Economic Analysis of the Potential for Nuclear Energy Investment in Eastern Europe

By
Nelson van de Lindt

A THESIS

submitted to

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Honors Baccalaureate of Science in Economics and Computer Science
(Honors Scholar)

Presented June 7, 2023
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AN ABSTRACT OF THE THESIS OF

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Abstract approved:____

Grant Jacobsen

This paper contributes to the ongoing discussion on the impacts of nuclear energy on the economy and energy security of select European countries. While previous literature has identified a connection between nuclear energy and economic growth, this study focuses on assessing the comparative effects of nuclear energy, measured by operable nuclear power capacity (MWe), on energy self-sufficiency across a range of European countries. By employing a two-way fixed effects model, this study analyzes the potential relationship between nuclear energy capacity and energy self-sufficiency while accounting for various factors that influence both variables. To ensure the robustness of findings, collinearity was examined using the variance inflation factor (VIF), which gauges the presence of multicollinearity among independent variables. Additionally, stationarity was investigated through unit root tests (ADF test) to assess the long-term behavior of the variables under inspection. This analysis reveals compelling results, suggesting that investment in nuclear energy has the potential to enhance energy self-sufficiency for multiple European countries, with a particular emphasis on certain Eastern European nations. By exploring the specific effects of nuclear energy capacity on energy self-sufficiency, this study provides valuable insights for policymakers, private nuclear companies, and researchers interested in the sustainable development of advanced nuclear energy systems in Europe.

Keywords: Nuclear Energy, Econometrics, Economic Analysis, Energy Economics

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

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Introduction

Carbon neutrality has been at the forefront of policy discussion among many countries. Claims of national carbon neutrality at some future date have been made with disappointing results on the path to fruition. As irreversible climate damage continues to emerge, the need for fast carbon neutrality is becoming more prevalent. Nuclear energy may be one of the only technologies that can achieve many countries' lofty climate goals. Nuclear reactors provide a level of stability that alternative energy production methods cannot rival. The capacity factor of nuclear in 2020 was measured to be 92.5% with the next closest source being geothermal at 74.3% capacity (Office of Nuclear Energy, 2021). Beyond capacity, nuclear reactors can provide district heating, desalination when located near coasts, and hydrogen production to store and use excess power in low energy demand times as discussed by Nuclear Process Heat for Industry (2021).

Despite this plethora of benefits, nuclear energy has been excluded from many climate action policies due to a stigma of fear and disapproval (Leppert, 2022; Nuclear Energy Agency, 2020). In the realm of energy systems and economic development in Europe, the role of nuclear energy has been subject to scrutiny and debate. The effect of these beliefs is nuclear energy's exclusion from renewable energy initiatives and the implementation of nuclear phase-out policies (World Nuclear News, 2018). These policies may have unintended effects due to the changes in energy security, and the corresponding stability of national power grids. Particularly in the European context, where a diverse range of countries are grappling with distinct socioeconomic and political conflicts, a nuanced investigation into the effects of nuclear energy on energy security through energy self-sufficiency becomes paramount. These concerns include energy security decreases due to dependencies on crude oil and natural gas imports from Russia during the current invasion of Ukraine. As nations strive to meet their energy demands while simultaneously addressing concerns about sustainability and energy security, understanding the impacts of nuclear energy on various aspects of national economies and energy grids becomes imperative.

Evaluating the effects of the initial implementation of nuclear energy in a country and determining the effects of nuclear energy on energy self-sufficiency can shed light on the impact of nuclear energy investment from a perspective of realized energy security gain. Similarly, an investigation into nuclear phase-out policies such as Germany's "Energiewende" serves as a cautionary case study to explore the impact of nuclear energy's exclusion from climate policies. Energiewende was enacted to remove the use of thermal power (coal, nuclear, and others). The goal of this policy was to rapidly move to renewable energy production. The exclusion of nuclear from this policy was due to fear associated with the recent (at the time of formulation) Chernobyl and Fukushima disasters. A review of the literature on the impacts of nuclear energy on economic growth and energy security can frame the macro effects contributing to the case for nuclear energy in Eastern Europe.

Nuclear phase-out policies are often reactionary to protests and claims of safety issues. Modern advanced nuclear energy systems push the overall risk of new nuclear energy investment to a level comparable to (or below) alternative power sources (World Nuclear Association, 2022). This already declining risk is falling as technology continues to evolve with passive safety systems, small modular nuclear reactors, safe onsite fuel storage, and other forms of innovation. By excluding nuclear energy from climate policy, nations may be decreasing their ability to move toward renewables in transitionary phases as seen with Germany's Energiewende. Deeper impacts on economic development may also play a role in quantifying the effects of nuclear energy investment. Research has been conducted on the causal relationship between nuclear energy and economic development (Apergis et al., 2010; Yoo & Ku, 2009; Chu & Chang, 2012; Omri et al., 2015). By examining these studies, the opportunity cost or lost economic development value from excluding nuclear energy in climate initiatives can begin to be understood. A cautionary focus on an existing nuclear phase-out policy in combination with causal explorations of nuclear energy and economic development can help frame the effects of nuclear energy implementation on energy security and economic development.

This study seeks to contribute to the ongoing discourse by delving into the comparative effects of nuclear energy, as measured by operable nuclear power capacity, on the critical aspect of energy self-sufficiency within European countries. To accomplish this objective, a rigorous analytical framework is employed, leveraging the power of a two-way fixed effects model. This approach aims to elucidate the dynamic trends that emerge from the empirical analysis.

Furthermore, to enhance the credibility of findings potential challenges arising from collinearity, are addressed by employing the variance inflation factor (VIF) as a diagnostic tool. This enables the assessment and mitigation of any concerns of multicollinearity that may impact the robustness of the results. Additionally, given the significance of stationarity in time series analysis, unit root tests are conducted to verify the stationarity properties of the variables under investigation. This step promotes the validity of the analysis and provides a solid foundation for the interpretation of results.

Ultimately, this study aims to shed new light on the implications of nuclear energy for energy self-sufficiency in European countries. By examining a wide range of European nations and employing a comprehensive analytical framework, this study endeavors to contribute to the existing body of knowledge, providing valuable insights for policymakers, private nuclear energy companies, and other stakeholders in their pursuit of sustainable and secure advanced nuclear energy system implementation.

Summary of Previous Literature

Previous literature regarding the impact of nuclear energy implementation suggests a relationship between nuclear energy to energy security and economic growth. Nuclear energy consumption and economic growth often establish a uni-directional or bi-directional causal relationship. This relationship prompts a positive feedback loop wherein nuclear energy consumption directly promotes economic growth. This growth then vivifies further nuclear energy consumption and production. To further highlight the positive relationship between economic growth and nuclear energy, the effects of Germany's Energiewende policy serve as a cautionary study for the impacts of nuclear's exclusion from climate policies. Empirical and theoretical research supports these causal linkages between economic growth and nuclear energy consumption. Nuclear energy has also been identified as a key component in climate policy due to its minimal carbon footprint and high-capacity factor resulting in increases to energy security.

Summary of the Literature - Nuclear Energy and Energy Security

Energy security has been a driving force behind the implementation of nuclear energy. With a high capacity factor of 92.5%, nuclear plants are well above other production methods according to the Office of Nuclear Energy (2021). This means nuclear energy is operating at peak energy production 92.5% of the time in any given period. A theoretical paper, Watson & Scott (2009), finds that there are other dimensions to consider when assessing energy security from nuclear energy production. The purpose of this paper is to explore how the construction of new nuclear plants in the United Kingdom can enhance the energy security of the country (Watson & Scott, 2009). This paper identifies the four common categories of threats to energy security - fossil fuel scarcity and external disruptions, lack of infrastructure and investment, technology and infrastructure failure, and domestic activism or terrorism.

In another theoretical study with the goal of exploring how China's energy security has changed over 30 years, Yao & Chang (2014), examines indicators (referred to as the 4-As) that are commonly used when assessing energy security including availability, affordability, applicability, and acceptability. The 4-As indicators share commonalities with the four threats to security explored by Watson & Scott (2009). Watson and Scott (2009) break down these threats in a table where threats, challenges, root causes, examples, effects, and possible indicators are all expressed for the different energy security threats. They then assess the current state of fossil fuel reserves against fossil fuel production using data from a 2007 British government report. This indicates the scarcity threat as oil prices rise. Next, they explore the energy mix of the UK focusing on the current security strategy of energy diversity. The paper then re-introduces the table of threats and concludes nuclear can be a solution for two or three of the four existing threats to energy security in the UK. They state that nuclear can be a solution for fossil fuel scarcity and external disruptions. They then find it will provide a solution for a lack of domestic investment in infrastructure. The threat determined in this category is insufficient capacity and storage to supply. The solution to security that nuclear energy provides is a capacity margin and limited load following. Meaning the production source can be running when needed and maintain its operational state of at least 92.5% capacity.

Similarly to Watson & Scott (2009), Yao & Chang (2014) quantitatively examines energy security indicators and risks for China and found nuclear to be a required component of China's new energy production investment initiatives. This theoretical paper takes a more quantitative approach as it explores the state of energy security in China using panel data from 1980 to 2021. The quantitative analysis uses a framework that investigates as many dimensions of energy security as possible while reducing complexity. This is done by taking raw data for 20 indicators that fall into the 4-As indicators for seven time periods in the given date range. The data is plotted in seven rhombuses that show the multivariate relationship between the 4-As for a given set of indicators in each time period. From their analysis, they were able to find that China's energy security had not improved for 30 years. They also found that the use of nuclear energy would be required to meet China's energy policy goals. Yao & Chang (2014) also state that a country defined as "energy secure" would have affordable energy resources, adequate energy diversity including nuclear energy, and address social and environmental concerns (Yao & Chang, 2014).

The importance of nuclear energy to foster energy security is further supported by the environmental aspect of energy security. With steep social and political environmental goals both Watson & Scott (2009) and Yao & Chang (2014) call on the importance of nuclear energy for energy security in the UK and China respectively. When examining China, it is found that to move past the 30-year stagnation of energy security China must decrease emissions. Yao & Chang (2014) note that investment in nuclear will be a required energy production method to achieve this decrease and meet China's climate goals.

Summary of the Literature - Economic Growth and Nuclear Energy

Another collection of papers (Apergis et al., 2010; Yoo & Ku, 2009; Chu & Chang, 2012; Omri et al., 2015) examine a causal relationship between nuclear energy consumption and economic growth. Using empirical methods, they find uni-direction and bi-directional causal relationships further illuminating the potential macroeconomic impact of new or additional nuclear energy investment.

Apergis et al. (2010) aims to highlight the causal dynamics between emissions, nuclear energy, renewable energy, and economic growth. The causal linkages between emissions of nuclear energy and economic growth found by Apergis et al. (2010) support the call for nuclear energy by Yao & Chang (2014) to reduce emissions in China. Apergis et al. (2010) explores this topic using an empirical approach. Their research involves a panel error correction model with panel data from 19 countries from 1984 to 2007. Their findings from a Granger causality test highlight the relationships between emissions, nuclear energy, renewable energy, and economic growth. The findings support the implementation of nuclear energy with a statistically significant (at 1%) negative association between nuclear energy consumption and emissions. This means as nuclear energy consumption increases emissions decrease in the long run. Interestingly their study found the opposite relationship between renewable energy consumption and emissions.

Three other empirical studies aim to highlight a causal relationship between nuclear energy and economic growth. Both Yoo & Ku (2009) and Chu & Chang (2012) use a Granger causality test, a similar approach to Apergis et al. (2010), in an attempt to highlight casual linkages between nuclear energy and economic growth. Omri et al. (2015), the third empirical study, uses a dynamic simultaneous-equation panel data method. Yoo & Ku (2009) specifically focus on six countries that have been using nuclear energy for at least 20 years. Their empirical methods for attempting to show a causal relationship include tests for unit roots, co-integration, and a Granger causality test. Their main purpose of finding causal relationships between nuclear energy consumption and economic growth proves fruitful. Yoo & Ku (2009) found a non-uniform relationship across countries. They found a uni-directional link, statistically significant at 1%, between nuclear energy consumption to economic growth in Germany and Argentina. This same link was found with feedback effects in Korea. Additionally, they found the opposite uni-directional link in France and Pakistan with feedback effects. The time series techniques implemented in this study used data from the world bank and BP. The focus of these sets is real GDP and nuclear energy consumption in the 20-year period preceding 2005. The time period selection was based on the availability of data.

Chu & Chang (2012) find a different relationship using G-6 countries between 1971-2010. The purpose of their empirical study was to test whether energy consumption causes economic growth. They find that nuclear energy consumption causes economic growth in the US, Japan, and the UK, statistically significant at 1%. However, in the US, the relationship appears to be bi-directional. Nuclear energy consumption was also found to provide no causal relationship in Canada, France, and Germany statistically significant at 1%. The different time periods between (Yoo & Ku, 2009) and (Chu & Chang, 2012) could account for the discontinuity between Germany in the two studies. Both studies use a Granger Causality Test and find causal linkages between nuclear energy consumption and economic growth with multi-directional relationships present in different countries.

Omri et al. (2015) also examines a similar question and aims to expand on the methods used to explore this causal relationship. Using dynamic simultaneous-equation panel data models on 17 countries they found both uni-directional and bi-directional causality similar to the previous two papers. This study found uni-directional causality from nuclear energy consumption to economic growth in Belgium and Spain, statistically significant at 5% and 10% respectively. They also found a bi-directional relationship in Argentina, Brazil, France, Pakistan, and the USA, statistically significant at 10%, 10%, 10%, 5%, and 10% respectively (Omri et al., 2015).

Summary of the Literature - Germany's Energiewende

Determining the potential positive effects on economic growth and energy security from nuclear energy investment can be beneficial for quantifying positive externalities that may not be considered in nuclear investment policy decisions. Additionally, examining a real-world application of a nuclear phase-out policy can provide insight into the opportunity costs associated with excluding these external elements through realized economic and energy security loss. Quitzow et al. (2016) and Kreuz & Musgens (2017) examine the impacts of Germany's Energiewende, which aimed to shut down all nuclear power production among other initiatives. These policy briefs discuss the effects of Germany's massive undertaking to move away from thermal energy production toward an almost entirely renewable energy mix.

The purpose of Quitzow et al. (2016) is stated as addressing the dynamic and complex process of Germany's Energiewende transition with an emphasis on critical issues for implementation. These issues included costs and funding, contestation and conflict resolution, regional diversity and disparities, and new modes of governance (Quitzow et al., 2016). Similarly, the policy review conducted by Kreuz & Musgens (2017) focuses on costs and funding both economic and societal. Conversely, to the previous study, Kreuz & Musgens (2017), looked at electricity price effects on households and industries. They gathered data from the original German government brief on the policy and focus on the installed energy capacity of Germany from 1990 to 2015. A specific focus on costs associated with renewable energy and subsidization from the German government helps the authors consider the societal and consumer cost of electricity from this policy. Their findings suggest German households saw a steady rise in electricity prices from a direct cost of the renewable energy transition. This rise totaled 8.1 billion Euros for households in 2015 alone (Kreuz & Musgens, 2017).

The high costs pushed to consumers from this energy transition were fueled by the rapid shutdown of Germany's nuclear plants. Quitzow et al. (2016) finds relatively low levels of emissions from nuclear energy as compared to the emergency coal that was reactivated during this policy because of a newly formed energy dependency. This dependency along with higher coal emissions put pressure on Germany's environmental targets. The authors discuss the irony of this energy security loss as Germany became more reliant on neighboring countries for energy imports, many of which used nuclear sources (Quitzow et al., 2016). Both papers find that Germany's Energiewende was expensive and left a hole in their energy needs and security. This decrease in energy security had to be made up for by imports from other existing nuclear power grids.

Analysis of the Literature - Internal Validity

Yoo & Ku (2009) uses various time series techniques including tests for unit roots, co-integration (with an error correctional model), and a Granger causality test. The Granger causality test addresses the stationary variable concerns. The robustness of this empirical study illustrates its internal credibility and the importance of the bi-directional and uni-directional linkages discovered between nuclear energy and economic growth in this study. Similarly, Apergis et al. (2010) and Chu & Chang (2012) also use robust Granger causality tests. Apergis et al. (2010) used a panel error correction model paired with unit root tests to validate the stationary properties in the data. Their use of a panel-based ADF test found that there was homogeneity in the dynamics of the coefficients for all panel units with cross-sectional independence (Apergis et al., 2010). This study also discusses how they opted to be robust by using more inclusive testing wherever possible. Chu & Chang (2012) ran cross-sectional dependency tests and slope homogeneity tests. Their findings support the other research.

Omri et al. (2015) is the most recent of the economic growth papers. This study uses dynamic simultaneous-equation panel models and a generalized method of moments to find linkages between nuclear energy and economic growth. Their extensive literature review includes the previous three papers. They also root their methods in theoretical production functions. This study was the most relevant and significant contributor to the examined causal relationships.

Watson & Scott (2009) and Yao & Chang (2014) both explored energy security. These papers used indicator ranking systems to assess the complex topic of energy security. Both papers consulted industry professionals to confirm various rankings and indicators but ultimately are subject to the qualitative nature of their structure. Yao & Chang (2014) attempted a more quantitative approach using government-gathered data from an external source and provided comprehensive indexing for the combinatoric relationship of indicators. Watson & Scott (2009) uses historic and panel data for their analysis.

In regard to the analysis of Energiewende, both Quitzow et al. (2016) and Kreuz & Musgens (2017) have policy briefs rooted in the factual historic outcomes of this policy. Kreuz & Musgens (2017) used a simpler, theory-based, market evaluation for economic costs. The data examined was a panel set although no empirical methods were conducted. Comparatively, Quitzow et al. (2016) simplified the view of issues to costs and funding, contestation and conflict resolution, regional diversity and disparities, and new modes of governance in a discussion-based format.

Analysis of the Literature - External Validity

Yoo & Ku (2009), Apergis et al. (2010), Chu & Chang (2012), and Omri et al. (2015) all use panel data across multiple countries allowing for a high level of generalizability at a macroeconomic scale, which can be plausibly extrapolated to Eastern Europe. Watson & Scott (2009), Yao & Chang (2014) create relatively custom energy security ranking systems for the UK and China respectively leading to less generalizable results. Watson & Scott (2009) explores an even more generalizable indicator system that could be outside of country-specific limitations. Yao & Chang (2014)'s approach is more specific to China with a smaller discussion of applicability to other countries. Additionally, gathering similar data to this study may prove difficult. In regard to Germany's Energiewende, Quitzow et al. (2016) and Kreuz & Musgens (2017) view the specific case study of Germany's nuclear phase-out policy which may be less useful in other countries but can provide context for energy markets in Europe. Many international effects such as energy insecurity are more generalizable across countries.

Summary of Previous Literature - Conclusion

Through various approaches, a causal relationship between nuclear energy and economic growth was found in many countries with both bi-directional and uni-directional connections. The methods to discover these relationships include Granger causality tests, Method of Moments, and other empirical methods. When exploring energy security, two studies find nuclear a necessary component of carbon neutrality. Additionally, Germany's Energiewende sheds light on the possible opportunity cost associated with not investing or removing nuclear energy. These effects include reliance on neighboring countries for energy imports, higher consumer energy prices, and energy insecurity through dependency. Nuclear energy is a key component on the path to carbon neutrality and provides a strong foundation for energy security. Nuclear energy has also increased economic growth for various countries and could be a catalyst for economic development in Eastern Europe. To further explore the influence nuclear may have on energy security, an analysis with a focus on energy self-sufficiency can be conducted to isolate benefits to grid stability from the addition of nuclear energy production.

Two-Way Fixed Effects - Methodology

A two-way fixed effects model is employed in this study to address several important assumptions and enhance the robustness of the empirical analysis. A two-way fixed effects model allows for the control of both country-specific effects and time-specific effects in the model associated with the relationship between nuclear energy and energy self-sufficiency in European countries over time. By including fixed effects for each country and year, the model accounts for unobserved heterogeneity that may be present across countries or over time in specific countries. This is important because countries vary in terms of their policy environments, energy infrastructure, and other factors that can influence the relationship between nuclear energy and energy self-sufficiency. Controlling for these unobserved factors allows the model to isolate the potential impact of nuclear energy on energy self-sufficiency, free from the confounding effects of country-specific and time-specific factors. The two-way fixed effects model also helps address endogeneity concerns. Endogeneity could arise when there is a reciprocal relationship between the exogenous variable (nuclear energy) and the endogenous variable (energy self-sufficiency). For example, countries with higher energy self-sufficiency or GDP may have incentives and resources to invest in infrastructure to generate more nuclear energy capacity. By including fixed effects for each country, the model helps mitigate the endogeneity issue. This mitigation is done by controlling for time-invariant country-specific factors that may simultaneously affect both nuclear energy and energy self-sufficiency. This improves the internal validity of the estimated relationship.

Furthermore, the two-way fixed effects model allows for the exploration of within-country variations over time. It enables the examination of how changes in nuclear energy capacity within a specific country are associated with changes in energy self-sufficiency. This temporal dimension provides valuable insights into the dynamics and time lags involved in the relationship. This further helps to uncover any potential lagged effects or long-term impacts of nuclear energy on energy self-sufficiency. In the context of this exploration into nuclear energy's potential impact on energy self-sufficiency, the theoretical model is defined by:

$$Energy\_SS_{it} = \beta_0 + \beta_1 Nuclear_{it} + \beta_2 GDP\_PPP_{it} + \beta_3 Renewables_{it} + \alpha_i + \delta_t + \varepsilon_{it}$$

Where Energy_SS is equal to energy self-sufficiency. β_0 is the arbitrary intercept. β_1 represents the key estimate coefficient of $Nuclear_{it}$ which is the operable nuclear energy capacity for country i in year t. This variable is measured in Mwe. After determining this key coefficient we can extrapolate the impact of an additional 750 MWe plant being introduced to the energy grid to gain insights into individual nuclear plant effects on energy self-sufficiency. β_2 represents the coefficient of GDP_PPP which is the gross domestic product purchasing power parity in 2017 international dollars for country i in year t. β_3 represents the coefficient of Renewables defined as the energy production from renewable sources for country i in year t. α_i represents the country-fixed effects, capturing unobserved country-specific characteristics that affect energy self-sufficiency. δ_t defines the year-fixed effects, capturing unobserved time-specific factors that may affect energy self-sufficiency. Finally, ε_{it} is the error term. This term captures the random variation and unobserved factors specific to each observation in the model.

The selection of these model variables passed through multiple iterations. Before testing for collinearity, the original model contained a variable for urbanization and population. After running a variance inflation factor (VIF) test there appeared to be a moderate level of collinearity between urbanization, population, and GDP. These variables were then excluded from the model as their impact is most likely contained in the GDP factor and controlled through the fixed effects model by design. Another variable considered and omitted from the model was energy intensity. This variable normalizes energy by source with GDP. The presence of GDP in this variable's calculation would result in collinearity in the results.

Two-Way Fixed Effects - Data Analysis

The data on renewable energy consumption, denoted in Quadrillion British Thermal Units (Quad Btu) from 1995 - 2021 for each country, was obtained from the U.S. Energy Information Administration, EIA (n.d.). This government agency is a reputable source widely recognized for its comprehensive and reliable energy data. The use of Quad Btu as the unit of measurement adheres to the standard convention in energy analysis, ensuring consistency and facilitating cross-country comparisons. A visualization of the per country spread over the given time period can be seen below.

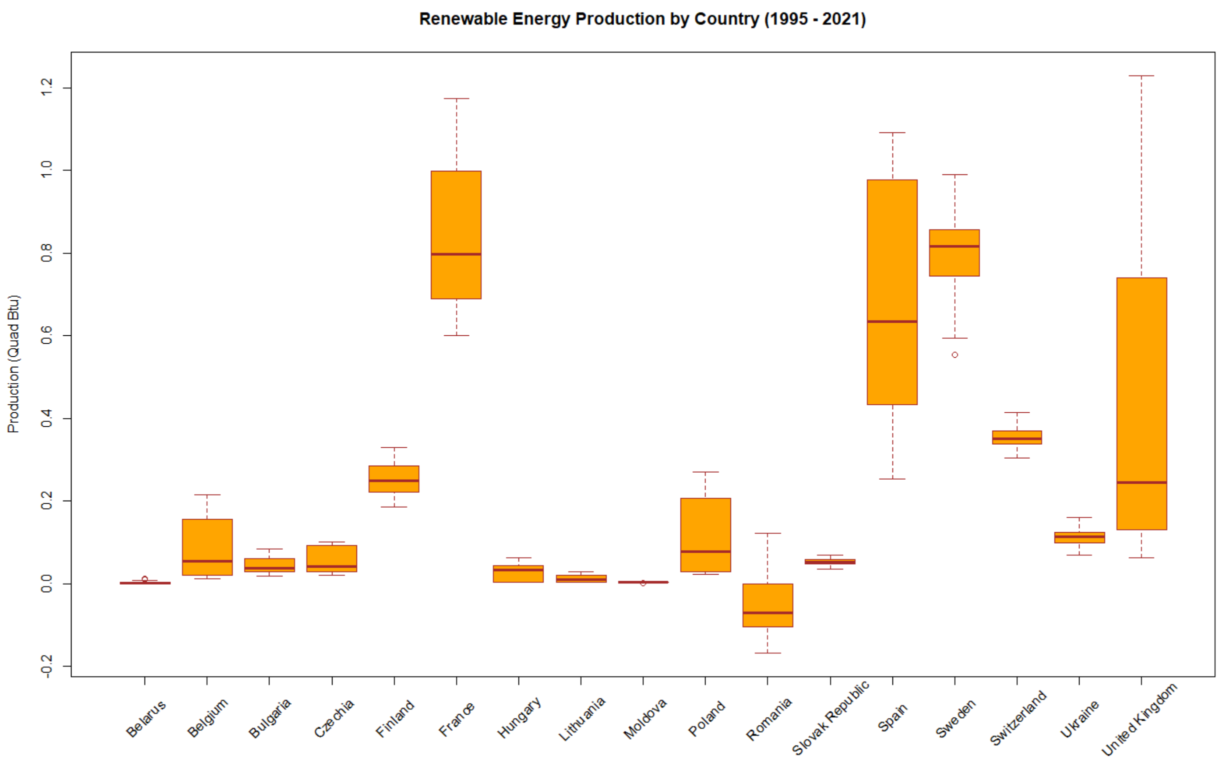

Figure 1: Renewable Energy Production (Btu from 1995 - 2021), **Data Source:** eia.gov

Energy self-sufficiency, the endogenous variable in this study, is measured in the percentage of domestic production over domestic consumption and was also collected from EIA (n.d.) from 1995 - 2021 for each country in the model. Energy self-sufficiency reflects a nation's ability to fulfill its own energy consumption from domestic production. The measure for this variable is the Terajoule. A unit that is widely employed in energy studies and provides a standardized measure of energy quantity, enabling meaningful quantitative analysis. This variable has been visualized over the given time period below.

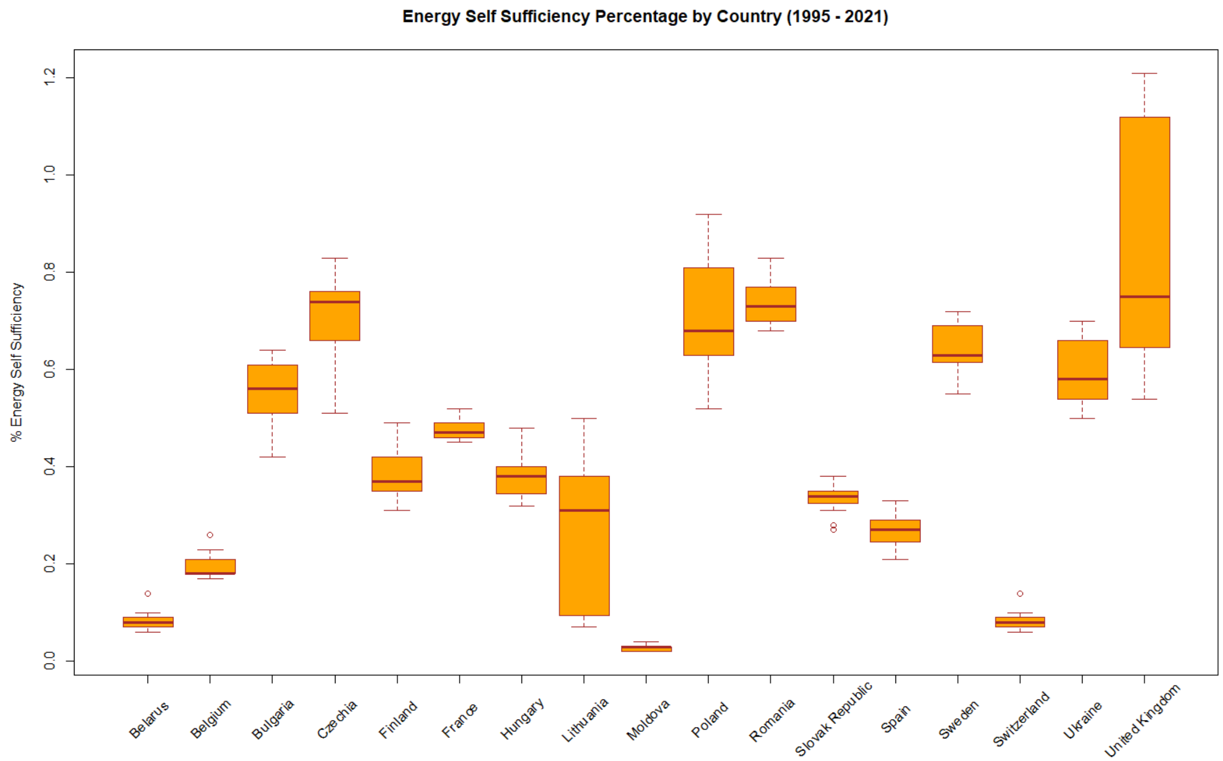

Figure 2: Energy Self-Sufficiency Changes over Time per Country, **Data Source:** eia.gov

The data pertaining to operable nuclear energy capacity from 1995 - 2021, quantified in Megawatts electric (MWe), was sourced from the World Nuclear Association (n.d.). As a prominent authority in the field of nuclear energy, the World Nuclear Association maintains a comprehensive database encompassing nuclear power plants globally. Country-specific data was extracted for operable nuclear capacity by country over time. The MWe unit serves as a standardized measure of the electrical output generated by nuclear reactors, facilitating accurate assessments and comparisons across countries. The dispersion of operable nuclear capacity in the given date range can be seen below.

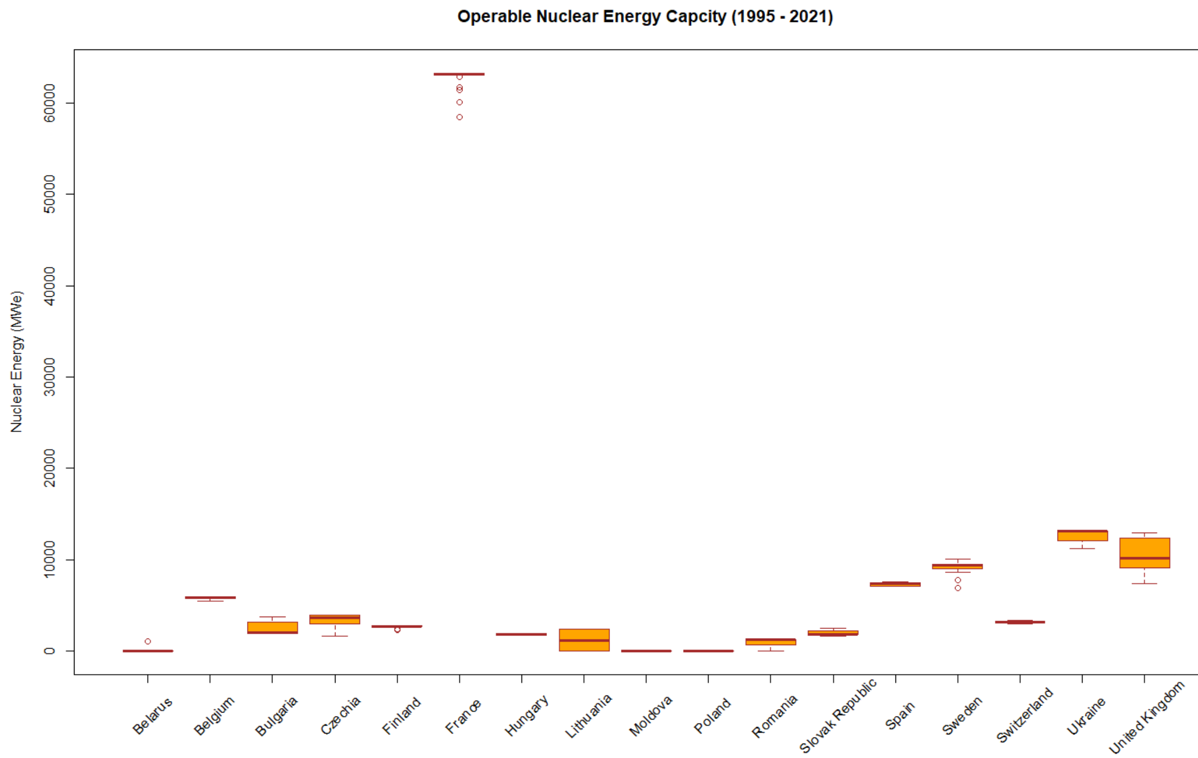

Figure 3: Operable Nuclear Energy Capacity by Country Over Time, **Data Source:** World Nuclear Association

Gross Domestic Product (GDP) Purchasing Power Parity (PPP) data from 1995 - 2021 for each country, denominated in international 2017 dollars, was collected from The World Bank, Khadan et al. (2023). The World Bank is widely recognized for its extensive collection of economic data and indicators and is often used in economic analysis. GDP PPP offers a measure of economic output that considers the varying purchasing power of currencies across countries, ensuring a more accurate, comparable, and useful representation of economic performance. GDP can be visualized below.

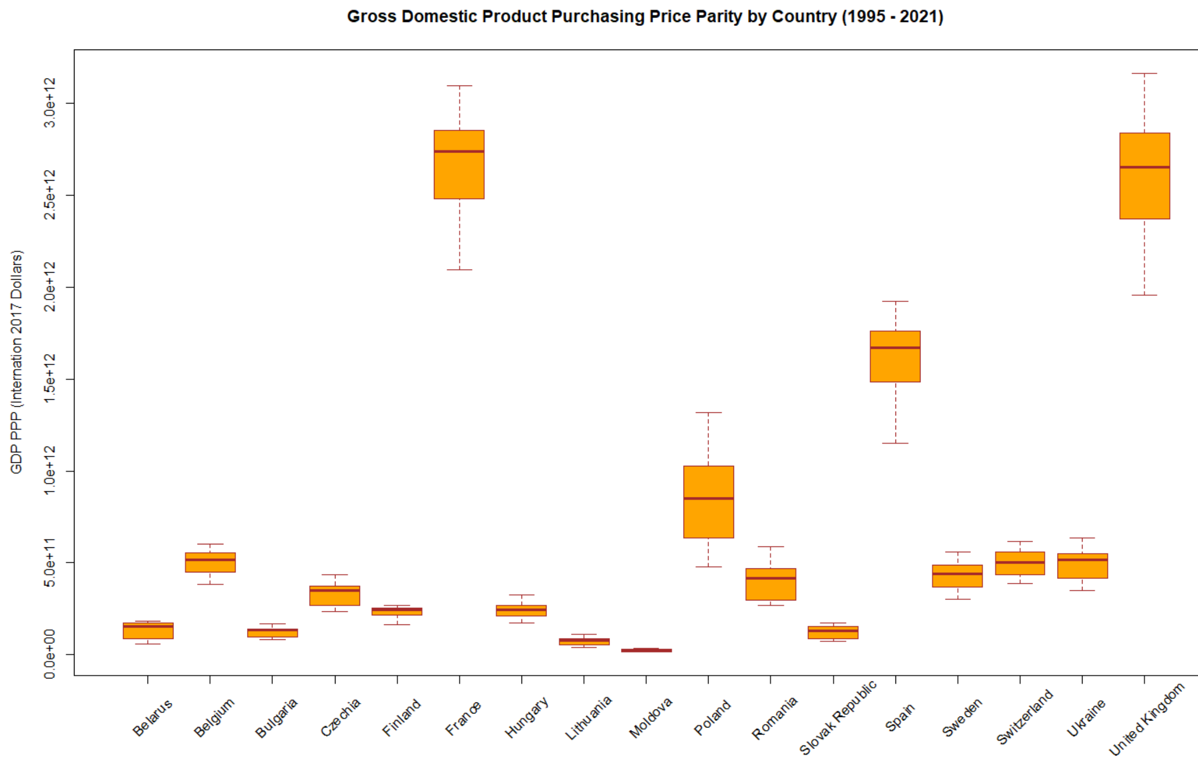

Figure 4: GDP PPP for Various Countries Over Time, **Data Source:** World Bank

By utilizing data from these trusted sources and employing standard units of measurement, this study ensures the robustness and comparability of the variables across European countries. This approach supports the generation of meaningful insights into the potential relationships under investigation. A table of summary statistics to begin examining the interplay of the exogenous, endogenous, and controlling variables can be seen below.

Table 1: Descriptive Statistics

Variable	N	Mean	Std. Dev.	Min	Pctl. 25	Median	Pctl. 75	Max
Energy_self_sufficiency	459	0.43	0.26	0.02	0.21	0.42	0.63	1.2
Nuclear_Energy	459	7400	14353	0	1300	2722	7450	63260
GDP_PPP	459	6.68E+11	8.18E+11	1.45E+10	1.57E+11	3.66E+11	5.90E+11	3.17E+12
Renewables	459	0.23	0.32	-0.17	0.02	0.075	0.32	1.2

Two-Way Fixed Effects - Results

Original Model

The initial model yields the fixed effects estimates displayed in *Table 6* of the appendix. Notably, the individual effects exhibit predominantly positive values, particularly in Eastern European regions that either lack nuclear energy or have recently implemented it. These findings suggest an ambiguously positive impact on energy self-sufficiency resulting from an increase in operable nuclear energy capacity while accounting for renewable energy production and comparative GDP. However, an interesting outlier emerges in France. Despite possessing a substantial share of nuclear energy in its energy mix, France consistently appears as an outlier in almost all explored categories in *Figures 1-4*. Intuitively, France's significant reliance on nuclear energy would make it comparatively less attractive than the reference country in the fixed effects model. The full model output can be viewed in *Table 2* below.

Table 2: Original Two-way Fixed Effects Model Output

Residuals:

Min	1Q	Median	3Q	Max	
-0.35565	-0.25024	-0.02144	0.22448	0.51568	

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	3.70E-01	1.51E-02	24.516	< 2e-16	***
Nuclear_energy	-1.68E-06	1.15E-06	-1.455	0.14637	
Renewables	-1.74E-01	5.06E-02	-3.433	0.000653	***
GDP_PPP	1.65E-13	2.21E-14	7.43	5.41E-13	***

Signif. codes	0 '***'	0.001 '**'	0.01 '*'		

Residual Standard Error:		0.2455 on 455 degrees of freedom		
Multiple R-squared:		0.1273,	Adjusted R-squared: 0.1215	
F-statistic:	22.12 on 3 and 455 DF,		p-value:	2.19E-13

Subsequently, an F test for the two-way effects confirms the model's significant effects, as evidenced by a p-value of less than 2.2e-16. To assess multicollinearity, the PLM model is converted to an LM model, allowing for the examination of the variance inflation factor (VIF). *Table 3* presents the results of this analysis. Notably, in the full model observable in *Table 2*, all variables, except nuclear energy, exhibit statistical significance. The interpretation of nuclear's coefficient of -1.68E-06 translates to a 1 MWe increase in operable nuclear capacity resulted in a -1.68E-06 percentage point decrease in energy self-sufficiency. Extrapolating to a 750 MWe plant, we could infer a decrease of energy self-sufficiency equating to a nearly 0.00126 percentage point decrease per additional plant. Notably, this rough estimate disregards any diminishing marginal effects. Particularly, renewables demonstrate a coefficient of -1.736e-01, implying a slight decrease in energy self-sufficiency as renewable energy production increases. It is important to consider that this result may be influenced by the selected time period. The current political pressure towards renewable energy may drive countries to adopt unstable or inadequate energy grids. Germany's Energiewende Policy serves as an example, as the rapid transition to renewables led to energy dependencies, such as imported Russian natural gas explored by Quitzow et al. (2016) and Kreuz & Musgens (2017). This dependency was later exploited and decreased Germany's energy security and self-sufficiency. It is plausible that similar effects could arise in other countries that swiftly adopt renewables.

Table 3: F Test for Original Model Effects

F Test for two-ways effects			
F = 140.13	df1 =42	df2 = 413	p-value < 2.2e-16
alternative hypothesis: significant effects			

Moreover, GDP exhibits a positive coefficient of 1.645e-13, indicating that energy self-sufficiency increases as GDP PPP rises. This finding aligns with intuition; wealthier countries possess the means to invest in their energy grids and develop the necessary infrastructure to support domestic energy demand.

To assess robustness, a test for multicollinearity using the VIF test is conducted. The results indicate VIF values of 2.07, 1.93, and 2.49 for nuclear energy, renewable energy, and GDP, respectively. These values, which can be viewed in *Table 7* in the appendix suggest an acceptably low level of multicollinearity in the model. Additionally, an ADF test for unit roots suggests that the assumption of stationarity may be violated by two variables in the model. This test can be viewed in *Table 8* of the appendix.

Considering the statistical insignificance of nuclear energy, the primary independant variable, and the potential violation of stationarity, the outcome remains uncertain. Additionally, this result is more uncertain when paired with the mostly positive individual fixed effects observed. Consequently, further investigation into the impact of nuclear energy on energy self-sufficiency involves a differencing model correction. This adjustment aims to enhance the stationarity of the original model. The results of this corrected model are described in the subsequent discussion.

Difference Correction Model

The objective of employing the differencing correction model was to uphold the assumption of stationarity, which was potentially violated in the original model. The differencing model yields individual fixed effects, as displayed in *Table 10* of the appendix. While the individual results bear less direct interpretation than the previous model, the negative coefficients of the differenced value of nuclear along with the negative coefficient of renewables implies an inverse relationship with energy self-sufficiency. The LM-Model results can be viewed in *Table 4* below. Notably, the differencing correction model rectifies any artificially large influence stemming from the potential outlier, France, observed in the original model.

Table 4: Differenced Two-way Fixed Effects Model Output:

Residuals:

Min	1Q	Median	3Q	Max
-0.53043	-0.01473	-0.00135	0.00905	0.87845

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	1.21E-03	3.56E-03	0.339	0.7349	
Nuclear_energy	-6.36E-06	1.23E-06	-5.158	3.72E-07	***
Renewables	-2.15E-02	4.54E-02	-0.473	0.6368	
GDP_PPP	4.70E-14	2.70E-14	1.741	8.24E-02	

Signif. codes	0 '***'	0.001 '**'	0.01 '*'

Residual Standard Error:	0.07621 on 455 degrees of freedom		
Multiple R-squared:	0.06127,	Adjusted R-squared: 0.055091215	
F-statistic: 9.9 on 3 and 455 DF,		p-value:	2.46E-06

The F test conducted to assess the significance of the effects in this corrected model yields a p-value of 0.1935. This value, shown below in *Table 5*, suggests that the significance of the corrected model may be lower compared to the previous uncorrected model. The results of the LM-converted differencing model demonstrate a change in the statistical significance, with the coefficient of the differenced value of nuclear energy now attaining significance with a coefficient -6.360e-06. This coefficient implies a one MWe differenced unit increase in nuclear results in a -6.360e-06 percentage point decrease in rate of energy self-sufficiency. However, the remaining variables in the LM model do not exhibit statistical significance in the corrected model.

Table 5: F Test for Original Model Effects

F Test for two-ways effects			
F = 1.197	df1 =42	df2 = 413	p-value = 0.1935
alternative hypothesis: significant effects			

Furthermore, the corrected model maintains an acceptable level of collinearity among variables, as evidenced by the VIF test, which yields values of 1.48, 2.06, and 2.34 for nuclear, renewables, and GDP, respectively. These results can be seen in *Table 10* in the appendix. Additionally, the ADF unit root test generates statistics of -14.79, -14.34, -15.52, and -14.08 for energy self-sufficiency, nuclear, renewables, and GDP, respectively. This result can be viewed in *Table 11* of the appendix. The absolute magnitude of these ADF statistics exceeds the critical value of -2.58 for a 1% significance level, underscoring the impact of the differencing correction in achieving stationarity.

Due to the high p-value obtained from the F test for the fixed effects, the overall significance of this corrected model is called into question. Nonetheless, the statistical significance of nuclear energy in the model and the improved stationarity resulting from the correction address some of the issues encountered in the previous model.

Conclusion and Implications for Future Work

The findings from the original model suggest that an increase in operable nuclear energy capacity, while controlling for the gross domestic product (GDP) and renewable energy production, may negatively impact energy self-sufficiency. However, the model provides ambiguous results and is sensitive to modeling assumptions. Additionally, the small negative statistically insignificant coefficient of nuclear in the original LM-adjusted model calls into question nuclear's importance in the overall effect. This result prompted the use of a differencing correction model. There are predominantly positive individual fixed effects, especially in Eastern European regions without nuclear energy or with recent nuclear implementation, possibly supporting nuclear energy use comparatively to other countries. However, the meaning of these individual effects are heavily sensitive to modelling assumptions and look to be deriving primarily from GDP's inclusion in the controlling variables. Additionally, France stands out as an outlier, despite its significant reliance on nuclear energy. It appears less attractive in comparison to the base country in the fixed effects model.

The robustness tests conducted indicate acceptable levels of multicollinearity between variables. However, the assumption of stationarity is potentially violated by two variables in the model, raising uncertainty regarding the outcomes. These results prompted a correction using a differencing correction model to address stationarity concerns.

The differencing correction model successfully maintains the assumption of stationarity and removes any outlier influence from France observed in the original model. The negative coefficient of nuclear and renewables, along with the positive individual fixed effects, again call upon the sensitivity to modelling assumptions resulting in ambiguous results.

Possible future work to address this ambiguity could focus on omitted variable bias along with checks for time invariant OLS estimation snapshots of individual years. Furthermore, future work could focus on improving the overall significance of the original model's endogenous variables. One avenue for improvement is to investigate further the influence of nuclear energy on district heating and hydrogen (H2) production. These areas hold the potential for enhancing energy self-sufficiency and reducing greenhouse gas emissions. Additionally, safety considerations play a crucial role in nuclear energy adoption, and future research should explore the development of safer modern reactor designs and improved safety protocols.

The transition from coal to nuclear facilities also presents opportunities for job creation. Policymakers should consider the potential benefits of promoting this transition and supporting workforce development in the nuclear energy sector. The findings suggest potential comparative benefits for Eastern Europe, specifically, in countries that may have previously had little to no nuclear energy production. However, this result is sensitive to modelling assumptions and the comparative nature of the fixed effects model. It is also important to note the coefficient of nuclear was negative in the model suggesting the average impact was inversely related to energy self-sufficiency.

To inform policy decisions effectively, it is essential to quantify the benefits of nuclear energy adoption in terms of energy security, economic stimulation, and job growth. Incorporating these benefits into a dollar value estimation, similar to a levelized cost of electricity (LCOE) model, would provide a comprehensive framework for decision-making.

In conclusion, the models' descriptions highlight the potential negative impact of operable nuclear energy capacity on energy self-sufficiency, although the overall significance of the models remains uncertain. Future work should explore the potential improvements in district heating and H2 production, address new safety innovations, and modern reactor efficiency increases, assess job creation during the transition from coal to nuclear facilities, and quantify the costs and benefits of nuclear energy adoption to inform policy decisions effectively.

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Appendix

Table 6: Fixed Effects from Original Model

Country	Estimate
Belarus	0.104399321
Belgium	0.046579866
Bulgaria	0.436345022
Czechia	0.630809715
Finland	0.261072295
France	-2.007914454
Hungary	0.350833403
Lithuania	0.200894685
Moldova	0.008346207
Poland	1.027457852
Romania	0.844164207
Slovak Republic	0.238834839
Spain	0.395407587
Sweden	0.144175356
Switzerland	0.023149933
Ukraine	0.065779733
United Kingdom	1.271970499

Table 7: Variance Inflation Factor Test for Multicollinearity for Original Model

VIF Values

Nuclear_energy	Renewables	GDP_PPP
2.074999	1.934567	2.494752

Table 8: ADF Test for Unit Roots in Original Model

ADF Test For Unit Roots

Variable:	ADF Statistic:

Energy_self_sufficiency	-1.403654
Nuclear_energy	-2.337103
Renewables	-3.049181
GDP_PPP	-1.929795

Critical Values [1%]: -2.58 Critical Values [5%]: -1.95 Critical Values [10%]: -1.62

Table 9: Fixed Effect from Differenced Model

Country	**Estimate**
Belarus	0.09990579
Belgium	0.11994608
Bulgaria	0.13094156
Czechia	0.13257341
Finland	0.12903843
France	0.12751816
Hungary	0.11423562
Lithuania	0.10917624
Moldova	0.11525525
Poland	0.13165163
Romania	0.12690303
Slovak Republic	0.10580045
Spain	0.10522562
Sweden	0.13018396
Switzerland	0.11636306
Ukraine	0.1204114
United Kingdom	0.10457582

Table 10: Variance Inflation Factor Test for Multicollinearity for Differenced Model

	VIF Values	
Nuclear_energy	Renewables	GDP_PPP
1.484075	2.063374	2.340711

Table 11: ADF Test for Unit Roots in Differenced Model

ADF Test For Unit Roots

Variable:	ADF Statistic:
Energy_self_sufficiency	-14.79081
Nuclear_energy	-14.34233
Renewables	-15.5226
GDP_PPP	-14.08149

Critical Values [1%]: -2.58 Critical Values [5%]: -1.95 Critical Values [10%]: -1.62

R Script: R Script Used to Conduct Analysis and Produce Visualizations

```
library(plm)
library(lmtest)
library(car)
library(glmnet)
library(urca)
library(vtable)
library(tidyverse)
library(rstatix)
library(ggpubr)

#get Working dir
print(getwd())

# Set current working directory
setwd("C:/Users/nelso/Desktop/Thesis/Thesis_5_30")

# Load the panel data from a CSV file
data <- read.csv("Model2TWFE.csv")

#fixing the country variable name from .csv compression
colnames(data)[1] <- "Country"

# Convert relevant columns to appropriate data types if needed
data$Country <- as.factor(data$Country)
data$Year <- as.factor(data$Year)
```

```
cat("[Validation] Data Columns: ", names(data), "\n")

# Print a sample of the DataFrame
cat("Data sample:\n")
head(data)

# Access the 'Energy_self_sufficiency' column directly
energy_column <- data$Energy_self_sufficiency
cat(energy_column, "\n")

#Data prep for visualization
cat("*----------------------------*\n")
st(data,
  vars = c('Energy_self_sufficiency', 'Nuclear_energy', 'GDP_PPP', 'Renewables'),
  title = "Descriptive Statistics",
  add.median = TRUE
)


# Plot for Self sufficiency
bxp <-boxplot (Energy_self_sufficiency ~ Country, data = data,
        main = "Energy Self Sufficiency Percentage by Country (1995 - 2021)",
        xlab = "",
        ylab = "% Energy Self Sufficiency",
        col = "orange",
        border = "brown",
        xaxt = "n"
)
tick <- seq_along(bxp$names)
axis(1, at = tick, labels = FALSE)
text(tick, par("usr")[3] - 0.09, bxp$names, srt = 45, xpd = TRUE)

#Plot of Nuclear
bxp <-boxplot (Nuclear_energy ~ Country, data = data,
            main = "Operable Nuclear Energy Capcity (1995 - 2021)",
            xlab = "",
            ylab = "Nuclear Energy (MWe)",
            col = "orange",
            border = "brown",
```

```
            xaxt = "n"
)
tick <- seq_along(bxp$names)
axis(1, at = tick, labels = FALSE)
text(tick, pos = 1, offset = 3.6, bxp$names, srt = 45, xpd = TRUE)

#Plot for GDP
bxp <-boxplot (GDP_PPP ~ Country, data = data,
            main = "Gross Domestic Product Purchasing Price Parity by Country (1995 - 2021)",
            xlab = "",
            ylab = "GDP PPP (Internation 2017 Dollars)",
            col = "orange",
            border = "brown",
            xaxt = "n"
)
tick <- seq_along(bxp$names)
axis(1, at = tick, labels = FALSE)
text(tick, pos = 1, offset = 3.5, bxp$names, srt = 45, xpd = TRUE)

#Plot for Renewables
bxp <-boxplot (Renewables ~ Country, data = data,
            main = "Renewable Energy Production by Country (1995 - 2021)",
            xlab = "",
            ylab = "Production (Quad Btu)",
            col = "orange",
            border = "brown",
            xaxt = "n"
)
tick <- seq_along(bxp$names)
axis(1, at = tick, labels = FALSE)
text(tick, par("usr")[3] - 0.1, bxp$names, srt = 45, xpd = TRUE)

#-------------------------#
# Prepare the data matrix
#X <- model.matrix(Energy_self_sufficiency ~ ., data = data)[, -1]
#y <- data$Energy_self_sufficiency

# Fit a ridge regression model
#ridge_model <- glmnet(X, y, alpha = 0, lambda = 0.1)
```

```
# Print the coefficients
#print(ridge_model$beta)
#-----------------------#

# Create the fixed effects model
#model <- plm(Energy_self_sufficiency ~ Nuclear_energy + Renewables + GDP_PPP,
#            data = data,
#            index = c("Country", "Year"),
#            model = "within")

#----------------------Original Model-------------------------#

# Create the two way fixed effects model
model <- plm(Energy_self_sufficiency ~ Nuclear_energy + Renewables + GDP_PPP,
            data = data,
            index = c("Country", "Year"),
            model = "within",
            effect = "twoways")

# Estimate the fixed effects model
fixed_effects <- fixef(model)

# Print the estimated fixed effects
#print(fixed_effects)

summary(fixef(model))
pFtest(Energy_self_sufficiency ~ Nuclear_energy + Renewables + GDP_PPP, data = data, effect =
"twoways")

# Convert the plm model to an lm model for VIF calculation
lm_model <- lm(model$formula, data = model$model)

summary(lm_model, stars = c('*' = .1, '**' = .05, '***' = .01))

# Check for collinearity using variance inflation factor (VIF)
vif <- car::vif(lm_model)

# Display the VIF values
print(vif)
```

```
# Perform stepwise regression with collinearity correction
model_corrected <- step(lm_model, direction = "both", trace = 0)

# Print the final model summary
#summary(model_corrected, stars = c('*' = .1, '**' = .05, '***' = .01))

# Perform unit root tests
perform_unit_root_test <- function(series) {
  result <- ur.df(series)
  cat("ADF Statistic:", result@teststat, "\n")
  cat("Critical Values [1%]:", result@cval[[1]], "Critical Values [5%]:", result@cval[[2]], "Critical
Values [10%]:", result@cval[[3]], "\n")
}

# Check unit root for the dependent variable
perform_unit_root_test(data$Energy_self_sufficiency)

# Check unit root for the independent variables
perform_unit_root_test(data$Nuclear_energy)
perform_unit_root_test(data$Renewables)
perform_unit_root_test(data$GDP_PPP)

#----------------------Original Model------------------------#

# Remove the first observation of the variable
data$Energy_self_sufficiency <- data$Energy_self_sufficiency[-1]

# Differencing for non-stationary variables
data$Energy_self_sufficiency_diff <- diff(data$Energy_self_sufficiency)
data$Nuclear_energy_diff <- diff(data$Nuclear_energy)
data$Renewables_diff <- diff(data$Renewables)
data$GDP_PPP_diff <- diff(data$GDP_PPP)

#Data Cleaning
data[1,7] = 0
data[1,8] = 0
data[1,9] = 0
data[1,10] = 0

#----------------------Differenced Model------------------------#
```

```
# Create the two way fixed effects model
model <- plm(Energy_self_sufficiency_diff ~ Nuclear_energy_diff + Renewables_diff +
GDP_PPP_diff,
        data = data,
        index = c("Country", "Year"),
        model = "within",
        effect = "twoways")

# Estimate the fixed effects model
fixed_effects <- fixef(model)

# Print the estimated fixed effects
#print(fixed_effects)

summary(fixef(model))
pFtest(Energy_self_sufficiency_diff ~ Nuclear_energy_diff + Renewables_diff + GDP_PPP_diff,
data = data, effect = "twoways")

# Convert the plm model to an lm model for VIF calculation
lm_model <- lm(model$formula, data = model$model)

summary(lm_model, stars = c('*' = .1, '**' = .05, '***' = .01))

# Check for collinearity using variance inflation factor (VIF)
vif <- car::vif(lm_model)

# Display the VIF values
print(vif)

# Perform unit root tests on the differenced log variables
perform_unit_root_test(data$Energy_self_sufficiency_diff)
perform_unit_root_test(data$Nuclear_energy_diff)
perform_unit_root_test(data$Renewables_diff)
perform_unit_root_test(data$GDP_PPP_diff)

#----------------------Differenced Model-------------------------#

# Replace -inf with a small positive value (e.g., 0.0001)
#data$CleanedRenew_log <- log(data$Renewables)
#data$CleanedRenew_log[data$CleanedRenew_log == -Inf] <- 0.00001
```

```
# Logarithmic transformation for differenced variables, replacing NaN with zero
data$Energy_self_sufficiency_diff_log <- log(data$Energy_self_sufficiency_diff)
data$Energy_self_sufficiency_diff_log[is.nan(data$Energy_self_sufficiency_diff_log)] <- 0

data$Nuclear_energy_diff_log <- log(data$Nuclear_energy_diff)
data$Nuclear_energy_diff_log[is.nan(data$Nuclear_energy_diff_log)] <- 0

data$Renewables_diff_log <- log(data$Renewables_diff)
data$Renewables_diff_log[is.nan(data$Renewables_diff_log)] <- 0

data$GDP_PPP_diff_log <- log(data$GDP_PPP_diff)
data$GDP_PPP_diff_log[is.nan(data$GDP_PPP_diff_log)] <- 0

# Replace -Inf with zero in the log-transformed variables
data$Energy_self_sufficiency_diff_log[is.infinite(data$Energy_self_sufficiency_diff_log)] <- 0
data$Nuclear_energy_diff_log[is.infinite(data$Nuclear_energy_diff_log)] <- 0
data$Renewables_diff_log[is.infinite(data$Renewables_diff_log)] <- 0
data$GDP_PPP_diff_log[is.infinite(data$GDP_PPP_diff_log)] <- 0

#----------------------------diff_log Model--------------------------#

# Create the two way fixed effects model
model <- plm(Energy_self_sufficiency_diff_log ~ Nuclear_energy_diff_log +
Renewables_diff_log + GDP_PPP_diff_log,
          data = data,
          index = c("Country", "Year"),
          model = "within",
          effect = "twoways")

# Estimate the fixed effects model
fixed_effects <- fixef(model)

# Print the estimated fixed effects
#print(fixed_effects)

summary(fixef(model))
pFtest(Energy_self_sufficiency_diff_log ~ Nuclear_energy_diff_log + Renewables_diff_log +
GDP_PPP_diff_log, data = data, effect = "twoways")
```

```
# Convert the plm model to an lm model for VIF calculation
lm_model <- lm(model$formula, data = model$model)

summary(lm_model, stars = c('*' = .1, '**' = .05, '***' = .01))

# Check for collinearity using variance inflation factor (VIF)
vif <- car::vif(lm_model)

# Display the VIF values
print(vif)

# Perform unit root tests on the differenced log variables
perform_unit_root_test(data$Energy_self_sufficiency_diff_log)
perform_unit_root_test(data$Nuclear_energy_diff_log)
perform_unit_root_test(data$Renewables_diff_log)
perform_unit_root_test(data$GDP_PPP_diff_log)

#----------------------------diff_log Model---------------------------#
```