given the right to choose how to comply with the ETS regulation. They can reduce their emissions by reducing production, adopting less carbon-intensive technologies, or, most importantly, engaging in allowance trading to reduce their cost of abatement.

**Figure 1.0**

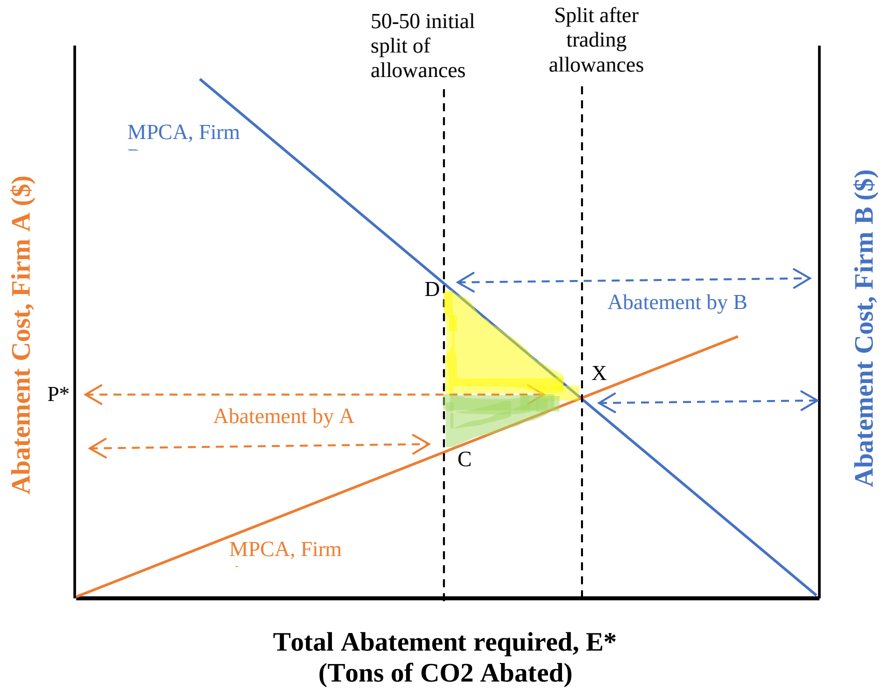



Figure 1 illustrates the process by which trading takes part between firms in an ETS. The marginal private cost abatement (MPCA) for firm A (orange) is measured from the left-hand y-axis. The curve rises as its cost of abatement increases and theoretically uses relatively low-carbon technology to produce. On the other hand, the MPCA for firm B is measured from the right-hand axis and rises to a greater extent as its cost of abatement increases because it uses more carbon-intensive technology to produce.

Initially, permits are issued through a 50-50 split of allowances. At this point, because firm B has a greater MPCA. If it can buy an extra allowance from firm A for a price less than its marginal cost, it will purchase the allowance rather than abate. If the MPCA of B exceeds the MPCA of A, both benefit by A trading allowances to B. Under a competitive market scenario, the trading is expected until the MPCA equalize across firms. This creates the possibility of gains from the trading of allowances shown by the triangle (D-C-X). Point P* is the price per allowance, equal to the marginal cost of abatement in the economy. The yellow area represents the share of gains from trade that Firm B receives, whereas the green area is firm A's share of gains from trade.

On the other hand, if firms decide not to trade, they must either pay a hefty fine, reduce production, or decarbonize their production processes. Such market conditions favor more environmentally friendly production processes, providing an incentive for innovation. This benefit primarily arose from the establishment of the European Union ETS. From 2005 to 2007, incentives provided by the EU ETS were shown to be the main driver for small-scale investments in Germany and increased the low-carbon patenting of regulated firms by almost 10% compared to other firms (Icap et al., 2018).

In contrast to other environmental policies, ETS provides a more straightforward emission reduction path as it sets an absolute limit on emissions; therefore, the emission reduction outcome is pre-defined. On the other hand, a carbon tax pre-defines the price to emit, expecting emissions to reduce as the price to emit rises, relying on the law of demand (Quantity demanded varies inversely with price). Likewise, approaches such as command-and-control, where firms increase their costs by installing anti-pollution equipment, do not establish an absolute limit on emissions because these can rise as production/utilization increases. Therefore, adopting a progressively declining cap in line with national and international climate targets such as the Paris Agreement offers greater certainty regarding emissions levels in the mid and long-term.

Most importantly, the establishment of an ETS encourages low-carbon development, decoupling emissions from economic growth (Icap et al., 2018). As covered in the introduction, economic development has primarily followed a carbon-intensive path from which it is necessary to break apart from to prevent a significant environmental tipping point. ETS's role in this transition has been studied concerning the introduction of The Regional Greenhouse Gas Initiative (RGGI) to California. The carbon intensity of California's economy fell 33% from 2001 to 2018, while at the same time, the state's economy grew 37% (California Air Resources Board, 2017). Similarly, all the states involved in the RGGI reduced emissions from the energy sector by 30% between 2008 and 2015, while the regional economy grew 25% (Icap et al., 2018). Although increases in unemployment may be expected in the short run as fossil fuel-intensive industries weaken, in the long run, innovation and the strengthening of carbon-neutral technologies are likely to attract the lost employment to a greater degree.

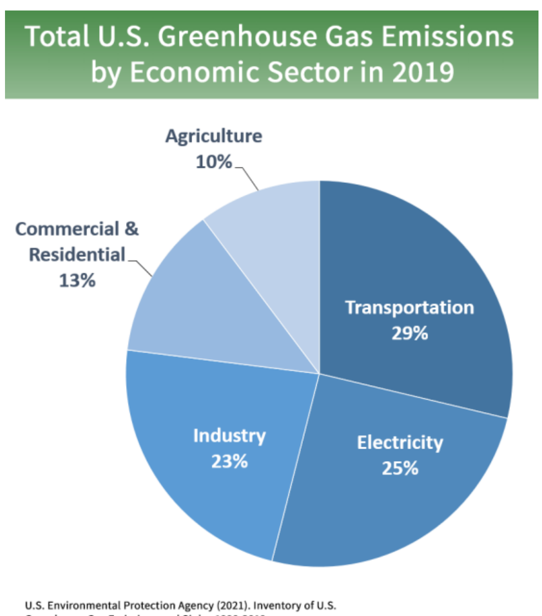
The argument above can be linked to the Porter Hypothesis formulated by economist Michael Porter that claims environmental policy can induce efficiency and encourage innovations that help improve commercial competitiveness. The same argues that there is no trade-off between economic growth and environmental protection, but a win-win situation instead for the benefit of the whole population as dynamic efficiency is achieved (Leeuwen and Mohnen, 2017). Therefore, according to such hypothesis, the cost savings that a well-designed ETS can achieve are sufficient to overcompensate the compliance costs directly attributed to new regulations and the innovation costs.

**U.S. Greenhouse Gas emissions**

The largest source of greenhouse gas emissions in the U.S. comes from burning fossil fuels for energy to supply the demands for electricity, heat, and transportation.

The EPA's *Inventory of US Greenhouse Gas Emissions and Sinks* report for 2020 revealed an estimate for total emissions associated with human anthropogenic activities. Figure 1.1 below illustrates total greenhouse gas emissions by the economic sector.

**Figure 1.1[1]:**




As shown, fossil fuel-intensive sectors include Commercial & Residential, Industry, Electricity, and Transportation, which together account for 90% of total U.S. emissions caused by human economic activity.

[1] (EPA, 2019)

**Transportation**: Greenhouse gas emissions come from burning fossil fuels for cars, trucks, ships, trains, and airplanes. Over 90% of the energy used for transport is petroleum-based, including gasoline and diesel (Metz et al., 2007).

**Industry**: The burning of fossil fuels for energy and specific chemical reactions necessary to produce goods from raw materials are the primordial sources of greenhouse gases arising from industrial processes.

**Electricity:** Approximately 62% of the electricity in the U.S. is generated from burning fossil fuels, mainly coal and natural gas (Energy Information Administration, 2016).

**Commercial and residential:** Emissions from this sector mainly arise from the use of fossil fuels for heat.

## Methodology:

To analyze where an ETS should be introduced on the production of Coal, Crude Oil, and Natural Gas in the U.S., each state's total carbon dioxide emissions will be examined concerning fossil fuel production. This allows the possibility to determine a potential correlation between fossil fuel production and total CO2 emissions, indicating the states where a production cap on each fossil fuel would be most favorable.

It is important to note that most emissions arise from burning the end-product or processed fossil fuel. However, determining the relationship between Coal, Oil, and Natural gas production volumes and total Co2 emissions instead of focusing on fossil fuel combustion sectors like electricity, transport, and industry allow us to account for all the emissions in the fossil fuel supply chain.

In the case of oil, the production of one barrel of oil all along the **Upstream** (flaring, stream flooding, venting**), Midstream** (heating, use of hydrogen, catalyst regeneration, use of electricity, and production of steam), and **Downstream** (processed to jet fuel, petroleum coke, gasoline, diesel) Are estimated to emit between 475 – 715 kg of carbon dioxide equivalents (Feldman & Feldman, 2016). Natural Gas production also accounts for significant emissions. Especially throughout the flaring process, carbon dioxide, carbon monoxide, sulfur dioxide, and nitrogen oxides (all greenhouse gases) are released. Likewise, Coal mining releases methane previously trapped within the coal seam into the air as layers of the coal face are freed. In terms of carbon dioxide equivalents, 1 kg of methane is equal to 25kg of carbon dioxide equivalents and is estimated to have 80 times the warming power of carbon dioxide.

Therefore, an ETS set on fossil fuel production limits emissions all along the supply chain that would not have been targeted by an ETS set on heavy fossil fuel consuming sectors.

The latest data from the U.S. Energy Information Administration will be used to analyze the relationship between the fossil fuel production volumes of the ten largest Crude Oil, Coal, and natural gas-producing states together with their respective total annual carbon dioxide emissions. The mathematical analysis will consist of linear regression and correlation coefficient calculations.

Analyzing the ten largest fossil fuel-producing states is appropriate because they produce and supply a significant fraction of the U.S. fossil fuel market. By targeting these, each state with significant fossil fuel production volumes can be examined to determine where the introduction of an ETS would be more economically convenient.

## Mathematical Analysis

### Linear Regression Analysis

Linear regression is a statistical approach to model the relationship between two variables by fitting a linear equation to observed data. In this case, the dependent variable (explained variable) is the total carbon dioxide emissions per state, and the independent variable (exploratory variable) is total fossil fuel production per state.

We will vary the independent variable (fossil fuel production) between Crude oil, Coal, and natural gas to determine the relationship with total carbon dioxide emissions by U.S. state, and we will use a simple linear regression model for each.

The Least-Squares Regression method will be used to fit a regression line onto the data points. This method works by calculating the best-fitting line for the observed data while minimizing the vertical distance between the data points to the regression line. This means the regression line with the lowest variance (sum of the squares of the errors) represents the line of best fit.

The following formula models simple Linear Regression for the observed data:

$$y = \beta_0 + \beta_1 x + \epsilon$$

Where,

$\boldsymbol{y}$ is the dependent variable (Total Carbon Dioxide emissions by U.S. state).
$\boldsymbol{x}$ is the independent variable (Fossil fuel (Crude Oil, Natural Gas, Coal) production by U.S. state).
$\boldsymbol{\beta_0}, \boldsymbol{\beta_1}$ Are the unknown parameters of the model (constant).
$\boldsymbol{\beta_0}$ Is the y-intercept of the model.
$\boldsymbol{\epsilon}$ is the error term.

Estimated regression line:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x$$

Where,
$\hat{\boldsymbol{y}}$ is the predicted value of $\boldsymbol{y}$
$\hat{\boldsymbol{\beta}}_0$ is a statistic that estimates the parameter $\boldsymbol{\beta_0}$
$\hat{\boldsymbol{\beta}}_1$ is a statistic that estimates the parameter of $\boldsymbol{\beta_1}$

$$\hat{\beta}_1 = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sum(x-\bar{x})^2}$$

$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x}$$

$\bar{\boldsymbol{x}}$ and $\bar{\boldsymbol{y}}$ Are sample means for $\boldsymbol{x}$ and $\boldsymbol{y}$ respectively.

$\hat{\boldsymbol{\beta}}_0$ and $\hat{\boldsymbol{\beta}}_1$ are chosen to minimize the sum of the squared residuals:

$$Residuals = Observed - Predicted$$

$$e_i = y_i - \hat{y}_i$$

Sum of the squared residuals ($SS_{Res}$):

$$SS_{Res} = \sum e_i{}^2 = \sum (y_i - \hat{y}_i)^2$$

$$= \sum (y_i - (\hat{\beta}_0 + \hat{\beta}_1 x))^2$$

Subsequently, a correlation coefficient is a statistical measure that quantifies the strength and direction of a linear relationship between two variables.

Correlation coefficient formula:

$$r = \frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum(x_i-\bar{x})^2 \sum(y_i-\bar{y})^2}}$$

The values for $r$ range between -1 and 1. An $r$ value of -1 shows a perfect negative correlation, whereas a value of 1 shows a perfect positive correlation.

For an $r$ value to be considered statistically significant:
Strong positive correlation: $0.8 \leq r \leq 1$
Strong negative correlation: $-1 \leq r \leq -0.8$

**Data analysis & Discussion (i)**

**Figure 1.2: Table Showing the total carbon emissions[2] and Crude Oil production data for the top 10 Crude Oil-producing U.S. states[3].**

| Rank | State | Total Carbon Dioxide Emissions (million metric tons) | Crude Oil Production (thousand barrels per day) |
|---|---|---|---|
| 1 | TX | 701.9 | 4745 |
| 2 | NM | 45.5 | 1155 |
| 3 | ND | 59.3 | 1027 |
| 4 | AK | 35.2 | 453 |
| 5 | OK | 98.1 | 404 |
| 6 | CO | 89.4 | 368 |
| 7 | CA | 363 | 364 |
| 8 | WY | 63.7 | 224 |
| 9 | LA | 211 | 98 |
| 10 | UT | 60.4 | 91 |

| **Regression line:** | **Correlation coefficient:** |
|---|---|
| $y = 5.37x - 34.8$ | $r = 0.812$ |

The linear regression calculations suggest a positive relationship between the production of crude oil and carbon dioxide emissions by state: States with higher crude oil production volumes tend to have greater levels of carbon dioxide emissions. The correlation coefficient confirms the positive correlation between the variables. The $r$ value is more significant than 0.8; therefore, the relationship can be considered significantly strong.

[2] (US Energy Information Administration, 2018)
[3] (US Energy Information Administration, 2021)

**Figure 1.3: Table Showing the total carbon emission[4] and Coal production data for the top 10 Coal producing U.S. states[5].**

| Rank | State | Total Carbon Dioxide Emissions (mmt) | Coal Production (thousand short tons) |
|---|---|---|---|
| 1 | WY | 63.7 | 276912 |
| 2 | WV | 90 | 93279 |
| 3 | PA | 221.6 | 50053 |
| 4 | IL | 210.4 | 45853 |
| 5 | KY | 120.9 | 36006 |
| 6 | MT | 30.7 | 34468 |
| 7 | IN | 191.2 | 31559 |
| 8 | ND | 59.3 | 26997 |
| 9 | TX | 701.9 | 23307 |
| 10 | NM | 45.5 | 14536 |

| **Regression line:** | **Correlation coefficient:** |
|---|---|
| $y = -92.99x + 79432$ | $r = -0.23$ |

The linear regression calculation for the relationship between crude oil production and total carbon dioxide emissions by state indicates a negative relationship: States with greater coal production tend to have lower levels of carbon dioxide emissions. Similarly, the correlation coefficient of -0.23 confirms the correlation is negative; however, the value is greater than -0.8 and so suggests the correlation is weak and likely insignificant.

These results may be attributed to the use of total carbon dioxide emissions and not solely emissions arising from the production of Coal. Texas, for example, has the largest volume of carbon dioxide emissions in figure 1.3, while having one of the lowest coal production volumes. Thus, when comparing the data, it seems like there is a negative relationship. However, total emissions reflect Texas' role as a number one Crude Oil and Natural Gas producer on top of emissions from key sectors like transportation.

Wyoming is the largest coal-producing state in the U.S.; however, it has relatively low carbon dioxide emissions. This means that although it supplies a large percentage (one-third) of Coal in the U.S., fossil fuel-intensive sectors (transportation, electricity, industrial, commercial, and residential) are not as large as they are in other states. This indicates that Coal produced in Wyoming is not primarily consumed locally but is distributed to other states. The top consumers of Wyoming's Coal are coal-fired power plants in Texas, Missouri, and Illinois (WSGS, 2021).

[4] (US Energy Information Administration, 2018)
[5] (US Energy Information Administration, 2019)

**Figure 1.4: Table Showing the total carbon emission[6] and Natural Gas production data for the top 10 Natural Gas producing U.S. states[7].**

| Rank | State | Total Carbon Dioxide Emissions (mmt) | Natural Gas Marketed Production (million cu ft) |
|---|---|---|---|
| 1 | TX | 701.9 | 9301616 |
| 2 | PA | 221.6 | 6896792 |
| 3 | LA | 211 | 3223642 |
| 4 | OK | 98.1 | 3175008 |
| 5 | OH | 208.8 | 2654186 |
| 6 | WV | 90 | 2155757 |
| 7 | CO | 89.4 | 1988714 |
| 8 | NM | 45.5 | 1787334 |
| 9 | WY | 63.7 | 1460477 |
| 10 | ND | 59.3 | 851750 |

| **Regression line:** | **Correlation coefficient:** |
|---|---|
| $y = 12189.2x + 1168523$ | $r = 0.895$ |

From the linear regression calculation, we can deduce a positive relationship between the production of natural gas and total carbon dioxide emissions by state. That is, states with greater natural gas production tend to have greater levels of carbon dioxide emissions. The $r$ value for the correlation coefficient confirms the positive correlation between the variables since the $r$ value is positive. It also suggests that the relationship is strong as the $r$ value exceeds 0.8.

**Figure 1.5: Table Showing the percentage of fossil fuels produced in the U.S. by the top 10 Crude Oil, Coal, and Natural Gas producing U.S. states[8].**

| | | | | | | | | | | | % of U.S. fossil fuel production |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Crude Oil | TX | NM | ND | AK | OK | CO | CA | WY | LA | UT | 96.0 |
| Coal | WY | WV | PA | IL | KY | MT | IN | ND | TX | NM | 89.7 |
| Natural Gas | TX | PA | LA | OK | OH | WV | CO | NM | WY | ND | 94.4 |

6 (US Energy Information Administration, 2018)
7 (US Energy Information Administration, 2019b)
8 Calculated using data from (US Energy Information Administration, 2019b), (US Energy Information Administration, 2019), (US Energy Information Administration, 2021).

**Multivariate Regression Analysis**

Multivariate linear regression is an extension of simple linear regression. It considers the least-squares method to establish a relationship between multiple independent (predictor) variables and a single dependent (response) variable, explain the variation or predicted value of the dependent variable.

In this case, we will analyze three independent variables: Crude Oil, Coal and Natural Gas production in the 17 US states examined and discussed, along with their relationship with carbon dioxide emissions in each state. This analysis allows us to further discover whether the imposition of an ETS scheme in these states would be favorable as we can determine the strength of the effect that the independent variables (fossil fuel production volumes) have on a dependent variable (carbon dioxide emissions).

The model for multiple regression is the following:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \epsilon$$

Where:

$\boldsymbol{y}$ is the predicted value of the independent variable.
$\boldsymbol{\beta_0}$ is the y-intercept.
$\boldsymbol{\beta_1 X_1}$ is the regression coefficient ($\boldsymbol{\beta_1}$) of the first independent variable ($\boldsymbol{X_1}$)
$\boldsymbol{\beta_2 X_2}$ is the regression coefficient ($\boldsymbol{\beta_2}$) of the second independent variable ($\boldsymbol{X_2}$)
$\boldsymbol{\beta_n X_n}$ is the regression coefficient of the last independent variable
$\boldsymbol{\epsilon}$ is equal to the error term.

The estimated multiple regression equation is the following:

$$\hat{y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n$$

Where:
$\boldsymbol{y}$ is the predicted value of the dependent variable.
$\boldsymbol{\beta_0}$ is the estimated y-intercept.
$\boldsymbol{\beta_1 X_1}$ is the estimated regression coefficient ($\boldsymbol{\beta_1}$) of the first independent variable ($\boldsymbol{X_1}$)
$\boldsymbol{\beta_2 X_2}$ is the estimated regression coefficient ($\boldsymbol{\beta_2}$) of the second independent variable ($\boldsymbol{X_2}$)
$\boldsymbol{\beta_n X_n}$ is the estimated regression coefficient of the last independent variable.
The error term $\boldsymbol{\epsilon}$ is assumed to be zero.

**Hypotheses:**
$H_1$: Crude Oil, Natural Gas and Coal production volumes would positively predict total carbon emissions in the 17 largest fossil fuel-producing US states.
$H_0$: Crude Oil, Natural Gas and Coal production volumes will not predict total carbon emissions in the 17 largest fossil fuel-producing US states.

For this calculation, Figure 1.6 shows our raw data with respective parameters which will be used to carry out the multiple regression analysis.

**Figure 1.6:**

| US STATES | Total Carbon Dioxide Emissions (mmt) ***(Y)*** | Crude Oil Production (thousand barrels per day) ***(X1)*** | Natural Gas Marketed Production (million cu ft) ***(X2)*** | Coal Production (thousand short tons) ***(X3)*** |
|---|---|---|---|---|
| TX | 701.9 | 4745.0 | 9301616.0 | 23307.0 |
| CA | 363.0 | 364.0 | 196823.0 | 0.0 |
| PA | 221.6 | 19.0 | 6896792.0 | 50053.0 |
| LA | 211.0 | 98.0 | 3223642.0 | 1538.0 |
| IL | 210.4 | 21.0 | 2210.0 | 45853.0 |
| OH | 208.8 | 53.0 | 2654186.0 | 7779.0 |
| IN | 191.2 | 4.0 | 5044.0 | 31559.0 |
| KY | 120.9 | 5.0 | 77882.0 | 36006.0 |
| OK | 98.1 | 404.0 | 3175008.0 | 227.0 |
| WV | 90.0 | 54.0 | 2155757.0 | 93279.0 |
| CO | 89.4 | 368.0 | 1988714.0 | 12868.0 |
| WY | 63.7 | 224.0 | 1460477.0 | 276912.0 |
| UT | 60.4 | 91.0 | 271870.0 | 14405.0 |
| ND | 59.3 | 1027.0 | 851750.0 | 26997.0 |
| NM | 45.5 | 1155.0 | 1787334.0 | 14536.0 |
| AK | 35.2 | 453.0 | 329361.0 | 975.0 |
| MT | 30.7 | 52.0 | 43263.0 | 34468.0 |

**Data Analysis & discussion (ii)**

Multiple regression equation to estimate the relationship between Crude Oil ($\boldsymbol{X_1}$), Natural Gas ($\boldsymbol{X_2}$) and Coal ($\boldsymbol{X_3}$) production volumes along with Total carbon dioxide emissions ($\boldsymbol{y}$) in the 17 largest fossil fuel-producing US states:

$$\hat{y} = 92.7564 + 0.0728(X_1) + 2.15291E^{-05}(X_2) - 0.0003(X_3)$$

**Figures 1.7, 1.8, 1.9: Multiple Regression Summary Output**

**Figure 1.7**

| ***Regression Statistics*** | |
|---|---|
| Multiple R | 0.78617251 |
| R Square | 0.618067215 |
| Adjusted R Square | 0.52992888 |
| Standard Error | 113.2762477 |
| Observations | 17 |

**Figure 1.8**

| ANOVA | | | | | |
|---|---|---|---|---|---|
| | *df* | *SS* | *MS* | *F* | *P-value* |
| Regression | 3 | 269941.6074 | 89980.53581 | 7.01246757 | 0.004765921 |
| Residual | 13 | 166809.6079 | 12831.5083 | | |
| Total | 16 | 436751.2153 | | | |

**Figure 1.9**

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
|---|---|---|---|---|
| Intercept | 92.75641378 | 39.50388534 | 2.348032681 | 0.04535548 |
| Crude Oil Production (thousand barrels per day) (**X1**) | 0.072754514 | 0.034088887 | 2.134259001 | 0.052440909 |
| Natural Gas Marketed Production (million cu ft) (**X2**) | 2.15291E-05 | 1.49321E-05 | 1.441804959 | 0.173012134 |
| Coal Production (thousand short tons) (**X3**) | -0.000270717 | 0.000434668 | 0.622812878 | 0.544178817 |

Multivariate regression results show that 0.61 (61%) of the variance in carbon dioxide emissions by state can be accounted for by the three predictors, collectively, $F(3{,}13) = 7.012, p < 0.05$.

Analyzing the unique individual contributions of the predictors, the result shows that Coal production (X3) (*t=0.623, p=0.544*) negatively predicts carbon dioxide emissions. Yet, the contribution was not significant since the p-value exceeded 0.05.

Furthermore, results also reveal that Crude Oil Production (X1) (*t=2.13, p=0.05*) and Natural Gas Market Production (X2) (*t=1.44, p=0.173*) positively predict total carbon dioxide emissions. Nevertheless, the contributions once again are classified as statistically insignificant.

This suggests that the null hypothesis should not be rejected. This means there is a definite difference in the response rate between Coal, Oil and Natural Gas, however; it did not meet the arbitrary cut-off for statistical significance.

However, among the 17 states, most specialize in the production of a specific fossil fuel, and therefore have lower production volumes to produce other sources of energy. This may therefore suggest multicollinearity in the analysis. Multicollinearity is the occurrence of high intercorrelations among two or more independent variables in a multiple regression model. In this case, having states specialize in the production of one fossil fuel may result in a negative linear relationship between production of different types of fossil fuel in each state, leading to multicollinearity. As a result, there may be wider confidence intervals that produce less reliable probabilities in terms of the effect of independent variables in the model.

Separately, Crude oil is a greater predictor of carbon dioxide emissions given it has a higher coefficient (X1= 0.072754514) than Coal and Natural gas. The p-value for carbon dioxide emissions is 0.052 which could be interpreted as close enough to be considered statistically significant.

**Conclusion**

The mixed results obtained from the mathematical analysis offer a great degree of support towards imposing an ETS on the production of Crude Oil, Coal, and Natural Gas which should include all producing firms within the ten largest fossil fuel-producing states. Although the multiple regression results were insignificant, the linear regression results suggest that the biggest fossil fuel-producing states are also the ones emitting the most. The reason behind this relationship may be that power plants are located near fossil fuel-producing locations, which could be logically argued to reduce transportation costs.

This can be done by setting a limit on the total supply of fossil fuels that each extracting/mining plant can produce. The limit (cap) can be set according to the average emissions arising from each unit produced of fossil fuel (e.g., a barrel of oil, 100 cubing feet of natural gas, a ton of Coal). These directly restraints the supply of fossil fuels, so the impact of the ETS spills over to the rest of the supply chain. As a result, fossil fuel producing, and consuming firms will be encouraged to invest in other low-carbon alternative fuels and technologies directed towards reducing their dependence on polluting fuels and avoiding the fine from exceeding the production limit outlined by the ETS. Thus, emission reductions can be achieved to a greater level of efficiency and certainty as the primary source of greenhouse gas emissions is restricted, reducing not only the emissions in extracting and processing the fuels but all along the supply chain. Therefore, the negative externality arising from fossil fuel consumption can be corrected to a greater extent.

Likewise, capping the production of the 17 states supplying most of the Crude Oil, Coal, and Natural Gas in the U.S. would provide incentives that will likely be more effective than those being provided by already established cap-and-trade mechanisms in the energy sector like the RGGI, Western Climate Initiative (WCI) and the Mid-Western Green House Gas Reduction Accord.

This grants the U.S. the opportunity to decouple fossil fuel-intensive activities from economic growth through a smooth transition to a decarbonized economy. Coincidentally the U.S. would have the option to lead the decarbonization of the global economy via the specialization on a low-carbon energy sector and technology. For this reason, the U.S. would likely experience greater opportunities for growth as countries worldwide attempt to abate their environment-degrading economic activity to comply with international and national climate targets.

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