An Analysis of the Impact of Household Size on Carbon Emissions

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Abstract:

This paper examines the sources of carbon emissions globally from 1750 to 2022, classifying them as Coal, Oil, Gas, Concrete, Flaring, or Other emissions. It also explores the impact of urban characteristics, such as house size, density, and GDP per capita, on emissions to understand the lifestyle and economic factors that contribute to emissions and determine whether these are more accurate predictors of per capita emissions than the source of the emissions themselves. The results indicate that oil is the most significant predictor of per capita emissions, but with a non-linear relationship with the dependent variable. Additionally, the average household size has a significant linear effect, increasing model accuracy by 20% when included in the urban characteristics regression. We utilized OLS regressions, regression trees, and bagging aggregations to identify the linear and non-linear effects of the variables. Early evidence suggests that increasing household size may induce economies of scale within society's primary unit, the family, and should be a major policy point for reducing emissions. Further research is needed to explore the relationship between household size and oil emissions, which could offer more insights into this issue. Other potential areas for future research include examining mean climate, car usage, and government type on emissions.

Keywords: Carbon emission sources, pollution, urbanization, linear regression, regression trees, bagging, environmental sustainability, energy policy

1. Introduction and Set-up

Despite the common consensus regarding the relationship between carbon emissions and global warming, emissions have kept on increasing (G Peters et al., “Carbon Dioxide Emissions Continue to Grow amidst Slowly Emerging Climate Policies,” Nature Climate Change, 2020) and many global treaties and agreements until now have been unable to fully solve or slow down emissions to an amount that would be less than catastrophic. This suggests that new avenues must be explored in order to fully address the problem of energy consumption and fossil fuel energy production.

This paper is part of the growing body of literature exploring the connection between urban planning methods and global warming. The research is heavily influenced by Katherine Ellsworth-Krebs' 2019 study, which examined the relationship between floor space and energy consumption (Ellsworth-Krebs, 2019). In this paper, we aim to expand on Ellsworth-Krebs' work by investigating how household size affects the sources of emissions, while accounting for variables such as density and, crucially, wealth, which may be strongly associated with household size.

Ultimately, this current paper will be a part of a series of papers exploring the issue, specifically in the realm of city planning and how good urbanization may lead to lower carbon emissions without necessarily requiring the degrowth policies many politicians fear espousing.

In order to perform my analysis, I will analyze data recovered from the Global Carbon (Project Robbie M Andrew and Glen P Peters, “The Global Carbon Project’s Fossil CO2 Emissions Dataset,” Zenodo, October 17, 2022) , to determine the general distribution of carbon emissions across countries, across time periods and the correlation each of them have with total emissions. Then, I recovered data from the United Nations Department of Economic and Social Affairs that recorded household size data for a number of different countries at different times (World Population Prospects - Population Division - United Nations, 2022), followed by adding in density and GDP per Capita data from the IMF (World

Economic Outlook Database, October 2022, 2022) and then population density data from the UN's previously mentioned Population division.

In this project, we will examine first: the relationship between the six carbon emission sources (coal, oil, gas, cement, flaring, other) and the total, as well as per capita emissions. This will be the basis for further research pertaining to the impact of household size on carbon footprints.

I have decided to choose the six emission sources since through them we can get a better understanding of the composition of the emissions, which can be used to provide more useful results by the end of the study. If cement is main source of emissions in countries with a high emissions per capita, wealthier governments should perhaps switch their priorities from focusing on energy sources to switching the material used in construction.

Intuitively all the emission sources should have a positive effect on total emissions, as total emissions is equal to the sum of the other emissions, however we will explore whether an increase in the emissions of one source actually decreases the emissions of other sources to the extent where the variable has a null or negative effect on total transmissions.

Once a breakdown of the carbon emissions data is created we will differentiate between the different carbon emission sources (how each of them affects the total) and can move onto how household size changes the emissions and emission sources.

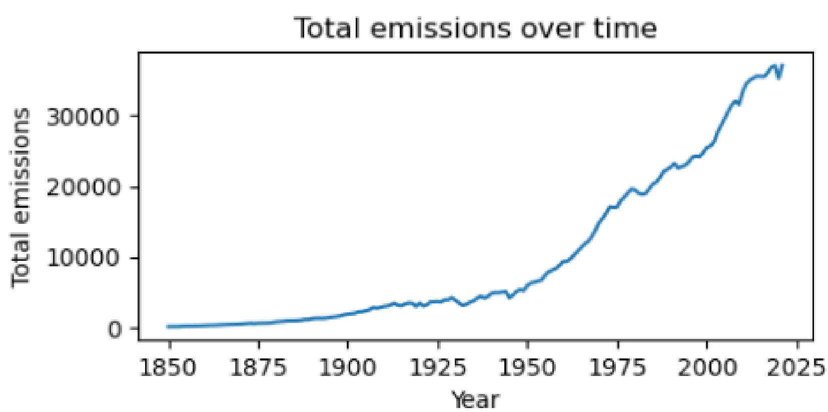
2. Overview of Emission Data

The fact that the dataset stretches back to 1750, means there is a high variance in the emission amounts provided. The table below (Table 1) helps to illustrate this point and communicates other important facts about the data. Some stats to notice would be the different means of the sources. As we can see, because of its general availability and long known energy dense properties, Coal is the source with the highest average consumption, followed by oil and then gas. In addition, by looking at the percentiles we can notice that there has been an explosive growth in the emissions, given that 80% of the dataset has emissions lower than 43.74 metric tons, yet, the mean total emissions is 160.1. Plots 1, 2 and 3 also indicate this relationship, with the later two displaying the growth and slight plateau of the two largest sources.

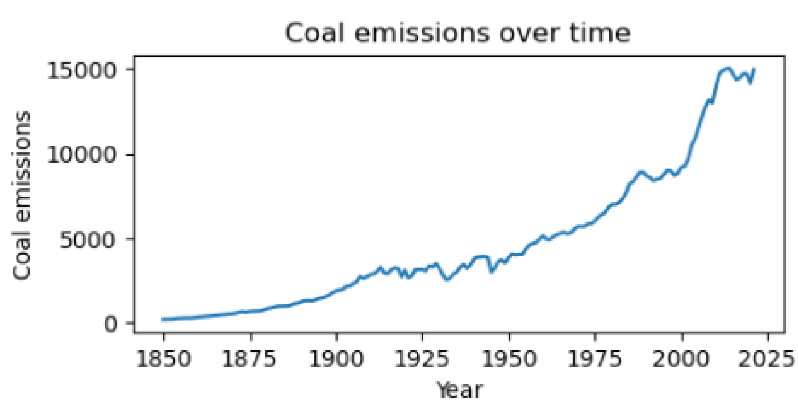
Table 1

	Total	Coal	Oil	Gas	Cement	Flaring	Other	Per Capita
count	21697.000000	21697.000000	21697.000000	21697.000000	21697.000000	21697.000000	21697.000000	21697.000000
mean	160.107852	74.129147	55.812023	23.418705	4.154208	1.701091	0.817682	3.859481
std	1398.498004	599.625528	519.270976	247.227495	49.278876	16.670896	11.044686	16.367617
min	0.000032	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
20%	0.252816	0.000000	0.040304	0.000000	0.000000	0.000000	0.000000	0.000000
40%	1.677927	0.032939	0.474898	0.000000	0.000000	0.000000	0.000000	0.363348
50%	3.605832	0.275102	1.047904	0.000000	0.010903	0.000000	0.000000	0.829750
60%	7.746593	1.132176	2.275344	0.000000	0.101610	0.000000	0.000000	1.686489
80%	43.744429	12.133374	14.274211	1.919097	0.869871	0.000000	0.000000	5.682274
max	37123.850352	15051.512770	12345.653374	7921.829472	1672.592372	439.253991	306.638573	834.192642

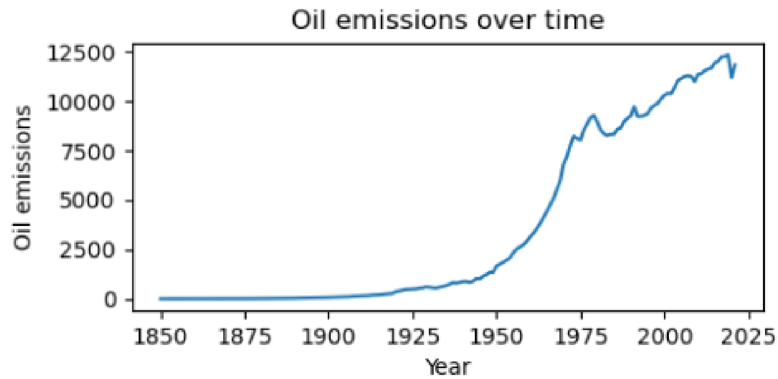
Plot 1



Plot 2

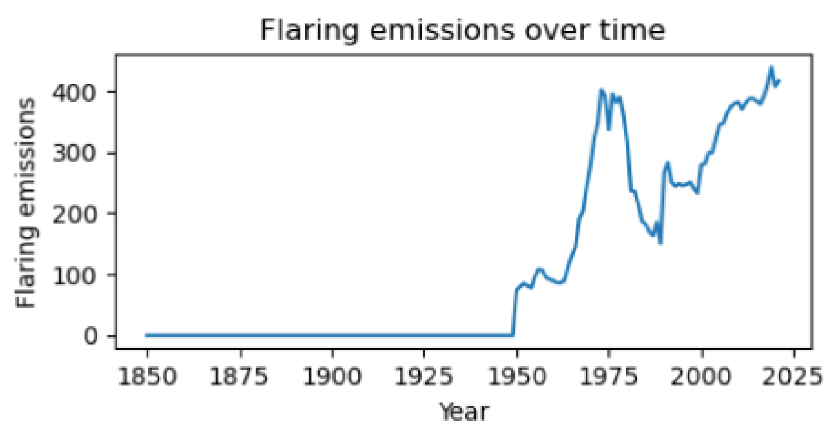


Plot 3

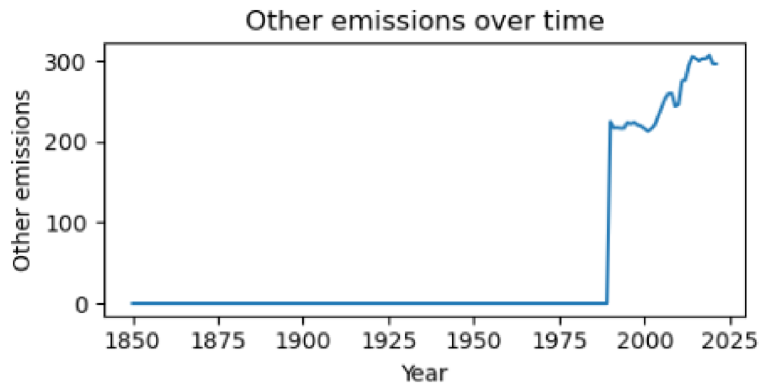


There are two notable changes in emissions data: a sudden increase in flaring emissions around 1950, and a rise in emissions from renewable energy sources around 1985 (see Plot 4 & 5). The increase in flaring emissions can be attributed to the fact that flaring became popularized in the mid-20th century, and until 1950 no country had begun to measure emissions from this source. On the other hand, the rise in emissions from other energy sources can be attributed to the growing awareness of carbon emissions from fossil fuels, which led to the increasing popularity of renewable energy sources in the late 20th century. This rise in emissions could come from both the production of the requisite technology, such as photovoltaic cells or wind turbines, and from the production of energy itself, as is the case with biomass.

Plot 4



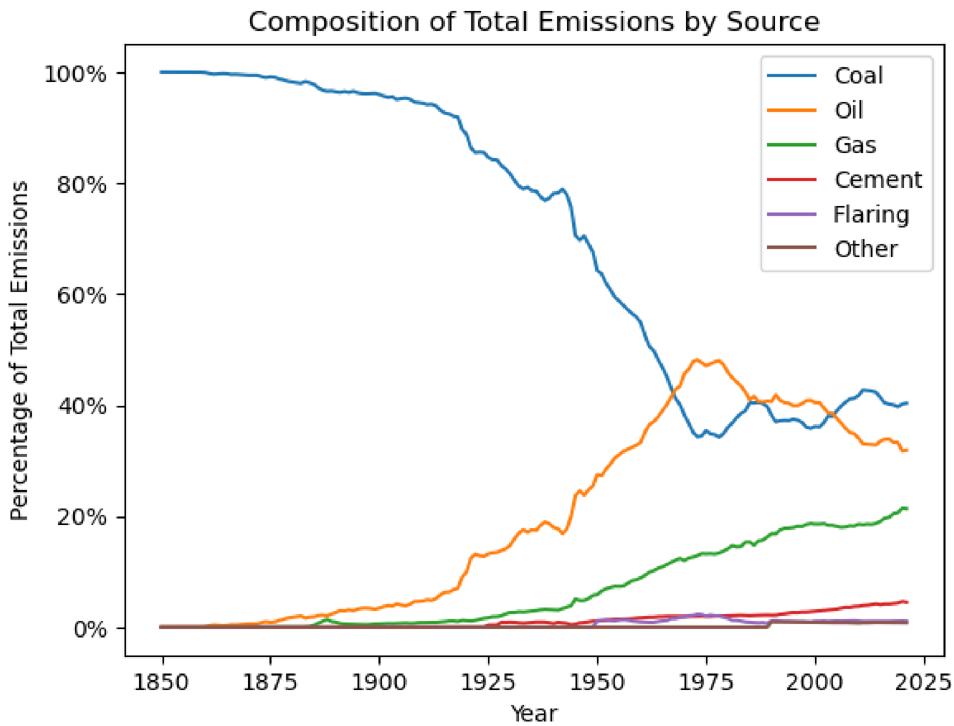
Plot 5



Emission Trends

Coal has for long dominated the emissions scene, most likely being one of the major sources of emissions well before 1750 because of its use in the smelting of metals in ancient China and Rome (John Dodson et al., “Use of Coal in the Bronze Age in China,”) (“Provenance of Coals from Roman Sites in England and Wales on JSTOR,” Jstor.org, 2023,). Nevertheless, it was after the industrial revolution that production of goal really started to ramp up thanks to the discovery of the steam powered engine and of coal’s capacity to supply the energy for it. In plot 6, we can see that from 1850 (starting from 1750 produces a near identical graph) until around 1970, coal was the dominant emissions source. After this period, most likely in part due to the increasing popularity of the car, along with other gas-powered vehicles, along with the increasing efficiency at which oil could be extracted through fracking, oil became the dominant emissions source. Ultimately, this was short lived, as coal has, somewhat against popular belief, made a resurgence and is now the biggest emission source, despite making up a much smaller percentage of total emissions than it had 60 years ago.

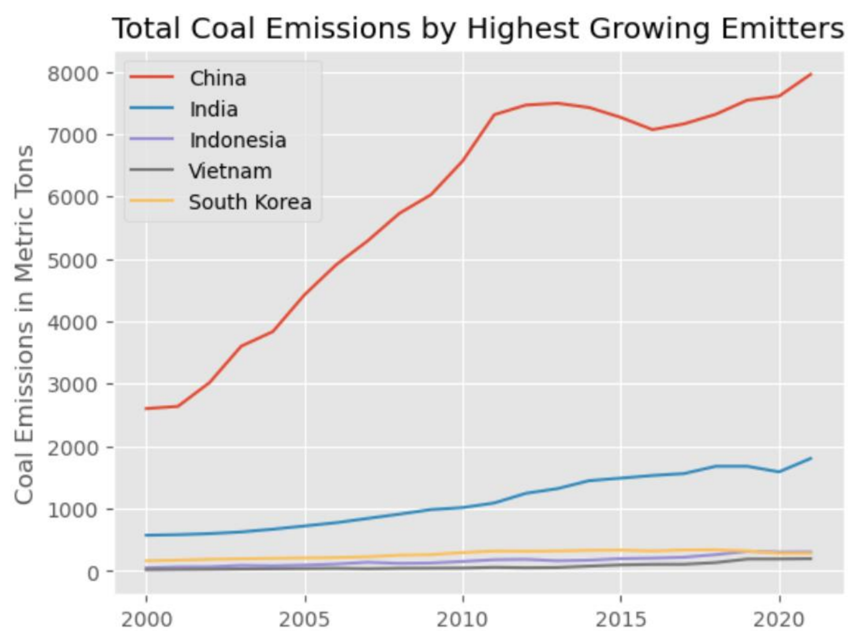
Plot 6



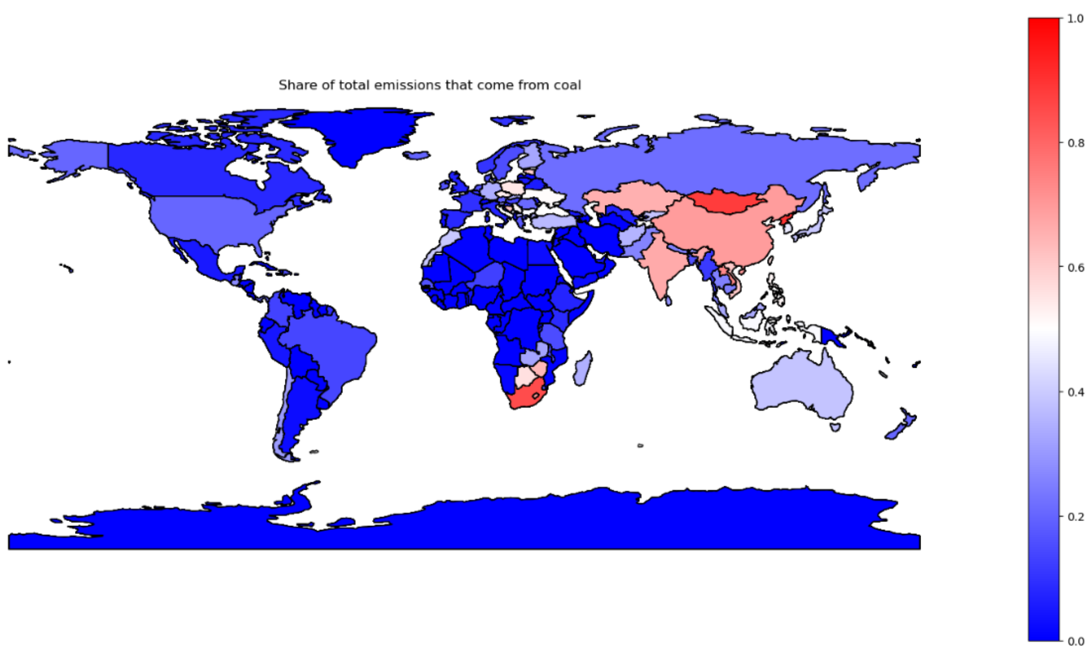
China is the main culprit behind the recent surge in coal emissions. Since 2000, the country has experienced a more than 200% increase in coal emissions (Myllyvirta et al. 2023). In fact, China is currently constructing six times more coal plants than the rest of the world combined (Myllyvirta et al. 2023). Despite this, China has been reducing the proportion of its energy mix that is accounted for by coal emissions (U.S. Energy Information Administration - EIA - independent statistics and analysis 2022). It is important to note, however, that China's decreasing proportion of coal emissions in its energy mix does not negate the fact that its overall coal emissions continue to rise at an alarming rate.

One of the challenges facing China and other countries on the list (with the exception of South Korea) is that as they develop and their economies grow, their energy consumption also increases. Coal has traditionally been a cheap and abundant source of energy, and many countries have turned to it to meet their growing energy needs. Despite its negative impact on the environment and human health, coal has been viewed as a reliable and secure source of energy by some countries, leading to its continued use even as renewable energy alternatives become more available. Nevertheless, any policy that seeks to reduce emissions globally must address the growing consumption of coal in East Asia, especially in China.

Plot 7



Map 1



3. Emissions and Household Size

Household sizes have been continuously decreasing ever since the early 1900's with 40% of Scandinavian homes and 30% of American and British homes being composed of one person, when only a hundred years ago they held more than 5 people on average (Ellsworth-Krebs, Katherine. "Implications of declining household sizes and expectations of home comfort for domestic energy demand." Nature Energy 5 (2019): 20-25.,). Yet, household sizes have not been decreasing at the same rate, with the growth of floor area increasing around 1.3% (Ellsworth-Krebs, 2019). Given that buildings account for around a "a third of final energy consumption" (Ibid), this is a pressing problem and one that is often overlooked in favour of economic or technological solutions to climate change.

In order to test Ellsworth-Krebs' findings, as well as provide more data as to what the shape of the effect could look like, a polynomial fit was run on a dataset containing household size and per capita emissions*.

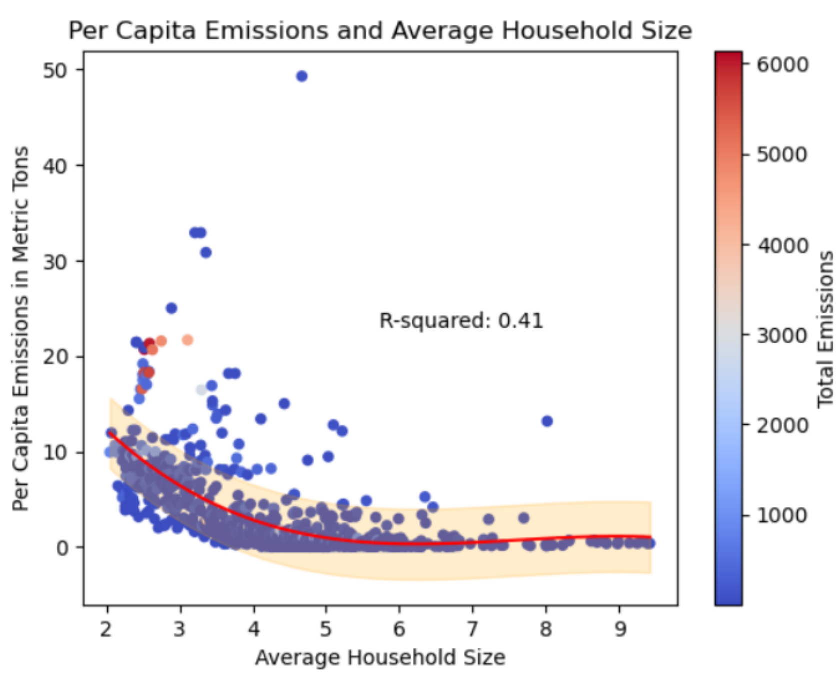
*Note: we use per capita emissions as they are less prone to confounding variables bias relative to total emissions; by using per capita instead of total emissions we can eliminate the effect a growth in population may have on the emissions figure.

The uniformity in the color of the dots is the first noticeable aspect of the graph. Most of them appear blue, indicating relatively low carbon emissions for most data points. This observation reinforces the idea of a significant carbon emissions inequality, which has been increasing over time and between countries. Additionally, we can observe an interesting relationship between household size and per capita carbon emission when household sizes are between 2 and 4. Notably, the per capita emissions stabilize after reaching four, and the relationship appears significant beyond the standard error. However, as household size increases beyond 4, the effect seems to taper off as the line of best fit does not change significantly. This suggests that the relationship is likely non-linear, a hypothesis that will be further explored in section 5.

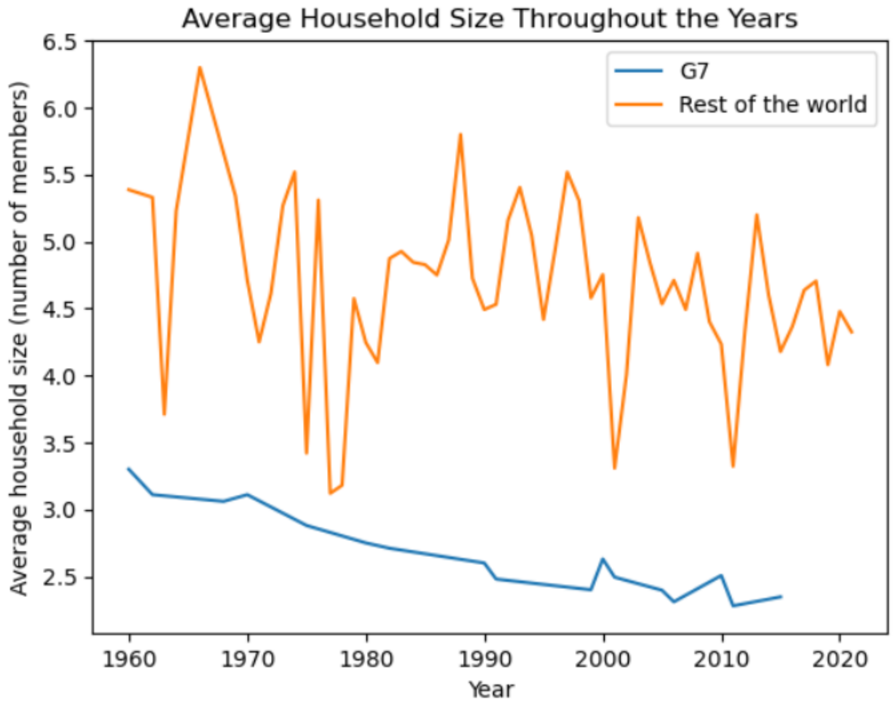
This effect could exist because of actual house size or endogeneity with per capita GDP. For the first possibility, as described in Katherine Kellsworth-Krebs 2019 paper, the apparent relationship household size has with carbon emissions, may be due more to house size than density. Kellsworth-Krebs found that energy efficiency gains from home maintenance have been offset by the trend of increasing house sizes and energy-intensive lifestyles, particularly among single and couple households in suburban areas with rising housing prices. The main driver of this energy intensive lifestyle has been single and couple housing, as due to the rising trend of suburbanization and rising city housing prices, these populations are buying bigger and bigger houses relative to what they were buying before.

The second possible reason for this relationship could be that many richer countries tend to, for cultural and economic reasons, have citizens that tend to live in smaller groups. In Kellsworth-Krebs' study she looks at the changing attitudes in the Japanese population whereby in the 1950's 60% of women expected to be taken care of by their children, which most of the time was done through cohabitation, while fourty years later this number was 16%. This means that rich countries tend to emit more, but also tend to have smaller households and so the effect of that wealth has on emissions is being captured here by household size serving as a proxy. Plot 9 depicts the average household size categorized by G7 countries and other countries, with the G7 acting as a proxy for developed nations.

Plot 8



Plot 9



4. Addition of Population Density and GDP Per Capita

In order to control for confounding variables and make our findings on the relationship between household size and carbon emissions more robust, we have decided to include population density and GDP per capita. As displayed on plot 9, household size and GDP per capita (proxied through G7 status) may be negatively correlated—with wealthier nations tending to have smaller household sizes.

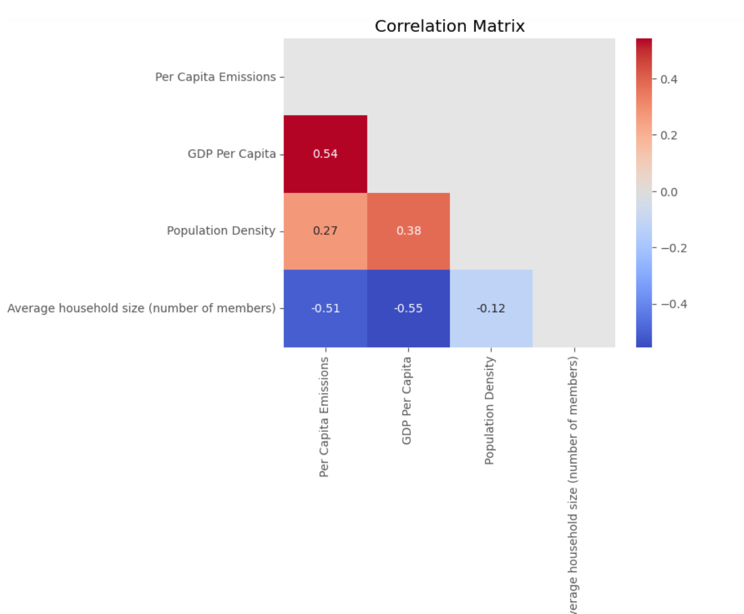
As for the inclusion of density, it's important to note that density is distinct from household size as it doesn't capture the housing unit situation or actual living conditions in a country. For instance, a country like Algeria may have a low population density due to the desert nature of its landscape but may have a high household size due to dense living in arable land. Therefore, controlling for density in our analysis is critical to accurately assess the impact of household size on carbon emissions, as it is better measure of how urban areas are organized, as opposed to how much livable land there is in the country.

To better understand the relationship between household size, GDP per capita, population density and per capita emissions we have included a correlation table in this stage of the paper. By controlling for other variables that may impact household size and carbon emissions, we hope to examine the effect of household size on emissions more effectively. Furthermore, this correlation matrix lays the groundwork for the upcoming multivariate regression analysis.

Population's purported link to carbon emissions may be due, in part, to its weak correlation with GDP per capita and the subsequent moderate effect GDP per capita has on per capita emissions. Because of this study's a global scope, it does not directly contradict Yonghong Liu's 2017 paper ("The impact of urbanization on GHG emissions in China: The role of population density," Journal of Cleaner Production 157 (2017): 299-309), which found that density played a significant role in increasing China's carbon emissions. However, it challenges the possible assumption that this conclusion could be extrapolated and considered universal.

Another intriguing finding is the negative correlation between average household size and population density. One might expect that less space/more density would result in more people living in each housing unit, but the relationship may not be statistically significant once a regression is run. Nevertheless, it is noteworthy that there is no positive relationship between the two. One possible explanation is the pattern of high-density urbanization in developed countries, where smaller households are more common due to cultural reasons, as singles and couples live without members of their extended family.

Plot 10



5. Regressions

At first glance, the relationship between household size and carbon emissions would seem to be linear; as more people cram into the same space there should be just more energy efficiency, even if we deal with the collinearity it has with GDP per capita. However, if we look at the household size and Per Capita emissions plot (plot 8) we can see that there is a negative linear relationship, until the household size reaches 5 people; once it reaches this point the relationship disappears as the line of best fit becomes almost completely horizontal.

The reasons why this could be the case are numerous. For one, there may be a decreasing marginal efficiency that one achieves within the household. For example, with four people in the household instead of two, the same appliances can be used but at a higher capacity rate. With more than five people, these inefficiencies may dissipate as families may have to buy more appliances and use some of them at similar capacity rates as a two-person household.

There's also factors external to the household that are influenced by holding high household sizes. First off, more than five people in a household may be indicative of bad urban planning whereby communities are dense but also chaotic, leading to higher per capita carbon emissions as energy, transportation and resources are not allocated efficiently. This can be tied back to Jevon's paradox, where an increase in the efficiency of resource use leads to an increase in that resource's consumption rather than a decrease. In this case, the efficiencies brought by denser households lead to an increase in energy consumption and a leveling off of the negative effect density had on carbon emissions.

All of these questions call for a regression that will be able to isolate the effects that each variable has on per capita emissions. First, we'll test with an OLS regression to determine the significance of each of the factors in a linear manner.

First OLS Regression: Urban Characteristics on Per Capita Emissions

Specification:

$$PerCapitaEmissions = \beta_0 + \beta_1\text{Household Size} + \beta_2\text{GDP Per Capita} + \beta_3\text{Density} + \epsilon$$

From this regression we can takeaway that average household size has a significant negative impact on per capita emissions, and the results are even stronger than those found in the correlation matrix (Plot 10) previously displayed (-0.975 vs -0.51).

In contrast, the regression shows that GDP per capita has a significant null effect, which is contrary to what was shown in the correlation matrix. This means that although there was a correlation between higher GDP per capita and higher per capita emissions, it was not a causal relationship and could have been influenced by its interaction with another variable, most likely average household size (as shown in the correlation matrix where they had a -0.55 correlation), as well as other variables not included in the analysis.

Lastly, population density was found to have an insignificant, close to null effect, which highlights the important distinction between household size and density.

Although the R-squared value of our first regression model is slightly lower than our polynomial fit model (0.354 vs 0.41), it will still be improved in the upcoming models. The aim is to explain a sufficient amount of the variance in per capita emissions in order to make the model significant.

Table 2

	Dependent variable:Per Capita Emissions
	Per Capita Emissions
	(1)
Average household size (number of members)	-0.975***
	(0.244)
GDP Per Capita	0.000***
	(0.000)
Population Density	0.001
	(0.000)
const	6.333***
	(1.231)
Observations	151
R^2	0.367
Adjusted R^2	0.354
Residual Std. Error	2.971 (df=147)
F Statistic	28.432*** (df=3; 147)

Second OLS Regression: Urban Characteristics with GDP per Capita Fixed Effects

Specification:

$$PerCapitaEmissions = \beta_0 + \beta_1 \text{Household Size} + \beta_2 \text{Density} + \delta_1 \text{0-1000 per capita} + \delta_2 \text{1000-2000 per capita} + \delta_3 \text{2000} < \text{per capita} + \epsilon$$

Due to the correlation between household size and GDP per capita, and the unexpected significant null effect of GDP per capita on per capita emissions found in the previous regression, we aim to disentangle the effects of GDP per Capita and household size through the inclusion of fixed effects. By controlling for the impact of GDP per Capita on emissions through household size, which may have been acting as an exogenous variable in the previous regression, we can better understand the individual effects of these variables on per capita emissions.

The ranges for the fixed effects were selected based on the median GDP per capita of the countries in the dataset, which was only $1,600. This relatively low median can be attributed to the fact that the dataset includes many developing countries and contains time-series data that spans several decades, including many recently independent states that were beginning to form modern institutions and had comparatively lower living standards than the developed nations of the time.

Table 3

	Dependent variable:Per Capita Emissions
	Per Capita Emissions
	(1)
Average household size (number of members)	-0.701***
	(0.254)
GDP_Range_2000 > 1000	0.308
	(0.549)
GDP_Range_< 1000	0.256
	(0.589)
GDP_Range_>2000	3.403***
	(0.324)
Population Density	0.001***
	(0.000)
const	3.966***
	(0.908)
Observations	151
R^2	0.415
Adjusted R^2	0.399
Residual Std. Error	2.866 (df=146)
F Statistic	25.934*** (df=4; 146)
Note:	*p<0.1; **p<0.05; ***p<0.01

We can immediately see that the household size effect has decreased meaning that some of its effect on emissions had to do with its correlation or negative correlation with household size. Nevertheless, the effect remains significant at the 1% level.

The regression table provides greater clarity into the specific effects of GDP per capita on emissions. Our results show that there is no significant effect of a country's per capita GDP on emissions when the GDP is less than $2,000. Even a decrease to $1,000 has no significant effect on emissions. However, once a country's GDP per capita rises above $2,000, we observe a significant effect of the country's wealth on emissions. This suggests that the effect of wealth on emissions is not linear and is staggered. In other words, only after a country has achieved a certain level of development will further wealth development lead to higher emissions. Therefore, the causal effect of GDP per capita on emissions is not linear.

Third Regression: Bagging Urban Characteristics

Specification:

$$\min_{j,s}\left[\sum_{i:x_{i,j}\leq s, x_i\in R1}(y_i-\hat{y}_{R1})^2+\sum_{i:x_{i,j}>s, x_i\in R2}(y_i-\hat{y}_{R2})^2\right]$$

For the all the regression trees the model will seek to reduce MSE at every node, stopping when $|R|=$ some chosen minimum size or when depth of tree = some chosen maximum. In this case, to optimize the accuracy of the regression tree while maintaining its interpretability and graphical clarity, a maximum depth of 4 will be selected as the regularization parameter, thereby minimizing the mean squared error. Anything higher would be very difficult to graph, as well as risk overfitting the data.

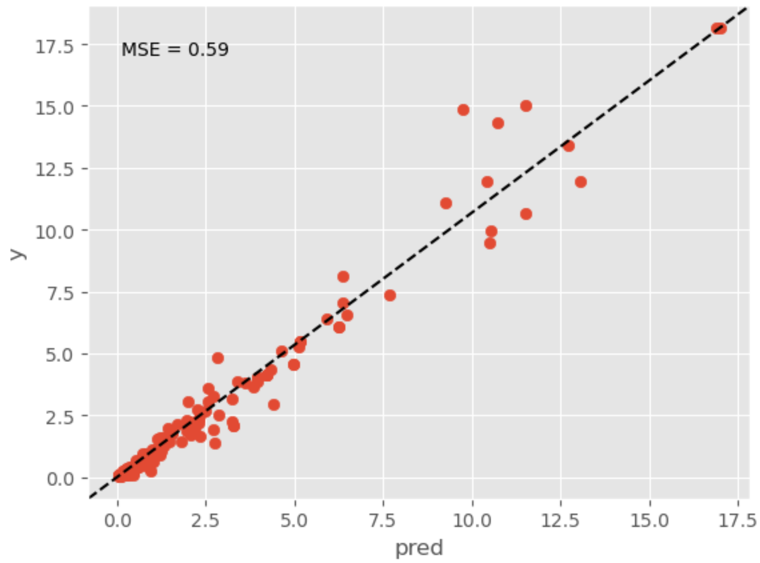
The bagging method involves training a model on multiple samples to reduce MSE, and is a more accurate way to quantify the relationships between dependent and explanatory variables. It does not rely on assumptions about the linearity of the data. By using this method, we can determine the importance of each variable and lay the groundwork for future studies. This may include using more robust statistical methods like IV, Diff and Diff to precisely measure the effect of household size on emissions, and develop policy suggestions based on the findings.

As is seen in Plot 11, this model is much more accurate than the one calculated using OLS regressions, with an MSE of 0.587 and a very high R-squared of 0.956, in other words creating a model that predicts nearly all the variance the per capita emissions data and is even more predictive of emissions than the previous regression tree modeling the effects of the emission source on per capita emissions.

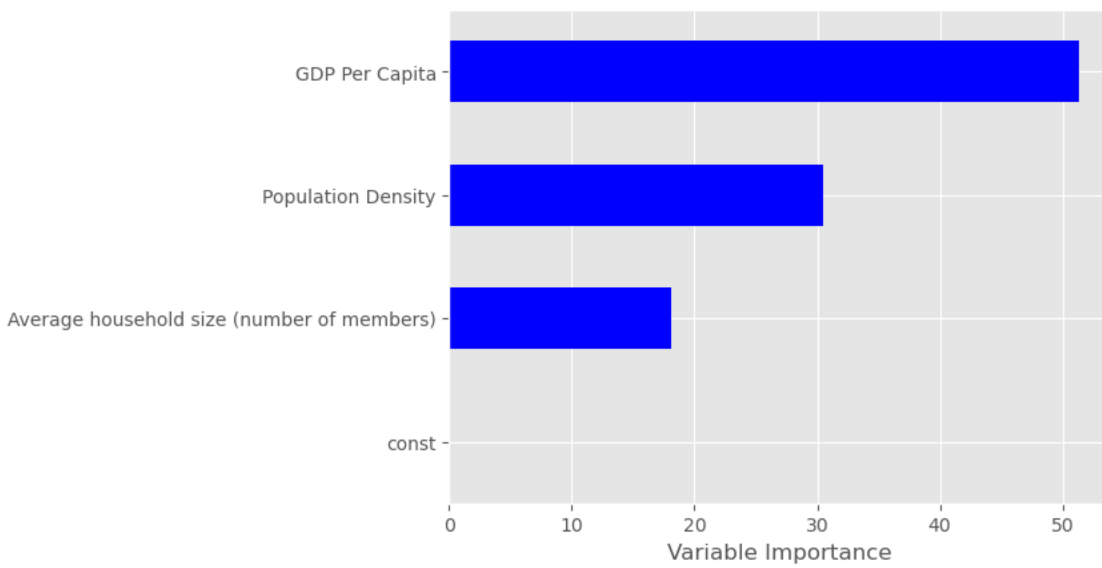
In addition, the model also shows that the inclusion of GDP per capita and population density increases the model's accuracy by around 50% and 30% respectively, while average household size only increases accuracy by around 20% (Plot 12). These results contradict the significant effects of household size found in the previous OLS regressions. One potential explanation for this could be that GDP per capita and population density both have strong non-linear effects on per capita emissions that were not captured by the OLS model. This was hinted at previously when we found that per capita wealth was significant and had the biggest coefficient when it was above $2000 in the GDP per capita fixed effects. A similar test could be done to determine the effect of population density as well.

It is important to note that the relatively low contribution of household size to the model does not necessarily disprove our thesis. While it only explains around 20% of the variance in emissions in our model, household size could still be a significant factor in understanding emission patterns and developing effective strategies to reduce total emissions and mitigate the impact of climate change. This is particularly relevant given the dearth of research on this factor in the context of climate change. Therefore, further investigation and exploration of the potential role of household size in driving emissions is warranted.

Plot 11



Plot 12



6. Conclusion

The main results of this paper can be summarized into two main findings: Firstly, the regression analysis shows that oil emissions are statistically significant in determining per capita emissions, they have a non-linear effect on per capita emissions and have a significant impact on the consumption of other energy sources. Secondly, the analysis also shows that household size has a significant negative linear effect on per capita emissions.

For the first point, we can examine the significance of oil in regressions 1 and 2. However, the most compelling evidence supporting this conclusion is the significant impact of oil emissions on per capita emissions accuracy, which is more than 80%. There are several reasons why this might be the case, such as the high emissions associated with oil (the second-largest source after coal), potential correlation with wealth (the process of receiving processed oil may require a developed trade network), or temporarily abundant supply. However, the most plausible reason is oil's dual effect as a substitute for coal and renewable energy, as demonstrated in Bloch et al.'s 2015 paper on energy source substitution in China. An increase in oil consumption is traditionally framed as a moving away from coal consumption, however, as this oil consumption keeps increasing it begins to crowd out other energy sources including low-carbon energy sources like nuclear or solar energy.

For the second point we can look at regressions 3,4 and to a certain extent 5 as well, as they demonstrate the robust effect of household size when different variables are included. We get to see that in all these regressions household size has a negative effect on emissions, whether that be total or oil emissions. These figures confirm Ellsworth-Krebs results on floor space and energy efficiency and builds upon her conclusion y by including the types of emissions that influence per capita emissions the most, as well as controlling for wealth and density,

7. Discussion and Next Steps

In order to provide more concrete policy recommendations, further research is necessary to determine the exact mechanism through which household size impacts emissions. One potential direction for future research is to explore the relationship between household size and oil emissions, given the latter's outsized influence and potential as an exogenous variable between household size and emissions. However, to establish household size's exogeneity to per capita emissions, relevance to oil emissions, and to prove the exclusion restriction is valid, more data and interpretation are needed. This paper provides an initial exploration of this topic, as seen in Appendix.

Other potential avenues for future research could include investigating the relationship between mean climate and energy consumption (to control for AC and heating energy usage), examining the relationship between car usage and density or household emissions, or even exploring the impact of government type on emission sources (such as whether dictatorships may prioritize economic development over the common good).

8. Appendix

A1: Regression on per capita emissions, using emissions sources

	Dependent variable:Per Capita
	Per Capita Emissions
	(1)
Cement	-0.042***
	(0.009)
Coal	0.002***
	(0.001)
Flaring	0.022
	(0.020)
Gas	0.010***
	(0.002)
Oil	-0.004***
	(0.001)
Other	0.011
	(0.029)
const	3.791***
	(0.112)
Observations	21,697
R^2	0.002
Adjusted R^2	0.002
Residual Std. Error	16.350 (df=21690)
F Statistic	8.980*** (df=6; 21690)
Note:	*p<0.1; **p<0.05; ***p<0.01

A2: Regression on per capita emissions with squared oil effect

	Dependent variable:Per Capita
	Per Capita Emissions
	(1)
Cement	-0.011
	(0.009)
Coal	0.000
	(0.001)
Flaring	0.084***
	(0.021)
Gas	0.016***
	(0.002)
Oil	0.001
	(0.001)
Oil_squared	-0.000***
	(0.000)
Other	0.016
	(0.029)
const	3.595***
	(0.114)
Observations	21,697
R^2	0.007
Adjusted R^2	0.007
Residual Std. Error	16.310 (df=21689)
F Statistic	23.017*** (df=7; 21689)
Note:	*p<0.1; **p<0.05; ***p<0.01

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