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2025 Yervand Martirosyan

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Abstract

This dissertation examines the long-term impacts of environmental and energy-related factors on human development and wellbeing, focusing on academic performance, socioeconomic outcomes, and environmental impacts. Each chapter contributes to understanding how environmental conditions and energy policy reforms shape individual and societal outcomes across different contexts.

The first chapter investigates the long-term impact of energy poverty and related policy interventions on academic performance in China. It uses the Huai River Policy, which provided free winter heating to northern regions but not to adjacent southern regions, to identify the causal effects of winter heating on individuals' academic outcomes. The findings suggest that winter heating has a significant positive influence on academic performance, particularly for individuals born during colder months.

The second chapter explores the long-run impact of the energy crisis that followed the collapse of the Soviet Union on human wellbeing in Armenia. This period was characterized by severe infrastructural and economic disruptions. The study shows that early-life exposure to these adverse conditions negatively affected education and income, especially for those born in winter months. However, proximity to forests mitigated some of the negative effects, underscoring the importance of access to natural resources. The results offer valuable insights for designing policies aimed at enhancing educational and economic outcomes.

The third chapter evaluates the environmental implications of electricity market reforms, focusing on the 1990 Norwegian Energy Act. This policy introduced liberalization and dynamic electricity pricing with the goal of improving efficiency. Using the synthetic control method and a machine learning-based variant, the study compares Norway's carbon dioxide emissions to a donor pool of similar countries that did not implement such reforms. The results indicate a notable reduction in emissions, highlighting both the environmental benefits of market-based electricity reforms and the utility of machine learning techniques in policy evaluation.

Together, these chapters contribute to the literature on environmental economics by highlighting the long-term effects of energy access, policy interventions, and market reforms on human and environmental outcomes.

Introduction

This dissertation consists of three essays in environmental economics. Each chapter examines the relationships between environmental conditions, policy interventions, and human outcomes. The central theme of this dissertation is the study of how environmental factors and policy responses impact human well-being.

The first chapter investigates the long-term impact of energy poverty and policy interventions on academic performance. It analyses the Huai River Policy in China, which provides free winter heating to the northern regions but not to adjacent southern regions. The study focuses on individuals from infancy and evaluates how winter heating influenced their future academic outcomes. The findings suggest that access to heating in colder months has a significant positive effect on academic achievement. For the group of northern and southern provinces with similar climates and distance from the policy line, the results indicate a statistically significant positive impact of free winter heating on standardized math test scores. The impact is distinct for those born during the winter months on the northern side, who scored approximately 0.1 standard deviations higher than their southern counterparts, while the math scores of individuals born during the summer on both northern and southern sides were similar.

The second chapter examines the case of Armenia after the collapse of the Soviet Union, during a nationwide energy crisis. From 1991 to 1994, almost the entire population had no access to natural gas and had limited access to electricity. This study analyzes how early-life exposure to this type of extreme environment affects future socioeconomic outcomes, including education and income levels. The results indicate that individuals born during this crisis tend to achieve lower educational attainment and earn lower incomes compared to those born before or after the crisis period. Specifically, in all model specifications, the energy crisis led to a statistically significant reduction in monthly income levels, ranging from approximately 16% to 25% for individuals born during the crisis years. The results also reveal a negative effect on educational attainment: individuals born during the energy crisis are approximately 40% less likely to attain higher education. The study also suggests that proximity to heat sources in the form of forests reduces the negative long-term effects.

The third chapter analyzes the environmental effects of electricity market liberalization and the introduction of dynamic pricing, using the case of Norway after the 1990 Energy Act. This policy reduced government regulation, encouraged market competition, and allowed customers to choose from different variable-priced electricity contracts. The study evaluates how these reforms contributed to a reduction in greenhouse gas emissions. Using a synthetic control method and a machine learning based variant, the results indicate a significant 34% decrease in CO2 emissions in Norway following the reform. This is comparable in magnitude to findings in similar studies analyzing climate and energy policies.

Together, these three essays contribute to understanding how energy-related policies and environmental conditions influence both human and environmental outcomes. By analyzing settings including household heating in China, the energy crisis in Armenia, and electricity market reforms in Norway, this dissertation demonstrates that policies addressing energy access and efficiency can have long-term positive effects on education, income, and environmental quality.

Chapter 1

The Long-Term Impact of Energy Poverty Mitigation on Educational Achievement: Evidence From China

1.1 Introduction

In addition to increasing average temperatures, climate change also drives greater variability in weather patterns. In recent years, there has been evidence of more frequent occurrence of extreme temperature shocks globally (WMO, 2011). One example is the occurrence of colder and snowier winters in various parts of the planet (Cohen et al., 2021), affecting over a billion people who have no access to modern heating sources or cannot afford them (IEA, 2018). This lack of access to heating sources is often referred to as *energy poverty*[1] (Reddy et al., 2000) and a body of research connects it to health, education, and household income (Thomson et al., 2017; Banerjee et al., 2021; Okushima, 2016). In addition to these studies, several others have demonstrated the negative impact of exposure to extreme temperatures on educational achievement (Goodman et al., 2018; Cook & Heyes, 2020).

This paper investigates the impact of exposure to specific heating policies during early childhood on individuals' academic performance in later life, focusing on China's Huai River Policy. This policy was introduced in the 1950s and grants free winter heating for provinces that are located to the north of the Huai river, but not for southern provinces.

The primary empirical objective of this paper is to examine the causal relationship between being exposed to specific heating policy during early-life stages on later life outcomes. This study examines whether people born in households in northern China that benefit from free winter heating exhibit higher levels of academic achievement compared to their southern counterparts.

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[1] In the context of this paper, the term energy poverty will be used to refer to households that do not fall under the heating policy.

Studies highlight the importance of early childhood development in shaping future outcomes (Campbell et al., 2014). I hypothesize that experiencing adverse environmental conditions during infancy may negatively affect cognitive development, contributing to worse academic performance later on. In the context of the Huai River Policy, access to winter heating plausibly alters early-life environmental conditions during cold months. However, while the empirical design allows for credible estimation of the policy's long-term effects, the specific channels through which the policy operates, such as indoor thermal comfort, health, or household resource allocation, are not directly observed in the data and are therefore I discuss these with appropriate caution.

To test this hypothesis, I construct a model analogous to a cross-sectional difference-in-differences design. This model controls whether individuals were born before or after the introduction of the policy, whether they are from northern (heating policy) or southern provinces, and they season of birth. The primary outcome variable is standardized math test scores. I focus on math scores, as the literature demonstrates that mathematical learning at an early age is important for later success in life (Clements & Sarama, 2011). Additionally, several studies have shown the importance of early mathematics education compared to other subjects for better achievement later in school (Duncan et al., 2007; Claessens et al., 2009). Given that cognitive skills are essential for early math learning (Decker & Roberts, 2015), negative effects on infant health from poor environmental conditions could hinder their ability to learn and have lasting impacts on their general well-being.

To measure the impact of the heating policy on academic performance, I use China family panel studies (CFPS, 2010) and Rozelle (2016) individual-level surveys, along with meteorological datasets. Using two datasets for the analysis provides distinct advantages. The CFPS (2010) dataset includes individuals born both before and after the introduction of the heating policy, enabling analysis of the policy's impact across different generations. However, it only allows for identification of individuals at the provincial level. In contrast, the Rozelle (2016) dataset provides information on individuals' cities of birth, facilitating a more granular analysis focused on groups of cities with similar weather conditions. This enables a more detailed analysis of the environmental impacts on early development.

In this study, I examine the differences in educational achievement between individuals born in provinces and cities on the north and south sides of the Huai River, both before and after the introduction of the heating policy. I distinguish two groups of infants based on their season of birth. The *Winter* group consists of individuals born in the winter months when average outdoor temperatures are below 5°C.[2] The *Summer* group comprises infants born during months when the average outdoor temperature was 15°C or higher. Following this, I assign dummy variables to represent these groups. I also account for outdoor temperatures and other climate variables for up to 3 months before and after the birth of a child.

For the group of northern and southern provinces and cities with a similar climate and distance from the policy line (Huai River), the results indicate a statistically significant positive impact of free winter heating on standardized math test scores. The impact is distinct for those born during the winter months on the northern side. They scored approximately 0.1 standard deviations higher compare to their southern counterparts.

An important feature of the results is their seasonality. Individuals born during the winter in northern regions after the introduction of the heating policy exhibit higher math test scores, while no similar effects are observed for summer born individuals. This seasonal pattern is informative about the underlying mechanism. If the policy operated only through a income channel, by increasing disposable income with free heating, then one would expect effects to smooth across the year and impact both winter and summer births. The presence of effects among only winter births therefore provides evidence against a purely income driven explanation, while not

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[2] According to historical climate data from Statistical Intelligence, in China an outdoor temperature below 5°C is considered winter season.

fully ruling out income related channels in the presence of imperfect consumption smoothing.

In light of these findings, I consider two primary mechanisms through which the heating policy could have impacted academic performance. The first mechanism is the direct effect of the policy in reducing cold spells, with the results indicating that the impact of the policy is larger for colder winters. The second mechanism relates to the use of height as a proxy for academic measurement. I show that before the policy, there were no significant differences in height between individuals born in the south and the north. However, after the policy was introduced, children born in the north during winter are significantly taller than their southern counterparts.

Next, I conduct a sensitivity analysis to examine the impact of expanding the geographic scope of the study. The results suggest that increasing the distance from the policy line and including provinces in the far south, where winter temperatures are relatively mild, can diminish the observed heating effect.

Further, I run a set of placebo tests to examine the impact of the heating policy among only northern and southern cities and provinces. I hypothesize that if the difference in math scores is driven by the heating policy, there should not be any significant difference between only northern (or southern) provinces and cities. The results of the placebo test show no statistically significant difference in the academic performance of individuals born during the summer and winter seasons in northern and southern provinces and cities. In addition, I did not find an impact for people in northern and southern provinces before the introduction of the policy. I also address the potential effects of air pollution, controlling for migration (e.g., from north to south), and examining birth rates within the sample across different seasons.

Furthermore, I investigate the long-term impact of outdoor climate on academic performance, finding a small but positive effect (approximately 0.06 standard deviations) of rising temperatures during pregnancy on the math scores of schoolchildren born in the winter months. However, no significant impact was found for children born during the summer months. Next, I find that a child's height is positively correlated with educational achievement, with taller children performing better. This result align with existing literature (Case et al., 2009). Lastly, I examine heterogeneity in the data, focusing on wealthier eastern provinces versus relatively poorer western provinces. I also conduct analysis to examine the impact of the policy on income levels and gender.

This paper contributes to several areas of the literature. Firstly, my study adds to the discussion on the negative impact of harsh environmental conditions on education by demonstrating that specific policies could mitigate this impact for populations exposed to such conditions in childhood. Several studies suggest that individuals born during the season with extreme temperatures have lower socio-economic outcomes later on. For instance, Isen et al. (2017) finds that that the season of birth and the associated temperature exposure has a lasting effect on individual well-being. The authors demonstrate that, during the first year of an infant's life, each additional day with a temperature above 32°C lowers his or her later annual earnings by approximately $30 at ages 29 to 31. Lawlor et al. (2006) investigates the relationship between the season of birth and the performance of childhood tests. Using a sample of individuals born in Aberdeen, Scotland, they found that children born during the winter months demonstrated lower reading abilities at age nine and arithmetic abilities at age eleven. In contrast to the studies mentioned above, my analysis focuses on individuals, some of whom benefited from heating policies, while others did not. I demonstrate that targeted heating policies can mitigate the negative effects of winter birth on academic performance.

Next, a body of literature demonstrates the impact of energy poverty on various dimensions of human life. Banerjee et al. (2021) analyzes the relationship between energy poverty, health, and education, using annual country-level data. The results of their study demonstrate a negative impact on health and years of schooling as a result of energy poverty. Another aspect of human life affected by energy poverty is household finances. Okushima (2016) demonstrates the short-term negative impact of energy poverty on household income levels, particularly for households consisting of a single parent (typically the mother) and child.

While the above papers highlight the negative impact of energy poverty on health, years of schooling, and income, they either conduct analyses at the country level or demonstrate only short-run impacts. My study utilizes more granular survey datasets consisting of individual-level observations from Chinese cities and provinces. These datasets provide an opportunity to generate more comprehensive results. Furthermore, my research focuses on individuals born before and during periods of energy poverty, examining its impact on their later-life well-being.

Lastly, education is key to economic growth (Barro, 1991), yet education levels remain low in many developing countries (World Bank, 2024). My study could therefore inform policy debates aimed at enhancing educational outcomes and human well-being.

The studies discussed above demonstrate that environmental conditions, such as outdoor temperature levels, impact various life outcomes. Other studies also highlight that child health and early childhood development are essential for the formation of human capital (Heckman, 2011, 2012). Further, it has been established that early-age interventions can be an effective strategy to reduce social costs and promote economic growth (Doyle et al., 2009; Attanasio et al., 2022). Therefore, investigating population groups born during extreme environmental conditions is crucial for improving future human well-being. This research thus contributes to the literature on early-life environmental conditions and later-life well-being.

The rest of this paper is organized as follows: Section 2 provides brief historical background on China, and Section 3 describes the data used for the analysis. Section 4 describes the empirical identification. Section 5 provides the main results. Section 6 include the sensitivity analysis and robustness checks. Section 7 describes the mechanisms. Section 8 concludes.

1.2. Background: Education, Energy Poverty and Heating Policy

1.2.1 Education

China is ruled under a unitary communist regime with no political separation of powers, and it is run by the Chinese Communist Party, which enacts its policies through the National People's Congress (Guo, 2012). Starting in the 1970s, China began to enact significant reforms across the country, including in the education system, nearly doubling the number of students in schools.

Currently, nearly all children of primary school age in China attend school, and the number of students in secondary schools is quite high (Lewin et al., 2001). Since the 1970s, schools in China have received increasing government financing, which is distributed by local authorities in each province. This financing is independent of heating policies, and literature demonstrates that Northern and Southern border provinces have similar higher education density indexes (Borsi et al., 2022).

1.2.2 Energy Poverty

Despite its economic growth, China is still considered a developing country (Benoit & Tu, 2020), featuring both hot and cold climates, and a significant part of its population has experienced or is experiencing energy poverty (Lin & Wang, 2020).

While electricity access in China reached nearly 100 percent by 2013 (World Bank, 2019), energy poverty remains a significant issue. This is largely due to disparities between the rich and poor, along with variations in climate, geographical location, and resource endowments, which result in heterogeneity in household energy consumption. For example, while citizens in urban areas typically use modern energy sources, many in rural areas continue to rely on fossil fuels, despite the extensive coverage of the power grid Jiang et al. (2020).

1.2.3 Huai River Heating Policy

The Huai River heating system was established in China between 1950 and 1980, in the era of centralized economic planning. During this time, heating was considered a fundamental right, and the government provided free heating to households and offices through state-owned enterprises or direct provision. However, the provision of free heating was limited to the northern regions of China, which are demarcated from the southern regions by the Huai River (Figure 1.1). Provinces situated north of the river have implemented a centralized heating infrastructure, ensuring unlimited free heating heating during the winter season.

Conversely, in the southern regions, heating was largely absent as the government did not establish heating infrastructure, and the private sector has only recently begun supplying it. Consequently, it is widely acknowledged that cities just south of the Huai River experience cold and uncomfortable winters (Ebenstein et al., 2017; Almond et al., 2009).

Figure 1.1: Free Winter Heating in the Northern Provinces

Notes: The figure shows Chinese provinces divided into northern and southern regions by the Huai River and the Qinling Mountains. Source: Yin et al. (2023)

1.3. Data and Summary Statistics

I use individual-level survey data from CFPS (2010) and Rozelle (2016) to analyze the impact of winter heating on academic performance. To assess climate conditions in provinces and cities on both sides of the policy line, I utilize meteorological data obtained from Custom Weather, and Statistical Intelligence. More about the data structure can be found in the Data Appendix section.

1.3.1 Survey Datasets

In order to empirically examine the impact of the Huai River Policy on educational achievement, I have obtained the CFPS (2010) data, which includes all Chinese provinces. This survey was conducted separately for adults and their children and includes individual-level observations of nearly 30,000 individuals, covering a wide range of characteristics, including birthdate, height measurements, birthweight, math test scores, and more. The dataset includes individuals who were born both before (parents) and after (parents and their children) the introduction of the heating policy from all Chinese provinces.[3] The outcome variable for the analysis is the math test scores collected by surveyors and standardized for the analysis. Using these scores allows me to avoid potential issues associated with test scores if they were collected from schools, such as test anxiety and gender bias (Putwain & Daly, 2014; Hanna & Linden, 2012).

In addition to the CFPS (2010), I use data from Rozelle (2016). This dataset consists of 18,888 observations of students in grades 4 to 6 and includes information on their academic performance, birth year and month, city of birth, gender, and parents' migration status. The measure of academic performance in this dataset is the standardized math test scores collected by Rozelle (2016) in 2014 and 2015. Similarly to the CFPS (2010) survey, here the math test scores are again conducted

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[3] In this paper, "parents" and "first generation" refer to the same individuals, while "children" and "second generation" refer to their offspring These terms will be used interchangeably throughout the analysis.

by the surveyors. The dataset encompasses students from 15 Chinese cities situated in both the northern and southern regions.

For the main analysis, I focus on a subset of cities that are located within approximately 100 km on either side of the policy line, ensuring that they share comparable climates (Appendix: Figure 1.A.2.1). The provinces in my main analyses are around 600 km from the policy line for weather consistency across winter and summer (Appendix: Figure 1.A.2.2).

1.3.2 Climate Dataset

For both datasets, I obtained the meteorological data from Custom Weather, and Statistical Intelligence. These datasets are comprised of average daily and monthly observations at the city and province level, including outdoor temperature, wind speed, and sea level pressure. I use these measurements to control for the impact of climate during pre-birth and infancy on the later math test scores.

Appendix: Table 1.A.1.3 presents summary statistics for the main variables. The summary statistics include the main individual-level variables from all cities and provinces, and from the subset of locations close to both sides of the boundary river, which share similar weather conditions.

1.4. Empirical Strategy

I examine whether the Huai River heating policy has a positive impact on academic performance. To test this hypothesis, I construct a linear model and analyze two datasets (CFPS (2010) and Rozelle (2016)). In both cases, the results show a similar pattern: a positive impact from the provision of free winter heating on math test scores for individuals born in the northern part of China.

1.4.1 Model

I estimate linear model in which the dependent variable is the standardized math test results. The explanatory variables include a dummy for individuals born in cities in northern regions with free heating, dummies for those born during summer and winter, dummies for those born after the introduction of the heating policy, and a set of climate variables. For each individual, I collect meteorological observations in the range of 3 months before and after their birth date. Additionally, I control for a set of individual-level variables, including gender, migration status, and other factors. For the analysis, I run several modifications of the following model:

$$Y_{icsmt} = \beta_1 \cdot \text{Policy}_i + \beta_2 \cdot \text{Heat}_i + \beta_3 \cdot \text{Winter}_{ismt} +$$

$$+ \beta_4 \cdot \text{Policy}_i \cdot \text{Heat}_i \cdot \text{Winter}_{ismt} +$$

$$+ \Sigma_{j=5}^{k} \beta_j \cdot \text{M}_{ismt} + \Sigma_{k+1}^{p} \beta_{k+1} \cdot \text{C}_i + \epsilon_s$$

Where Y_{ismt} is the standardized math test score of individual ***i***, born in year ***t***, in month ***m***, who was born and raised in city (province) ***s***. $Policy_i$ is a dummy variable that equals 1 for individuals born after the introduction of the heating policy. $Heat_i$ is a dummy variable that equals 1 for individuals born in cities located in northern regions with access to free winter heating. $Winter_{ismt}$ (and $Summer_{ismt}$) are dummy variables representing the seasons of birth. $\Sigma_{j=6}^{k} \beta_j \cdot M_{ismt}$ represents a set of meteorological variables. Climate measurements for each infant are collected within a 6-month range, covering 3 months before and after their birth. $\Sigma_{j=k+1}^{p} \beta_{k+1} \cdot C_i$ consists of control variables, including height, gender, and school grade at the time of testing. Finally, ϵ_s denotes the error term, and the standard errors are clustered at the household and city level.

The coefficient of interest is β_4, which captures the impact of winter heating on standardized math test scores for infants born during winter in northern regions after the introduction of the heating policy.

1.4.2 Identifying Assumptions and Balance

The identification assumption of this study is that, by controlling for an infant's birthplace (north versus south), birthdate (before or after introduction of the heating policy), migration status, and climate measurements at the time of their birth, there should not be any unobservable variables that could be systematically correlated with both heating policy exposure in early life and later academic performance.

The empirical setup in this paper is analogous to a cross-sectional triple difference-in-differences setup for adults (1st generation). For adults, I control for three dimensions: whether they were born before or after the policy introduction, whether they were born in northern (heating policy) or southern provinces, and whether they were born during summer or winter. In the robustness checks, I demonstrate that, prior to introduction of the policy, there were no significant differences in educational achievement (or income levels) between individuals born in northern versus southern provinces across summer and winter.

For children (2nd generation) born after introduction of the heating policy, the empirical setup follows a cross-sectional difference-in-differences design. For them, I control for their place of birth (north versus south) and their birth season (summer versus winter). Again, in the robustness checks, I provide analyses in which I change the policy line and show no significant differences in academic performance between infants born during summer versus winter.

Lastly, in all specifications, I control for migration status to ensure that individuals born in northern (or southern) provinces did not subsequently migrate to the south (or north), as this could affect the outcomes being measured.

According to the balance tables (Appendix: Table 1.A.1.4), The samples from the northern and southern regions near the policy line appear to be balanced. The adult participants in these samples show similar distributions of males and females, height measurements (prior to the introduction of the policy), number of siblings and other factors. The children in the samples exhibit similar proportions of males and females, comparable ages, and school grades. The outdoor temperature levels in northern and southern provinces and cities are somewhat different. However, these differences are relatively small. The temperature differences at the city level vary by less than 1°C in winter months. I am not aware of any literature suggesting that these small differences could significantly impact my outcomes. Lastly, I conduct multiple hypothesis tests to adjust the significance level.[4]

1.5. Main Results

I investigate the long-term effects of winter heating on academic performance, focusing on individuals exposed (or not) to heating policies to heating policies during infancy. The findings show that individuals born during the winter in northern provinces of China achieve greater educational success than their counterparts in the south. No significant impact was found for individuals born during the summer months. Furthermore, the winter heating effect extends to the second generation.

1.5.1 Heating Impact

I begin my examination by focusing on provinces and cities located close to both sides of the river policy line. Tables 1 to 3 [5] shows the results for the main specifications from the CFPS (2010) and Rozelle (2016) surveys, respectively.[6] Results obtained from the CFPS (2010) dataset reveal that individuals born during the winter period in northern regions exhibit higher math test scores if they were born after introduction of the heating policy. The coefficient of interest, individuals born in winter after 1950, is statistically significant and, depending on the specification, corresponds to an increase of approximately 0.1 standard deviations in standardized math test scores. These effects persist through the second generation, with children

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[4] The tests results can be found in Appendix: Table 1.A.1.2

[5] The tables with additional coefficients can be found in Appendix: Table 1.A.2.1, Table 1.A.2.4, and Table 1.A.2.6

[6] For the CFPS (2010) dataset, I also conducted analyses (Appendix: Table 1.A.2.2) using a reduced time span (1946 to 1980), concluding with the Huai River policy.

born in winter showing an increase of approximately 0.4 standard deviations in math test scores. In contrast, the coefficient for those born during the summer remains small and statistically insignificant.

Results from Rozelle (2016) dataset are from cities within approximately 100km from the policy line in both directions. The interaction between the heating policy and the winter dummy is positive and significant, leading to an increase in standardized math test scores of approximately 0.12 standard deviations, depending on the specification. This interaction highlights a positive impact on infants born during winter in cities within northern provinces. Conversely, the interaction between heating and the summer dummy is small and statistically insignificant. This suggests that children born during the summer period (when heating is unnecessary) in both northern and southern regions perform similarly.

I also conduct analyses using climate variables for 1, 2 and 3 months after (column 1 to 3) and before (columns 4 to 6) the births of subjects (Appendix: Table 1.A.2.6). These results could be evidence that free winter household heating has a positive lasting impact on academic performance. In other words, reduction of energy poverty in households improves the future academic performance of infants.

The rest of the results demonstrate no statistically significant impact of winter household heating on standardized Chinese language test scores (Appendix: Table 1.A.2.3, Table 1.A.2.5). An explanation for this could be that math and language learning require different cognitive skills, and that math learning involves more complex cognitive demands (Geary, 2011; Peters & Ansari, 2019).

Next, boys in both datasets perform worse than girls (Appendix: Table 1.A.2.1, Table 1.A.2.6). One possible explanation could be that exposure to adverse environmental conditions has a different impact scale for boys and girls (Hanna & Oliva, 2016). Moreover, the literature indicates that in China, boys often have lower executive functioning compared to girls (Thorell et al., 2013).

Furthermore, having a migrant father has a negative impact on math test scores

(Appendix: Table 1.A.2.6). Parental migration often negatively impacts children's psychosocial well-being and can result in insufficient assistance and care for the children (Zhao et al., 2018; Liu et al., 2018). However, this impact is not statistically significant in most cases.

Lastly, as expected, air pollution has a negative impact on academic performance, while individuals' height measurements are positively correlated with educational achievement (Appendix: Table 1.A.2.1, Table 1.A.2.4), which is in line with the literature (Mankiw & Weinzierl, 2010; Case et al., 2009).

Table 1: Impact of Heating on Academic Performance (CFPS: Adult)

Dependent Variable: Standardized Math Test Scores

	Math	Math
Born During Summer (t>1950, North)	0.024	0.025
	(0.030)	(0.030)
Born During Winter (t>1950, North)	0.098**	0.096**
	(0.033)	(0.033)
Observations	8098	8098
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar distance from policy line. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.

Standard errors in parentheses

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

Table 2: Impact of Heating on Academic Performance (CFPS: Children)

Dependent Variable: Standardized Math Test Scores		
	Math	Math
Born During Summer (North)	0.054	0.060
	(0.259)	(0.258)
Born During Winter (North)	0.457*	0.474*
	(0.231)	(0.229)
Observations	712	712
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar and distance from policy line. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.
Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3: Household Heating and Outdoor Climate Impact (Rozelle, 2016)

Dependent variable: Standardized Math Test Scores						
	(1)	(2)	(3)	(4)	(5)	(6)
Born in Summer (North)	-0.037	-0.037	-0.019	-0.176	-0.182	-0.188
	(0.060)	(0.039)	(0.018)	(0.087)	(0.082)	(0.075)
Born in Winter (North)	0.155*	0.145*	0.115*	0.198*	0.186*	0.155**
	(0.035)	(0.028)	(0.016)	(0.026)	(0.028)	(0.014)
Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1192	1192	1192	1192	1192	1192

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern cities with similar climates and at similar distances from the policy line. Each column includes a different set of meteorological variables. Columns 1 to 3 include average monthly meteorological measurements after 1, 2, and 3 months after birth. Columns 4 to 6 include measurements for 1, 2, and 3 months before an infant is born. Fixed effects are at the individual level. Standard errors are clustered at the city level, and wild bootstrap approach is used.
Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

1.6. Sensitivity Analysis and Robustness Checks

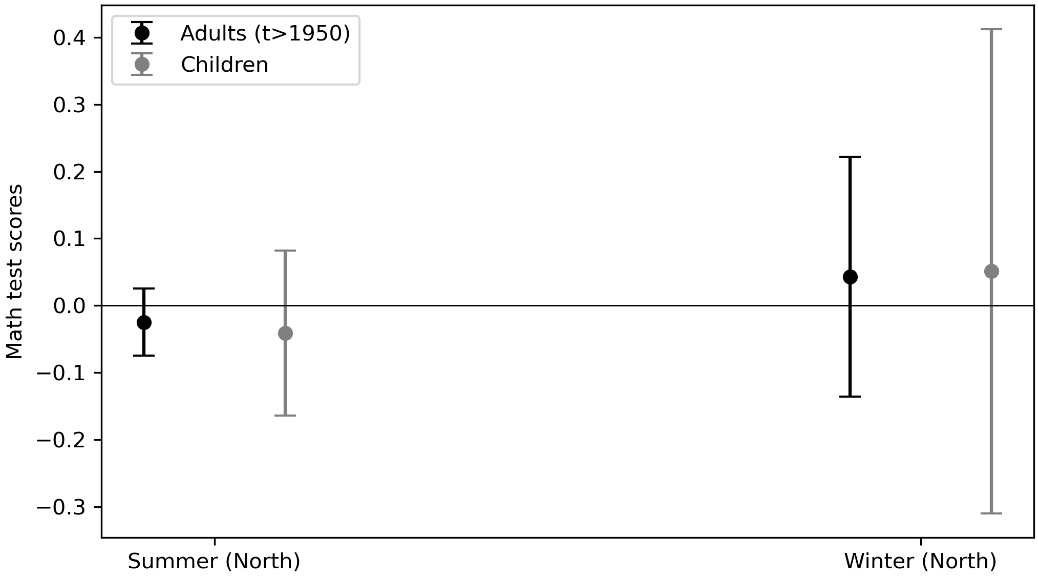
I extend the analysis by increasing the distance from the policy line to evaluate how the impact of heating diminishes as more southern provinces with milder winters are included. I conduct a series of placebo tests to further validate the findings. These include verifying the absence of a heating impact prior to the policy's introduction and examining the effect separately in northern and southern regions.

1.6.1 Sensitivity Analysis

In Section 5, I examined the impact of winter heating, hypothesizing that the difference in math test scores could be attributed to the absence of free heating in southern parts of China near the policy line, where winters are similarly cold to those in the northern regions.

If this hypothesis is correct, the following should also hold: when comparing individuals born during winter in northern China, where free winter heating is provided, to those born in far southern China, where there is no free heating but winters are relatively mild (around 12°C to 15°C), there should be no significant differences in test results. To test this, I choose provinces located within 1,200 km from the policy line (Appendix: Figure 1.A.2.3). I run the model for the specified regions of China and find no statistically significant differences in math test scores for individuals born in the summer versus winter (Figure 1.5).

Figure 1.5: Impact of Heating on Academic Performance (Sensitivity Analysis)



Notes: The figure shows the impact of the heating policy in northern (winter heating) and far southern provinces.

1.6.2 Robustness Checks

To indirectly assess the validity of the identification assumption, I run a placebo test to ensure that the observed impact comes from winter heating. In this tests, first I shift the heating policy line to the north and focus only on the northern locations with free heating during winter. For the CFPS (2010) data, I take the northern provinces and divide them into 2 groups: group 1 includes the treated provinces with free heating, and group 2 consists of the untreated (false) provinces that in reality have free winter heating, but I treat them as if they do not. In other words, I move the policy line up (to the north) and treat northern provinces that are now under the new policy line as provinces with no heating. I do the same for southern provinces, by shifting the policy line down to the south (Appendix: Figure 1.A.2.4). I run a model for those provinces (only northern and only southern), and find no significant impact (Appendix: Table 1.A.3.3 and Table 1.A.3.4).The results from similar placebo tests hold for the Rozelle (2016) dataset (Appendix: Table 1.1.A.3.1 and Table 1.A.3.2). For the CFPS (2010) dataset, I also run an analysis for the period before initiation of the heating policy. The goal of this placebo test is to check whether there is a large and significant impact among individuals born during winter and summer, before the policy introduction, in the North versus the South. The results demonstrate no such impact (Appendix: Table 1.A.3.3).

Lastly, I conduct analyses over different time spans to investigate the magnitude of the heating impact on various population groups. The results demonstrate that the impact of heating on academic performance persists throughout the entire time span for individuals born during winter, while no significant results are observed for those born in summer (Appendix: Figure 1.A.3.1).

1.7. Mechanisms

I explore the mechanisms driving the results and consider channels that could offer alternative explanations or influence the findings. I also conduct a series of heterogeneity analyses.

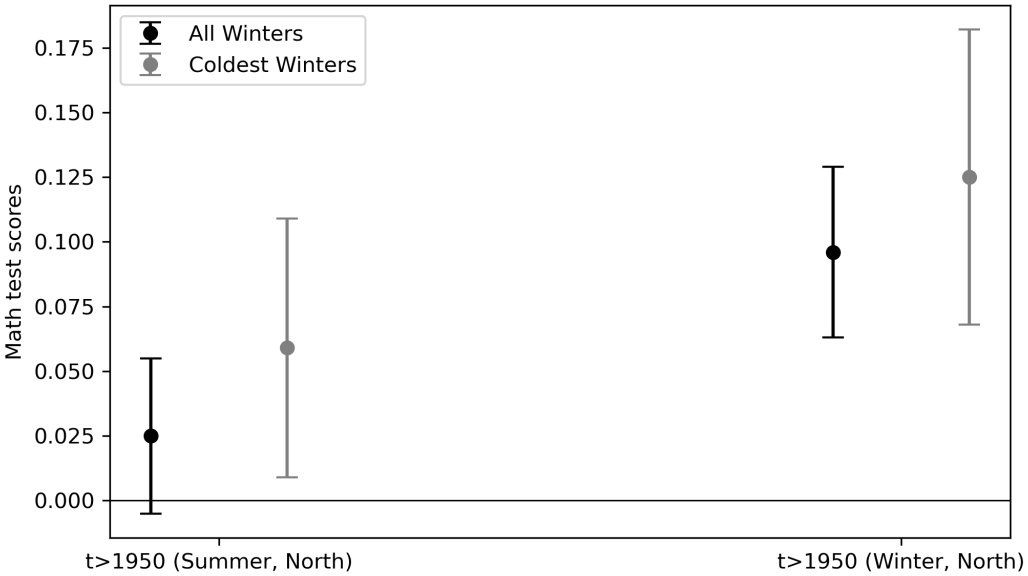
However, before discussing specific mechanisms, I would like to clarify a limitation of the analysis. The data do not contain direct measures of indoor temperature, or household thermal conditions during infancy. As a result, the analysis cannot separately quantify the relative contribution of improvements in indoor thermal conditions versus potential reductions in indoor pollution exposure. Both channels are consistent with the estimated effects and may jointly contribute to the beneficial effects observed in the data.

Lastly, though birthweight would be a natural outcome for testing prenatal mechanisms, that information in the available surveys is limited and uneven across cohorts and regions. The resulting sample is too small and unrepresentative to support a credible analysis. For this reason, birthweight outcomes are not examined in this study; instead I examine the height outcomes.

1.7.1 Coldest Winters

In this study, I hypothesize that provision of free heating mitigates energy poverty and improves academic performance. This implies that the impact should be greater during colder winters. I examine the effects of free heating during the coldest winters, and compare the results to those of milder winters. I analyze winter temperatures by province and year, identifying the coldest winters based on average outdoor temperature measurements. I then apply the model to this subset of the dataset. As expected, the impact was more pronounced in years with the coldest winters (Figure 1.6).

Figure 1.6: Impact of Heating on Academic Performance (CFPS: Coldest Winters)



Notes: The figure compares the heating impact for all years and for the coldest winters.

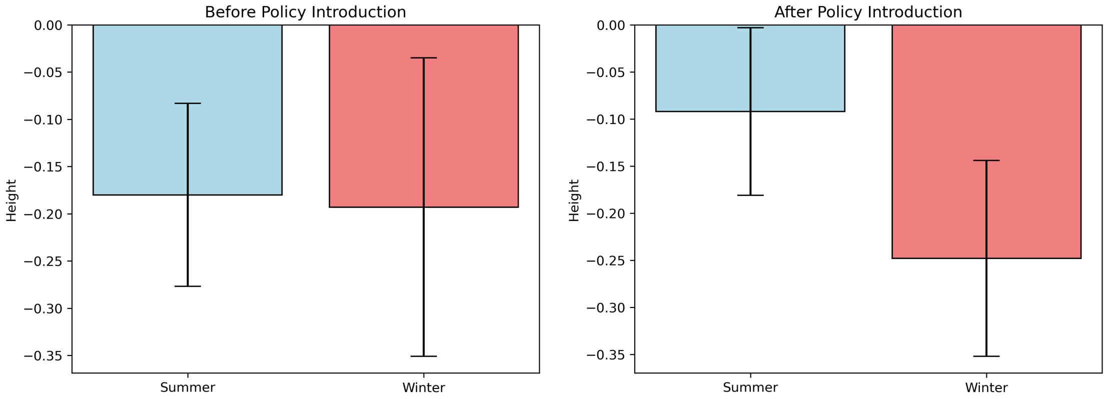
1.7.2 Height Analyses

The literature demonstrates that individuals' height measurements are positively correlated with cognitive performance. Several studies show that taller individuals tend to experience better outcomes, including higher income, greater happiness, and higher achieved education levels. These outcomes are closely linked to cognitive skills acquired early in life, highlighting the critical importance of early childhood health and development (Case & Paxson, 2008; Deaton & Arora, 2009; Behrman & Rosenzweig, 2004).

In my study, I find that the math test scores of individuals born after the introduction of a heating policy in the northern parts of China during the winter season are significantly higher than those of their counterparts from southern regions. This difference can be attributed to early-life exposure to harsh winter conditions and the presence (or absence) of heating. The impact should be observable not only in cognitive outcomes, such as math test scores, but also in physical development, particularly in height measurements.

Figure 1.7 illustrates that, prior to the policy introduction, the differences in mean height measurements for individuals born during winter and summer are similar in the southern and northern regions. However, after the policy implementation, the height measurements of individuals born during the winter in northern regions are higher than those in the south, with no significant differences for individuals born in the summer. These findings provide supportive evidence of a positive impact of heating policies on academic performance.

Figure 1.7: Comparison of Height Measurements



Notes: The figures show the mean difference of southern and northern groups by seasons. In the left figure (pre-policy), there are no significant height differences for those born in summer or winter. In the right figure (post-policy), while summer-born heights remain similar, winter-born individuals in the north are significantly taller than those in the south.

1.7.3 Temperature Impact

I use the Rozelle (2016) dataset to analyze the impact of outdoor climate on infants born in winter versus summer. The results (Appendix: Table 1.A.2.6) show that, for schoolchildren born during winter, rising temperature levels before birth (pregnancy period) have a small but positive and significant impact on their future educational achievement. Specifically, during the winter, a 1°C increase in outdoor temperature during pregnancy is associated with an improvement in academic performance of around 0.06 standard deviation. The impact of higher temperatures is close to zero and not statistically significant for children born in summer. These results may highlight the importance of suitable environmental conditions during pregnancy for an unborn child. I run the model again, including meteorological variables both before and after birth with the following range: one, two, and three months before and after the infant's birth. For each case (one, two, and three months) I have two, four, and six months of climate measurements for each child. The results (Appendix: Table 1.A.2.7) again demonstrate that, during pregnancy, higher outdoor temperatures have a positive and significant (but only in one specification) impact on math test scores. I did not find a significant impact of summer temperatures on academic performance. One possible explanation is that, in my sample, the outdoor temperature range for the cities in the analysis is between 2°C and 28°C. These findings align with studies that examine the effects of extreme temperature exposure on human well-being, which show that negative impacts on various outcomes tend to become noticeable only when outdoor temperatures exceed 32°C (Isen et al., 2017).

1.7.4 East vs West

It has been generally established that eastern China is more economically developed than the western areas of the country (Wei, 2013). To reflect this disparity, I divide the provinces in my dataset into western and eastern, aligning them closely with the river policy demarcation line. This division allows me to analyze the two groups separately. The results demonstrate that the impact of heating is stronger on math test scores in the eastern provinces (Appendix: Table 1.A.3.5, Table 1.A.3.6). The difference in educational achievement between wealthier eastern and relatively poorer western provinces is consistent with the literature and can be attributed to factors including the availability of extracurricular activities for students and higher levels of parental involvement (Reardon, 2018).

1.7.5 Income Effect

The literature suggests that early exposure to adverse weather shocks has a lasting impact on income levels in adulthood (Isen et al., 2017; Maccini & Yang, 2009). In light of this, I examine the impact of heating policies on the income levels of adults within the CFPS (2010) dataset. First, I demonstrate that there are no significant differences in income levels between those born before the introduction of the heating policy on either side of the river (Appendix: Table 1.A.3.7). Subsequently, I conduct analyses for the period following introduction of the policy. The results indicate a significant positive effect of the provision of heating for individuals born during the winter, whereas no significant effect is observed for those born during the summer season (Table 4). These findings are consistent with the existing literature.

The positive impact on income underscores the broader importance of such policies. Given that the first generation (Parents) in southern provinces and cities near the policy line have lower income levels in adulthood, this could worsen negative outcomes for the second generation (Children). Children in southern regions near the policy line not only remain excluded from the benefits of the heating policy, but may also experience lower household incomes. This implies that parents have fewer resources to allocate for heating and other purposes, increasing child vulnerability to energy poverty. To address this potential issue, I control for factors, including the availability of health insurance for children, access to a computer and Internet at home, whether the child receives pocket money, and other relevant factors.

Table 4: Impact of Heating on Income Levels (CFPS: Adults)

	Income	Income
Born During Summer (t>1950, North)	0.028	0.033
	(0.093)	(0.093)
Born During Winter (t>1950, North)	0.212*	0.224*
	(0.103)	(0.104)
Observations	4674	4674
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar distance from policy line. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.
Standard errors in parenthesis
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

1.7.6 Air pollution

In China, coal serves as the primary source of heating (Almond et al., 2009). This contributes to air pollution, which can hinder academic performance by negatively affecting infant health. Therefore, I control for air pollution measurements. It is notable that, around the time of the introduction of the heating policy, air pollution levels in China were quite low. In fact, air pollution measurements were lower than those in the rest of Asia (Appendix: Figure 1.A.2.5). While these patterns reduce the concern that discontinuities in ambient air pollution across the policy line are driving the results, they do not rule out the role of indoor air quality. Indoor pollution exposure depends on household heating and cooking technologies, which are not observed in the data. As a result, the analysis cannot disentangle improvements in indoor thermal conditions from potential reductions in indoor pollution exposure, and both channels may plausibly contribute to the estimated effects.

1.7.7 Further Insights

One of the potential concerns regarding my analysis could be that, given the heating policy, the parents could plan the pregnancy to avoid adverse environmental conditions. However, in the data, the share of births per season is similar (Appendix: Table 1.A.1.1).

Furthermore, it is possible that an infant was born in a given location, but at some point changed the city of residence (i.e. migrated from a southern to a northern city). This could potentially affect the results, and thus I control for the individuals' migration status to avoid this issue. Lastly, I find that boys perform worse than girls in general, but the policy seems to favor males more, although this difference is not statistically significant (Appendix: Figure 1.A.2.6). These results align with the existing literature (Thorell et al., 2013).

1.8. Conclusion

Climate change, coupled with rising average temperatures, has resulted in an increase in extreme weather events globally, including severe winters. A significant portion of the global population exposed to adverse conditions lack access to modern heat sources or the financial means to afford them.

This study explores the long-term effects of energy poverty and targeted heating policies on educational achievement. By examining the Huai River Policy, which provides free winter heating to northern Chinese regions, this study finds a positive impact on academic performance. By analyzing cohorts born before and after the policy's implementation, and their second-generation descendants, the study shows that individuals born during the winter season who benefit from free heating exhibit improved math scores compared to those who do not receive such benefits.

However, these findings should not be interpreted as an evaluation of free heating relative to alternative policy instruments such as cash transfers, heating subsidies, or investments in insulation. Rather, the Huai River Policy serves as a source of exogenous variation in early-life exposure to heating access and environmental conditions. The primary contribution of this chapter is to document the long-term association between early life heating access and later life outcomes.

Given the importance of early childhood development during infancy for human capital formation, this study contributes to the literature by examining the relationship between early-life environmental conditions and later-life well-being, with a particular focus on the case of China. The results from this study can be valuable for formulating targeted policies to enhance the well-being of future generations.

Appendix

Data: 1.A.1

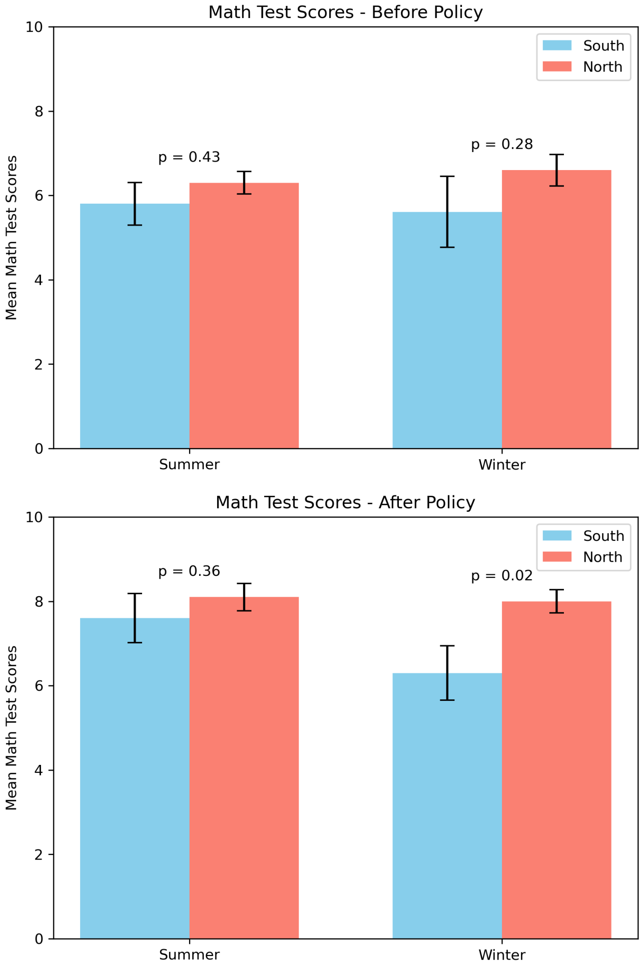
Survey Datasets

The CFPS (2010) survey is an individual-level dataset consisting of two parts: the first part includes adults (first generation) born both before and after the policy's introduction, and the second part consists of their offspring (second generation). Both datasets provide individual and household-level identifiers, allowing me to track the children of the first generation.

These surveys contain a rich set of individual-level information. For adults, I control for birth year, birth month, location, height measurements, and more. For children, I control for variables including birth year (and month), place of birth, gender, school grade, health insurance status, and other relevant factors. The birth years for adults in my sample range from 1943 to 1994, and 2002 to 2010 for children. Further, I control for whether individuals live in urban or rural areas, and for both adults and children, I account for migration status. For children, I also control for their parents' migration status. The surveys include test scores in mathematics (Appendix: Figure 1.A.1.1) and Chinese language, administered by survey personnel.

The Rozelle (2016) survey is also an individual-level dataset, but is conducted at the city level and focuses on schoolchildren born after the policy's introduction. In this dataset, I use math test scores conducted by survey personnel as an indicator of academic performance.

Figure 1.A.1.1: Math test scores



Notes: The figure shows the mean math test scores for the northern and southern groups before and after the policy introduction.

Climate Dataset

For the analysis, I collected meteorological data from Custom Weather and Statistical Intelligence. These datasets provide monthly average readings of various climate measurements, including outdoor temperature, wind, sea-level pressure, humidity, precipitation, and other variables. I use this data primarily to identify comparable climate conditions on both sides of the policy line and to control for them in the analysis. Furthermore, for the Rozelle (2016) dataset, I utilize these measurements to demonstrate the lasting impact of outdoor temperature on educational achievement.

Table 1.A.1.1: Birth Rate per Season

	Spring	Summer	Fall	Winter
North (CFPS: Adult, t<1950)	22%	24%	29%	25%
South (CFPS: Adult, t<1950)	23%	26%	27%	23%
North (CFPS: Adult, t>1950)	24%	24%	27%	25%
South (CFPS: Adult, t>1950)	21%	25%	28%	26%
North (CFPS: Children)	24%	24%	27%	25%
South (CFPS: Children)	23%	23%	32%	22%
North (Rozelle, 2016)	28%	22%	27%	23%
South (Rozelle, 2016)	27%	22%	28%	23%

Notes: This Table display the birth rates per season for CFPS, and Rozelle (2016) datasets. Source: Author's calculations.

Table 1.A.1.2: Multiple Hypothesis Testing for Provinces and Cities Close to the Policy Line

	Model p-values	Benjamini-Hochberg
Winter-Born (CFPS: Adult, North)	0.005	0.020
Winter-Born (CFPS: Child, North)	0.012	0.018
Winter-Born (Rozelle 2016, North)	0.005	0.009

Notes: I perform multiple hypothesis tests for the main coefficients of interest.

Table 1.A.1.3: Summary Statistics

All Provinces (CFPS)

	Mean	SD	Min	Max	N
Male	0.48	0.49	0.00	1.00	30062
Birth Year	1968	13.69	1940	1994	30062
Urban	0.46	0.49	0.00	1.00	30062
Born in Summer	0.31	0.46	0.00	1.00	30062
Born in Winter	0.22	0.41	0.00	1.00	30062

Provinces Close to the Policy Line (CFPS - adult)

	Mean	SD	Min	Max	N
Male	0.48	0.49	0.00	1.00	19479
Birth Year	1968	13.81	1940	1994	19479
Urban	0.46	0.49	0.00	1.00	19479
Born in Summer	0.31	0.46	0.00	1.00	19479
Born in Winter	0.27	0.44	0.00	1.00	19479

Provinces Close to the Policy Line (CFPS - child)

	Mean	SD	Min	Max	N
Male	0.52	0.49	0.00	1.00	5734
Birth Year	2002	4.53	1995	2010	5734
Urban	0.35	0.47	0.00	1.00	5734
Born in Summer	0.45	0.49	0.00	1.00	5734
Born in Winter	0.28	0.45	0.00	1.00	5734

All Cities (Rozelle, 2016)

	Mean	SD	Min	Max	N
Male	0.52	0.49	0.00	1.00	10934
Birth Year	2003	1.13	1998	2009	10934
Grade	4.66	0.52	4.00	6.00	10934
Migrant Father	0.29	0.45	0.00	1.00	10934
Temperature - Winter	-1.01	4.59	-10.13	5.3	10934
Temperature - Summer	24.69	3.73	14.99	34.74	10934

Cities With Similar Climate and Distance From the Policy Line (Rozelle, 2016)

	Mean	SD	Min	Max	N
Male	0.50	0.50	0.00	1.00	1192
Birth Year	2003	0.93	1999	2009	1192
Grade	5.01	0.69	4.00	6.00	1192
Migrant Father	0.39	0.49	0.00	1.00	1192
Temperature - Winter	4.22	0.90	2.38	5.3	1192
Temperature - Summer	21.96	3.42	14.99	29.8	1192

Notes: The table presents summary statistics for the CFPS and Rozelle (2016) data sets.

Table 1.A.1.4: Balance Tables for Northern vs Southern Provinces and Cities

Provinces Close to the Policy Line (CFPS - Adult; t<1950)

	Mean-S	Mean-N	Mean Diff	N	SE	p-value
Male (Summer)	0.510	0.480	0.030	514	0.049	0.537
Male (Winter)	0.578	0.514	0.064	246	0.088	0.464
Height (Summer)	-0.218	-0.037	-0.180	491	0.097	0.065
Height (Winter)	-0.243	-0.050	-0.193	239	0.158	0.225
Temperature (Summer)	22.432	21.835	0.596	514	0.412	0.148
Temperature (Winter)	3.226	-0.787	4.013	248	0.616	0.000
Birth Weight	-0.183	-0.106	-0.076	157	0.143	0.593
Number of Siblings	3.141	3.395	-0.254	974	0.142	0.074
Birth Year	1946.769	1946.692	0.076	986	0.125	0.538

Provinces Close to the Policy Line (CFPS - children)

	Mean-S	Mean-N	Mean Diff	N	SE	p-value
Male (Summer)	0.502	0.528	-0.026	4691	0.014	0.078
Male (Winter)	0.511	0.515	-0.003	4691	0.015	0.812
Have Insurance	0.605	0.566	0.039	4682	0.029	0.176
Grade	3.114	3.083	0.030	2624	0.133	0.818
Friends	0.878	0.902	-0.024	1778	0.025	0.349
Birth Year	2002.45	2002.071	0.378	4691	0.158	0.665

Cities With Similar Climate and Distance From the Policy Line (Rozelle, 2016)

	Mean-S	Mean-N	Mean Diff	N	SE	p-value
Male (Summer)	0.483	0.538	-0.055	1211	0.030	0.068
Male (Winter)	0.498	0.534	-0.036	1211	0.046	0.434
Age (months)	134.965	135.309	-0.343	1192	0.310	0.615
Migrant Father	0.341	0.402	-0.061	1192	0.031	0.051

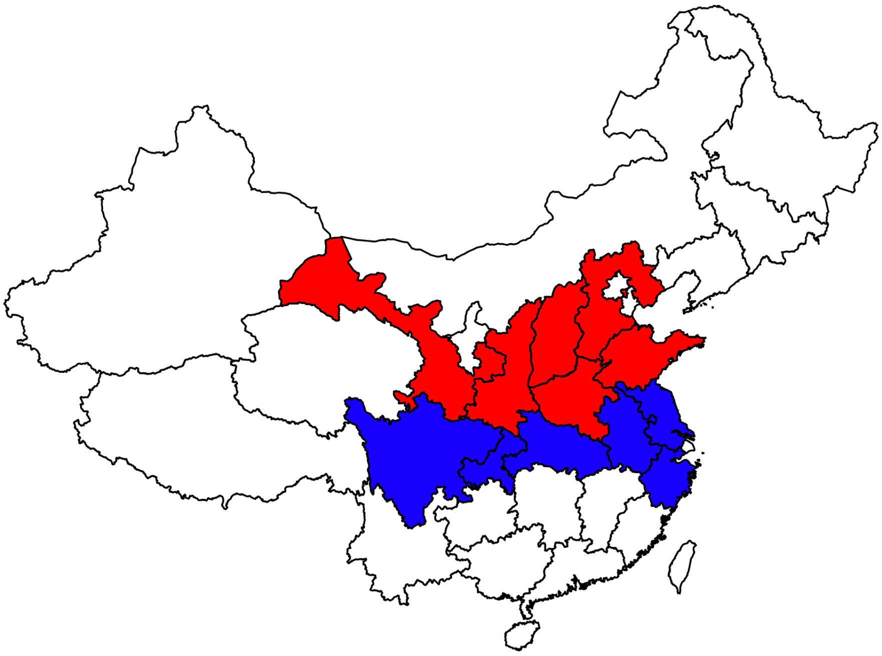
Average Monthly Outdoor Temperature Levels (Rozelle, 2016)

	Mean-S	Mean-N	Mean Difference	N	SE	p-value
Whole Year	14.567	16.214	-1.646	1192	0.460	0.000
Winter	0.411	0.715	-0.303	1192	0.091	0.000
Summer	8.577	10.068	-1.490	1192	0.732	0.000

Notes: The table includes balance table results for both datasets used for the analysis.

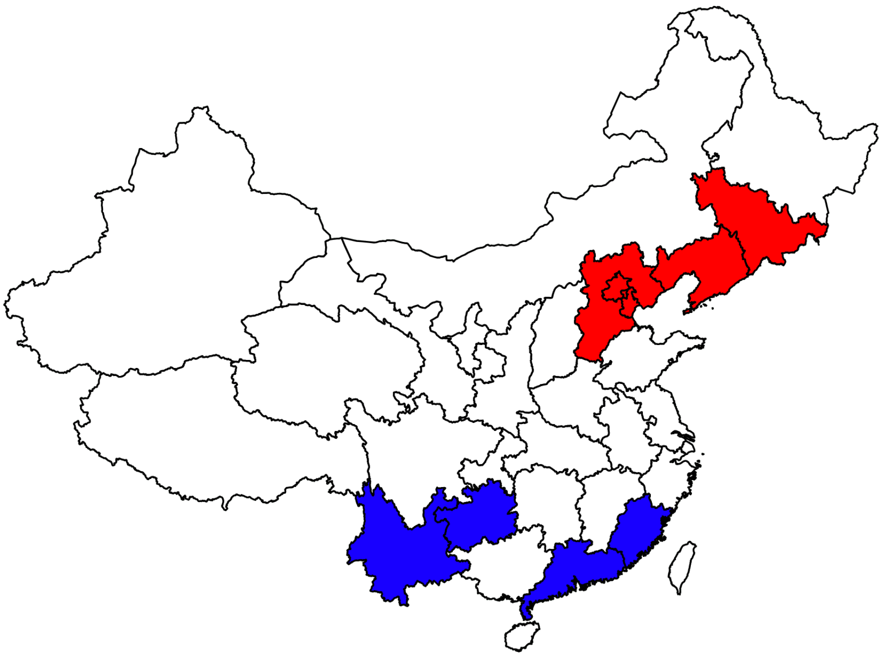
Additional Tables and Figures: 1.A.2

Figure 1.A.2.2: Provinces Close to the Policy Line



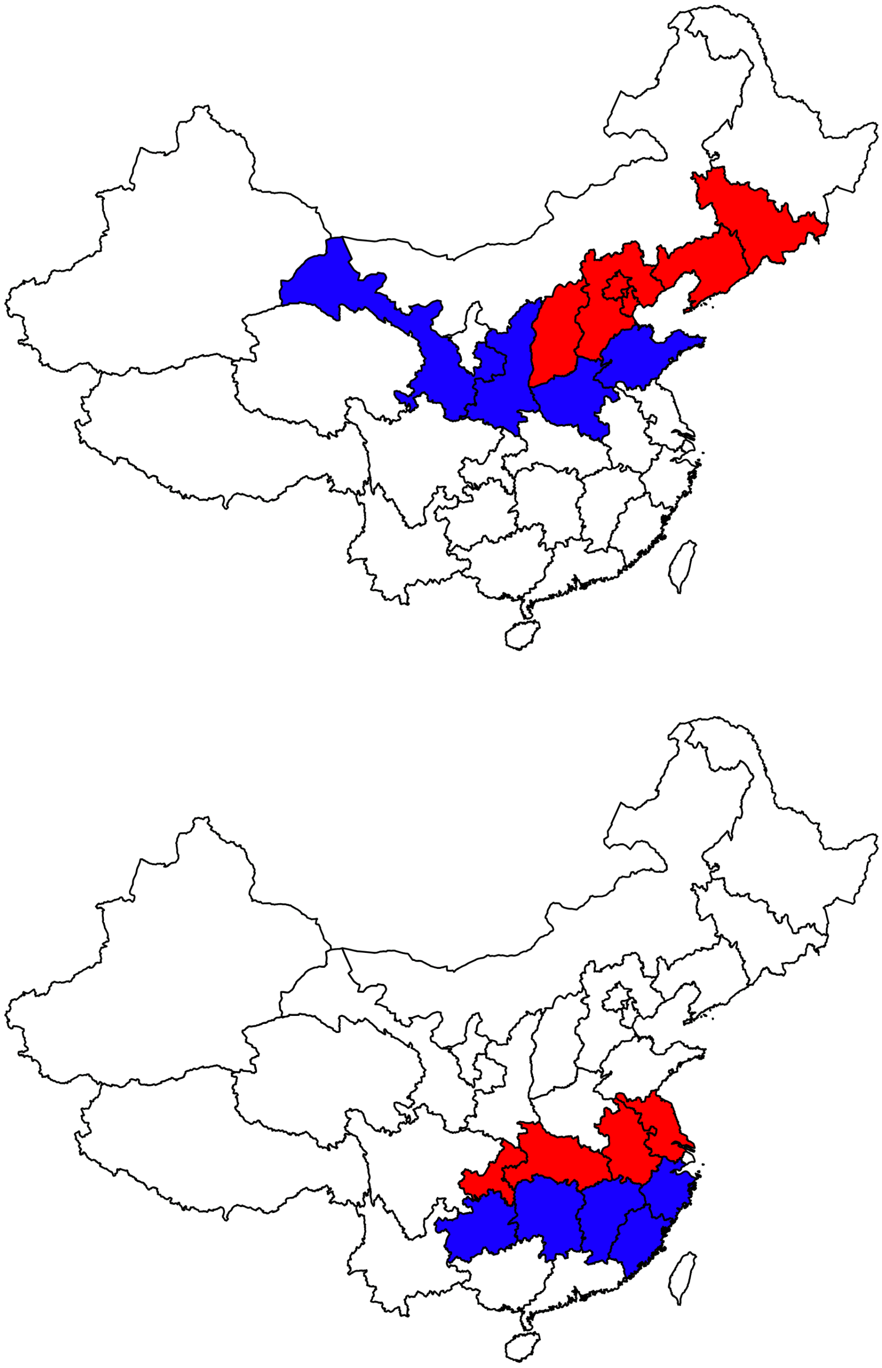
Notes: The figure shows the provinces chosen for the analyzes. Source: https://simplemaps.com/

Figure 1.A.2.3: Sensitivity Analyses



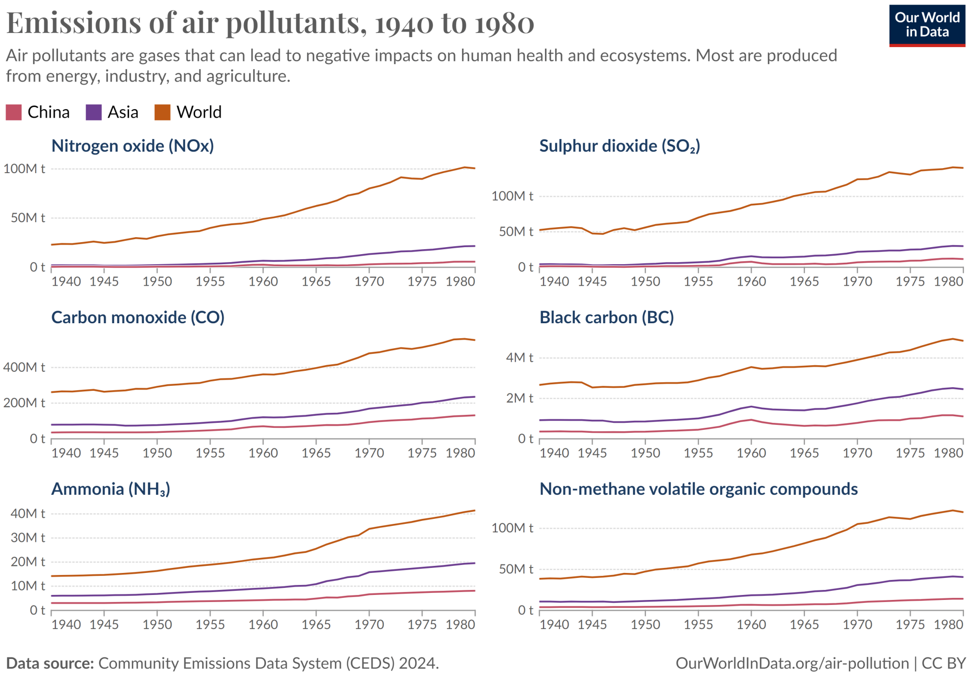
Notes: The figure demonstrates the northern and southern provinces chosen. Source: https://simplemaps.com/

Figure 1.A.2.4: Placebo Test (North and South)



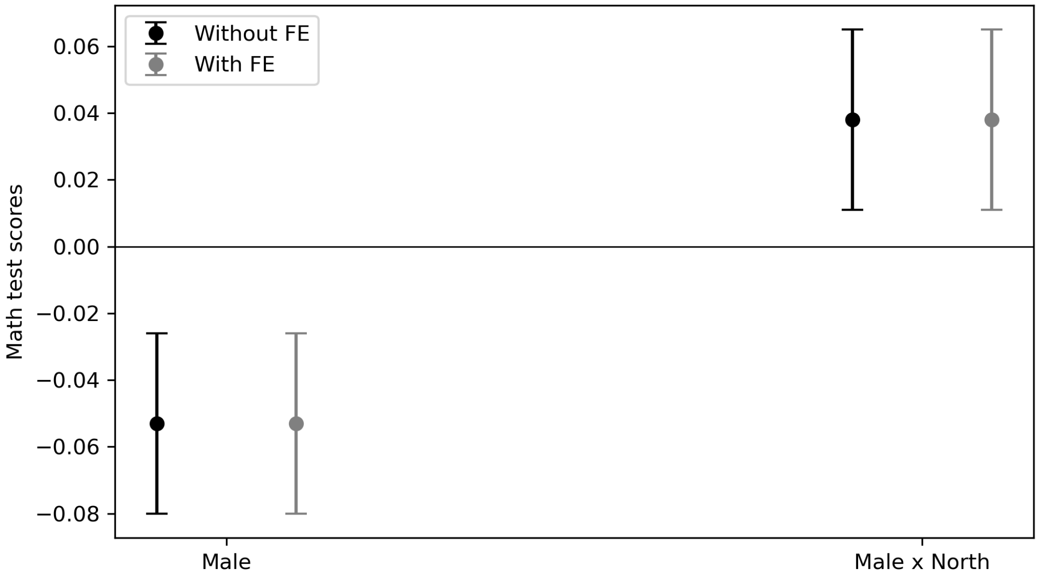
Notes: The figure demonstrates the new placebo policy lines for only northern and southern cities and provinces. Source: https://simplemaps.com/

Figure 1.A.2.5: Air Pollution Measurements in China



Notes: The figure shows different air pollution measurements for China, Europe, and Asia for the period from 1940 to 1980. Source: Our World in Data

Figure 1.A.2.6: Heating Impact on Gender



Notes: The figure shows the general performance and the the heating impact by gender.

Table 1.A.2.1: Impact of Heating on Academic Performance (CFPS: Adult)

Dependent Variable: Standardized Math Test Scores

	Math	Math
Born During Summer (t>1950, North)	0.024	0.025
	(0.030)	(0.030)
Born During Winter (t>1950, North)	0.098**	0.096**
	(0.033)	(0.033)
Height	0.045***	0.045***
	(0.009)	(0.009)
Male	-0.053*	-0.053*
	(0.027)	(0.027)
Observations	8098	8098
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar distance from policy line. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.

Standard errors in parentheses

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

Table 1.A.2.2: Impact of Heating on Academic Performance (CFPS: Adult)

Dependent Variable: Standardized Math Test Scores		
	Math	Math
Born During Summer (t>1950, North)	0.052	0.052
	(0.031)	(0.031)
Born During Winter (t>1950, North)	0.097**	0.097**
	(0.036)	(0.036)
Observations	5636	5636
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar distance from policy line for a reduced time period (1946-1980). Fixed effects are at the community and province levels. Standard errors are clustered at the household level.

Standard errors in parentheses

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

Table 1.A.2.3: Impact of Heating on Academic Performance (CFPS: Adult)

Dependent Variable: Standardized Language Test Scores		
	Language	Language
Born During Summer (t>1950, North)	-0.014	-0.014
	(0.035)	(0.035)
Born During Winter (t>1950, North)	0.016	0.016
	(0.042)	(0.042)
Observations	8102	8102
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar distance from policy line. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.

Standard errors in parentheses

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

Table 1.A.2.4: Impact of Heating on Academic Performance (CFPS: Children)

Dependent Variable: Standardized Math Test Scores

	Math	Math
Born During Summer (North)	0.054	0.060
	(0.259)	(0.258)
Born During Winter (North)	0.457*	0.474*
	(0.231)	(0.229)
Air Pollution	-0.005*	-0.008**
	(0.002)	(0.003)
Using Internet	0.221**	0.215***
	(0.069)	(0.069)
Have Good Friends	0.339*	0.362*
	(0.091)	(0.093)
Observations	712	712
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar and distance from policy line. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.
Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1.A.2.5: Impact of Heating on Academic Performance (CFPS: Children)

Dependent Variable: Standardized Language Test Scores

	Language	Language
Born During Summer (North)	0.129	0.119
	(0.222)	(0.220)
Born During Winter (North)	0.398	0.388
	(0.365)	(0.361)
Observations	693	693
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar and distance from policy line. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.
Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1.A.2.6: Household Heating and Outdoor Climate Impact (Rozelle, 2016)

Dependent variable: Standardized Math Test Scores

	(1)	(2)	(3)	(4)	(5)	(6)
Born in Summer (North)	-0.037	-0.037	-0.019	-0.176	-0.182	-0.188
	(0.060)	(0.039)	(0.018)	(0.087)	(0.082)	(0.075)
Born in Winter (North)	0.155*	0.145*	0.115*	0.198*	0.186*	0.155**
	(0.035)	(0.028)	(0.016)	(0.026)	(0.028)	(0.014)
Father Migrant	-0.107	-0.106	-0.106*	-0.098	-0.096	-0.097
	(0.031)	(0.026)	(0.024)	(0.027)	(0.022)	(0.023)
Male	-0.104**	-0.104**	-0.104**	-0.096**	-0.103***	-0.105**
	(0.004)	(0.004)	(0.003)	(0.007)	(0.003)	(0.003)
Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1192	1192	1192	1192	1192	1192

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern cities with similar climates and at similar distances from the policy line. Each column includes a different set of meteorological variables. Columns 1 to 3 include average monthly meteorological measurements after 1, 2, and 3 months after birth. Columns 4 to 6 include measurements for 1, 2, and 3 months before an infant is born. Fixed effects are at the individual level. Standard errors are clustered at the city level, and wild bootstrap approach is used.

Standard errors in parentheses

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

Table 1.A.2.7: The Outdoor Temperature Impact (Rozelle, 2016)

Dependent Variable: Standardized Math Test Scores

	(1)	(2)	(3)	(4)
Winter x Temp (2)	-0.059			
	(0.693)			
Summer x Temp (2)	0.048			
	(0.338)			
Winter x Temp (3)		-0.001		
		(0.990)		
Summer x Temp (3)		0.041		
		(0.318)		
Winter x Temp (B2)			0.053*	
			(0.050)	
Summer x Temp (B2)			0.010	
			(0.493)	
Winter x Temp (B3)				0.063**
				(0.002)
Summer x Temp (B3)				0.007
				(0.551)
Controls	Yes	Yes	Yes	Yes
Observations	1192	1192	1192	1192

Notes: The table examines the impact of outdoor temperature on academic achievement. Each column represents the intersection of the dummy variable for season of birth with temperature measurements for that season. The temperature measurements are taken 2 and 3 months before birth (Temp (B2) and Temp (B3)), and 2 and 3 months after birth (Temp (2) and Temp (3)). Standard errors are clustered at the city level, and wild bootstrap approach is used.

p values in parentheses

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

Table 1.A.2.8: Household Heating and Outdoor Climate Impact (Rozelle, 2016)

Dependent Variable: Standardized Math Test scores			
	(1)	(2)	(3)
Born in Winter (North)	0.148**	0.145**	0.139**
	(0.009)	(0.007)	(0.005)
Born in Summer (North)	-0.040	-0.057	-0.063
	(0.459)	(0.359)	(0.343)
Heat	0.595*	0.589*	0.583*
	(0.022)	(0.023)	(0.023)
Summer	0.076	0.006	-0.007
	(0.436)	(0.942)	(0.936)
Winter	-0.104	-0.056	-0.047
	(0.181)	(0.388)	(0.466)
Temp (1)	-0.007		
	(0.483)		
Temp (B1)	0.011**		
	(0.005)		
Temp (2)		0.004	
		(0.568)	
Temp (B2)		0.006	
		(0.135)	
Temp (3)			0.008
			(0.435)
Temp (B3)			0.008
			(0.240)
Controls	Yes	Yes	Yes
Observations	1192	1192	1192

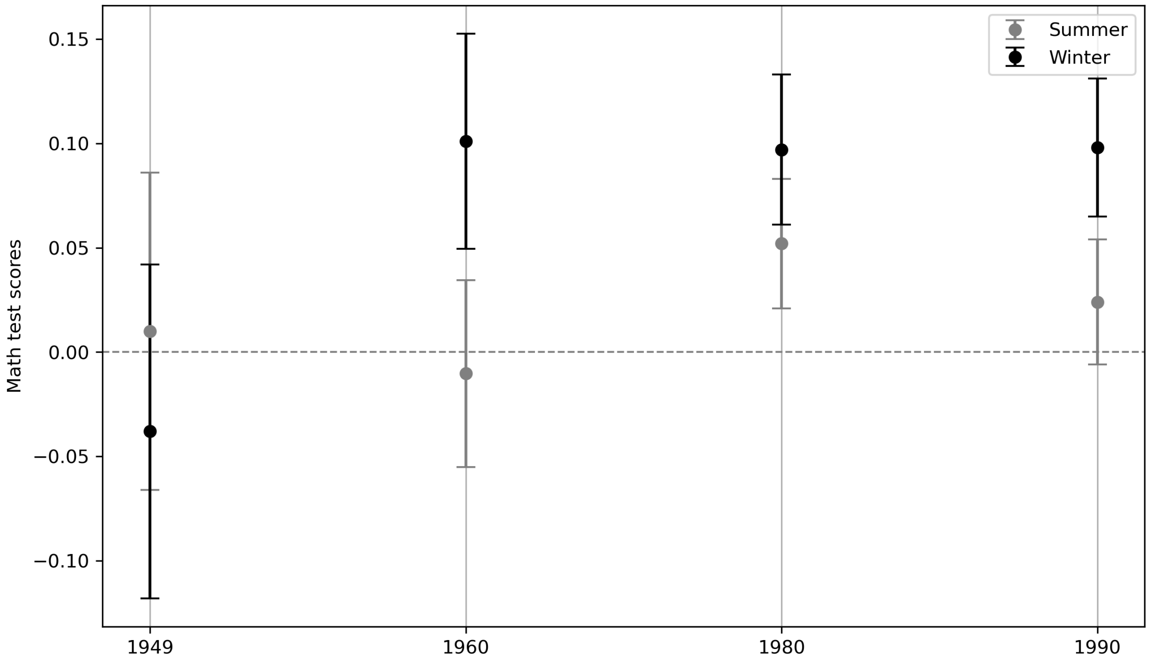
Notes: The table tests the impact of the heating policy in northern (free winter heating) and southern cities with similar climates. Each column includes outdoor temperature measurements both before and after the birth.The temperature measurements are taken one, two and three months before birth (Temp (B1), Temp (B2) and Temp (B3)) as well as one, two and three months after birth (Temp (1), Temp (2) and Temp (3)) Standard errors are clustered at the city level, and the wild bootstrap approach is used.

p values in parentheses

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

Robustness Checks 1.A.3

Figure 1.A.3.1: Heating Impact on Academic Performance



Notes: The figure shows the heating impact on academic performance for different time spans.

Table 1.A.3.1: Heating and Climate Impact (Rozelle, 2016; Placebo - North)

Dependent Variable: Standardized Math Test Scores						
	(1)	(2)	(3)	(4)	(5)	(6)
Born in Winter (North)	-0.110	-0.114	-0.115	-0.108	-0.111	-0.114
	(0.160)	(0.128)	(0.116)	(0.152)	(0.137)	(0.126)
Born in Summer (North)	-0.151	-0.136	-0.130	-0.156	-0.151	-0.151
	(0.155)	(0.170)	(0.154)	(0.077)	(0.070)	(0.072)
Heat	0.163	0.167	0.169	0.162	0.160	0.157
	(0.531)	(0.516)	(0.507)	(0.536)	(0.541)	(0.549)
Summer	0.132	0.086	0.066	0.153	0.146	0.139
	(0.623)	(0.697)	(0.703)	(0.252)	(0.146)	(0.084)
Winter	0.082	0.101	0.094	0.054	0.053	0.051
	(0.596)	(0.287)	(0.113)	(0.614)	(0.491)	(0.421)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8058	8058	8058	8058	8058	8058

Notes: The table includes the results from a placebo test conducted among only northern cities, with the policy line shifted to the north. Each column includes a different set of meteorological variables. Standard errors are clustered at the city level, and the wild bootstrap approach is used.
p values in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1.A.3.2: Heating and Climate Impact (Rozelle, 2016; Placebo - South)

Dependent Variable: Standardized Math Test Scores						
	(1)	(2)	(3)	(4)	(5)	(6)
Born in Winter (North)	-0.030	0.019	0.019	-0.018	-0.002	0.007
	(0.274)	(0.649)	(0.782)	(0.378)	(0.931)	(0.804)
Born in Summer (North)	0.098	0.073	0.059	0.086	0.021	-0.008
	(0.184)	(0.069)	(0.117)	(0.096)	(0.825)	(0.894)
Heat	0.046	-0.064	0.004	0.121	-0.094	-0.175
	(0.491)	(0.350)	(0.940)	(0.147)	(0.448)	(0.513)
Summer	0.103	0.143	0.149	0.081	0.077	0.017
	(0.628)	(0.520)	(0.512)	(0.386)	(0.371)	(0.838)
Winter	-0.116	-0.172	-0.180	-0.126	-0.116	-0.051
	(0.168)	(0.087)	(0.115)	(0.081)	(0.099)	(0.313)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2886	2886	2886	2886	2886	2886

Notes: The table includes the results from a placebo test conducted among only southern cities, with the policy line shifted to the south. Each column includes a different set of meteorological variables. Standard errors are clustered at the city level, and the wild bootstrap approach is used.
p values in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1.A.3.3: Impact of Heating on Math Test Scores - Placebo (CFPS: Adult)

	Math (t<1950, North)	Math (North)	Math (South)
Born During Summer	0.011		
	(0.076)		
Born During Winter	-0.038		
	(0.080)		
Born During Summer		0.034	0.021
		(0.020)	(0.035)
Born During Winter		0.022	-0.012
		(0.022)	(0.049)
Fixed Effects	Yes	Yes	Yes
Controls	Yes	Yes	Yes
Observations	1011	14692	7331

Notes: The table includes the results from a placebo test conducted among only northern and only southern provinces, with the policy line shifted to the north and to the south respectively. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.
Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1.A.3.4: Impact of Heating on Math Test Scores - Placebo (CFPS: Child)

	Math (North)	Math (South)
Born During Summer	-0.217	-0.185
	(0.171)	(0.190)
Born During Winter	-0.277	-0.153
	(0.190)	(0.276)
Controls	Yes	Yes
Fixed Effects	Yes	Yes
Observations	838	517

Notes: The table includes the results from a placebo test conducted among only northern and only southern provinces, with the policy line shifted to the north and to the south respectively. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.
Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1.A.3.5 Impact of Heating on Academic Performance (CFPS: Adult - East)

Dependent Variable: Standardized Math Test Scores

	Math	Math
Born During Summer (t>1950, North)	-0.025	-0.025
	(0.047)	(0.047)
Born During Winter (t>1950, North)	0.129**	0.127**
	(0.048)	(0.048)
Observations	4207	4207
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar distance from policy line in the Eastern part. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.

Standard errors in parentheses

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

Table 1.A.3.6 Impact of Heating on Academic Performance (CFPS: Adult - West)

Dependent Variable: Standardized Math Test Scores

	Math	Math
Born During Summer (t>1950, North)	-0.003	-0.003
	(0.047)	(0.047)
Born During Winter (t>1950, North)	0.108*	0.108*
	(0.054)	(0.054)
Observations	3688	3688
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar distance from policy line in the Western part. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.

Standard errors in parentheses

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

Table 1.A.3.7: Impact of Heating on Income (CFPS: Placebo)

	Income	Income
Born During Summer (t<1950, North)	0.068	0.065
	(0.345)	(0.344)
Born During Winter (t<1950, North)	0.059	0.063
	(0.337)	(0.338)
Observations	522	522
Fixed Effects	No	Yes
Controls	Yes	Yes

Notes: The table tests the impact of the heating policy in northern (winter heating) and southern provinces with similar distance from policy line. Fixed effects are at the community and province levels. Standard errors are clustered at the household level.
Standard errors in parenthesis
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Chapter 2

Born into an Energy Crisis: the Long-Term Impact on Human Capital in Armenia

2.1. Introduction

The energy sector plays an important role in supporting human well-being, particularly within the residential sector during extreme weather conditions (Fell, 2017). A short-term malfunction of energy systems can cause significant discomfort, while prolonged disruptions may lead to severe consequences (Mchunu et al., 2023). However, the situation becomes more critical when an entire country faces an energy sector shutdown. This phenomenon is also referred to as energy poverty[7], and a number of papers establish a link between it and various aspects of human life, including education, household income levels, and health (Thomson et al., 2017; Banerjee et al., 2021; Okushima, 2016). Additionally, several studies illustrate the long-term negative impacts of adverse environmental conditions on the health of newborns (Heckman, 2012; Campbell et al., 2014; Doyle et al., 2009; Campbell, 1994). However, despite these studies not much is known about the lasting effects of early life exposure to national level energy crises as most studies are focused on short run outcomes.

In this paper, I narrow this gap by analyzing how early life exposure to a nationwide energy crisis affects socioeconomic outcomes, including educational attainment and income. Additionally, I investigate whether proximity to heating sources, such as forests, reduces the negative effects of energy poverty. The rationale behind this hypothesis is that, historically, humans have used forests as a primary source of heating. That is to say, after natural gas and electricity, wood is the next most accessible heating source.

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[7] (Reddy et al., 2000) define energy poverty as “The absence of sufficient choice in accessing adequate, affordable, reliable, high-quality, safe, and environmentally benign energy services to support economic and human development”(p.44).

To explore these questions, I examine the case of the energy crisis in Armenia following the collapse of the Soviet Union in 1991. The period from 1991 to 1994 was economically difficult for Armenia. Specifically, after the collapse of the Soviet Union, almost the entire Armenian population, regardless of financial or social status, had to survive the subsequent years (1991–1994) without a natural gas supply and with limited access to electricity. Thus, this time interval provides a suitable context to analyze the effects of energy poverty and climate conditions on education and income levels. The impact of such a crisis is significant, with long-term effects that can influence the well-being of entire generations, depending on its duration. Moreover, the magnitude of the impact may vary depending on the season of birth (e.g., summer vs. winter).

Using nationally representative individual-level survey data from the International Labour Organization (ILO) and geographic information on forest coverage, this study exploits variation in birthplace, birth year, and season to assess the long-term impacts of the crisis. To isolate the effect of early-life energy poverty, I apply a methodology similar to a cross-sectional difference-in-differences strategy, comparing cohorts born before, during, and after the energy crisis. The results indicate that Armenians born during the period of energy poverty (1991–1994) who experienced winters without natural gas and electricity tend to achieve lower levels of education, being approximately 40% less likely to attain higher education. In addition, their incomes are approximately 16% to 25% lower than those born before or after this period. However, forest proximity appears to mitigate this impact. This suggests that the observed long-term negative effects likely result from energy poverty rather than other consequences of the collapse of the Soviet Union.

The rest of this paper is structured as follows: Section 2.2 reviews the related literature, Section 2.3 describes the historical background, Section 2.4 presents the context and data, Section 2.5 outlines the empirical strategy, Section 2.6 introduce the results, Section 2.7 presents the robustness analyses and Section 2.8 concludes.

2.2. Literature Review

There is a growing body of literature that explores the impact of energy poverty on various dimensions of human development. Banerjee et al. (2021) analyze the relationship between energy poverty, health, and education using country-level panel data from approximately 50 countries over the period from 1990 to 2017. The authors use night-time satellite light data as a proxy for energy access, and life expectancy at birth and average years of schooling as indicators of health and education outcomes, respectively. Their findings reveal that energy poverty has a significant negative impact on both health and educational attainment.

Another aspect affected by energy poverty is household financial stability. Okushima (2016) investigates energy poverty in Japan between 2004 and 2013 using micro-level survey data from approximately 50,000 households. The study demonstrates that energy poverty is negatively associated with household income levels, and that the burden is especially severe among single-parent households, particularly those led by mothers.

While these studies provide valuable insights into the consequences of energy poverty, they are focused on macro-level trends or short-term effects. In contrast, this study contributes to the literature by using more granular, individual-level data to assess the long-term impacts of early-life exposure to an energy crisis on adult socioeconomic outcomes. Specifically, it examines individuals born during a period of national energy crisis and tracks their well-being in later life.

Another important dimension explored in this research is the long-term impact of temperature exposure during infancy. Isen et al. (2017) examine over 12 million individuals born in the United States between 1969 and 1977 to assess how seasonal temperature variations at birth affect future outcomes. Their results indicate that an additional day with temperatures higher than 32°C during an infant's first year of life reduces annual earnings by approximately $30 by ages 29 to 31.

Similarly, Maccini & Yang (2009) investigate the long-term consequences of early-life rainfall exposure in Indonesia. Analyzing individuals born between 1953 and 1974, they find that higher rainfall levels in infancy are associated with improved health and socioeconomic outcomes in adulthood for women, though the results are not statistically significant for men.

Collectively, these studies point to the importance of early-life environmental conditions, including temperature and rainfall, in shaping long-term socioeconomic outcomes. This research builds on the existing literature and my earlier work on China (Martirosyan, 2024) by examining a national-level energy crisis as an environmental shock affecting early-life conditions. While the case of China focuses on centrally provided heating as a policy-driven intervention, the Armenian context highlights household responses to energy shortages. In this dissertation, the two chapters illustrate how different conditions affecting energy access during early life can influence long-term human capital outcomes. My research aims to contribute to a broader understanding of how adverse environmental conditions in early life, particularly those related to energy access, shape later-life well-being.

2.3. Historical Background

Armenia is a developing country located in the South Caucasus region of Eurasia. It is a landlocked nation bordered by Turkey, Azerbaijan, Georgia, and Iran. Historically, Armenia was part of the Soviet Union and was integrated into the Soviet energy policy and electrical grid. Given that Armenia lacks domestic natural gas resources, it relied on imports, primarily from Turkmenistan, with the pipeline passing through Azerbaijani territory.

Geopolitically, Armenia has faced ongoing challenges due to strained relationships with two of its four neighbors (Turkey and Azerbaijan), both of which have historically maintained adversarial stances toward Armenia. Following the collapse of the Soviet Union in 1991, Armenia was left in a unfortunate situation, lacking the necessary infrastructure and resources to meet its domestic electricity demands. A key factor worsening the crisis was the closure of Armenia's only nuclear power facility, the Metsamor Nuclear Power Plant, which had been shut down a few years earlier due to safety concerns following a devastating earthquake in 1988.

Intensifying the crisis, Armenia's natural gas supply was suspended, as Azerbaijan refused to allow the transit of gas through its territory. As a result, the country experienced severe energy shortages beginning in 1991, a situation that persisted until approximately 1995. This period, often referred to as the "dark and cold years," was marked by widespread energy deficiency, particularly during the harsh winter months. Statistical yearbooks from Armenia indicate that this period saw a significant increase in deforestation, as many households began to cut down large areas of forest to use wood for heating. At the same time, fuel markets and transportation networks were severely constrained during this period, limiting households' ability to rely on transported wood and increasing the importance of nearby forest access. This historical context highlights the severity of Armenia's energy crisis in the early 1990s and underscores the country's vulnerability to geopolitical tensions and dependence on external energy sources (Haroutounian, 2015).

2.4. Data and Summary Statistics

The data on individual-level characteristics are obtained from the School-to-Work Transition Surveys conducted by the International Labour Organization (ILO) in 2012 and 2014. The dataset contains approximately 5,000 observations and includes information on individuals' birth years (ranging from 1982 to 1999), region of birth, highest level of education attained, and current monthly income. This dataset provides the basis for the cohort-based analysis of long-term outcomes.

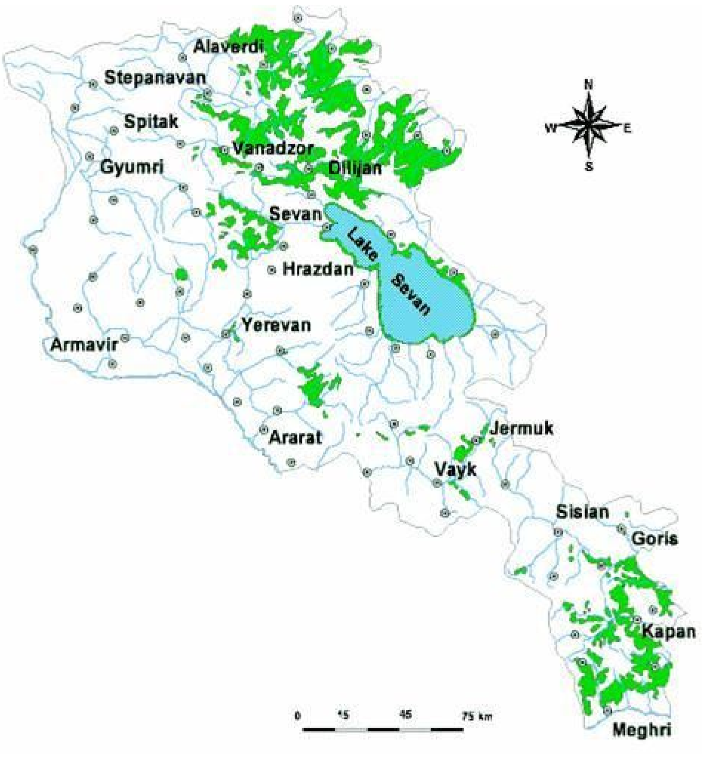
To account for access to alternative heating sources, forest proximity is measured based on regional-level classifications, identifying whether a respondent's region of birth is near forested areas (Figure 2.1). Rather than capturing overall regional development or resilience, this measure reflects contrasting access to locally available heating sources during the crisis period, when energy access and fuel supply were heavily disrupted. These classifications are constructed using data from Armenia's Statistical Yearbooks (ARMSTAT). According to the yearbooks, deforestation rates remained low and forestation levels were relatively stable before 1991. However, between 1991 and 1996, deforestation increased significantly, primarily due to the extensive use of forests for firewood. These changes are incorporated into the empirical analysis to capture environmental constraints.

For the robustness analyses, I extract the road distances from regional capital cities to the nearest forest areas and use these distances as a continuous measure of regional accessibility to locally available wood resources during the energy crisis. The distance data are obtained from Forest Atlas.

Meteorological data are obtained from Custom Weather and the World Bank Climate Knowledge Portal. These datasets cover the period from 1982 to 2015 and include monthly average temperature and rainfall at the regional and city levels. This climate information is used to control for seasonal weather variations that may influence energy needs and health shocks during infancy. Weather data are matched to individuals by region, birth year and month.

Detailed descriptions of data and variable construction are provided in Appendix 2.A.1. Summary statistics and balance tables can be found in Appendix 2.A.2.

Figure 2.1: Forests in Armenia



Source: Vardanyan (2025)

2.5. Empirical Strategy

2.5.1 Model

I begin by examining the long-term impact of early-life exposure to energy poverty on monthly income using the following regression model:

$$Y_{ismt} = \beta_1 \cdot EP_i + \beta_2 \cdot Forest_s + \beta_3 \cdot (EP_i \cdot Forest_s) + \beta_4 \cdot Temp_{ismt} + \beta_5 \cdot Rain_{ismt} + \beta_6 \cdot Male_i + \epsilon_{ismt}$$

Where: Y_{ismt} is the logarithm of monthly income for individual i, born in month m and year t, in region s. EP_i is a binary indicator equal to 1 if the individual was born during the energy crisis. $Forest_s$ is a binary indicator equal to 1 if the individual's birth region is near a forested area. $Temp_{ismt}$ represents the average monthly temperature in the birth region and month. $Rain_{ismt}$ denotes the average monthly rainfall. $Male_i$ is a gender dummy equal to 1 for males. The interaction term $(EP_i \cdot Forest_s)$ captures whether proximity to forests moderates the effect of energy poverty.

2.5.2 Identifying Assumptions

The key identification assumption is that, conditional on birth place, month and year, and climatic conditions, unobserved factors correlated with early-life exposure to the energy crisis are not systematically different across regions with varying forest proximity in ways that would fully explain the observed outcomes. Under this interpretation, forest proximity serves as a context-specific proxy for heating access during the crisis, rather than as a comprehensive measure of regional characteristics. This empirical framework is similar to a cross-sectional difference-in-differences design. It compares cohorts born before and after the energy crisis, while exploiting geographic variation in forest proximity. As a robustness check, I assess whether pre-crisis cohorts differ significantly by region or forest proximity in terms of income and educational attainment.

According to the balance tables (Appendix 2.A.2: Table 2.A.2.2), individuals born before the crisis show no significant differences in educational or income levels across regions. Moreover, average temperature differences by region vary by less than 1°C across seasons. To the best of my knowledge there is no existing literature suggesting that such minor climatic variations would substantially affect the outcomes of interest.

2.6. Main Results

2.6.1 Energy Poverty and Monthly Income

The results (Table 1) demonstrate the lasting negative impact of energy poverty. Specifically, across all model specifications, spanning birth cohorts from 1982 to

1999, the energy crisis led to a statistically significant reduction in monthly income levels, ranging from approximately 16% to 25% for individuals born during the crisis years. In contrast, the placebo test (1982–1990), where the treatment year is set to 1989–1990 instead of 1991, shows no statistically significant effect, suggesting that the observed income drop is not driven by pre-existing trends.[8]

Next, Figure 2.2 examines the heterogeneity of the impact based on season of birth and proximity to forested areas.[9] Individuals born during the winter months were more negatively affected by the crisis than those born in summer. Additionally, winter-born individuals who lived near forests experienced a notable income advantage relative to their counterparts farther from forests. This supports the hypothesis that forests may have served as a substitute heating source during the crisis. Finally, the effect of temperature shows a small but positive impact on income for winter-born individuals, possibly due to reduced heating needs during warmer winters.

To further illustrate these findings, Figure 2.3 plots the cohort-level log wages over time. Among the general population (top panel), wages remain relatively stable before the crisis, drop sharply for cohorts born between 1991 and 1994, and then gradually recover. In contrast, for individuals born in forested regions (bottom panel), wages show an opposite trend: no advantage before 1991, followed by an income increase during the crisis years (1991–1994), and then a decline as the crisis ends. This pattern again underscores the buffering role of forest proximity during periods of energy poverty.

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[8] See Appendix 2.A.2, Table 2.A.2.3

[9] See Appendix 2.A.2, Table 2.A.2.4.

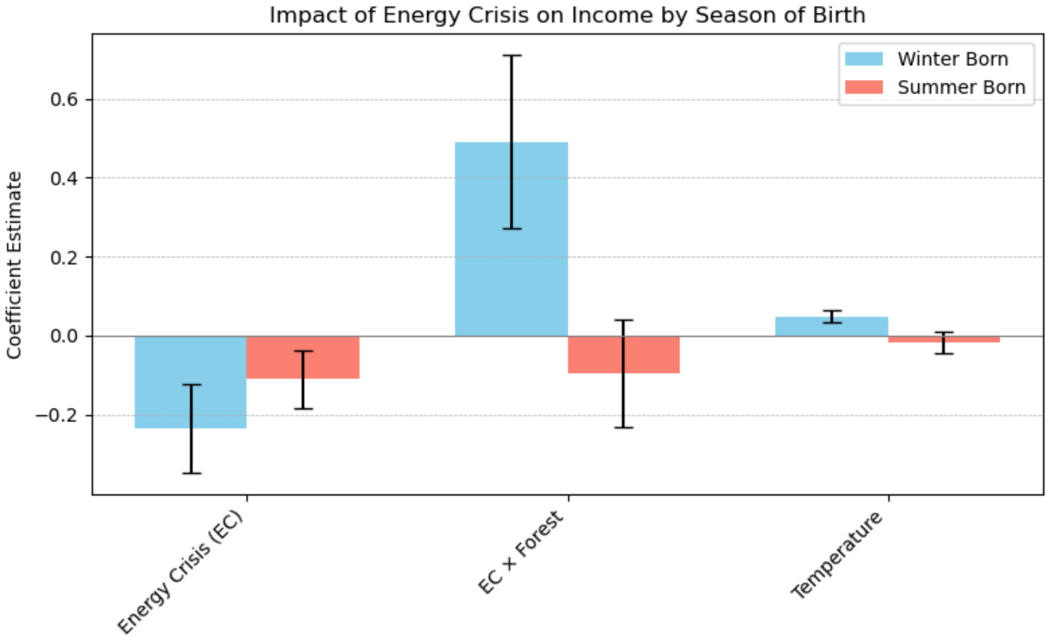
Table 1: Impact of energy poverty on monthly income

	1987–1993	1982–1990
Energy Crisis	-0.252***	0.0524
	(0.030)	(0.089)
Energy Crisis x Forest	0.207*	-0.194
	(0.075)	(0.137)
Treatment Years	1991-1993	1989-1990
Fixed Effects	Yes	Yes
Controls	Yes	Yes
Observations	604	710

The table presents the impact of the energy crisis on wage levels for individuals born during the crisis years. 1991 to 1993 are treatment years, and last column shows a placebo test, where the treatment years were set to 1989 and 1990. Standard errors are clustered at the regional level.

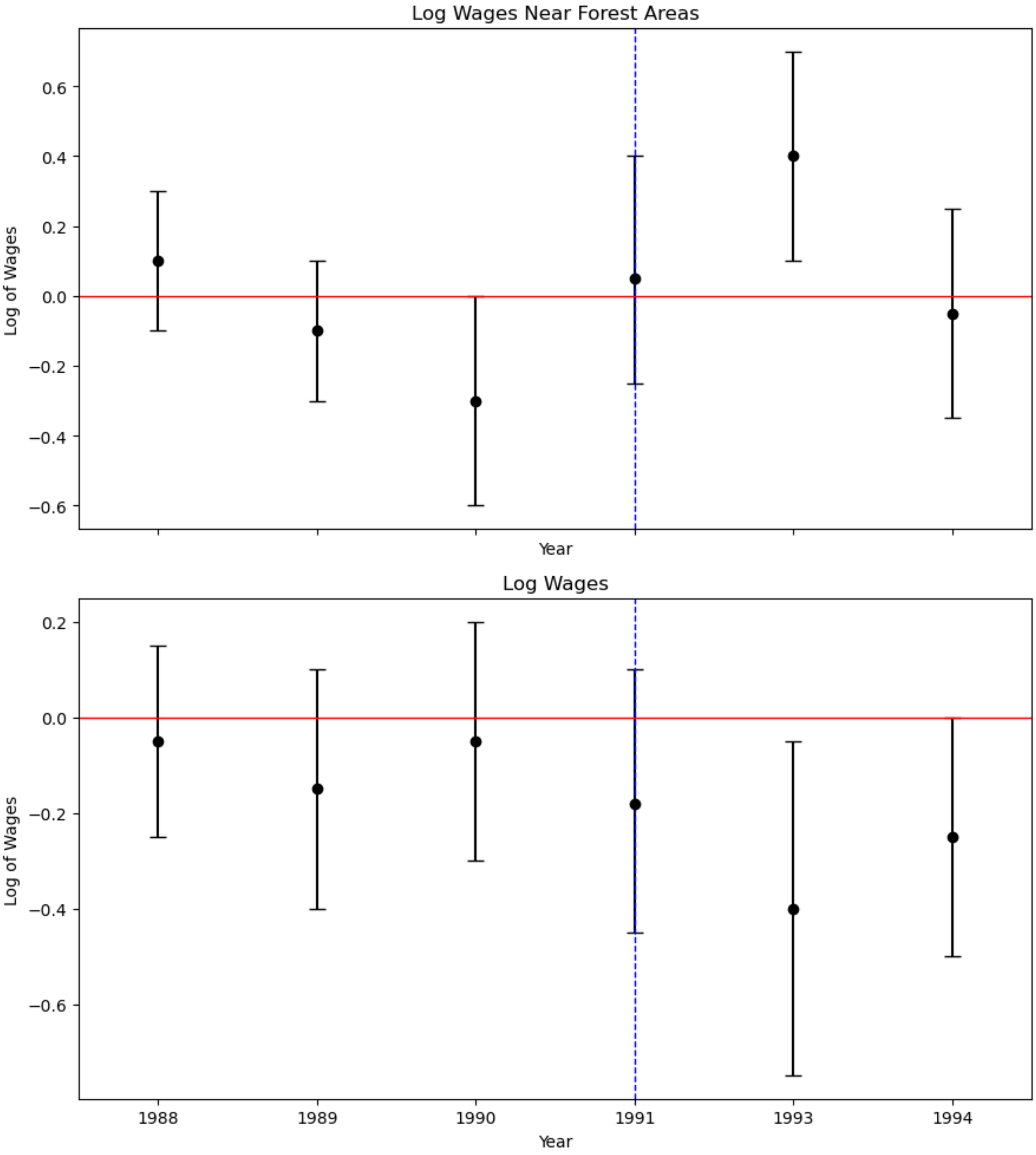
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 2.2



Notes: Bars show coefficient estimates with standard errors for the impact of the energy crisis on income by birth season. The energy crisis has the strongest impact on winter-born individuals. However, forest proximity provides a positive mitigating effect.

Figure 2.3



Notes: The blue line marks the 1991 energy crisis. Wages drop after 1991 but start to recover afterwards. For those born near forest areas, the picture is opposite, showing a temporary positive impact from forest proximity after the crisis, but no benefits in the pre-crisis period.

2.6.2 Energy Poverty and Attained Education Level

In this section, I analyze the long-term impact of early-life energy poverty on education levels attained. Given the similarity between mechanisms that influence both education and income, such as household resources, early-life health, and learning conditions, it is reasonable to expect similar patterns.

To assess this, I use a multinomial logistic regression model where the dependent variable is the individual's highest level of completed education. The key explanatory variables include: a dummy for individuals born during the energy poverty period (1991–1993), seasonal birth dummies (Winter or Summer), and a dummy for forest proximity. The model also controls for gender and postnatal temperature exposure measured after the first month of birth.

The dependent variable is grouped into two categories: (1) the baseline group includes individuals who attained only primary or secondary education; (2) the higher education group includes those who completed a university degree or postgraduate studies.

The results (Table 2) reveal a strong negative effect of energy poverty on educational attainment.[10] Specifically, individuals born during the energy crisis were substantially less likely to attain higher education, with estimated reductions ranging from approximately 37% to 52% across specifications, though the magnitude should be interpreted with caution given data limitations. Importantly, this effect is absent in the placebo specification where the treatment year is set to 1989–1990, reinforcing the credibility of the main result.

Figure 2.4 explores heterogeneity by birth season and forest proximity.[11] The negative effect of energy poverty is notably larger for winter-born individuals, consistent with increased exposure to cold-related deprivation. As expected, proximity to forests partially mitigates the negative effect for winter-borns, suggesting that

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[10] See Appendix 2.A.2, Table 2.A.2.5.

[11] See Appendix 2.A.2, Table 2.A.2.6.

access to alternative heating sources may have buffered the impact on educational outcomes.

While these findings support the hypothesis that energy poverty during early life significantly hinders long-term human capital development, in future research I will aim to expand the dataset and explore additional mechanisms to strengthen causal inference.

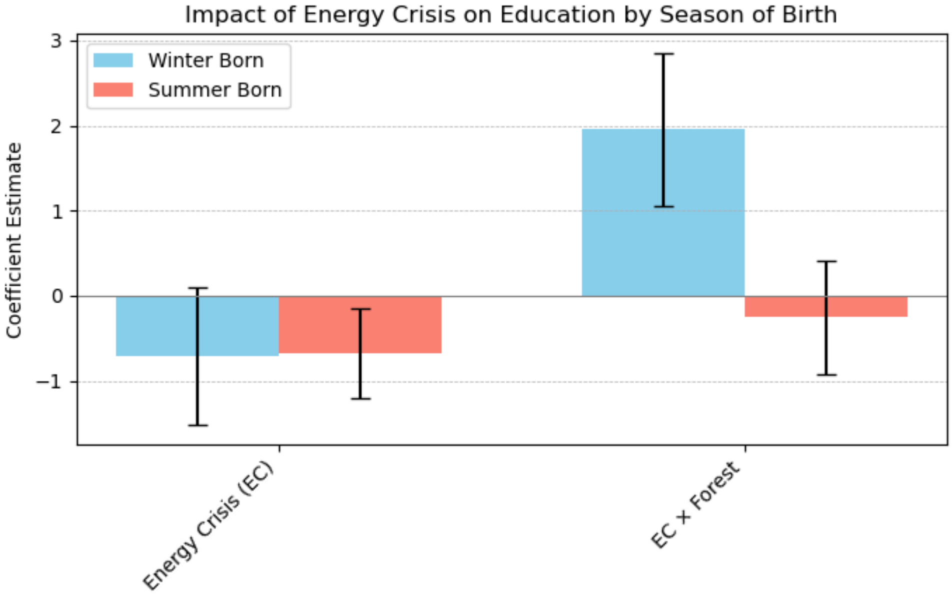
Table 2: Impact of energy crisis on education level

	1987-1991	1987-1999	1987-1990
Energy Crisis (EC)	-0.525*	-0.371*	-0.028
	(0.242)	(0.175)	(0.191)
EC x Forest	0.114	0.152	-0.403
	(0.284)	(0.381)	(0.532)
Treatment Years	1991	1991-1993	1989-1990
Fixed Effects	Yes	Yes	Yes
Controls	Yes	Yes	Yes
Observations	612	1177	1177

The table presents the impact of the energy crisis on education level attained for individuals born during the crisis years. The treatment year is 1991 in the first column and is extended to 1993 in the second column. The third column presents a placebo test using treatment years 1989 and 1990 to assess whether the observed effects are specific to the true crisis period. Standard errors are clustered at the regional level.

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

Figure 2.4



Notes: Bars show coefficient estimates with standard errors for the impact of the energy crisis on attained education levels. Winter-born individuals are more adversely affected, though forest proximity appears to have a mitigating effect.

2.7. Robustness Analysis

To evaluate the robustness of the results to alternative measures of heating access, I replace the binary forest proximity indicator with a continuous measure of distance to forested areas. Distance to the nearest forest is measured as the road distance from the regional capital city.[12] This serves as a proxy for the main population and administrative center of each region. This approach captures average availability to locally available wood sources within the region, while remaining consistent with the structure of the data.

Table 3 presents results from specifications interacting energy crisis exposure with distance to a forest. The estimates again indicate that individuals born during the energy crisis experienced worse adult outcomes. While the positive interaction term suggests that closeness to the forest area mitigates the negative impact from

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[12] I transform the distance values using an inverse-distance index defined as 1/(1+Distance), so that higher values correspond to closer distance to forest.

the energy crisis. This is consistent with the interpretation that proximity to local wood resources provides some protection against the energy crisis.

These results are broadly consistent with the baseline analysis using a binary forest indicator, strengthening the hypothesis that access to locally available heating resources has an impact during the crisis period. However, the estimates should be interpreted with caution given the limited sample size, and the fact that distance is an imperfect proxy for actual household fuel access. Nevertheless, the robustness exercise reinforces confidence in the direction of the effect.

Table 3: Impact of energy poverty on monthly income

	Income	Education
Energy Crisis	-0.179*	-0.368*
	(0.0731)	(0.187)
Energy Crisis x Distance	0.506*	0.449
	(0.179)	(1.617)
Treatment Years	1991-1993	1991-1993
Fixed Effects	Yes	Yes
Controls	Yes	Yes
Observations	604	1177

The table reports estimates of the impact of early life exposure to the energy crisis on adult monthly income and educational attainment. The main variables of interest are energy crisis and its interaction with distance to the nearest forest, measured as distance from the regional capital city. Treatment years are defined as 1991 to 1993. Standard errors are clustered at the regional level.

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

2.8. Conclusion

Early-life conditions play a crucial role in shaping human capital, and exposure to adverse environments during infancy can have lasting effects on individual well-being.

The findings of this study demonstrate that exposure to an energy crisis during infancy has a negative impact on socio-economic outcomes in adulthood, particularly in terms of educational attainment and income. The effects are more pronounced for individuals born during the winter months, suggesting that heating deficiency during colder seasons may intensify the consequences of energy poverty. Additionally, higher winter temperatures appear to have a small but positive effect on these outcomes, potentially due to reduced heating needs during infancy. The consistent seasonal patterns in the estimates, together with robustness analyses and placebo tests, suggest that the results are unlikely to be driven by pre-existing regional trends or unrelated cohort effects.

While the current datasets provide valuable insights, they have certain limitations. The survey data is cross-sectional, which constrains the ability to fully control for unobserved heterogeneity or to explore within-individual changes over time. Additionally, forest proximity is used as a proxy for alternative heating access, which may not capture the full variation in household-level resource use. More granular data on household behaviors during the crisis period would strengthen the analysis.

Future research could benefit from longitudinal data that would support more reliable identification of causal relationships. Expanding the analysis to include other post-Soviet countries that experienced similar crises could also help generalize the findings. Moreover, integrating satellite-based measures of environmental conditions and deforestation could provide more precise indicators for environmental exposure.

Despite these limitations, the study contributes to the growing literature on early-life shocks and long-term outcomes. It highlights the importance of energy security as a critical component of child development policy. These findings may inform targeted interventions to mitigate the long-term effects of energy poverty and support the well-being of future generations.

Appendix

Data: 2.A.1

Survey Datasets

The School-to-Work Transition Surveys used in this study were obtained from the International Labour Organization. Two waves of the survey, conducted in 2012 and 2014, are utilized. These surveys are conducted at the individual level and contain detailed information on demographic, educational, and labor market characteristics. The birth years of respondents range from 1987 to 1999, allowing for the identification of cohorts born during, before, and after the energy crisis period. Information on individuals' birthplaces is also included, enabling region-level analysis.

To account for geographic variation in access to alternative heating sources, regional forest proximity is constructed using data from the Statistical Yearbooks of Armenia, accessed through the Armstat archive.

Climate Dataset

Meteorological data were collected from Custom Weather and the World Bank Climate Knowledge Portal. These datasets provide monthly averages of outdoor temperature and precipitation at both regional and city levels. This information is used to control for climatic variation across regions and birth seasons, helping to isolate the effects of energy poverty from weather-related influences.

Additional Tables and Figures: 2.A.2

Table 2.A.2.1: Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Birth Year	5049	1991	4.40	1982	1999
Temperature	5049	7.95	9.79	-13.30	26.10
Rain	5049	35.04	26.61	0	186.7
Income	975	90286	65687	0	1000000
Education	1,177	1.25	0.44	1	2
Male	4,153	0.49	0.50	0	1

Notes: This table shows summary statistics for key variables used in the analysis.

Table 2.A.2.2: Balance Table

Balance Table for years 1987 to 1990						
Variable	Mean-C	Mean-T	Mean Diff	N	SE	p-value
Born in Winter	0.252	0.237	0.015	1336	0.0236	0.531
Born in Summer	0.088	0.077	0.011	1336	0.0152	0.463
Male	0.484	0.439	0.046	1336	0.0274	0.094
Income	94877	92206	2670	421	6621	0.687
Male (Winter)	0.111	0.102	0.009	1336	0.0170	0.587
Male (Summer)	0.041	0.037	0.004	1336	0.0107	0.731
Education	1.454	1.460	-0.006	492	0.0451	0.896
Temperature (Winter)	-1.023	-1.380	0.357	1335	0.1453	0.014
Temperature (Summer)	1.515	1.341	0.174	1335	0.2636	0.509

Notes: The table includes balance table results for both datasets used for the analysis.

Table 2.A.2.3: Impact of energy poverty on monthly income

	1982-1991	1987-1991	1987-1993	1987-1999	1982-1990
Energy Crisis	-0.157	-0.204	-0.252***	-0.154*	0.0524
	(0.115)	(0.117)	(0.030)	(0.051)	(0.089)
Energy Crisis x Forest	0.035	0.134	0.207*	0.198	-0.194
	(0.171)	(0.143)	(0.075)	(0.157)	(0.137)
Forest	-0.111	-0.081	-0.088	-0.145	0.027
	(0.167)	(0.086)	(0.087)	(0.198)	(0.0891)
Treatment Years	1991	1991	1991-1993	1991-1993	1989-1990
Fixed Effects	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
Observations	795	503	604	681	710

The table presents the impact of the energy crisis on wage levels for individuals born during the crisis years. I first selected 1991 as the treatment year, followed by a range of years from 1991 to 1993. The last column shows a placebo test, where the treatment years were set to 1989 and 1990. Standard errors are clustered at the regional level.

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

Table 2.A.2.4: Impact of Energy Crisis on Income by Season of Birth

	Winter Born	Summer Born
	(1982–1993)	(1982–1993)
Energy Crisis (EC)	-0.235	-0.110
	(0.112)	(0.0737)
Forest	0.0254	0.0271
	(0.142)	(0.0736)
EC × Forest	0.491^{*}	-0.0960
	(0.220)	(0.136)
Temperature	0.0478^{**}	-0.0171
	(0.0150)	(0.0265)
Rainfall	0.00593^{*}	0.000797
	(0.00242)	(0.00272)
Treatment Years	1991–1993	1991–1993
Fixed Effects	Yes	Yes
Controls	Yes	Yes
Observations	148	170

The table presents the effect of being born during the energy crisis years on monthly income, disaggregated by season of birth. "Summer Born" and "Winter Born" refer to individuals born in the respective months within the 1982–1993 window. Treatment years are defined as 1991 to 1993. All models include controls for temperature, rainfall, forest proximity, gender, and relevant interaction terms. Standard errors are clustered at the regional level.

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

Table 2.A.2.5: Impact of energy crisis on education level

	1987-1991	1987-1999	1987-1990
Energy Crisis (EC)	-0.525*	-0.371*	-0.028
	(0.242)	(0.175)	(0.191)
Forest	0.396	0.258	0.601
	(0.250)	(0.180)	(0.425)
EC x Forest	0.114	0.152	-0.403
	(0.284)	(0.381)	(0.532)
Treatment Years	1991	1991-1993	1989-1990
Fixed Effects	Yes	Yes	Yes
Controls	Yes	Yes	Yes
Observations	612	1177	1177

The table presents the impact of the energy crisis on education level attained for individuals born during the crisis years. The treatment year is 1991 in the first column and is extended to 1993 in the second column. The third column presents a placebo test using treatment years 1989 and 1990 to assess whether the observed effects are specific to the true crisis period. Standard errors are clustered at the regional level.

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

Table 2.A.2.6: Impact of Energy Crisis on Education by Season of Birth

	Summer Born	Winter Born
	(1987–1991)	(1987–1991)
Energy Crisis	-0.678	-0.713
	(0.524)	(0.807)
Forest	0.361	0.520
	(0.454)	(0.493)
Energy Crisis × Forest	-0.253	1.959*
	(0.669)	(0.898)
Temperature	-0.0138	0.0220
	(0.155)	(0.0506)
Treatment Year	1991	1991
Fixed Effects	Yes	Yes
Controls	Yes	Yes
Observations	151	152

The table shows the impact of the energy crisis on education level achieved, by season of birth. The sample includes individuals born between 1987 and 1991. The treatment year is 1991. All regressions control for temperature, rainfall, forest proximity, gender, and relevant interaction terms. Standard errors are clustered at the regional level.

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

Chapter 3

Electricity Market Reforms and Greenhouse Gas Emissions: Lessons from Norway

3.1. Introduction

To preserve the environment, governments in many countries have begun implementing policies aimed at reducing greenhouse gas emissions. A significant share of global electricity is produced from fossil fuels (Figure 3.1, Appendix 3.A.2), which are major contributors to rising greenhouse gas levels. Although this issue is widely recognized, rapid growth of the global population makes it increasingly difficult for electricity producers to meet rising demand while simultaneously protecting the environment.

This study examines the impact of electricity market liberalization and introduction of dynamic pricing on CO_2 emissions, focusing on Norway's 1990 Energy Act as a case study. This act was a foundational piece of legislation aimed to ensure the efficient and socially rational use of energy resources. Among various directives, the act includes measures to reduce government regulation and promote competition in the market, increase interest in market-oriented electricity sales and purchases, and improve customer efficiency in electricity usage (Oen & Johansen, 1992; Mirza & Bergland, 2012).

Given Norway's hydro-dominant electricity systems, the analysis in this study does not imply that reductions in electricity consumption mechanically lead to proportional reductions in CO_2 emissions. Instead, the estimated effects should be interpreted as reflecting broader behavioral responses to market liberalization and dynamic pricing, including changes in peak demand, efficiency improvements, and adjustments in energy use across sectors. While mechanisms, such as fuel substitution, are consistent with this interpretation, the aggregate nature of the data does not allow the seperate identification of the channels.

Building on this policy shift, liberalization of the electricity market and opening it to competition enabled introduction of consumer dynamic electricity pricing, allowing the option to purchase variable-price electricity contracts, in which prices fluctuate in real time based on supply and demand. While the main focus of this paper is the introduction of market competition and consequent variable pricing, it should be mentioned that the Norwegian Energy Act also includes other factors that can affect CO_2 emissions. In particular, market liberalization creates the possibility of cheaper electricity production, which can increase supply levels for export to other countries and hence increase CO_2 emissions. My future research will aim to address such considerations. The results presented in this study should be interpreted as the effects of the overall reform, with market liberalization and variable pricing serving as the primary driving factors.

To empirically assess the impacts of these reforms, this research applies both classical and machine learning-based synthetic control methods. Accordingly, it contributes to the literature in two ways. First, by employing both the classical synthetic control method (SCM) and a novel machine learning-based synthetic control learner, this research not only evaluates the effectiveness of electricity market liberalization and dynamic tariffs in reducing emissions, but also demonstrates the improved accuracy and robustness of machine learning techniques, even with relatively small datasets. Second, this study offers new empirical evidence on how market-based reforms can benefit the environment by analyzing the case of Norway.

A clear understanding of electricity consumption patterns is essential for evaluating such policies. Although high electricity demand may appear economically beneficial for producers, consumption actually fluctuates throughout each day and across seasons. These daily and seasonal peaks in demand (Figure 3.2, Appendix 3.A.2) increase electricity production costs, particularly during peak load periods.

To address these challenges, governments have introduced policies aimed at reducing overall electricity consumption. One such policy is dynamic pricing, in which electricity prices vary across specified time periods (Figure 3.2, Appendix 3.A.2). Time-of-use (TOU) pricing is a subtype of dynamic pricing (Yang et al., 2013).[13] Under TOU pricing, electricity costs per kWh differ depending on whether consumption occurs during peak hours (highest prices) or off-peak hours (lowest prices).

These price differences arise from the structure of electricity generation. Nuclear and large hydroelectric power plants are typically used for baseload generation due to their low cost per kWh and specific operational characteristics; for instance, nuclear power plants are not designed to adjust their workload frequently. In contrast, thermal power plants, which are less environmentally friendly because they produce a significant amount of greenhouse gases and have a higher cost per kWh, can be employed to meet demand peaks due to their flexible output. Consequently, both producers and consumers have financial incentives to minimize consumption during peak periods. Following this logic, this study hypothesizes that countries that adopt dynamic pricing policies can observe reductions in greenhouse gas emissions.

Although the 1990 Energy Act was not introduced as a pure climate policy, it had a significant impact on electricity pricing and market incentives in ways that are directly relevant for environmental outcomes. By exposing both producers and consumers to dynamic pricing, the reform altered electricity use patterns and substitution across energy sources. In a hydro dominant system, these effects may operate through reduced dependence on small thermal generation during peak-load periods or through long-run efficiency responses, even when average electricity production is largely carbon neutral. From an environmental economics perspective, the reform therefore provides a setting in which market design and price incentives can generate meaningful CO_2 effects, even in the absence of explicit climate objectives.

To empirically investigate this hypothesis, I use time-series data from Norway and a set of comparable countries. The 1990 Energy Act of Norway, which liberalized the

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[13] In this paper, I use the terms dynamic pricing and time-of-use pricing interchangeably.

Norwegian electricity market by introducing competition and enabling consumer switching, serves as the treatment. Since then, various forms of dynamic pricing have been implemented in Norway.

For the estimation, this paper employs the synthetic control method (Abadie & Gardeazabal, 2003; Abadie et al., 2010), which is well-suited for evaluating policy effects when treatment is applied at the aggregate level and only one or a few units are treated. The study compares Norway's CO_2 emissions trajectory to a weighted average of similar countries (the synthetic control) that did not adopt dynamic pricing during the same period. The results suggest a substantial decline in CO_2 emissions in Norway following the implementation of the policy, with an estimated reduction of around 34%, which is comparable in magnitude to findings in similar studies analyzing climate and energy policies (Lessmann & Kramer, 2024; Tello, 2025).

The analysis uses Root Mean Squared Prediction Error (RMSPE) as a diagnostic tool to assess the pre and post treatment fit. The results show a post/pre RMSPE ratio of approximately 2.6. To strengthen the robustness of the findings, I also apply the machine learning-based Synthetic Control Learner method with bias correction proposed by Viviano & Bradic (2023). This method shows an even tighter pre-treatment fit and a more pronounced post-treatment divergence, with a post/pre RMSPE ratio of around 9, offering further evidence of the treatment effect and the efficiency of machine learning techniques in policy evaluation.

The remainder of the paper is organized as follows: Section 2 provides background on Time-of-Use Tariffs and a literature review. Section 3 describes the data used for the analysis. Section 4 presents the empirical findings, including comparisons between the classical synthetic control and machine learning-based methods. Section 5 discusses robustness checks. Section 6 concludes.

3.2. Time-of-Use Tariffs and Literature Review

The Norwegian Energy Act of 1990 is widely recognized as an influential electricity market liberalization reforms. Existing studies mainly examine its implications for market efficiency, pricing behavior, and competition, while relatively less attention has been given to environmental outcomes. This chapter builds on the literature by focusing on CO_2 emissions and by applying both classical and machine learning-based synthetic control methods to assess the reform's aggregate environmental effects.

TOU programs are price-oriented initiatives designed to motivate consumers to adjust their electricity usage throughout the day according to a predetermined schedule of on-peak and off-peak hours. Research shows that, as a consequence, electricity demand falls during peak periods, saving companies from generating high-cost electricity (Faruqui & Sergici, 2010; Faruqui et al., 2010) and avoiding the necessity to build new power plants solely to meet peak demand periods (Yang et al., 2013).

Increased attention to dynamic pricing followed the electricity crisis in California during 2001 to 2003. Subsequently, three major investor-owned utilities in California conducted a statewide pricing pilot experiment from 2003 to 2004, which showed a 7.6% to 27% reduction in electricity usage during peak periods (Faruqui & George, 2005).

However, the effectiveness of TOU pricing depends on a country's energy portfolio. Although the literature highlights the positive effects of TOU pricing, it is important to note that such tariffs are most effective in countries in which the baseload is supplied by renewable (e.g., hydroelectric) or alternative (e.g., nuclear) power sources, which do not increase CO_2 emissions. In contrast, if thermal power plants provide the baseload, shifting peak loads can potentially lead to higher CO_2 emissions (Zhang et al., 2014). Given Norway's extensive renewable energy resources (Oen & Johansen, 1992), it is well-suited to be a treatment country for analyzing the effects of TOU pricing.

While most studies focus on electricity demand and emissions, only few apply empirical evaluation methods to dynamic pricing and market reforms. For instance, Lessmann & Kramer (2024) analyse California's cap-and-trade program, which includes a shift to renewable energy sources and the introduction of environmental policies, and its effect on emission levels. They implement the Synthetic Control Method, in which the treated unit was California and the synthetic control unit consisted of 38 other US states, analyzing the period from 2005 to 2019. Their results demonstrated an approximate 48% reduction in CO_2 emissions compared to the synthetic counterfactual.

Tello (2025), analyzes national climate and energy policies, including carbon taxes and emissions trading systems, to assess their impact on CO_2 reductions in the electricity generation sector. Using data from 109 countries over a 30 year period, the study demonstrates that, particularly in developed countries such as those in the European Union (EU), there were notable reductions in CO_2 emissions. Notably, the most effective policies are those that integrate carbon pricing with renewable energy support mechanisms. The results indicate that, depending on the specification, the reduction in CO_2 emissions per capita in the EU ranges from 10% to 43%.

The estimated effect in this study shows a reduction of around 34%, which is comparable in magnitude to the results found in the other studies. Given the large share of renewables in Norway, this study adds to the literature by suggesting that electricity market liberalization, coupled with dynamic electricity pricing and supported by renewable infrastructure, can play a significant role in reducing greenhouse gas emissions.

3.3. Data

For the empirical estimation, this paper employs time-series data covering the period from 1960 to 2010. The dataset time period ends in 2010 because of data availability constraints. However, the data includes a sufficiently long post-treatment period to assess the medium and long run effects of the reforms. The dataset, obtained from the World Bank (2025), includes annual observations on CO_2 emissions, GDP per capita, fertility rates, life expectancy at birth, death rate, and food production. The selection of control variables is guided by the existing literature (Abadie & Gardeazabal, 2003), the paper's focus on the electricity sector, and the availability of sufficiently long data series.

The sample includes European countries: Norway (treated), France, Ireland, the Netherlands, and Iceland. As a robustness exercise, the synthetic control unit is expanded to include Belgium, Denmark, Sweden, Switzerland, and the UK. These countries experience climate conditions similar to those of Norway and also have access to renewable and/or alternative energy resources, making them plausible candidates for the implementation of dynamic pricing. The donor pool consists of countries that maintained fixed-rate tariffs throughout the period under analysis.[14] Complete and consistent electricity price data over the full sample period are not available across countries and therefore are not included in the analysis, consequently limiting the direct examination of price mechanisms. Additional details on the dataset and summary statistics are provided in Appendix 3.A.1.

3.4. Estimation

3.4.1 Classical SCM

Before proceeding with the estimation, it should be noted that although the Energy Act was officially introduced in 1990, Norway's CO_2 emissions had already begun to decline sharply from 1989. An analysis of Norway's economic conditions in 1989 and 1990 shows that sectors influencing CO_2 emissions, such as oil production, the transport sector, and overall export levels, were increasing during this period. Ad-

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[14] Information about tariffs is sourced from Europe's Energy Portal, Reykjavik Energy, Sustainable Energy Authority of Ireland, and Mountain (2012).

ditionally, population levels remained stable, which rules out population decline as a cause of reduced electricity demand.[15] In other words, while several policy developments occurred in Norway during this period, the Energy Act represents a major structural break in the electricity market. The synthetic control framework is designed to account for gradual and unobserved confounding trends by matching Norway's pre-treatment trajectory to that of comparable countries. However, the results should be interpreted in the context of a broader reform environment.

In addition to the Energy Act, Norway introduced a fixed CO_2 tax in 1991, which is a closely timed and related policy intervention. Given the time proximity of these reforms and aggregate nature of the data, estimated treatment effects should be interpreted as capturing the combined impact of both energy and climate policies. It is likely that preliminary policy measures taken in preparation for the Act were already influencing emissions prior to its official announcement.[16] Thus, it is reasonable to choose 1989 as the threshold year for treatment.

I proceed with the synthetic control method (Abadie & Gardeazabal, 2003; Abadie et al., 2010), which is designed for policy evaluation when the intervention occurs at the aggregate level (e.g., countries, regions). When the number of treated units is small, this method allows for more accurate comparisons using a weighted combination of control units (Abadie, 2019).

The results from the classical synthetic control method are shown in Figure 3.1. After 1989, Norway's CO_2 emissions decline sharply, by approximately 17,869 kilotons in the first year, and remain consistently below the synthetic control unit. This indicates a significant negative impact of the Energy Act of 1990, and by extension, the dynamic pricing policy, on emissions. However, further research is needed to isolate the effects of dynamic pricing from other concurrent measures included in the reform package.

To assess the quality of the classical synthetic control fit, I report the Root

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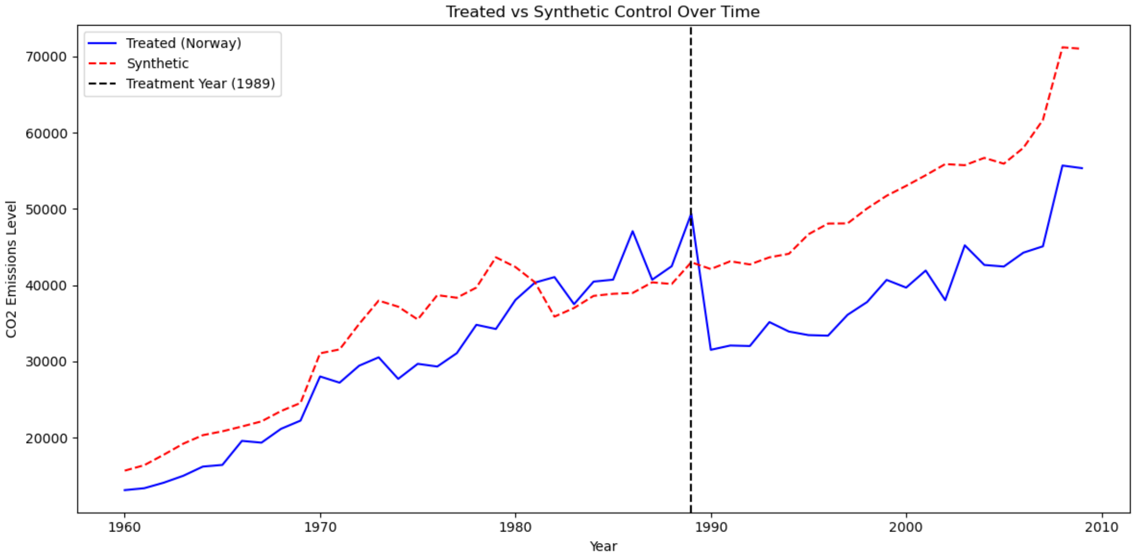
[15] For more details, see Appendix 3.A.1.

[16] Refers to pre-implementation actions for the 1990 Energy Act.

Mean Squared Prediction Error (RMSPE), which measures the average discrepancy between actual and synthetic values over time. For Norway, the pre-treatment RMSPE is approximately 5,034, while the post-treatment RMSPE rises to about 13,089, resulting in a post/pre RMSPE ratio of roughly 2.6. This increase suggests a substantial divergence following the intervention year, consistent with a treatment effect. A similar placebo analysis was conducted on countries in the donor pool, where post/pre RMSPE ratios is around 1.2, supporting the credibility of the results.

Figure 3.1



Notes: The figure shows Norway's CO_2 emissions compared to a synthetic control unit using the classical SCM method. The vertical line denotes the treatment year.

3.4.2. Machine Learning SCM

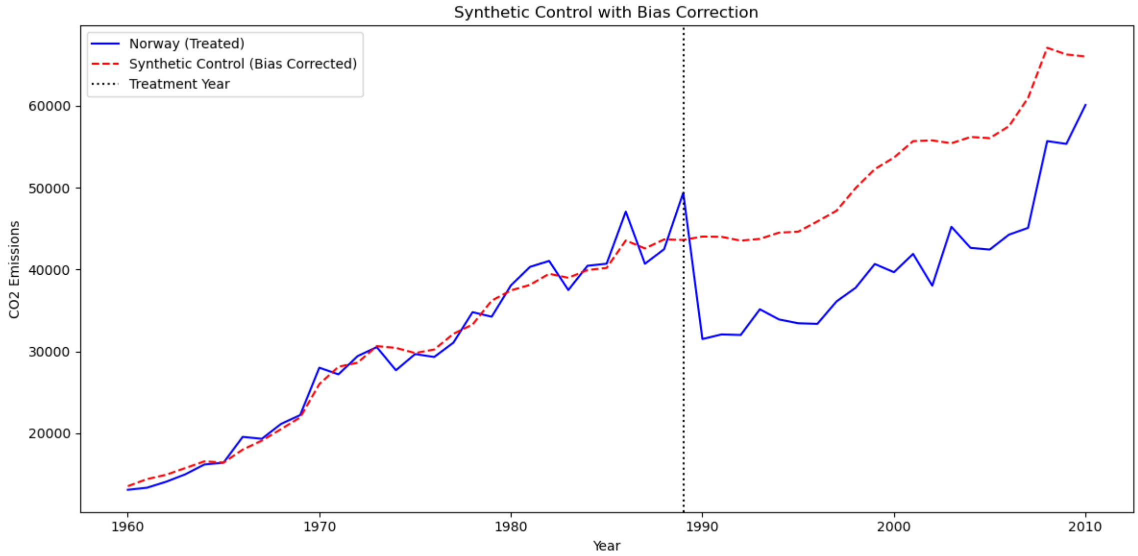
This study contributes to the literature not only by analyzing the impact of electricity market liberalization and the introduction of Time-of-Use (TOU) pricing, but also by applying a novel estimation technique: the machine learning-based synthetic control method. I follow the framework proposed by Viviano & Bradic (2023), whose methodology combines ridge regression and Random Forest supervised learning algorithms to estimate counterfactual outcomes.

While the classical Synthetic Control Method relies on optimally weighting control units from the donor pool to construct the counterfactual, the machine learning-based SCM complements or replaces this approach by using flexible predictive algorithms. In this paper, I employ both ridge regression (a regularized linear model) and Random Forest (a non-linear ensemble method) to model the pre-treatment CO_2 levels of Norway, using data from the donor pool. I then use these models to predict the CO_2 emission trajectory that would have occurred in the absence of the treatment.

The approach takes the average of predictions from the two models to reduce bias and mitigate overfitting, while a bias correction step aligns the pre-treatment predictions more closely with the actual observed values. This improves the quality of fit, particularly in non-linear settings. Moreover, combining both linear and non-linear learners allows the method to capture complex relationships in the data that classical SCM may fail to detect. Finally, the machine learning-based SCM addresses key limitations such as overfitting in small sample settings and insufficient pre-treatment fit.

The empirical results confirm the advantages of this approach. Figure 3.2 illustrates a tighter pre-treatment fit compared to the classical method. The pre-treatment RMSPE is approximately 1,372, while the post-treatment RMSPE increases to about 12,105, yielding a post/pre RMSPE ratio of around 9. These findings highlight the strength and robustness of the estimated treatment effect, and demonstrate the value of integrating machine learning techniques into synthetic control frameworks for policy evaluation.

Figure 3.2



Notes: The figure shows Norway's CO_2 emissions compared to a synthetic control unit using the Viviano & Bradic (2023) Synthetic Control Learner method with bias correction. The vertical line denotes the treatment year.

5. Robustness Analysis

To assess whether the assumptions of the synthetic control method hold, I examine the possibility of treatment spillovers and linkages between the treated and control countries.

Regarding the possibility of atmospheric dispersion, CO_2 emissions are measured based on the territory of origin rather than the location to which emissions may be transported. Moreover, CO_2 is an integrated global pollutant, which is not concentrated in locally and is not significantly influenced by short-term wind currents. Therefore, this is not considered a meaningful channel of interference (Intergovernmental Panel on Climate Change, 2021).

A more plausible concern involves indirect spillover effects through electricity market connections. Norway exports electricity to the European market via several inter-connectors. Specifically, Norwegian electricity has been connected to the Netherlands through the NorNed cable since 2008 and has participated in the broader European electricity system via the ENTSO-E network, formally established in 2009 (Behrens et al., 2012; Vision, 2022). Although both NorNed and ENTSO-E were implemented after the treatment, I conduct robustness checks by excluding both the Netherlands and France from the donor pool to examine whether their inclusion affects the results.

The findings (Figures 3.3, Appendix 3.A.2) remain robust to these exclusions. The estimated treatment effects are consistent and statistically similar to the baseline results, suggesting that potential electricity market spillovers from Norway to these countries are unlikely to bias the main conclusions.

Lastly, as a robustness exercise, I increased the donor pool by adding additional European countries and run the analyses with this larger pool. The results (Figures 3.4, Appendix 3.A.2) again remain consistent, with an even further increased RMSPE ratio reaching around 11. This adds to the robustness of the analyses and demonstrating the efficiency of the machine learning model.

To further validate the robustness of the results, I conduct placebo tests as proposed by Abadie & Gardeazabal (2003); Abadie et al. (2010). These tests compare the synthetic controls of countries that have not adopted dynamic pricing with their actual emissions levels. I selected Ireland and Iceland for this analysis based on their weights in the donor pool. The placebo test results (Figures 3.5, Appendix 3.A.2) indicate acceptable outcomes for both Ireland and Iceland.

In the case of Iceland, the synthetic control method demonstrates a good pre-treatment fit for CO_2 emissions, followed by only a small divergence after the treatment year. This outcome suggests that the model does not detect non-existent significant effects, strengthening the credibility of the findings obtained for Norway.

For Ireland, the synthetic control method also shows a strong pre-treatment fit; however, a more visible divergence emerges after the treatment year. Specifically, emissions in Ireland increase more sharply than those in its synthetic control counterpart. This contrasting trend relative to Norway may suggest that electricity market liberalization and the introduction of dynamic pricing are contributing factors to the observed reduction in emissions in the Norwegian case. Lastly, it is worth noting that, in the years immediately following the treatment year, both Iceland and Ireland exhibit similar CO_2 emissions levels between their actual and synthetic trajectories.

Although the machine learning-based synthetic control method produces a strong pre-treatment fit in both placebo cases and shows acceptable alignment in the early post-treatment years, the study would benefit from further improvements. Future research could enhance the predictive performance of the model by expanding the synthetic control donor pool, preferably with additional EU countries, incorporating a broader set of variables related to energy use and industrial activity, and extending the time span, especially for the pre-treatment period, in order to improve the model's training set and increase its predictive accuracy.

6. Conclusion

To meet the growing demand for electricity, particularly during peak periods, energy producers frequently rely on fossil-fuel based power generation units. These units are not only economically inefficient but also contribute significantly to environmental degradation through greenhouse gas emissions.

In an effort to curb electricity demand during peak periods, governments have increasingly turned to dynamic pricing mechanisms such as TOU tariffs. This paper examines the impacts of these reforms by analyzing time-series data from Norway, where dynamic pricing was implemented, against a set of comparable countries that maintained fixed-rate tariffs.

The empirical evidence suggests that TOU pricing, implemented as part of broader market liberalization, is associated with meaningful reductions in greenhouse gas emissions by encouraging consumers to shift or reduce their peak electricity usage. While this study acknowledges certain methodological limitations, including limited data availability and imperfect pre-treatment fit, the results provide valuable insights into the effectiveness of market-based reforms as an environmental policy tool. Specifically, the findings highlight how targeted pricing strategies can simultaneously promote economic efficiency and environmental sustainability in the electricity sector.

Future research should aim to expand the dataset to include more countries and longer time horizons, and further isolate the specific effects of dynamic pricing from other concurrent energy reforms. Additionally, exploring the distributional impacts of TOU tariffs on different consumer groups could help inform more balanced policy design. Overall, this analysis provides a foundation for policymakers interested in designing electricity market interventions that balance economic and environmental goals.

Appendix

3.A.1 Data

3.A.2 Additional Tables and Figures

Data: 3.A.1

Datasets

In addition to the main variables described in the data section, I consulted other variables to support the plausibility of results and to verify alternative explanations. These include export levels (OECD Export Data), land transport data (Statistics Norway - Land Transport), oil production (Index Mundi - Oil Production), and total population (World Bank - Population). These variables ensure that before and after the treatment year, no structural changes occurred that could affect the CO_2 emissions rate in Norway other than the treatment itself. The results support the conclusion that the observed reductions in emissions are attributable to the treatment; electricity market liberalization and the introduction of time-of-use/dynamic electricity tariffs.

Table 3.A.1.1: Summary Statistics: Main Analysis and Robustness Check Samples

Variable	Obs	Mean	Std. Dev.	Min	Max
Main Analysis Sample					
Year	255	1985	14.75	1960	2010
CO_2 Emissions	255	125354.70	147170.80	2614.28	529155.40
GDP per Capita	255	19292.75	18491.87	685.61	97007.94
Fertility Rate	255	2.29	0.67	1.47	4.29
Life Expectancy	255	75.91	3.02	69.80	81.90
Death Rate	255	8.83	1.51	6.10	12.30
Food Production	255	83.09	14.87	40.15	107.74
Population Growth	255	0.84	0.50	-0.43	2.89
Robustness Check Sample					
Year	468	1985	15.02	1960	2011
CO_2 Emissions	468	5363.85	3350.87	695.04	16020.98
GDP per Capita	458	20015.81	17450.17	685.61	88415.63
Fertility Rate	468	2.07	0.59	1.38	4.29
Life Expectancy	468	75.79	3.11	69.70	82.70
Death Rate	468	9.60	1.62	6.10	12.70
Population Growth	468	0.66	0.50	-0.57	2.89

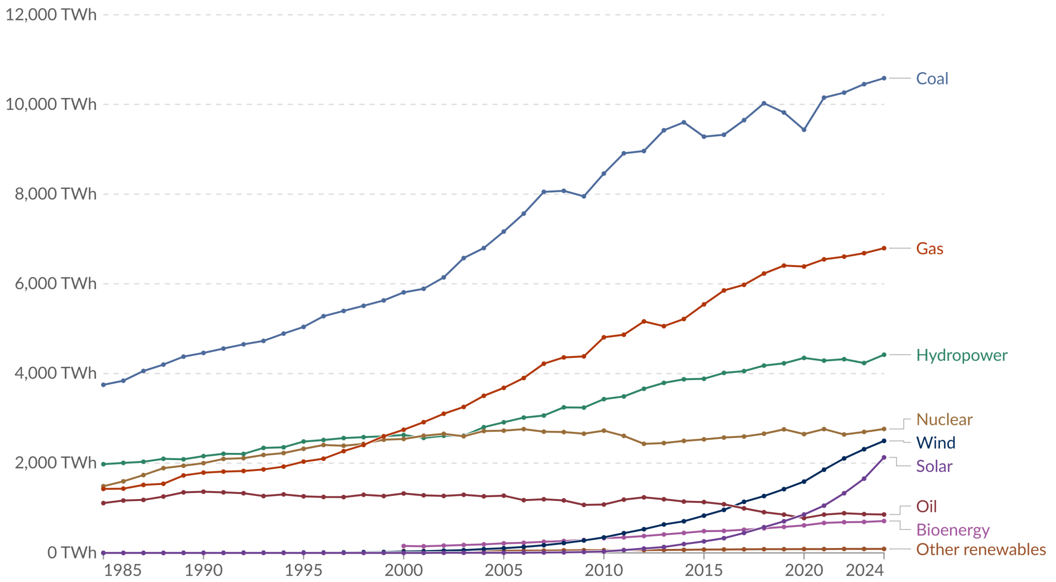
Note: This table presents the summary statistics for the variables used in both the main analysis and robustness check samples. The variable "Food Production" is only included in the main sample.

Additional Tables and Figures: 3.A.2

Figure 3.A.2.1

Electricity production by source, World

Measured in terawatt-hours[1].



Data source: Ember (2025); Energy Institute - Statistical Review of World Energy (2024)

OurWorldinData.org/energy | CC BY

Note: "Other renewables" include geothermal, wave, and tidal energy.

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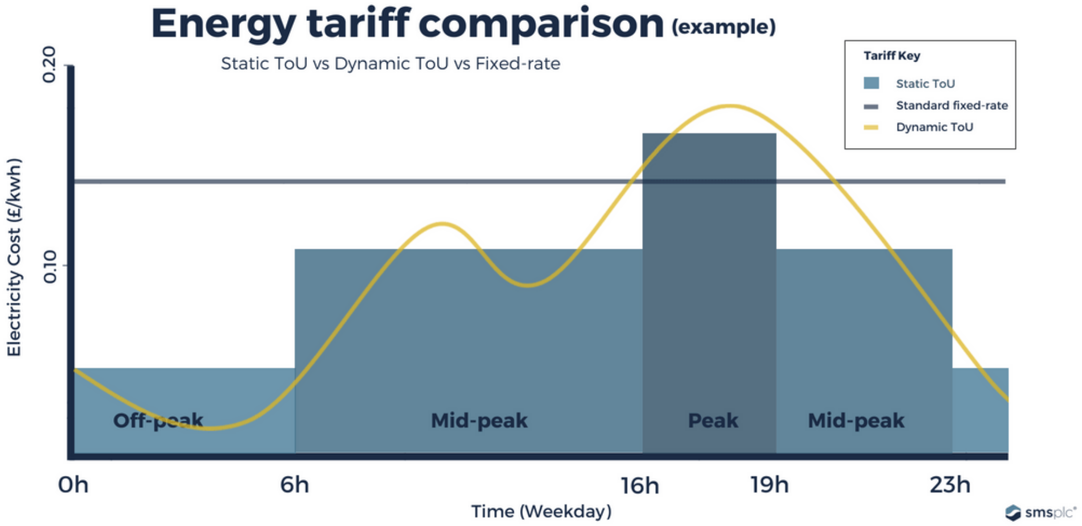
[1] **Watt-hour** A watt-hour is the energy delivered by one watt of power for one hour. Since one watt is equivalent to one joule per second, a watt-hour is equivalent to 3600 joules of energy.
Metric prefixes are used for multiples of the unit, usually:
- kilowatt-hours (kWh), or a thousand watt-hours.
- Megawatt-hours (MWh), or a million watt-hours.
- Gigawatt-hours (GWh), or a billion watt-hours.
- Terawatt-hours (TWh), or a trillion watt-hours.

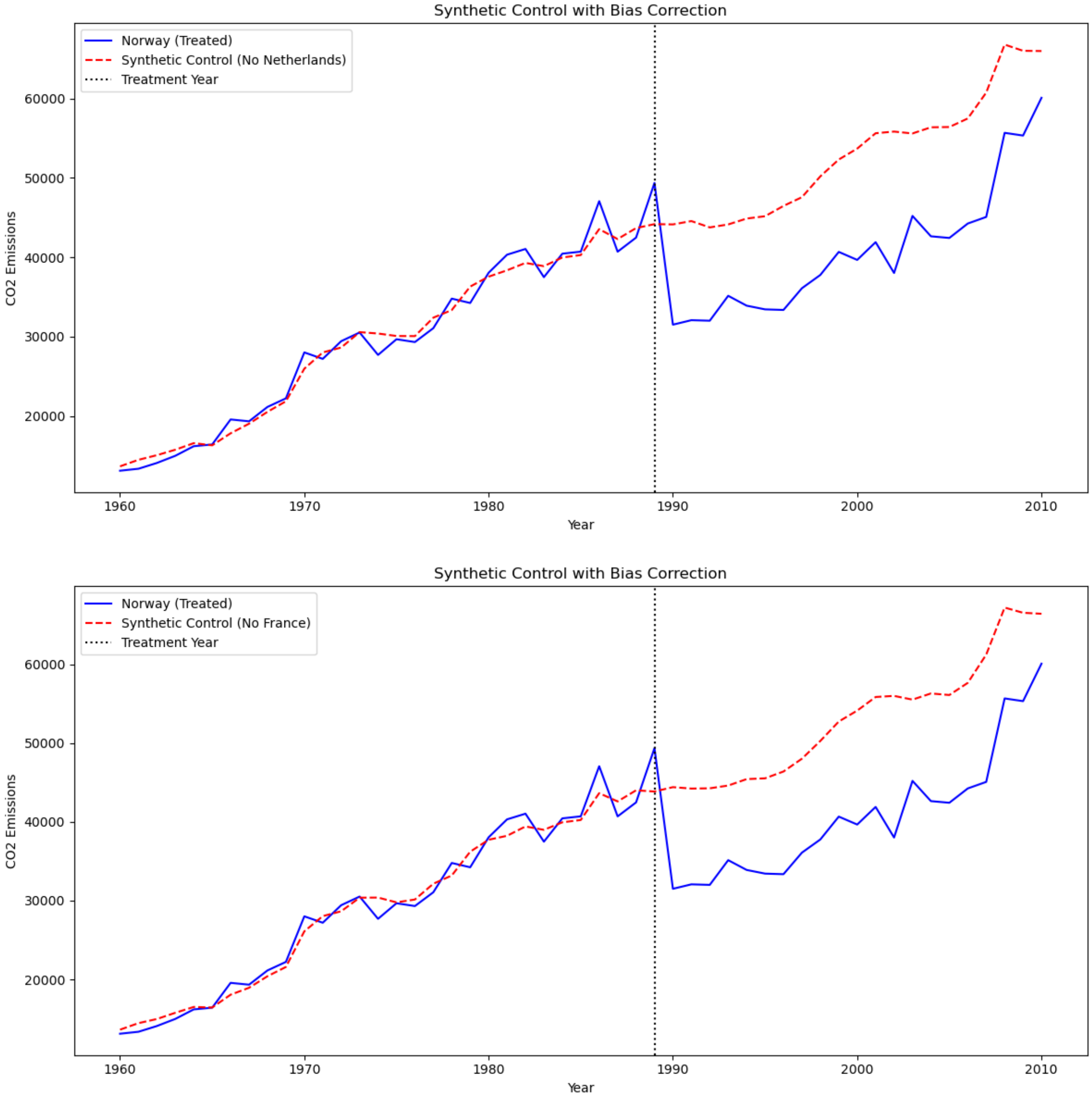
Source: Our World in Data

Figure 3.A.2.2



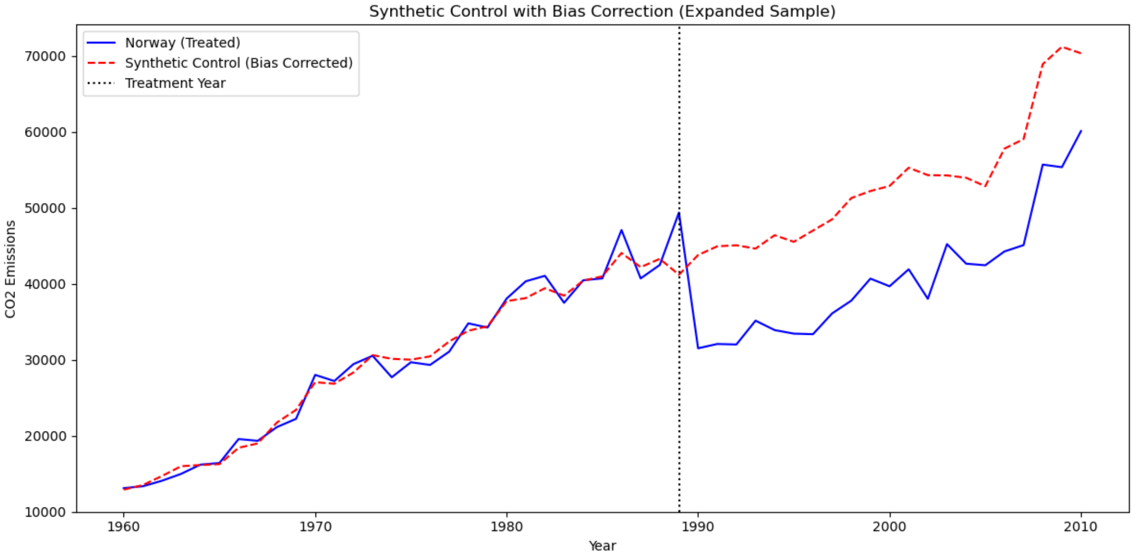
Source: SMS: Energy and Carbon Reduction Solutions

Figure 3.A.2.3



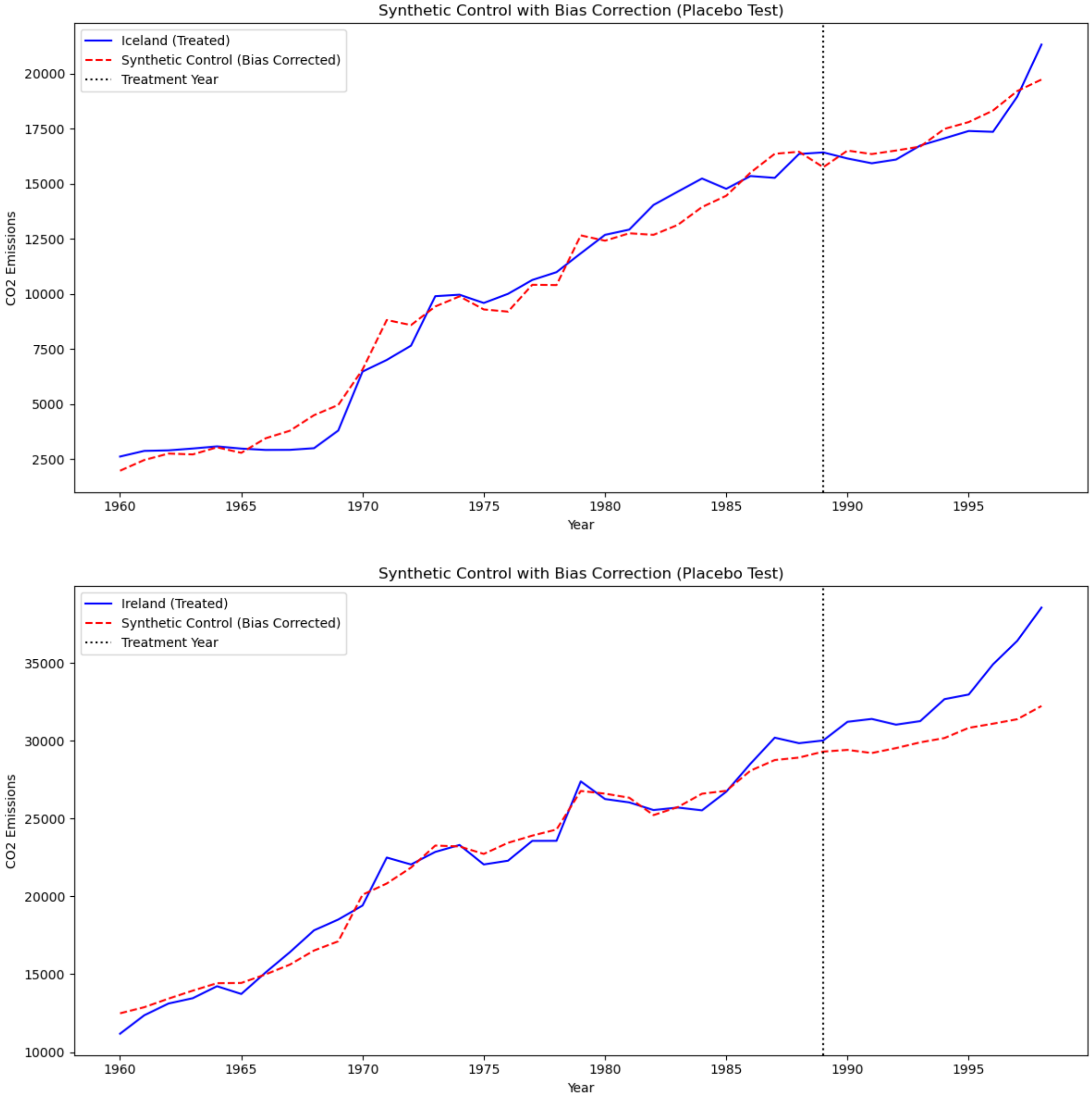
Notes: This figures presents CO_2 emissions for Norway, comparing actual values to the synthetic control constructed after excluding the Netherlands and France from the donor pool. The vertical line indicates the treatment year.

Figure 3.A.2.4



Notes: The figure shows Norway's CO_2 emissions compared to an expanded synthetic control unit using the Synthetic Control Learner method with bias correction. The vertical line indicates the treatment year.

Figure 3.A.2.5



Notes: These figures present CO_2 emissions for countries in the synthetic control unit as a placebo test, comparing actual values to their synthetic counterparts. The vertical line indicates the treatment year.

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