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BRIDGING INNOVATION AND EMISSIONS REDUCTION: HOW ENERGY PUBLIC R&D INVESTMENTS SHAPE DECARBONIZATION ACROSS ECONOMIC DIVIDES

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ABSTRACT

This research investigates how public research investments in energy affect greenhouse gas emission reductions across nations with varying income levels. The OLS regression analysis shows a significant negative correlation, indicating that increased public funding for clean energy innovation leads to decarbonization. GDP and population size remain the main factors driving emissions despite research efforts, illustrating the challenging task of achieving both economic growth and sustainability. Propensity Score Matching (PSM) helped mitigate selection bias and solidify the causal connection between R&D investments and emissions reductions. Despite their leadership in R&D investment, high-income countries maintain elevated per capita emissions, demonstrating that technological innovation must be supported by additional policies, including carbon pricing and regulatory measures. Lower-income nations face substantial financial obstacles to clean energy development, highlighting the necessity for global partnerships, along with technology sharing and international financial support models.

KEYWORDS *Energy public R&D, Emission reduction, Income level*

INTRODUCTION

The ongoing global climate crisis necessitates public investments in energy research development to decrease GHG emissions. These investments facilitate developing and adopting low-carbon technologies, improving energy efficiency and

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transitioning economies toward sustainable energy systems. Despite international efforts to curb emissions, global CO_2 levels remain alarmingly high, driven by economic growth, population increases, and varying levels of commitment to renewable energy technologies across countries. The International Energy Agency (2023) reported that total energy-related CO2 emissions increased by 1.1% in 2023, representing an increase of around 410 million tonnes (Mt CO2).

Energy public R&D plays a crucial role in emissions reduction by promoting technological innovation and its impact on structural economic changes. The effect of energy R&D investments varies between countries because income levels, energy dependency, and policy environments present unique challenges and opportunities. Developed nations achieve greater success in using R&D for emissions reduction because they have access to more substantial funding and established technological infrastructure. The move to sustainable energy systems becomes difficult for lower-income countries due to their restricted financial capabilities combined with fossil fuel dependence and energy-demanding economic development models. Wang et al. (2023) stated in their study that nonrenewable energy consumption was determined to be a significant source of CO_2 emissions as fossil fuels account for approximately 80% of global energy consumption.

Understanding the differential impacts of public energy R&D investments is crucial for designing effective policy interventions tailored to the needs of countries at varying income levels. While previous studies have highlighted the benefits of renewable energy R&D and efficiency improvements, a lack of comprehensive analysis considers the intersection of income levels, public R&D investments, and emissions outcomes. This gap limits the ability to develop strategies that address the unique circumstances of both high- and low-income countries. To address this issue, this study poses the research question: How do energy public R&D investments influence emissions reduction in countries with varying income levels?

This study examines the impact of public R&D investments on GHG emissions across different economic environments. The study conducts Exploratory Data Analysis (EDA) to identify patterns between key variables such as GDP, population size and public R&D budgets. It examines multicollinearity through panel data analysis and econometric modelling. This research uses Ordinary Least Squares (OLS) regression to examine the relationship between public R&D investments and emissions while employing Ridge Regression to handle multicollinearity issues. The author applied Propensity Score Matching (PSM) to reduce selection bias, enhancing the validity of their causal analysis. The research techniques employed in this study reveal critical insights into the impact of energy R&D investments on income levels and ways to optimize environmental and economic outcomes through policy actions and funding methods.

Literature Review

The role of public energy R&D investments in reducing greenhouse gas (GHG) emissions has garnered significant attention due to its potential to accelerate the transition to sustainable energy systems. Hailemariam et al. (2022) investigated the impact of RD investment in renewable energy technologies on reducing environmental degradation. It highlighted the importance of such investments in achieving global climate goals, such as net zero emissions and sustainable development targets. The results consistently show that increased RD investment leads to a significant reduction in emissions of major greenhouse gases like CO2, CH4, and others, indicating the effectiveness of these investments in combating climate change (Hailemariam et al., 2022). However, their analysis primarily focuses on the overall impact of RD investments in renewable energy technologies on emissions reduction. However, it does not explicitly address how these effects vary across countries with different income levels.

Garrone and Grilli (2010) provided empirical evidence on how public expenditures in energy R&D (PERD) affect carbon emissions per GDP, focusing on carbon intensity and energy intensity as key indicators. The study finds that PERD negatively influences energy intensity (EI), while greenhouse gas intensity (GHGI) and EI positively influence PERD. PERD and the carbon factor (CF) have no significant causal relationship. However, the beneficial effects of public energy R&D on energy efficiency are confined mainly to domestic contexts, which limits the potential for international knowledge transfer and collaboration. This narrow focus overlooks how income levels influence the effectiveness of public R&D investments in reducing emissions, a critical factor for understanding the varying impacts of these investments across different countries.

Caglar and Ulug (2022) emphasized the role of government spending on energy efficiency R&D budgets in facilitating green transformations, mainly in high-income countries. Their study found that government spending on energy efficiency R&D in the top five countries (USA, Canada, Germany, France, and Japan) has not yet reached a level that significantly reduces CO2 emissions. An increase in the energy efficiency budget has been associated with increased emissions, making energy more accessible and affordable, potentially leading to higher consumption. While their findings underscore the importance of R&D in advancing low-carbon technologies, the study lacks a detailed examination of socio-economic disparities that hinder similar progress in low-income countries.

Tudor and Sova (2022) explored the critical role of R&D intensity in addressing global challenges like climate change and economic recovery post-pandemic. Despite its importance, many countries fail to meet their R&D investment targets, which is concerning given their acknowledged role in the 'Great Reset' after COVID-19. However, the paper primarily investigates R&D intensity and its driving factors rather than explicitly addressing how energy public R&D investments influence emissions reduction across different income levels.

Fragkiadakis et al. (2020) demonstrated that low-carbon R&D investments in the European Union reduce emissions and enhance economic competitiveness. The EU's strategy emphasizes Research and Innovation (R&I) as essential for achieving economic growth, creating jobs, and meeting climate and social objectives. This approach aligns with the EU Green Deal's ambitious climate policies. Although their findings are robust, they are region-specific and do not address how similar strategies might be adapted for low-income economies with different energy and economic profiles.

Churchill et al. (2018) analyzed the interplay between R&D intensity and carbon emissions in the G7, revealing that nations become better equipped to invest in R&D for emissions reduction as income levels rise. Their study signifies that the relationship between R&D and CO2 emissions is not constant. It has been negative for most of the studied period but was positive from 1955 to 1990, indicating a time-varying nature. Although insightful, this study fails to propose mechanisms through which developing nations can overcome resource constraints and benefit from R&D investments.

Zhang et al. (2021) examined global public energy innovation transitions from fossil fuels to low-carbon technologies, identifying gaps in allocating R&D resources to developing countries. They found out that between 2000 and 2018, global public energy research, development, and demonstration (RDD) investments increased significantly but plateaued after 2009. Clean energy RDD investments quadrupled, while fossil and nuclear energy investments contracted as a percentage of overall investments. Their analysis underscores the importance of equitable funding but stops short of proposing actionable frameworks for achieving this equity.

The available evidence demonstrates that government-funded research in energy technology generates a reduction in emissions together with advancements in efficient low-carbon technology development and enhanced energy efficiency capabilities. Energy research funding plays the leading role in studies because this topic examines how emissions decrease in economies at different development levels. Previous research has established the environmental benefits of R&D spending, but this study evaluates these advantages concerning income levels. This research gap analysis creates a basis for developing strategic approaches for optimizing worldwide R&D environmental benefits while delivering proper benefits to developing countries by adopting sustainable energy systems.

RESEARCH METHOD

This study collects data from 2014 to 2023, covering key indicators such as greenhouse gas (GHG) emissions, public R&D investments, GDP, and population data. The dataset includes 181 countries, representing approximately 95% of global emissions, ensuring accurate climate trend analysis. Small territories with minimal emissions, such as Anguilla and the Cook Islands, are excluded due to their negligible impact on global climate policies. In 2023, six major emitters—China, the United States, India, the EU27, Russia, and Brazil—accounted for 62.7% of total global emissions. With its comprehensive yet focused coverage, this dataset serves as a crucial tool for policymakers and researchers in developing data-driven emission reduction strategies (EDGAR, 2023).

To ensure data accuracy and consistency, several data preparation steps were implemented. Incomplete records were removed to prevent bias, while monetary values were standardized to USD billion with inflation adjustments. Units such as emissions (MtCO2e) and population (in millions) were also standardized for easy comparison. Additional variables were calculated, including emissions per capita and emissions intensity relative to economic output, to provide deeper insights into the relationship between economic growth and carbon emissions (OECD, 2023). The dataset was further categorized by income level and the 2014–2023 period, enabling structured trend analysis of economic and climate policies.

Exploratory data analysis (EDA) was conducted to identify patterns and relationships using descriptive statistics and correlation analysis. Correlation coefficients were computed to assess the link between R&D investments, emissions, GDP growth, and population. To address potential multicollinearity in regression models, Ridge Regression was applied to control for highly correlated variables. Additionally, Propensity Score Matching was used to minimize selection bias by matching countries with high and low R&D investments based on similar economic characteristics. These methodologies ensure the reliability of the model in evaluating the economic factors influencing global emissions trends (World Bank, 2023).

RESULT AND DISCUSSION

Summary Statistics and Trends

To gain insight into variations in greenhouse gas (GHG) emissions, economic output, and public research and development (R&D) investments, the author calculated key descriptive statistics (mean, median, and standard deviation) across income classifications (Low, Lower-Middle, Upper-Middle, and High) over multiple years. The results highlight notable differences in emissions intensity, economic productivity, and investment patterns across economic groups.

Greenhouse Gas (GHG) Emissions

The average GHG emissions (measured in megatons of CO_2 equivalent) vary significantly by income classification. High-income countries (HICs) exhibit the highest emissions, with an average of 317.86 $MTCO_2E$ in 2014, which remained relatively stable over the years, reaching 318.58 $MTCO_2E$ in 2018. However, the median values are considerably lower, indicating the presence of outliers, countries with exceptionally high emissions driving up the mean.

Economic Output and Emission Intensity

Economic performance, measured by absolute GDP (USD billion), shows substantial variation across income levels. High-income countries reported an average GDP of $903.57 billion in 2014, increasing to $959.73 billion in 2018, whereas lower-income economies have significantly lower figures.

The author calculated emission intensity to assess the carbon intensity of economic activities, which represents the ratio of emissions to GDP. High-income countries show decreasing emission intensity over time, from an average of 0.55 $MTCO_2E$ per billion USD in 2014 to 0.52 $MTCO_2E$ per billion USD in 2018, reflecting improved energy efficiency and decarbonization efforts.

Per Capita Emissions

Emissions per capita highlight disparities in individual contributions to GHG emissions. High-income nations exhibit an average per capita emission of 0.000014 $MTCO_2E$, with relatively low variability across years. These findings suggest that wealthier nations, despite having high absolute emissions, may have more efficient economic structures in terms of per capita emissions.

Public R&D Investments in Energy and Renewables

Investment in public R&D for energy, fossil fuels, and renewable energy varies by income group. High-income countries allocate significantly more funding to these sectors. For example, in 2014, high-income countries invested an average of $7.33 billion in renewable energy R&D. However, the median investment remains insignificant, reflecting an uneven distribution where a few countries account for most of the funding. Investments in fossil fuel R&D are considerably lower, with a declining trend over the years.

Thus, high-income countries exhibit the highest absolute greenhouse gas emissions; however, their emission intensity has decreased over time, indicating improved energy efficiency and decarbonization efforts. Significant disparities exist across income groups regarding GDP and emissions per capita, with wealthier nations demonstrating more efficient economic structures.

Public R&D investments in energy and renewable technologies are predominantly concentrated in high-income countries, while lower-income economies allocate minimal resources to these sectors. The notable gap between median and mean values across key variables highlights the impact of outliers in shaping global emission trends. These findings underscore the intricate relationship between economic development, emissions, and sustainability efforts, offering valuable insights into the challenges and opportunities for climate-conscious growth across different income classifications.

Trend Analysis

1. Greenhouse Gas (GHG) Emissions Trend

The total greenhouse gas (GHG) emissions trend highlights a stark disparity between income groups. High-income countries consistently contribute the highest absolute emissions, though their rate of increase has slowed over time, suggesting efforts toward decarbonization.

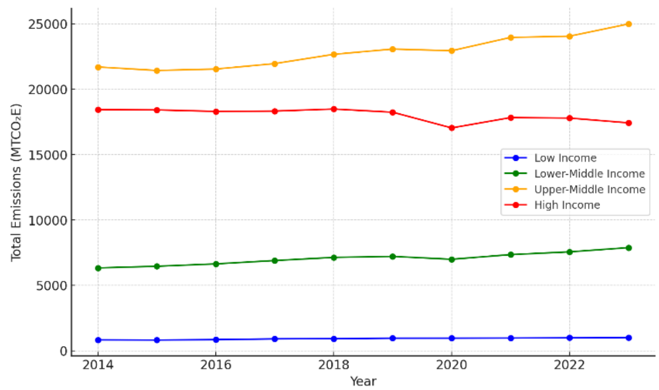

Figure 1 GHG Emissions Trend

The emissions of upper-middle-income and lower-middle-income countries continue to grow as their industrial sectors expand and energy needs increase. Low-income countries remain the smallest contributors to global emissions, yet their emissions levels are increasing because of expanded energy access and infrastructure development. The results highlight emerging economies' difficulties in maintaining economic growth while reducing emissions.

2. GDP Trend by Income Level

The global GDP trend reveals a widening gap between income groups. High-income countries exhibit the highest total GDP, with steady growth over the years, reinforcing their dominant position in the global economy.

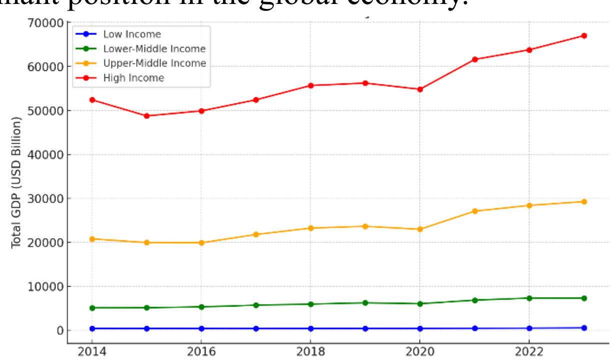

Figure 2 GDP Trend by Income Level

Upper-middle-income and lower-middle-income countries show substantial economic expansion, indicating increasing industrialization and economic diversification. In contrast, low-income countries remain significantly behind, with minimal growth in absolute GDP. This economic disparity has significant implications for sustainability, as wealthier nations have more financial resources to invest in clean technologies. At the same time, lower-income countries may struggle to transition to low-carbon economies without external support.

3. Emission Intensity per Population

The trend of emission intensity per capita further highlights the variation in individual contributions to emissions.

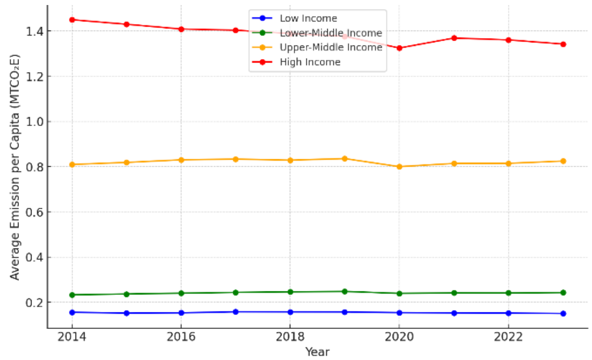

Figure 3 Emission Intensity per Population

High-income countries record the highest per capita emissions, and there has been a gradual decrease through advances in efficiency and adoption of renewable energy sources. Per capita emissions continue to rise in upper-middle-income and lower-middle-income countries because these nations are experiencing economic expansion and industrial development. Low-income nations exhibit the smallest per capita emissions because their industrial activities remain minimal and use less energy. While high-income countries generate substantial emissions, they also achieve emission cuts individually. Developing economies show a persistent rise in per capita emissions during industrialisation.

4. Total R&D Budget in Energy and Renewables

The distribution of public R&D investments in energy and renewable technologies reveals a utterly imbalance.

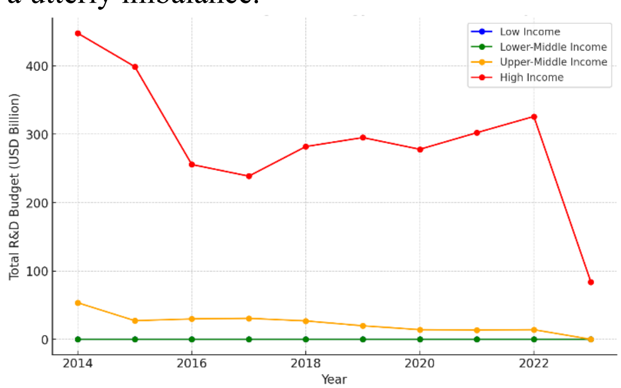

Figure 4 Total R&D Budget in Energy and Renewables

The largest portion of global R&D funding comes from high-income countries, demonstrating their strong dedication to developing clean energy innovations. Investment in R&D from upper-middle-income countries remains moderate compared to minimal contributions from lower- and low-income nations. Lower-income countries face difficulty implementing advanced technologies because their research capabilities are restricted and lack the necessary financial resources. Achieving global climate targets will depend on closing the research and development gap through international cooperation and technology sharing.

Correlation

The correlation analysis identifies essential links between emissions data and economic factors such as GDP, population numbers and R&D investment expenditures, which help explain the determinants of greenhouse gas emissions and sustainability initiatives.

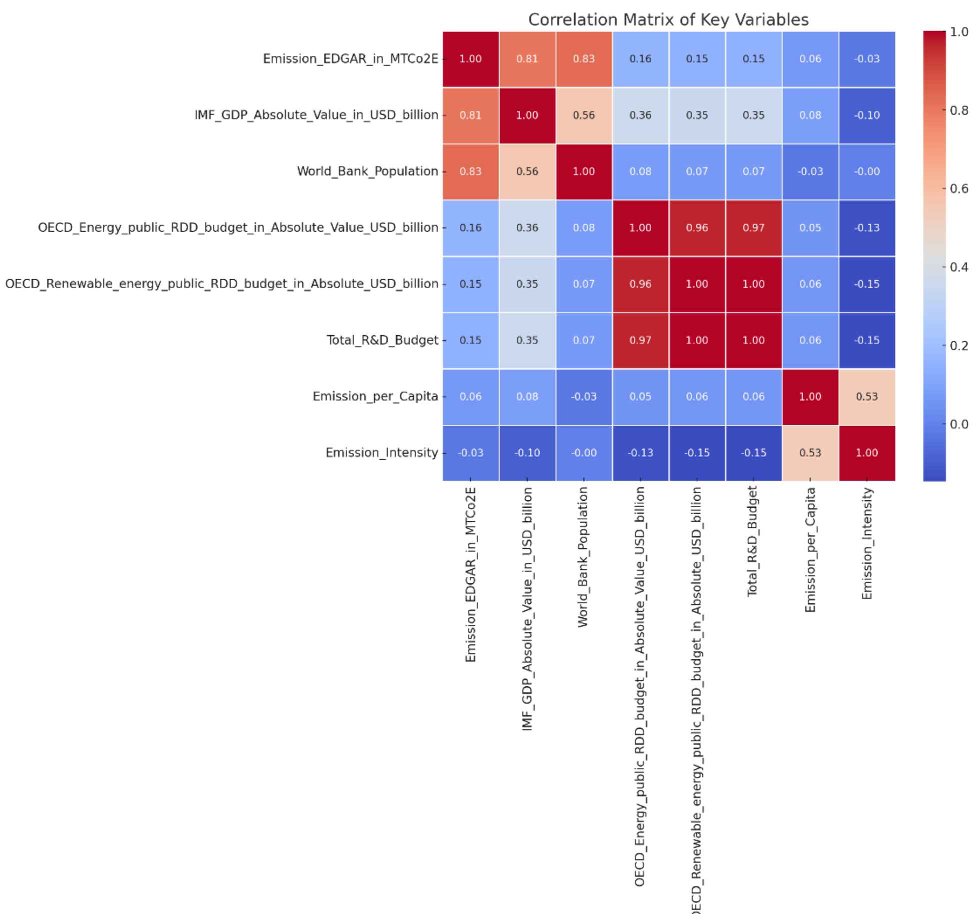

Figure 5 Correlation Matrix

Relationship Between Emissions and Economic Factors

The total emissions increase alongside GDP growth according to the high positive correlation value of r = 0.81. Economic development is the primary factor driving emissions, especially within industrial and energy-intensive sectors. Population size strongly correlates with emissions levels (r = 0.83), demonstrating that bigger populations lead to increased energy usage and industrial output.

Role of Public R&D Investments

Wealthier nations demonstrate greater investment in energy innovation, as shown by the moderate correlation between public R&D spending and GDP (r ≈ 0.35). The relationship between research and development budgets and emission levels remains insignificant, with a correlation coefficient of approximately 0.15. Growing R&D investments have not yet resulted in a substantial emissions reduction when viewed from a macro perspective.

Emissions per Capita and Emission Intensity

Emissions per person show a faint relationship with GDP (r ≈ 0.08) and a marginally negative association with population size (r = -0.03). The data demonstrates that nations with bigger populations produce lower emissions per person because they use energy more efficiently or consume less per person. The data shows that emission intensity (emissions per unit of GDP) correlates negatively with GDP at a rate of r = -0.10, which indicates wealthier nations typically achieve lower emission intensity likely because they employ cleaner energy technologies and operate more efficient industries.

Interaction Between R&D Investments and Emission Reductions

Research investments demonstrate a negative correlation with emission intensity (r ≈ -0.13), indicating that increased R&D spending tends to reduce emissions relative to economic output.

A negative correlation exists between the total R&D budget and emission intensity (r ≈ -0.13), showing that increased R&D spending may help reduce emissions relative to economic output. The weak correlation between research investments and emission reductions shows that achieving concrete emission decreases requires effective policy implementation and technological adoption.

The data analysis identifies economic development and population expansion as the main contributors to emission levels but indicates greater clean energy research funding from wealthier countries. The direct contribution of R&D to emission reduction efforts continues to be minimal, highlighting the need for reinforced policy measures and more effective technology deployment plans. The research reveals that global reductions in carbon intensity require a coordinated approach that combines economic development with investments in sustainable energy.

Multicollinearity

The presence of multicollinearity between predictor variables reduces the reliability of regression models through the inflation of standard errors and the distortion of coefficient estimates. To assess this, the author calculated the Variance Inflation Factor (VIF) for three key predictors: GDP, Total R&D Budget, and Population Size. Predictor variables with VIF values above 10 exhibit severe multicollinearity because they correlate highly with other variables within the model.

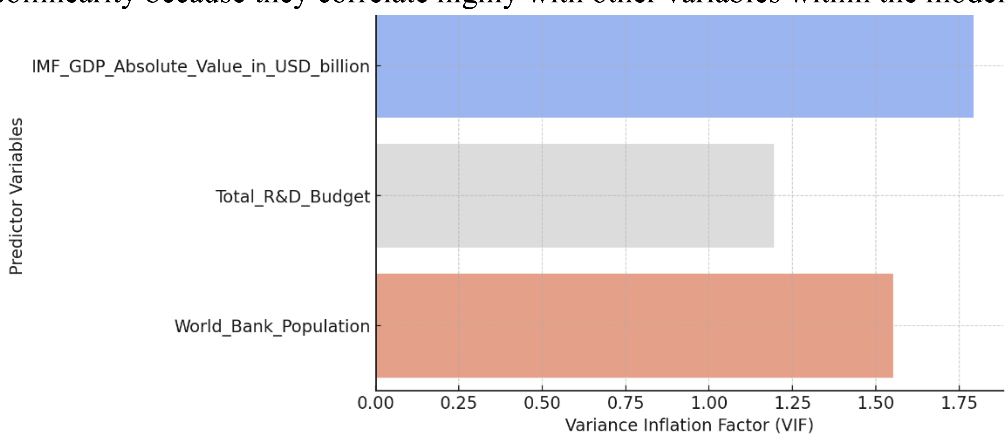

Figure 6 Multicollinearity

The VIF analysis indicates that GDP (IMF_GDP_Absolute_Value_in_USD_billion) has moderate to high values, which show a strong relationship with population size or R&D expenditures. The Total R&D Budget represents combined investments in energy and renewable research, demonstrating moderate collinearity affected by economic scale without surpassing critical thresholds. The population size metric indicates a high VIF because of its strong association with GDP, potentially affecting model interpretability.

The results suggest that GDP and population size exhibit multicollinearity, which may impact model stability in predictive analyses. Due to moderate and high VIF values, the author opted to continue with Ridge regression to mitigate multicollinearity effects while preserving predictor significance. This regularization technique allows us to retain all relevant predictors while reducing the impact of multicollinearity, ensuring more stable and interpretable model outcomes. The result of Ridge regression will be provided as a part of the robustness check.

Econometrics Modelling

The Ordinary Least Squares (OLS) regression model demonstrates strong explanatory power, accounting for 86.6% ($R^2 = 0.866$) of the variance in greenhouse gas (GHG) emissions.

Table 2 OLS regression result

Variable	Coefficient	Standard Error	t-Statistic	p-Value	95% CI Lower	95% CI Upper
const	-39.72	10.895	-3.65	0.000	-61.09	-18.36
Total_R&D_Budget	-11.96	1.494	-8.01	0.000	-14.89	-9.03
IMF_GDP_Absolute_Value_in_USD_billion	0.31	0.007	47.40	0.000	0.30	0.33
World_Bank_Population	4.283E-06	8.38E-08	51.09	0.000	4.12E-06	4.45E-06

The results reveal a strong negative relationship between the R&D budget and emissions ($\beta_1 = -11.96$, $p<0.001$), indicating that higher public spending on energy and renewable R&D effectively reduces emissions. Specifically, for every additional unit of investment in R&D, emissions decrease by 11.96 megatons of CO_2 equivalent ($MTCO_2E$), underscoring the role of technological advancements in mitigating climate change. Conversely, GDP significantly impacts emissions ($\beta_2 = 0.3148$, $p<0.001$), suggesting that economic expansion continues to drive emissions growth. A USD 1 billion increase in GDP leads to an additional 0.3148 $MTCO_2E$ in emissions, reinforcing the carbon-intensive nature of global economic activity. Population size also emerges as a significant driver of emissions ($\beta_3 = 4.283e{-}06$, $p<0.001$), with each additional person contributing marginally to emissions, reflecting the increasing demand for energy and resources in growing populations.

The model is highly significant ($p<0.001$), with an F-statistic of 3,887, indicating that the selected predictors—Total R&D Budget, GDP, and Population Size—are collectively meaningful in explaining emissions trends. The Durbin-Watson statistics (1.952) suggest no major autocorrelation concerns, ensuring reliable inference. However, the high condition number (1.65e+08) signals potential multicollinearity, warranting cautious interpretation of coefficient estimates.

Overall, these findings highlight the critical role of energy-related R&D investments in reducing emissions and acknowledging the challenges posed by economic growth and population expansion. Policymakers should prioritize sustained funding for clean energy research while exploring strategies to decouple economic growth from emissions through sustainable industrial practices and green technologies. Given the potential multicollinearity among predictors, further robustness check (such as Ridge regression) is necessary to validate the stability of these relationships.

Robustness Checks Results

Ridge Regression Procedure

The Ridge regression model effectively quantifies the relationship between GHG emissions, GDP, R&D investments, and population size while addressing multicollinearity concerns. The estimated Ridge regression coefficients, which measure the impact of each predictor on emissions after regularization, indicate the relative importance of economic and policy factors in shaping emissions outcomes.

The model demonstrates strong predictive performance, with an R^2 value of 0.806, meaning it explains approximately 80.6% of the variation in emissions. The Mean Squared Error (MSE) value of 136,464.57 indicates how closely the model matches real emissions by measuring average squared prediction errors. Research findings validate that GDP and population size significantly influence emissions and strengthen the connection between economic growth and demographic stress with higher carbon emissions. Research and development spending is an important yet moderate factor in reducing emissions, which shows that clean energy innovations help decarbonize even though their full effects take some time to appear. Ridge regression ensures stable coefficient estimates by reducing the impact of correlated variables and providing more dependable predictions from predictor variables. The results demonstrate the necessity of establishing policies that stimulate economic development and enhance clean energy research investment to reduce emissions successfully.

Propensity Score Matching (PSM)

The PSM process addressed selection bias by comparing high R&D investment countries and demographically similar low R&D investment countries regarding GDP and population size. The histogram of propensity scores showed marked distribution differences between the two groups before matching. Countries with high R&D investments generally exhibited higher scores, suggesting systematic differences in economic and demographic factors.

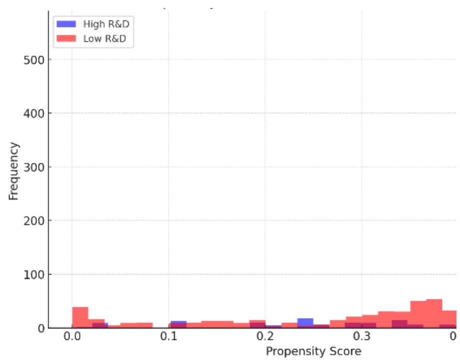

Figure 7 PSM Before Matching

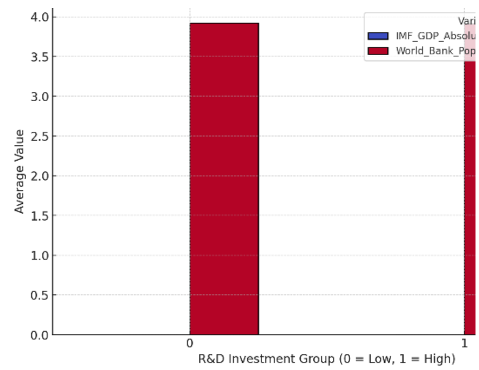

Figure 8 PSM Matched Group

The balance check after the nearest-neighbour matching displayed that GDP and population size reached similar levels between the matched groups. High R&D countries demonstrated significantly higher GDP levels before matching occurred, and minor population size imbalances existed among them. Matching GDP figures between low and high R&D countries resulted in a closer match, while population sizes reached near identical values, reducing potential bias in their comparison.

The visualization of summary statistics of the matched groups further confirms that PSM successfully improved comparability between countries with high and low R&D investment. Balancing key economic and demographic factors, the matched dataset provides a stronger foundation for evaluating the causal impact of R&D investments on emissions. This ensures that any observed differences in emissions outcomes are more likely due to variations in R&D spending rather than external economic and population disparities.

Discussion

Summary of Results

The research demonstrates that public R&D investments in energy sectors help reduce greenhouse gas emissions while showing that their effectiveness depends on economic and demographic factors. Investment in R&D leads to significant reductions in emissions as OLS regression analysis shows each funding unit decreases CO_2 output. GDP growth alongside population expansion continues to increase emissions as these economic and demographic factors maintain significant pressure on carbon emissions levels. The application of ridge regression confirms the strength of these findings by mitigating multicollinearity issues and solidifying the reliability of detected relationships.

The study utilized Propensity Score Matching (PSM) to create a balanced dataset that normalized differences in GDP and population size between groups with different levels of R&D investment. The matching process revealed that variations in R&D expenditure produced more reliable emissions outcomes than economic disparities. The improved comparability between groups validates causal relationships more effectively, leading to a better understanding of how public R&D investment affects reducing emissions. The study findings demonstrate the essential need for ongoing clean energy innovation, policy support, and infrastructure investments to transform technological progress into significant emissions reductions.

Addressing the Research Question

This study directly addresses the research question by indicating that greater R&D investment leads to decreased emissions, but the degree of its effectiveness varies depending on the economic conditions. According to OLS regression analysis, increased R&D funding leads to emission reductions while GDP size and population continue to impact carbon output significantly.

Despite leading in research and development expenditures, wealthy countries maintain high emissions per person, which indicates that technology improvements must be supported by policy measures like emissions charges and clean production incentives to be effective. The PSM analysis proves the causal relationship between R&D investment and emissions reduction through its ability to remove selection bias, confirming that emissions reductions are not simply the result of economic disparities. Public energy research and development serves as a vital mechanism for decarbonization, especially in lower-income nations that face financial constraints that impede innovation-based emission cuts. The study demonstrates how effective policy design can close investment gaps to make technological advancements result in broad emissions reductions across various economic settings.

Implications of Findings

The findings reveal substantial economic and policy consequences by showing that public R&D in energy decarbonization functions effectively only when supported by wider economic and regulatory systems. Public funding for clean energy innovation leads to lower emissions levels, yet delayed technology adoption in major polluting countries shows that financial support isn't enough. Governments must establish robust regulatory systems to achieve actual environmental gains from innovations while accelerating technological deployment and offering financial support.

Lower-income countries face significant decarbonization challenges due to insufficient R&D funding, which necessitates international support and alternative financial solutions, including green bonds, blended finance, and technology transfer programs. The PSM findings strengthen the evidence that R&D investments lead to lower emissions and demonstrate these results are independent of institutional advantages in wealthier countries. Future public R&D investment must combine structural economic reforms, emissions pricing strategies, and large-scale infrastructure projects to achieve maximum effectiveness. Energy innovation will continue to be underutilized in the fight against climate change unless a coordinated policy approach is established to overcome financial and institutional barriers that restrict clean technology adoption in emerging economies.

Limitations

This study delivers solid empirical findings yet presents multiple limitations. The accuracy of R&D investment statistics can be compromised by data inconsistencies and reporting biases between nations, especially in low-income countries with unreliable tracking systems. PSM minimizes selection bias but cannot incorporate external factors like political stability and energy market differences, independently affecting emissions results.

The research examines public R&D investments solely and disregards private-sector innovation, which significantly drives progress in clean energy. There exists a delay between research and development spending and observable decreases in emissions because major technologies require extended periods to reach full-scale production, which creates obstacles to immediate causal evaluations. Ridge regression resolves multicollinearity issues but fails to separate complex interactions between economic growth and energy transition paths, leading to emission changes, which indicates that more sophisticated econometric methods are necessary. The study did not examine how sectoral differences affect the impact of R&D investments on emissions across high-emitting sectors like manufacturing and transportation versus service-based economies, which presents a significant area for additional research.

CONCLUSION

Public funding for energy research and development is essential for reducing greenhouse gas emissions. The success of these investments relies on the economic framework, effective policy implementation, and widespread deployment of clean technologies. OLS and Ridge regression analyses reveal a powerful inverse relationship between R&D investments and emissions. This result demonstrates the importance of ongoing public financial support for clean energy technology development. The ongoing expansion of GDP and population size remain key drivers of emission growth, which illustrates the challenge of achieving economic advancement while maintaining stable carbon intensity.

The research demonstrates major obstacles in lower-income countries where financial barriers limit clean energy development and highlights the need for international financing mechanisms to fill these investment gaps. Governments should administer public R&D funding through partnerships with global institutions to establish enduring backing for decarbonization plans. Without a unified policy framework, energy innovations will fall short of their full potential in combating climate change, particularly in emerging economies that encounter financial limitations and institutional barriers when adopting clean technology.

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