A Closer Look at Environmental Economics: The Correlation Between Energy Consumption and CO2 Emissions and Their Trend Patterns

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March 28, 2023

Abstract

What effect do changes in energy consumption have on CO_2 emissions, and what does this mean on a global stage? This study investigates the causal relationship between total energy consumption and CO_2 emissions and their trend patterns using a time-series panel data model. By uncovering these intervariable relationships this study reveals an extensive positive relationship between them and a positive correspondence in their trend patterns, as communicated in the relevant literature by Liu et al. (2018) and Alharthi et al. (2021). We follow up by suggesting policies directed towards reducing CO_2 emissions through energy consumption, highlighting the impacts of CO_2 emissions globally. Finally, we address all limitations to the model posed by threats to external and internal validity.

1. Introduction

CO_2 emissions as a cause of global warming and energy consumption are not novel concepts and have been hot topics in recent decades. Historically, especially with the introduction of social media, the effects of carbon emissions have been discussed in a similar demeanour as a fad. People often want to be more environmentally friendly reducing energy consumption, but the opportunity cost of doing so isn't quite that enticing. Considering countries like Canada which are countries who choose to mainly consume energy and countries that lack the resources to produce energy, energy consumption takes up a large portion of the energy demand. Recently, there has been much more attention on the causes of carbon emissions, where environmental and economic innovations attempt to address and minimise their effects. This is seen especially surrounding energy consumption, which is where this study directs its focus.

Focusing on the work done by Liu et al. (2018) and the policy recommendations by Alharthi et al. (2021), we consider the relationship between total energy consumption and CO_2 emissions, while also accounting for other emission factors and regional fixed effects. Within our analysis, we found that total energy consumption and CO_2 emissions have a relatively large and significant positive relationship carried into the linkage of their trends. This highlights the magnitude of the effect the prior has on the latter. This reinforces the ideology that a singular person's consumption matters economically, environmentally and statistically. Though sorting all data into 7 regions we find that regional factors heavily affect a country's level of average consumption.

2. Context and data

We commence our analysis with data collected from a data database Kaggle, which was sourced from Enerdata; an energy intelligence and consulting company. Our data is a panel structure comparing different countries over the same time period, presenting the causal relationships between dependent and independent variables. The data collected is sampled from 44 different countries during the same time. The sampled countries provide a variety of regional factors for energy consumption, and production, as well as a variety of economic performances. Regarding the analysis, our population of interest is these 44 countries spanning the years 1990-2020. Each country is sorted by region: Arab States, South/Latin America, Asia & Pacific, Europe, North America, Middle East, and Africa. For our analysis, when we account for regional fixed effects, with North America as the base. As shown in Table 2. The primary variable of interest is the CO_2 emissions from fuel combustion measured in Mtco2 (millions of tons of CO_2). The main independent variable is the total energy consumed by that country within a given year measured in Mtoe (millions of tons of oil equivalent).

Within our data we can see that China holds the largest total energy consumption value of 3381.399 mtoe. Additionally, this similar ranking holds for CO_2 emissions values. it can be seen that total energy consumption has reduced slightly in recent years, which can also be seen in lower CO_2 emission levels in recent years. This suggests that there have been policies and efforts to reduce CO_2 emissions over the years that largely prove efficient.

3. Regression

3.1 Linear regression

Our fundamental model concentrates on the relationship between CO_2 emissions and total energy consumption. The model is as follows:

$$co2efc = \beta_0 + \beta_1\ tec + \varepsilon$$

We use robust standard errors to account for heteroscedasticity.
We can see that there is a strong positive relationship between total energy consumption and CO_2 emissions as seen in the outcomes of specification (1). This specification shows that a one million unit increase in total energy consumption increases causes a 2.699 million unit increase in CO_2 emissions, as reflected in Figure 1. We expect 95 percent of other samples' β_1 measure to fall within 2.6135 and 2.7844. This means that 95% of other samples will also reflect the strong positive relationship between the independent and dependent variables. Considering that the average American consumed 1.5636 tonnes of oil equivalent of energy in 2020, which is correlated to 4.2202 million tonnes of CO_2 emissions from fuel combustion, we can see that any CO_2 emission is undesirable. Because the null (Ho: $\beta_1 = 0$) can be rejected at all levels with a t-value of 61.94, we can conclude that there is a statistically significant interrelation between the CO_2 emissions from fuel combustion and total energy consumption. Due to the panel nature of the data collected, the Least Squares Assumption 2 of independent and identically distributed data is violated while also failing the Ramsey reset test for omitted variables. The Ramsey reset test aims to check for the presence of missing variables in the econometric model and the test's statistic significance itself. Specifications (1), (3) and (4) fail the Least Squares Assumption 1; E(u | X) = 0, therefore β_1 is biased.

The model fails to consider other factors involved in total energy consumption such as geographical factors. These effects include things like whether the country is mainly an energy producer or consumer, and whether the country has cheap access to an enriched environment for natural gas, nuclear energy, and coal. This causes β_1 to be underestimated and negatively biased. In specifications (2), (5) and (6) we consider these fixed-effects by accounting for the region. We account for the fact that more modernized regions such as North America tend to have higher energy consumption due to more widely available energy access. Countries within specific regions tend to face similar access to energy and production, which causes their energy consumption to be relatively similar. Due to accounting for region fixed-effects in specification (2), our β_1 is now 0.0897 more than in specification (1) where $E(\widehat{\beta_1})$ was 2.699. Due to this and the shrinking of the confidence interval at the 95 percent level, this tells us that specification (2) is a more accurate representation of the population and that a one-unit change in total energy consumption has a slightly larger effect on CO_2 emissions. Despite this correction, the Least Squares Assumption 2 is still violated and our model still contains an omitted variable bias.

3.2 Multiple linear regression

In order to better and further analyze the true relationship between CO_2 emissions and the total energy consumption specifications (3), (4), (5) and (6) focus on multiple regressions by increasing and modifying the variables to acquire a more accurate picture of CO_2 emissions. Assuming all Least Squares assumptions hold, the model is as follows:

$$co2efc = \beta_0 + \beta_1 tec + \beta_2 aco2ef + \beta_3 co2icpp + \beta_4 eigdpcp + \beta_5 ngdc + \varepsilon$$

In specification (3), we find that the average CO_2 emission factor, CO_2 intensity at constant purchasing power parity, and energy intensity of GDP at constant purchasing power parities seem to have extremely large effects on CO_2 emissions. These effects have coefficient values of 166.0871,-273.5853, and 768.9464 respectively. Whereas total energy consumption's effect has only increased slightly by 0.1524. Due to the extremely high standard errors on average CO_2 emissions factor, CO_2 intensity, and energy intensity of GDP [15.3919, 78.8054, and 185.4315 respectively], the sample representation of these variables does not closely represent the population and holds no economic significance. With all having p-values of 0 but CO_2 intensity; which has a p-value of 0.001, the variables are statistically significant, however the model still has an omitted variables bias.

Through viewing the mean, maximum, and minimum values for the variables in Table 1 we can see that many of the variables' maximum values are far from their mean. Specifically, CO_2 emissions and total energy consumption and thus need to be scaled in hundreds of millions starting in specification (4), as opposed to millions in the previous specifications. The value of β_1 remains unchanged, and we have a one hundred million unit change in total energy consumption causing a 2.94 hundred million unit change in CO_2 emissions. The other coefficients have been converted into β_2 =1.6609, β_3 =-2.7358, and β_4 = 7.6895 respectively with lower standard errors, therefore we may conclude that the sample is closer to the population. Moreover, considering Canada alone consumed 0.21 hundred million tonnes in oil equivalent of energy in 2020 compared to 2019, that is 0.6174 hundred million tonnes less of CO_2 emissions, which is of economic significance. In addition, with the same p-values as previously, all variables remain statistically significant at the 1% level.

Upon looking at the scatter plots of the independent variables against scaled CO_2 emissions, we can see that there are a few non-linear relationships [Figures 1-5]. To correct this in specification (5) we take the ln of the model, this leads to significant changes in the way variables are measured and changes in their coefficients. We have β_1 = 0.9711 measures a one percent change in the total energy consumption constituting a 0.97 percent change in CO_2 emissions. This effect seems smaller than that previously drafted, along with the coefficients of the other independent variables as seen in Table 2. However, any change in CO_2 emissions, even minor is greatly detrimental to the environment showing economical importance. In Table 3 we can see changes in the t-values for all independent variables, however with p-values on all coefficients still less than 0.01, they are all statistically significant at the 1% level.

Finally, specification (6) is the same as specification (5) but controls for region-fixed effects, showcasing the difference in regional access and regional energy consumption, taking North America as the base. Considering regional fixed-effects, we resolve the negative bias within the coefficients for scaled total energy consumption; average CO_2 emissions factor; and energy intensity of GDP, and the positive bias within the coefficients for CO_2 intensity and the percent change in natural gas domestic consumption. This reduces standard errors and better reflects the population, allowing the model to more effectively compare CO_2 emission levels between each region.

4. Extension

4.1 CO_2 Emissions and Total Energy Consumption Sorted by Region

According to the literature by Liu et al. (2018) and Alharthi et al. (2021), total energy consumption and CO_2 emissions are typically linked to economic growth. These regressions are commonly based on the Environmental Kuznets Curve (EKC) Hypothesis and its validity, which is reflected in their work as well. Our study aims to shift the focus on environmental and economic relations away from the EKC curve and towards a regression of CO_2 emissions on total energy consumption. This is done in numerous multiple non-linear regression models under robust standard errors, which varyingly account for regional fixed-effects and additional varying effects on CO_2 emissions. Taking these conditions into consideration is necessary to guarantee the accuracy of our results. By not considering regional fixed effects, we allow for potential bias in our coefficients nullifying the first condition for the Least Squares Assumption. Moreover, accounting for other variables allows us to attempt to eliminate threats to internal validity such as omitted variable bias.

Based on our analysis, we can see there's a strong positive linear relationship between total energy consumption and CO_2 emissions. This is shown in Figure 1. This relationship expresses the direct impact and importance of energy consumption and CO_2 emissions on the world stage. Any small increase in energy consumption is then magnified as CO_2 emissions, advancing ideas on decreasing energy consumption to decrease its environmental impacts. The regression displays that a 1 percent increase in total energy consumption causes a 0.9835 percent increase in CO_2 emissions, which is statistically significant at the 1 percent level. Not to mention Canada alone had a 1.3 percent average consumption increase per year from 2010 until 2019, making a 1.278 percent increase per year in CO_2 emissions on average. So despite seeming relatively small, any positive relationship affecting CO_2 emissions is not ideal.

Despite shifting the focus towards a smaller target of the readings' overall regression analysis, the underlying relationships still hold. Liu et al. (2018), based their study on the papers by Acaravci and Ozturk and Nasreen and Anwar, conclude that the EKC hypothesis is valid showing that carbon dioxide emissions are mainly deduced from energy consumption. This supports our model's main finding, in Table 4 correlating a one percent increase in total energy consumption to a 0.971 percent increase in CO_2 emissions.

4.2 Forecasting Trends for CO_2 Emissions Using Trends for Total Energy Consumption

The positive linear relationship and significantly positive regression results also forecast CO_2 emissions trends. Based on previously determined trends regarding total energy consumption, this trend forecasting technique aims to predict future trends in CO_2 emissions. The Canadian Association of Petroleum Producers predicts that upward trends in the global population and living standards will increase global total energy consumption substantially. Although this may be true, our data shows that the total energy consumption in recent years is actually taking a downward trend. In the reading by Liu et al. (2018) they mention that a country's carbon emission levels are directly mirrored in its social and economic development of a low-carbon economy. It is understood that CO_2 emissions in developed countries have passed the peak period and have shown a downward trend in carbon emissions, reinforcing the conclusions of our regression-based trend. This can be explained by a variety of factors. Firstly, the media has an immense impact on climate change awareness affecting the actions of viewers globally. The media has been accused of bothsidesism; where it reports both sides even if one is more scientifically accredited, and that reports on climate change tend to follow political and economic impacts. Examples of such trends are the 2007 recession and the peak of the Trump administration in 2017. The 2020 level of total energy consumption being lesser than other recent historical values and can be due to media-accredited awareness, expressed as a historical high since 2004 and a 34% hike in media coverage compared to 2018. Secondly, the introduction of Covid-19 in 2020 was accompanied by a series of global flight restrictions and self-isolation policies such as the transition from a work to home model. Reductions in the services and industries sector resulted in a drop in electricity demand as a result of these restrictions. Demand is crucial to understanding long-term trends in energy consumption, meaning drops in demand are reflected in drops in consumption and vice versa. Moreover, these extensive drops in demand in the services and industries sectors are only slightly counteracted by the increase in energy consumption within households. The indicated variables are directly seen in the data where 2020 levels of total energy consumption are at record lows, even below the 2019 and 2018 levels. All things considered reflected in the regression models, a positive relationship between the dependent variable and the main independent variable, means the overall long-term increasing trend prediction of energy consumption predicts a long-term trend for increased CO_2 emissions. In like manner, the short-term negative trends in total energy consumption are reflected in the decreasing trends for CO_2 emissions.

4.3 Other Variables to CO_2 Emissions

Moreover, in addition to total energy consumption the CO_2 intensity and energy intensity of GDP (measured in kco2/$15p and koe/$15p in USD$ under constant purchasing power parities respectively) prove to have sufficient effects on CO_2 emissions as well. CO_2 intensity, which measures how much CO_2 is discharged for the production of a kW/h of electricity, tells us how clean our electricity is. In Table 4 we can see that a one-unit change in CO_2 intensity causes a 78.818 percent change in CO_2 emissions. This means that more energy produced in an inadequate manner will produce more CO_2 emissions at an alarming rate. Our analysis is reflective of other studies and policies urging more environmentally friendly energy production. In addition to that, energy intensity, which measures the energy inefficiency of an economy, causes a -78.166 percent change in CO_2 emissions. Energy intensity at increased levels is typically reflected in the high prices and costs to modify energy into GDP. Historically the energy intensity level has been at an average of -1.5% a year between 2000 and 2019.

4.4 CO_2 Emissions and Policies

In the event that the positive total energy consumption trend productions hold true, the domino effect reflects a positive trend in CO_2 emissions. This addresses many urgent aspects within the environmental sector on the world stage. Over the years many countries and their governments have taken responsibility and introduced many policies aiming to decrease CO_2 emissions by decreasing total energy consumption. In the reading by Alharthi et al. (2021), the authors highlight the United Nations Sustainable Development Goals for 2030. Specifically mentioning goal 12: responsible consumption and production. Likewise, there are many other policies globally that focus on decreasing or changing the form of energy consumption. Firstly, policies on promoting energy efficiency aim to reduce energy demand, decreasing fossil fuel consumption. In 2020 fossil fuels are accredited to about 76% of the total terawatt hours of energy consumed. This policy is aimed at replacing fossil fuels with alternatives, which would alter our regression model. It can be expected that the relationship between total energy consumption and CO_2 emissions will weaken, lowering the value of β_1. Secondly, there are policies being implemented that aim to reduce residential energy consumption. The policy called the 10-point plan urges the renovation of homes and buildings through upgrades in insulation, accelerating heat pump installation, and installing digital thermostats, to decrease and monitor energy consumption. Policy empathy and increased presence in the community encourage people to take action in reducing energy consumption and a government subsidisation program will be required. Finally, there are policies that increase renewable energy sources, as well as others that use a reduction in energy consumption to reduce energy bills and ameliorate supply chain issues. Alharthi et al. (2021) highlight the KEC curve and the estimators in their regression show that renewable energy consumption greatly reduces CO_2 emission levels and that policymakers in the MENA region need to consider implementing policies and regulations geared towards the adoption and use of renewable energy, mitigating carbon emissions.

5. Limitations of Results

In the first place, the panel nature of my data collection alone poses many limitations affecting my regression. Panel regression as stated in the reading by Hill et al. (2019), especially when accompanied by fixed-effects, is exposed to a limitation culture consisting of omitted variables, limited external validity, and heterogeneity. Typically, fixed-effects in panel regression use each data entry as its own control group in an attempt to remove the estimating equation for variation limiting the variation to within individuals as opposed to between individuals. My regression model at all levels reports omitted variables with a p-value within the reach of 0, despite accounting for non-linearity in my regression and adding additional variables as seen in specification (6). In order to avoid multicollinearity variables that are highly correlated with CO_2 emissions were omitted. In addition to that, any COVID-related variable is not present in the model which also adds to the omission of variables that could explain the differences in the dependent variables' values over the studied time period. By disregarding these variables the model becomes biased and contains threats to internal validity. Moreover, due to the distinctions between time and location, the model holds many threats to external validity. The regression model cannot be extended to include different time periods as well as different regions. It is also evident in the introduction or removal of regions that CO_2 emissions and total energy consumption from the 1920s or 2022 will significantly change the magnitude of the relationship between the independent variables. If the data was biased towards OECD countries or third-world countries the data interpreted in a global demeanour would be positively and negatively skewed respectively. The creation of bias through external validity would make my current regression futile. Finally, heterogeneity in fixed-effect models often takes an unobserved form. This unobserved heterogeneity is caused by immeasurable characteristics that tend not to change over time, these immeasurable characteristics unknowingly skew variable data and typically alter the consistency of the variance. Within my model heterogeneity is observed in variance, causing heteroscedasticity. This heteroscedasticity is accounted for by taking the robust form of standard errors.

6. Conclusion

This study highlights the impact of energy consumption on CO_2 emissions through a panel of multiple non-linear regressions while restricting regional fixed effects. The empirical observations are in support of the notion that there is a largely positive relationship between total energy consumption and CO_2 emissions, reinforced by the papers by Liu et al. (2018) and Alharthi et al. (2021). We then explore trends using the trend of total energy consumption, to predict the trend of CO_2 emissions. We find our model exposes a positive relationship through trends in both variables. We do this by considering many social variables and forecasting the CO_2 emissions trend under those same conditions. Furthermore, we analyze the solution to the environmental damage by CO_2 emissions caused by total energy consumption through political policies. We refer to the work by Alharthi et al. (2021) as well as other global policies circulating on the world stage, concluding that most policies that aim to reduce total energy consumption focus their attention towards energy efficiency and reducing fossil-fuel consumption. In essence, this study uses regression to analyse the relationship between CO_2 emissions and total energy consumption and their trend patterns to answer the question posed initially about the effect on humanity.

7. References

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Figures

Figure 1: Scatter Plot of Total Energy Consumption against CO2 Emissions

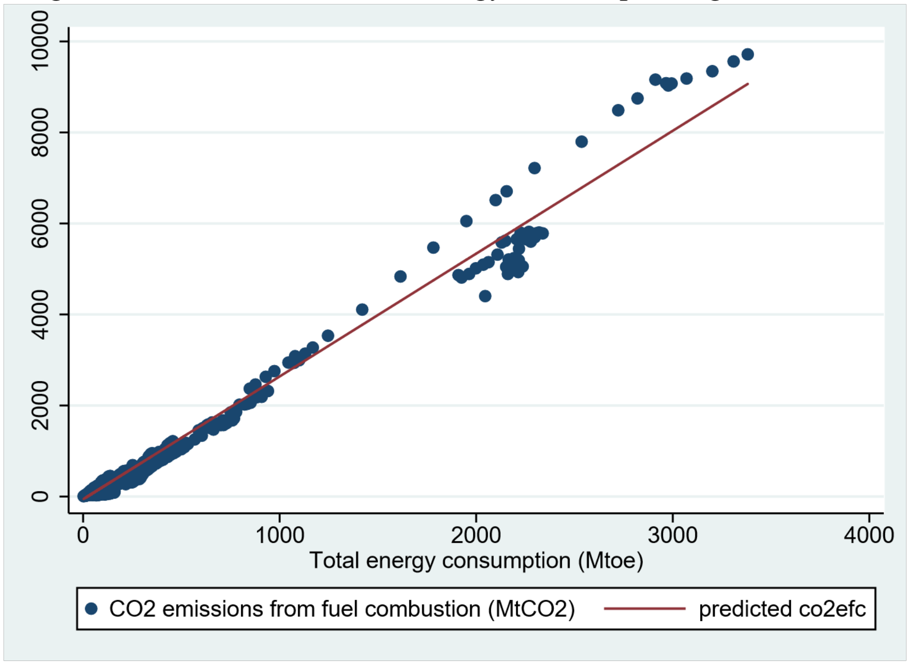


Figure 2: Scatter Plot of Average CO2 Emissions Factor against CO2 Emissions

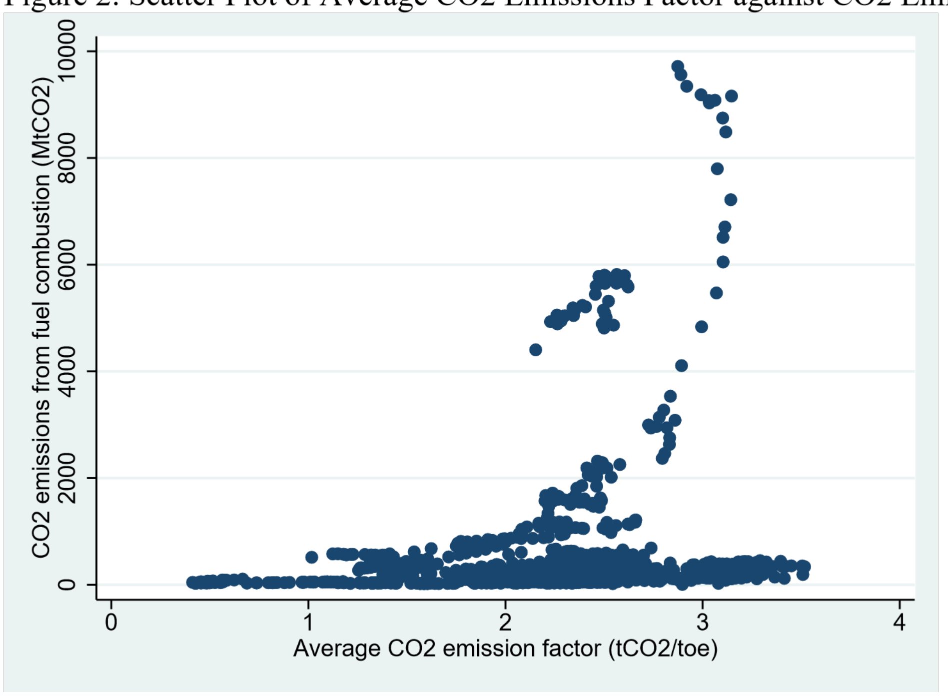


Figure 3: Scatter Plot of CO2 Intensity at CPP against CO2 Emissions

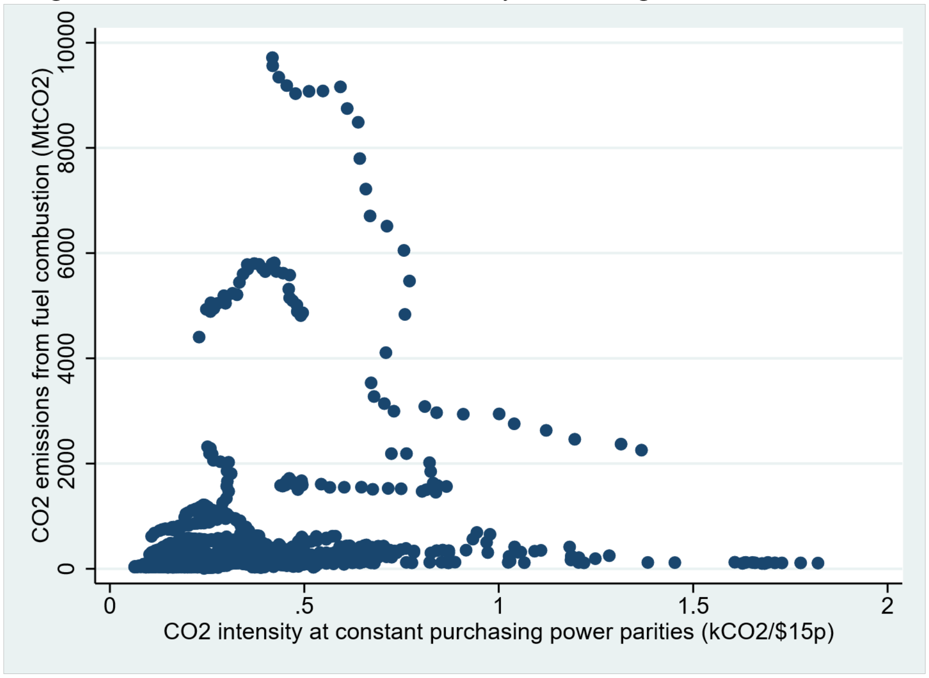


Figure 4: Scatter Plot of Energy Intensity of GDP at CPP against CO2 Emissions

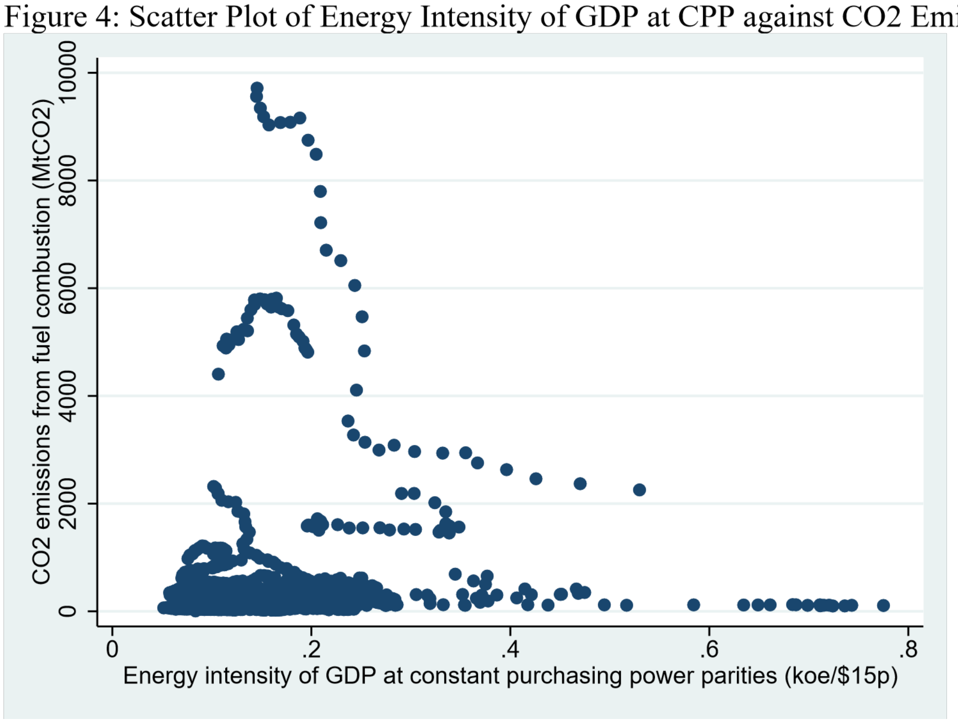


Figure 5: Scatter Plot of Natural Gas Domestic Consumption against CO2 Emissions

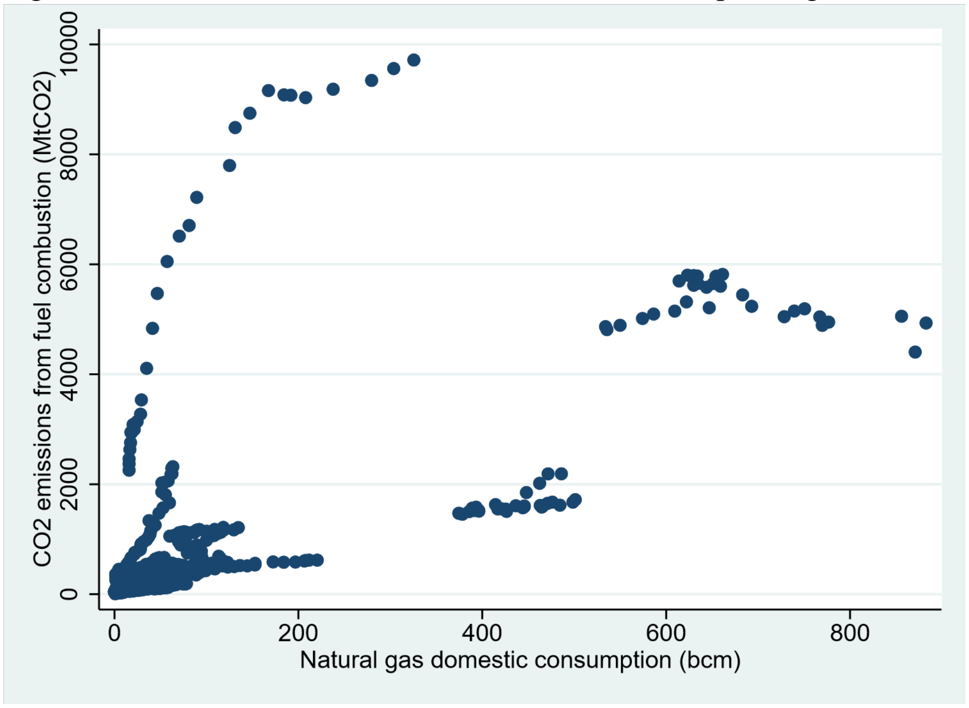
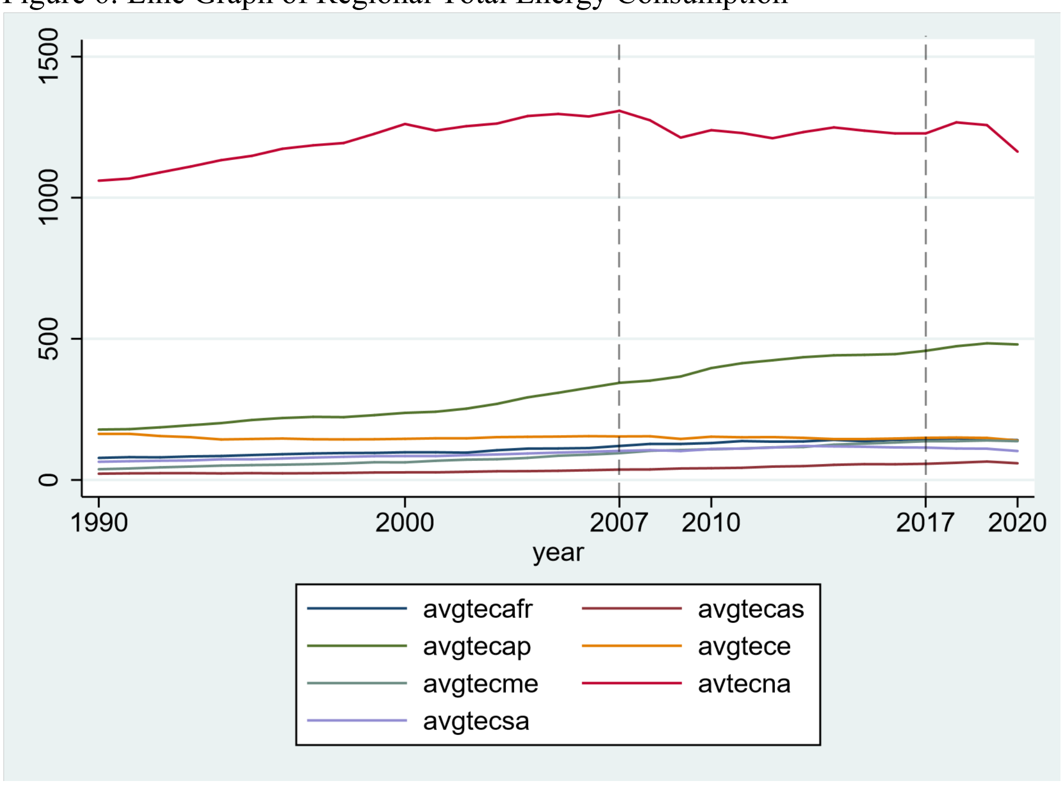


Figure 6: Line Graph of Regional Total Energy Consumption



Tables

Table 1: Summary of Statistics

Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
co2efc	1364	550.375	1213.058	7.598	9716.772
tec	1364	225.968	445.243	2.623	3381.399
aco2ef	1364	2.239	.561	.412	3.517
co2icpp	1364	.339	.247	.064	1.821
eigdpcp	1364	.148	.091	.052	.775
ngdc	1364	59.809	117.396	0	882.637

Table 2: Linear Regression

	Model 1	Model 2
	b/se	b/se
Total energy consu~)	2.6990***	2.7887***
	(0.0436)	(0.0390)
Africa		365.4640***
		(60.0175)
Arab States		458.6677***
		(59.0294)
Asia & Pacific		431.6199***
		(57.6450)
Europe		397.5071***
		(56.4112)
Middle east		446.0582***
		(57.6869)
North America		0.0000
		(.)
South/Latin America		394.4305***
		(58.0758)
constant	-59.5028***	-473.5433***
	(6.6209)	(60.0482)

R-Squared	0.981	0.986
dfres	1362	1356

* p<0.05, ** p<0.01, *** p<0.001

Table 3: (4) and (5) Multiple Non-linear Regressions with t-stats

	Model 4	Model 5
	b/se/t	b/se/t
tect	2.9411***	
	(0.0350)	
	83.9118	
Average CO2 emissi~O	1.6609***	0.4212***
	(0.1539)	(0.0299)
	10.7906	14.0711
CO2 intensity at c~a	-2.7359***	0.5812**
	(0.7881)	(0.2232)
	-3.4717	2.6034
Energy intensity o~t	7.6895***	-1.5217**
	(1.8543)	(0.5534)
	4.1468	-2.7498
Natural gas domest~n	-0.0136***	
	(0.0011)	
	-12.4743	
ltect		0.9711***
		(0.0032)
		307.1485
lngdc		0.0510***
		(0.0040)
		12.8873
constant	-4.2591***	-0.3001***
	(0.3639)	(0.0651)
	-11.7046	-4.6084
R-Squared	0.992	0.991
dfres	1358	1351

* p<0.05, ** p<0.01, *** p<0.001

Table 4: Multiple Non-linear Regressions

```
Model 3          Model 4          Model 5          Model 6
b/se             b/se             b/se             b/se
Total energy consu~)       2.9411***
                          (0.0350)
Average CO2 emissi~O     166.0871***       1.6609***       0.4212***
0.4719***
                         (15.3919)        (0.1539)        (0.0299)        (0.0220)
CO2 intensity at c~a    -273.5853***      -2.7359***       0.5812**        0.3089*
                         (78.8054)        (0.7881)        (0.2232)        (0.1456)
Energy intensity o~t     768.9464***       7.6895***      -1.5217**       -0.7766*
                        (185.4315)        (1.8543)        (0.5534)        (0.3539)
Natural gas domest~n      -1.3598***      -0.0136***
(0.1090)        (0.0011)                                    tect
2.9411***
(0.0350)                                  ltect
0.9711***       0.9836***
(0.0032)        (0.0029)   lngdc
0.0510***       0.0181***
(0.0040)        (0.0035)
Africa                                                                     -
0.4822***
                                                                          (0.0409)
Arab States                                                                -
0.2110***
                                                                          (0.0286)
Asia & Pacific                                                             -
0.2111***
                                                                          (0.0286)
Europe                                                                     -
0.2022***
                                                                          (0.0287)
Middle east                                                                -
0.2190***
                                                                          (0.0285)
North America                                                               0.0000
                                                                               (.)
South/Latin America                                                        -
0.1882***
(0.0286)   constant                -425.9087***       -4.2591***       -0.3001***
-0.1175                           (36.3880)         (0.3639)         (0.0651)
(0.0618)

R-Squared                      0.992            0.992            0.991            0.994
dfres                           1358             1358             1351             1345

* p<0.05, ** p<0.01, *** p<0.001
```