The Political Economic Determinants of Nuclear Power: Evidence from Chernobyl (Very Preliminary – Do Not Cite without the Authors' Permission)*

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Abstract

This paper investigates the political-economic determinants of nuclear energy investment using the Chernobyl accident as a natural experiment. We document several facts. First, Chernobyl reduced worldwide growth in the number of nuclear power plants. Second, the reduction is driven by increased construction delays in democracies. Third, the nuclear growth slowdown in democracies is more pronounced in the presence of large fossil fuel reserves, and uncorrelated to accident rates. These results are robust to a large number of controls, including prices for alternative energy sources. Finally, nuclear plant capacity reduces coal-fired power plants and air pollution. Together, the results provide evidence that political factors are an important driver of nuclear energy investment.

1 Introduction

The global push to reduce carbon emissions and transition to renewable energy is critical for moderating climate change, one of the key challenges of the 21st century. Amidst the policy discussions of boosting worldwide investment in non-fossil fuel energy sources – wind, solar, geothermal, hydro – nuclear energy

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is notably absent. Nuclear power can more easily scale up than other renewable energies because it can work anywhere (i.e., in places without much wind, sun, water). It is also one of the most reliable sources of energy. Nuclear energy currently provides 10% of power worldwide. It expanded rapidly during the 1960s and 70s, but then stagnated. Today, investment in nuclear energy is relatively low and it is left out of most climate-focused policy making. In many countries, such as the United States, nuclear energy is not eligible for government clean-energy subsidies.

Explanations for this phenomenon fall broadly into two categories. The first is purely about economics and view the decline in nuclear investment as an outcome of the fall in the persistently low world oil and gas prices during the 1980s and 90s. Recent technological improvements in wind, solar, and other renewable energies further reduced demand for nuclear energy. The second is political and argues that fossil fuel and environmental interest groups have exploited and exaggerated public fears over nuclear safety. Policymakers' response has been to increase regulation of nuclear energy so that it is less profitable than other sources of energy. These two explanations have very different implications for the political economy of clean-energy investment, and for policymakers interested in nuclear energy. There has been no systematic attempt to distinguish between the two motives.

The primary goal of this paper is to provide novel and rigorous empirical evidence on the causes of the relatively slow growth in nuclear power. Specifically, we ask whether the decline in nuclear power investment in the past four decades is due to political (non-economic) reasons?

Our study proceed in several steps. First, we exploit variation in public fear caused by the accident at Chernobyl Nuclear Power Plant in 1986. This unanticipated disaster led to tremendous human and environmental damage in nearby areas and shocked the world about the possible harms of nuclear reactor accidents. The accident did not affect the supply of alternative energy sources. Thus, if nuclear power investment declines because of public fear, then we should observe a decline in nuclear power investment subsequent to Chernobyl.

To test this hypothesis, we collect annual plant-level data, which we merge with a large number of other political, economic and geographical variables. We first use these data to construct a cross-country panel. We show that after the Chernobyl accident, there was an immediate and permanent decline in the growth of NPPs worldwide. These results go against the alternative fuel price explanation and support the political explanation.

Second, to investigate whether the decline after Chernobyl is due to political reasons, we estimate the differential response for democracies and autocracies. Democratically elected leaders are more accountable to voters. If the decline in nuclear investment is due to a political response triggered by public fear, we should find a stronger decline in democracies. We document that the decline in the growth of NPP is increasing in magnitude with how democratic the political process is in a nation (i.e., constraints on the executive). This heterogeneous treatment effect is robust to controlling for alternative fuel reserves as well as a large number of other economic and demographic variables, and geographic features. These results are consistent with stronger political accountability in democracies.

The third part of the analysis seeks to understand the motives of the political response. Politicians may respond to public fear by increasing regulation, which increases the cost of building and maintaining reactors. This is likely to have happened in all countries immediately after the accident, but is likely to have had a more pronounced effect for democracies. However, in the longer run, special interest groups can also take advantage of the public fear to lobby against nuclear power. These two motives are not mutually exclusive.

We investigate the safety hypothesis as an explanation for the long-run results by examining the effect of Chernobyl on the the age of nuclear power plants in democracies relative to autocracies. Using the plant-level data, we show that the cross-country patterns are driven by extensive delays in the completion of plants in democracies after the accident occurred. The inability to build new plants led to prolonged operation of older Gen I plants, which we show to be less safe than new Gen IV plants.

To investigate whether the post-Chernobyl decline in democracies is driven by fossil fuel interests, we estimate heterogeneous treatment effects to examine whether the decline in democracies is increasing in magnitude with the size of fossil fuel reserves. If fossil fuel interests driven the decline, then we should find that the decline is larger in countries with more fossil fuels. We find that this is true. In contrast, the presence of fossil fuel reserves is unrelated to nuclear power investments in autocracies. These results support the fossil fuel special interest capture hypothesis.

One concern for interpreting the triple interaction estimate of post-Chernobyl, democracy and fossil fuel reserves as political is that large fossil fuel reserves also increases the opportunity cost of nuclear power. To address this concern, we conduct a falsification exercise, where we show that the presence of renewable energies does not influence the nuclear investments in democracies (or autocracies).

In the final part of the paper, we document the environmental consequences of the limited investment in nuclear power and examine air pollution as a downstream outcome. We construct a panel of nuclear power plants, satellite AOD data and economic data to construct a panel of disaggregated geographic units. We find that the introduction of nuclear power plants is associated with a significant reduction in coal-powered fire and AOD in the region. This is true controlling for a large number of economic and demographic variables than can influence AOD and the demand for energy. Linking these results to the cutting-edge estimates on the health impacts of ambient air pollution, our back-of-the-envelope calculation suggests that, the global slow down of nuclear power developmnt led to a total loss of 380 million expected life years.

Taken together, the results imply that political reaction to public fear severely limits the ability of democracies to invest in nuclear power, which undermines the safety of nuclear power and efforts to reduce carbon emissions.

Our paper contributes to two literatures. The first is the literature about the political economic determinants of climate change. The second is the literature about the differences between democracies and autocracies.

The paper is organized as follows. Section 2 presents the background. Section 3 presents the estimated impact of Chernobyl. Section 4 presents the estimated effect of nuclear power on emissions. Section 5 concludes.

2 Background

2.1 Nuclear Power Plants

A nuclear reactor first generated electricity for the first time ever on September 3, 1948, in the United States; and generated power for an electric grid for the first time on June 27, 1954 in the Soviet Union. The first full-scale power station opened in 1956 in the U.K. Today, the International Atomic Energy Agency (IAEA) reports that there are 441 nuclear reactors in operation in 30 countries around the world.

Uranium or Plutonium is used to fuel nuclear power plants. Once a nuclear reactor turns on, there is little cost for producing additional energy. Nuclear power stations typically have high capital costs (construction and maintenance), but low direct fuel costs. We will later also discuss the high regulatory costs of nuclear power.

The process of energy creation creates no carbon emissions and nuclear energy is considered a "clean" energy. Nuclear's capacity factor, essentially how often a plant produces power, is 2.8 times higher than the other energy sources. Its nameplate capacity is 3.8 times higher. However, its annual

NOx emissions (a precursor to smog) and SO2 emissions (which contribute to acid rain and haze), and CO2 emissions (which contribute to global warming) are less than one percent of the fossil fuel average.[1] The main environmental cost is the disposal of radioactive waste. In principle, spent nuclear fuel can be recycled to avoid the disposal problem. But in practice, fuel and disposal prices have been so low that there has not been any bulk recycling of NPP waste.

The main dangers of NPP come from the mining of radioactive fuel, improper disposal of waste, potential terrorist attacks or nuclear weapons proliferation, and reactor meltdowns. We will focus on the latter disasters, the fear of which is the most commonly cited reason in popular opposition against NPP development.

There have been three reactor meltdowns in history. This first was a partial meltdown of the Three Mile Island, on March 28, 1979. It is the most significant accident in U.S. commercial nuclear power plant history. On the seven-point International Nuclear Event Scale (INES), it is rated at Level 5 "Accident with Wider Consequences". The Chernobyl disaster occurred on 26 April 1986 in the north of the Ukrainian SSR in the Soviet Union, and was the result of human error. The Fukushima Daiichi nuclear disaster occurred 11 March 2011 in Ōkuma, Fukushima Prefecture, Japan. The proximate cause of the disaster was the 2011 Tōhoku earthquake and tsunami. Chernobyl and Fukushima are rated at INES Level 7, the maximum severity of accidents.

All of these accidents occurred with older Generation II reactors. New power plant designs (Generation III+) are safer than the NRC's requirements by orders of magnitude (as measured by the probabilistic risk assessments for core damage frequency, CDF). Generation III reactors have been improved to have lower core damage frequencies (3 to 60 events per 100 million reactor-years versus 1,000 events per 100 million reactor years). They address the problems from past accidents by including passive safety features that do not require active controls or operator intervention but instead rely on gravity or natural convection to mitigate the impact of abnormal events. For comparison, note that Gen III AP1000 designs, which is in Georgia and popular in South Korea, have a 1/60 million chance of CDF in a year, and is safer than U.S. Nuclear Regulatory Commission (NRC) requirements by a factor of 6,061. In contrast older Gen II plants, which constitute all other currently operating plants in the U.S. today have a 1/20000 CDF per year, and is two times safer than NRC requirements.[2] Operating procedures also changed to improve safety. Since Three Mile Island in 1979, the NRC found

[1] See AMERICANACTIONFORUM.ORG

[2] See "Putting Nuclear Regulatory Costs in Context" *American Action Forum*, Sam Batkins, Philip Rossetti and Dand Goldbeck, JULY 12, 2017

that the rate of shut-down-the-reactor-level problems in the U.S. (using Gen II NPP) dropped from 2.5 per plant per year to around 0.1.

The first Generation III NPP was built in 1996. Seven Generation III NPPs operate currently in Japan, China, and India. Nuclear scientists are currently research Generation IV NPPs. Generation III+ plants also to use fuel more efficiently and operate for longer.[3]

2.2 Regulation

Many have argued in recent years that NPP is undermined by excessive regulation, particularly during construction. "Regulatory burdens on nuclear plants are making them expensive," stresses the Institute for Energy Research (IER).[4] This is especially notable in the West. For example, "The American Action Forum (AAF) found the average nuclear plant bears an annual regulatory burden of around $60 million — $8.6 million in regulatory costs, $22 million in fees to the Nuclear Regulatory Commission (NRC), and $32.7 million for regulatory liabilities." The IER identifies regulatory costs as "clearly contributing to the premature retirement of nuclear plants" while discouraging new build.

There is no disagreement that regulation is important for making sure that NPPs are safe and effective. In all democracies with NPPs, citizens and the local community are allowed to participate in the process. This is seen as an important mechanism for holding politicians and NPPs accountable to community safety concerns. While the exact process varies across countries, the general problem is that regulatory authorities in democracies are unable to commit to requirements at any point in the construction process because regulators and citizens are able to protest at several points. The uncertainty is highly problematic from the perspective of investors in nuclear energy. Regulators often introduce new requirements while a plant is already under construction and shift the regulatory goal-posts, which cause cost over runs.[5] A study of NPP construction concluded that licensing, regulatory delays, and back-fit requirements were significant contributors to the rising cost trend.[6]

[3]The Bureau of Labor Statics (BLS) keeps data on both the "Incidence Rates of Nonfatal Occupational Injuries" and fatalities. From 2006 to 2015, the nuclear generation industry is on average 4.7 times safer than hydroelectric power, five times safer than fossil fuel, 6.6 times safer than electric power transmission, and nearly seven times safer than natural gas distribution. For fatalities, the picture is the same. Since 2003, BLS has recorded just one fatality for nuclear power generation, which was unrelated to radiation exposure. There have been 12 fatalities in hydroelectric power, 39 in fossil power, and 184 in electric power distribution. However, this doesn't account for the number of power plants in each respective industry. There are hundreds of fossil fuel power plants and only 61 nuclear plants. Yet, on this count, nuclear still leads the field in safety. Per terawatt hour of electricity generation (equivalent to 1,000 gigawatts), nuclear is still the safest: 2.9 times safer than hydroelectric, 128 times safer than solar, and 131 times safer than fossil fuel power generation.

[4]https://www.instituteforenergyresearch.org/nuclear/regulations-hurt-economics-nuclear-power/

[5]https://energypost.eu/putting-nuclear-energy-on-the-critical-path/

[6]"Regulations Hurt Economics of Nuclear Power" IER January 19, 2019, https://www.instituteforenergyresearch.org/about/ier-site/manager/articles. Also see 2016 Energy Policy paper

Observers cite excessive and inefficient regulation as the main reason that Western countries have slowly moving away from nuclear. Of the 51 reactors currently under construction, only three are in Western and Central Europe (UK, France and Finland), and two are in the U.S.[7]

The uncertainty can be seen in the long time it takes to construct a new NPP. This often leads investors to abandon construction after already sunk billions of dollars of investment. Worldwide, companies have stopped construction on 90 reactors, but 40 of those were in the U.S. alone. The NRC requires six-to-seven-years to approve NPPs. The total construction time afterwards ranges from decades to indefinite. Cost overruns and changing regulatory requirements during the construction process sometime forces construction to be abandoned after significant sunk costs have been made. For example, in 2017, two South Carolina utilities abandoned two unfinished Westinghouse AP1000 reactors due to significant construction delays and cost overruns. At the time, this left two other U.S. AP1000 reactors under construction in Georgia. The original cost estimate of $14 billion for these two reactors rose to $23 billion. Construction only continued when the U.S. federal government promised financial support. These were the first new reactors in the U.S. in decades. In contrast, a typical natural gas plant takes just over two years to construct. The regulatory process is also long for expanding output of existing plants (uprates). For example, it takes an average of 80 months in the U.S. and 54 months in the U.K. The uncertainty of being granted a license renewal and the long wait time for a license extension have caused some plants to shut down prematurely rather than wait multiple years.[8]

2.3 Chernobyl

The Chernobyl reactor meltdown was caused by a combination of operator negligence and critical design flaws had made the reactor primed to explode. The core melted down and two or more explosions ruptured the reactor core and destroyed the reactor building. This was immediately followed by an open-air reactor core fire. The USSR built the protective Chernobyl Nuclear Power Plant sarcophagus by December 1986, followed by another sarcophagus in 2017.

It released airborne radioactive contamination for about nine days. Contamination from the Chernobyl accident depended on weather conditions, such as wind and rain. The wind blew north and west. Approximately 70% of fallout landed in Belarus SSR, which experienced black rain. Significant

https://www.sciencedirect.com/science/article/pii/S0301421516300106.

[7]See http://www.world-nuclear.org/informationlibrary/current-and-future-generation/plans-for-new-reactors-worldwide.aspx

[8]See 2016 Energy Policy paper https://www.sciencedirect.com/science/article/pii/S0301421516300106.

amounts of fallout also landed in the Ukraine and Russia SSRs. Much of it deposited on mountainous regions such as the Austrian and Swiss Alps, the Welsh mountains and the Scottish Highlands, where adiabatic cooling caused radioactive rainfall. Sweden and Norway also received heavy fallout when the contaminated air collided with a cold front-induced rainfall. Other countries that were affected include Finland and Bulgaria.

Groundwater was not badly affected by the Chernobyl accident, with the exception of the exclusion zone around Chernobyl which was affected by waste disposal. Radioactive contamination of fish caused short-term concern in parts of the UK and Germany and long term concerns in the affected areas of Ukraine, Belarus, and Russia as well as in parts of Scandinavia.

The initial emergency response, together with later decontamination of the environment, involved more than 500,000 personnel and cost an estimated 18 billion Soviet rubles—roughly US$68 billion in 2019, adjusted for inflation. In the 2003–2005 reports, The Chernobyl Forum stated that between five and seven percent of government spending in Ukraine is still related to Chernobyl, while in Belarus more Chernobyl-related expenses fell from 22% of the national budget in 1991 to six percent by 2002.

The accident at Chernobyl attracted worldwide attention and raised much alarm about nuclear safety than the earlier partial meltdown at Three-mile island. This was partly due to the scale of the accident and also to distrust in the Soviet government. In direct response to the Chernobyl disaster, the International Atomic Energy Agency strengthened its safety protocols. Signatory member states pledged to provide notification of any nuclear and radiation accidents that occur within its jurisdiction that could affect other states, and to provide support and assistance for radiological emergencies.

Public reaction varied across countries. Strong reactions sometimes occured in countries that were not directly affected. For example, Italy, which received very little contamination, held a referendum in response. As a result, Italy began phasing out its nuclear power plants in 1988, but continued to import nuclear power.[9] In Germany, which received less contamination than Italy, Chernobyl led to the creation of a federal environment ministry, which increased regulation of NPPs.[10]

Consistent survey data on public attitudes toward nuclear energy before and after Chernobyl is notoriously difficult to obtain. However, data from Finland (OECD, 2019) suggest that the share of individuals having positive opinion of nuclear energy fell dramatically in the immediate aftermath of

[9] This decision was reversed in 2008. But another referendum following Fukushima in 2011 abrogated the government's decision of 2008.

[10] The events are also credited with strengthening the anti-nuclear movement in Germany, which culminated in the decision to end the use of nuclear power that was made by the 1998–2005 Schröder government. As in Italy, a temporary reversal of this policy was in turn reverted after the Fukushima nuclear disaster.

Chernobyl from 35% to 22%. At the same time, the share with negative attitudes has risen from 32% to 44%. Similarly, Gallup survey suggests that the share of Americans in favor of nuclear energy has dropped from 62% in 2010 to 44% in 2016, five years after the Fukushima disaster (Gallup, 2016). Curiously, among the people who consider themselves very well informed about nuclear energy, 69% are in strongly favor – in contrast, for respondents who consider themselves somewhat informed or not too informed, the shares are 25% and 7%, respectively (Bisconti, 2016).

3 The Impact of Chernobyl

3.1 Data

Our primary data source is the Power Reactor Information System (PRIS) by the International Atomic Energy Agency (IAEA). The system contains data on a variety of indicators, such as the number of operating reactors by country-year, total capacity of operating reactors by country-year (in MW), number and capacity of reactors under construction by country-year, and so forth. Democracy score comes from Polity IV. Data on reserve, consumption, and production of oil, gas, coal, and biofuels are from the U.S. Energy Information Administration (EIA). Data on distance between countries are from the CEPII. We merge these data into a country-year panel with countries that ever built a nuclear power plant. In total, there are 34 such countries.

3.2 Event Study

To examine the impact of Chernobyl on world NPP, we begin by plotting the number of NPP in the world over time. Figure 1 shows that there is a rapid rise during 1960 to 1985, but the rise flattens out immediately after Chernobyl and remains at the flatter slope for the remainder of the period. Figure 2 plots the growth in the number of NPP over time. We observe a sharp discontinuous drop after Chernobyl occurs.

To estimate the magnitude of these drops, we estimate the simple regression below.

$$y_{it} = \alpha + \beta PostChernobyl_t + \Gamma X_{it} + \gamma_i + \varepsilon_{it}$$

The outcome of interest in Table 1 is the growth in the # of nuclear power plants in country i year t. Depending on the specification, it is a function of the interaction of a dummy variable for post

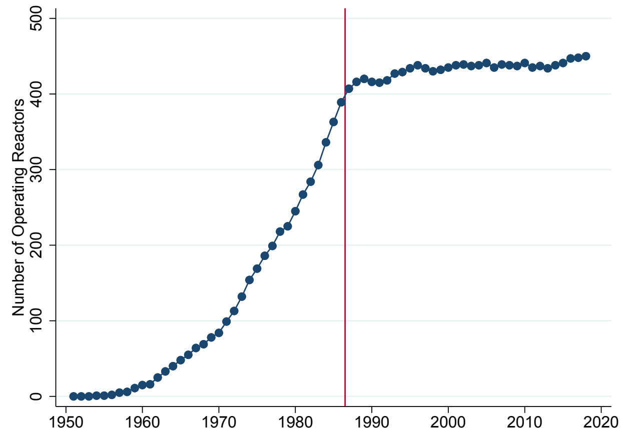

Figure 1: Total Number of Operating Nuclear Reactors in the World

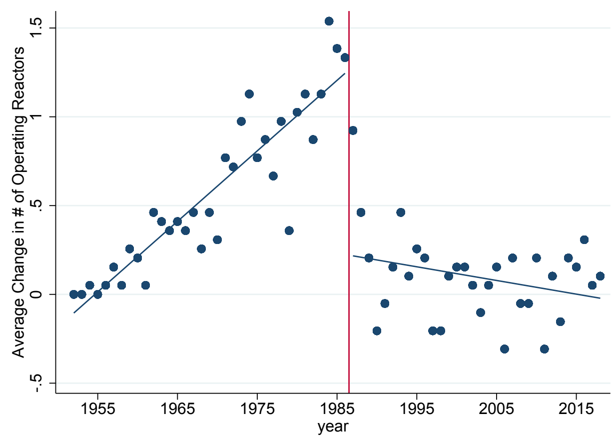

Figure 2: Year-to-Year Change in Total Number of Operating Nuclear Reactors in the World

Chernobyl, country fixed effects, and a country-specific linear trend. In column (4), we also control for log GDP per capita. We estimate Huber-white robust standard errors to address heteroskedasticity.

The estimates show that, consistent with the figures above, the yearly growth in the number of nuclear operating reactors plummeted in the aftermath of Chernobyl. The magnitudes range from 0.3 to 0.6 fewer NPP per country per year. Note that the country fixed effects already control for invariant country-level factors such as reserves in alternative energy sources. Overall, the sharp decline in NPPs support the hypothesis that Chernobyl, and not changes in world prices in other energy sources, reduced world NPPs.

Table 1: The Effect of Chernobyl on NPP

	Dependent Variable: Growth in # of Operating Reactors			
	(1)	(2)	(3)	(4)
Dep. Var. Mean	0.206	0.206	0.206	0.235
Dep. Var. SD	0.949	0.949	0.949	1.064
Post Chernobyl	-0.301**	-0.301**	-0.609***	-0.653***
	(0.126)	(0.126)	(0.167)	(0.219)
Log GDP				0.373*
				(0.199)
Country FE		Y	Y	Y
Country-Specific Trends			Y	Y
Obs	2,176	2,176	2,176	1,533
Countries	34	34	34	33
R-squared	0.03	0.14	0.26	0.32

Notes: The baseline sample contains countries that have ever had a NPP for all years for which data are available. The standard errors in parentheses are clustered at the country level. * p<0.1, ** p<0.05, *** p<0.01.

3.3 Democracies vs. Autocracies

The discussion in the Background Section suggests that Chernobyl increased public fears over NPP. To investigate this mechanism, we estimate the heterogeneous impact of Chernobyl for countries with different degrees of voter accountability, which we proxy for with the Polity2 variable of constraints on the executive. The logic is that democratically elected leaders are more accountable to citizens and will therefore be more responsive to public fear.

To visualize the data, we first divide countries into those that are above and below the sample median measure of Polity 2. To avoid endogeneity, we use Polity 2 in a baseline year (for 1985) from the Polity IV Database. For brevity, we focus on the growth in the # of nuclear power plants in country i year t as the outcome. Figure 3 plots the growth in NPP over time for the two types of countries. We see that the decline in the number of operational nuclear reactors after Chernobyl was much more pronounced for more democratic versus less democratic countries, with a similar effect also present for another nuclear disaster of Fukushima.[11] Figure 4 displays a breakdown in the growth rates by the baseline levels of democracy in a country, with a clear discontinuity after Chernobyl, which was much more pronounced for more democratic nations.

[11] In this paper, we focus on Chernobyl and not on Fukushima for two main reasons. First, there was much more nuclear power construction in the 1980s across countries, so we have more variation around the time of the event. Second, and partly related, the differential change after 2011 is driven fully by a rapid growth in nuclear power investment in China and the process of denuclearization in Germany. While this pattern is fully in line with our core argument and motivates

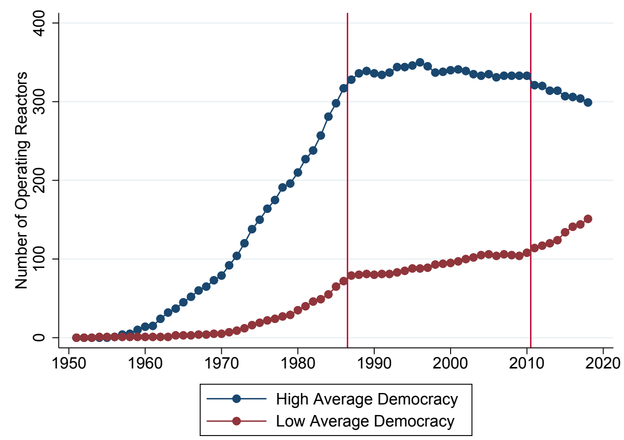

Figure 3: Total Number of Operating Nuclear Reactors in the World by Baseline Democracy Levels

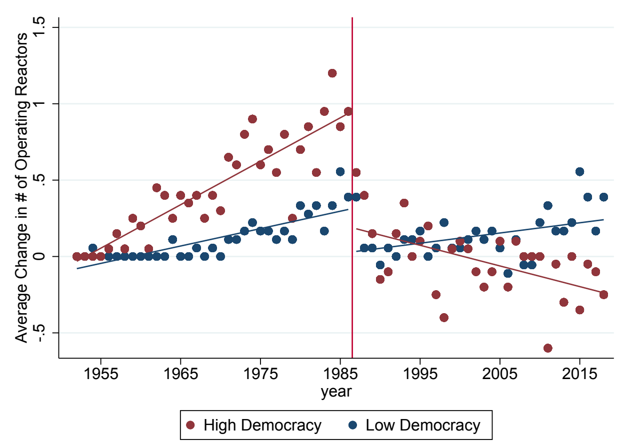

Figure 4: Year-to-Year Change in Total Number of Operating Nuclear Reactors in the World by Baseline Democracy Levels

Next, we estimate the equation below.

$$y_{it} = \alpha + \beta demo_{i,1985} \times PostChernobyl_t + \Gamma X_{it} + \gamma_i + \delta_t + \varepsilon_{it} \quad (1)$$

For brevity, we focus on the growth in the # of nuclear power plants in country i year t as the outcome. It is a function of the interaction of whether the country is a democracy last year and a dummy variable for post Chernobyl, country fixed effects and year fixed effects. Standard errors are clustered at the country level.

Table 2 presents the results, where we gradually add the controls. Column 1 presents the estimates without the two-way fixed effects, suggesting that democracies built more NPPs on average. Column 2 displays our baseline estimates: controlling for the country and year fixed effects, moving from full autocracy (a score of 0) to full democracy (a score of 10) is associated with 0.74 fewer nuclear reactors in operation per year.

Columns 3–8 probe further robustness of the estimates. Column 3 adds country-specific trends. Column 4 controls for distance to Ukraine interacted with the year fixed effects, with the idea that democratic countries could simply be located closer to the disaster area. Column 5 accounts for a country's log GDP per capita in a given year. Column 6 replaces the 1985 democracy score with a lagged democracy score. Column 7 uses a high-democracy indicator equal to one if the democracy score is equal or above the median (a score of 4) and zero otherwise. Finally, column 8 flexibly controls for the amount of fossil fuel reserves countries had at baseline. Across all these specifications, we find that democracies exhibit a much stronger reaction to the Chernobyl disaster relative to more autocratic regimes.

our paper well, it does not allow for rigorous statistical analysis.

Table 2: The Heterogeneous Effect of Chernobyl on NPP for Democracies

	Dependent Variable: Growth in # of Operating Reactors							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		Baseline				Lagged Democracy Score	High Democracy Indicator	
Dep. Var. Mean	0.206	0.206	0.206	0.206	0.235	0.208	0.206	0.209
Dep. Var. SD	0.949	0.949	0.949	1.013	1.064	0.954	0.949	0.926
Post Chernobyl × Democracy	-0.074***	-0.074***	-0.067*	-0.069*	-0.105*	-0.092***	-0.634***	-0.073***
	(0.025)	(0.025)	(0.035)	(0.040)	(0.031)	(0.033)	(0.230)	(0.026)
Post Chernobyl	0.048							
	(0.103)							
Democracy Score	0.051**							
	(0.022)							
Log GDP					0.421**			
					(0.201)			
Country FE		Y	Y	Y	Y	Y	Y	Y
Year FE		Y	Y	Y	Y	Y	Y	Y
Country-Specific Trends			Y	Y	Y			Y
Distance to Ukraine × Year FE				Y	Y			
Coal, Oil, and Gas Reserves × Year FE								Y
Obs	2,176	2,176	2,176	1,769	1,533	2,154	2,176	2,112
Countries	34	34	34	34	34	34	34	33
R-squared	0.06	0.21	0.30	0.33	0.26	0.21	0.21	0.38

Notes: The baseline sample contains countries that have ever had a NPP for all years for which data are available. Democracy is an index measured in the base year. unless if otherwise stated in the column headings. The standard errors in parentheses are clustered at the country level. * $p<0.1$, ** $p<0.05$, *** $p<0.01$.

3.4 Sensitivity

To examine the extent that our estimates are driven by outliers, we re-estimate the baseline on a restricted sample where we omit outliers. We define outliers using Cook's Distance. Table 3 column (2) shows that estimate is smaller but remains highly statistically significant and of similar magnitude in terms of a share of the standard deviation. Next, we omit the United States. The Three-Mile Island partial meltdown took place in 1979. If our main results are driven by the U.S., then our interpretation for Chernobyl would be confounded. Column (3) shows that the interaction coefficient is slightly smaller than the full sample but negative, statistically precise, and again statistically similar to magnitude to the full sample. In columns (4) and (5), we alternatively omit the U.S.S.R. and former Soviet republics, and China. The estimate is similar to the full sample.

Table 3: Robustness of the Heterogeneous Effect of Chernobyl to Omitting Parts of the Sample

	Dependent Variable: Growth in # of Operating Reactors					
	(1)	(2)	(3)	(4)	(5)	(6)
	Baseline	Omit Outliers defined by Cook's Distance	Omit U.S.	Omit USSR	Omit China	Control for Baseline # NPP × Year FE
Dep. Var. Mean	0.206	0.137	0.166	0.207	0.191	0.206
Dep. Var. SD	0.949	0.484	0.796	0.985	0.917	0.949
Post Chernobyl × Baseline Democracy Score	-0.074***	-0.032***	-0.056***	-0.084***	-0.065**	-0.047*
	(0.025)	(0.010)	(0.020)	(0.027)	(0.024)	(0.024)
R-squared	0.21	0.17	0.17	0.22	0.23	0.4
# of Observations	2,176	2,084	2,112	1,920	2,112	2,176
Countries	34	33	33	30	33	34

Notes: The baseline sample contains countries that have ever had a NPP for all years for which data are available. Sample restrictions are stated in column headings. All regressions control for country and year fixed effects. The standard errors in parentheses are clustered at the country level. * p<0.1, ** p<0.05, *** p<0.01.

In column (6), we control for the base year number of NPP interacted with year fixed effects. This addresses the concern that our baseline exaggerates the effect of Chernobyl for NPP in democracies because democracies had more NPP to begin with and there is mean reversion in the process of NPP expansion. At the same time, these additional controls are likely to over-control and absorb meaningful variation. Column (6) shows that the interaction coefficient is negative and statistically significant at the 10% level. Consistent with over controlling, it is slightly smaller in magnitude.

3.5 Safety

One explanation for why democracies responded more negatively to Chernobyl is that elected leaders implement higher standards for safety to better safeguard their citizens. If this is true, then we should see safer NPP in democracies after Chernobyl. However, the counter argument is that public fears are exaggerated. "A reason for this discrepancy is that the dangers associated with nuclear have been widely exaggerated for years, which has compelled regulators all over the world to introduce safety requirements due to growing public pressure. Consequently, nuclear builders and operators are required to abide by certain redundant regulations."[12]

To investigate the safety hypothesis, we examine the best proxy for safety, which is the age of the plant, as the outcome variable in equation (1). Before presenting the regression estimates, we first provide evidence to support the claim that newer plants are safer. Wheatley et al. (2017) compiles a comprehensive dataset on the universe of incidents and accidents that happened within the nuclear energy system between 1950 and 2014, which had material relevance to safety, caused property damage, or resulted in human harm. To be included in the sample, a nuclear accident needs to appear in a published source, such as peer-reviewed academic literature, press releases, project documents, public utility commission filings, reports, and newspaper articles.[13]

Using the data compiled by Wheatley et al. (2017), in Figure 5, we estimate Poisson regressions of nuclear accidents on plant age, and plot the fitted curves separately for different generations of NPPs. As we can see, NPPs become more prone to safety accidents as they age; and conditional on the same plant age, earlier-generation NPPs are more likely to have accidents. These patterns support the Background Discussion earlier in the paper.

Table 3.5 shows that Chernobyl increased the age of the average operating reactor by 0.5-0.8 years in a one-score more democratic country. This reflects the facts that Chernobyl halted the construction of new plants, and older generation plants operated for longer, often pass their initial retirement dates. This goes against the safety hypothesis.

[12]"How Red Tape Hampers Nuclear and the Climate" *Sustainability Times*.

[13]For more details, see https://xyotta.com/v1/index.php/Nuclear_events_database

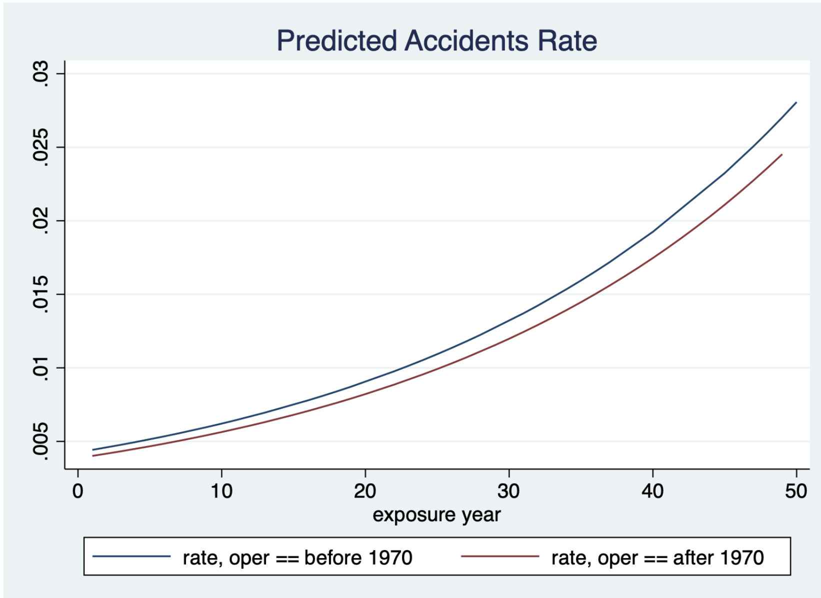

Figure 5: Age and NPP Accidents

Table 4: Chernobyl and Average Reactor Age

	Dependent Variable: Average Operational Reactor Age		
	(1)	(2)	(3)
Dep. Var. Mean	17.10	17.10	17.85
Dep. Var. SD	13.78	13.78	13.45
Post Chernobyl × Democracy	0.929***	0.563*	0.853**
	(0.314)	(0.307)	(0.400)
Post Chernobyl	12.489***		
	(1.236)		
Democracy Score	0.178**		
	(0.086)		
Log GDP			-3.125**
			(1.317)
Country FE		Y	Y
Year FE		Y	Y
Obs	1,540	1,540	1,265
Countries	34	34	33
R-squared	0.416	0.14	0.32

Notes: The baseline sample contains countries that have ever had a NPP for all years for which data are available. The standard errors in parentheses are clustered at the country level. * p<0.1, ** p<0.05, *** p<0.01.

3.6 Fossil Fuel Interests

Many industry observers allege that fossil fuel interest groups have taken advantage of the public fear caused by Chernobyl to reduce nuclear power. Specifically, they note that the fossil fuel industry have allied with environmental organizations to form a coalition against nuclear power. For example, Green Peace and the Sierra Club receive money from fossil fuel industry groups, though the amount is not disclosed to the public. One way for us to investigate the hypothesis that the political response to NPP in democracies is partly driven by fossil fuel interests is to examine whether the response to Chernobyl is more negative in countries where the fossil fuel interest is presumably stronger. To investigate this we estimate the triple interaction effect of post-Chernobyl, the democracy variables, and the extent of reserves of coal, gas or oil in the country.

Table 5 columns (1)–(4) show that indeed the triple interaction is negative, large and significant. The size of fossil fuel reserves increases the elasticity of NPPs with respect to how democratic a country. For comparison purposes, we use a standardized measure of reserves (standard deviations). Strikingly, the double interaction between reserves and post-Chernobyl is statistically zero. The exception is natural gas but as the results in column (3) show, the effect is fully driven by Russia. Besides that, the size of fossil fuel reserves has no impact on NPPs in non democracies after Chernobyl. These results support the fossil fuel special interest hypothesis.

Table 5: Heterogeneous Effect of Chernobyl by Fossil Fuel Reserves

	Dependent Variable: Growth in # of Operating Reactors						
	X = Fossil Fuels				X = Renewable		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Coal	Gas	Gas: Omitting Russia	Oil	DPI Hydro	DPI Solar	DPI Wind
Dep. Var. Mean	0.209	0.209	0.209	0.209	0.206	0.212	0.206
Dep. Var. SD	0.926	0.926	0.926	0.926	0.949	0.962	0.949
Post Chernobyl × Democracy × Reserve X	-0.061*	-0.302***	-0.316***	-0.132***	-0.002	-0.021	-0.010
	(0.031)	(0.091)	(0.091)	(0.016)	(0.017)	(0.027)	(0.019)
Post Chernobyl × Democracy	-0.068***	-0.129***	-0.132***	-0.095***	-0.073***	-0.079***	-0.069***
	(0.020)	(0.030)	(0.030)	(0.014)	(0.025)	(0.028)	(0.025)
Post Chernobyl × Reserve X	0.133	-0.121***	0.014	0.032	-0.029	0.174	-0.048
	(0.281)	(0.030)	(0.064)	(0.102)	(0.060)	(0.113)	(0.116)
# of Observations	2,112	2,112	2,048	2,112	2,176	2,112	2,176
Countries	33	33	32	33	34	33	34
R-squared	0.26	0.26	0.25	0.28	0.21	0.22	0.22

Notes: The baseline sample contains countries that have ever had a NPP for all years for which data are available. Fossil fuel reserves are measured as standard deviations. All regressions control for country and year fixed effects. The standard errors in parentheses are clustered at the country level. * p<0.1, ** p<0.05, *** p<0.01.

4 The Effect of NPP on Emissions

4.1 Data

Our main measure of air pollution is Aerosol Optical Depth (AOD), which reflects the amount of solid and liquid particles suspended in the atmosphere, and is commonly used as an omnibus proxy for air quality. AOD is calculated based on satellite images, since the particles in air change the way the atmosphere reflects and absorbs visible and infrared light. We obtain our AOD data from NASA's Terra satellite with Moderate Resolution Imaging Spectroradiometer (MODIS).[14] The data provide information on the monthly average AOD for all 1 x 1 degree grids worldwide, during 2001 to 2020.

4.2 Estimates

To understand the impact of NPPs on air pollution, we study how the operation of new NPPs affect the average AOD of the nearest city (in terms of straight-line distance), between 2001 and 2020. Specifically, we estimate the following event study specification:

$$y_{it} = \sum_{k \neq -1} D_{it}^{k} \cdot \beta_k + \Gamma X_{i,t-1} + \gamma_i + \delta_t + \varepsilon_{it}, \tag{2}$$

where y_{it} is the AOD in the city adjacent to NPP i in year t; D_{it}^{k} corresponds to the event dummies indicating the k_{th} year before/after the operation of NPP i; $X_{i,t-1}$ is the lagged population and night-time lights of the city adjacent to NPP i; γ_i and δ_t are the NPP and year fixed effects. The standard errors are clustered at the NPP level. To avoid putting negative weights on the average treatment effect of certain groups in conventional two-way fixed effects models, we follow the recent econometrics literature and adjust the conventional event study approach with an "interaction-weighted" estimator (Sun and Abraham, 2020).

As shown in Figure 6, there is no pre-trend in AOD prior to the start of operation of an NPP. However, after the NPP starts operating, AOD declines. The magnitude of the decline increases in magnitude for several years. Since the start year of an NPP is defined by the first year that at least one reactor started working, the downward-sloping trend in the post-operation period could reflect the fact that new NPPs are gradually launching their reactors over time and/or that polluting energy production (e.g., coal) declines gradually in response to the NPP.

To quantify the AOD reductions, we estimate the following DiD model:

[14] For more details, see https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD08_M3#overview

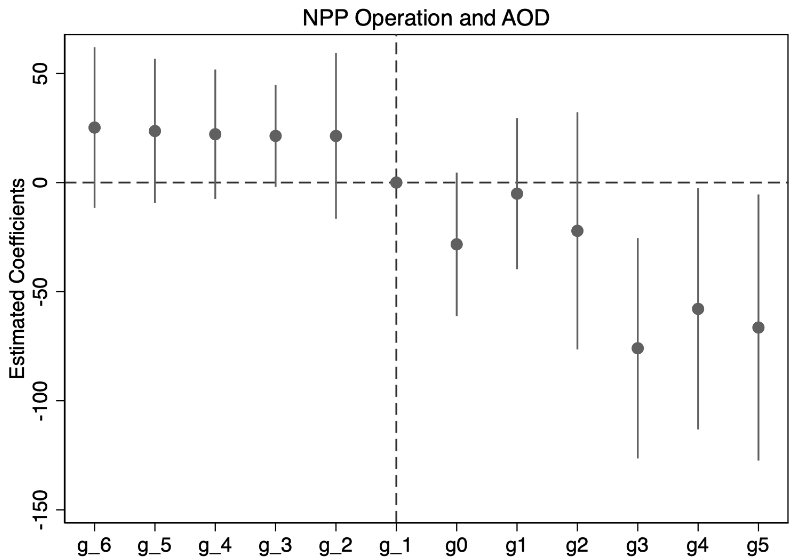

Figure 6: NPP Operation and City AOD

$$y_{it} = \beta \cdot NPP_{it} + \Gamma X_{i,t-1} + \gamma_i + \delta_t + \varepsilon_{it} \tag{3}$$

As shown in Table 6, following the operation of a local NPP, a city's AOD falls by more than 46, which is more than 15% of a reduction from the baseline mean. The estimates are robust to controlling for the mean and range of yearly temperature, as well as the specific dynamics of country, latitude, border, coast, and reserves for other energy sources. Appendix Table A.2 lists the definitions and sources of all the variables used in this analysis. The estimates are similar if we drop specific countries that play major roles in NPP operation, such as China, Russia, or the US.

Since the distance between NPPs and the nearest urban area can vary, we can alternatively define the unit of observation to be a circle around each NPP. We calculate the average AOD for all the grids in the circles for a range of radii. Table 7 shows that the results are consistent with that for cities, and the findings are not sensitive to specific radius choices.

Table 6: NPP Operation and City AOD

	(1)	(2)	(3)	(4)	(5)
	AOD	AOD	AOD	AOD	AOD
NPP Operation	-60.912***	-67.804***	-46.591***	-68.584***	-67.642***
	(16.861)	(17.396)	(16.665)	(17.352)	(17.363)
Other Energy DPI*Year FE		YES	YES	YES	YES
Lagged Population/Nighttime Lights		YES	YES	YES	YES
(Latitude,Border,Coast)×Year FE		YES	YES	YES	YES
Mean Temperature, Temperature Range		YES	YES	YES	YES
Unit FE	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
Dep. Var. Mean	240.1	238.7	238.9	239.9	243.7
Dep. Var. SD	106.8	111.1	111.1	116.0	116.5
R2	0.92	0.93	0.93	0.94	0.93
Sample	all	all	drop China	drop Russia	drop US
Observations	470,866	412,613	406,933	371,191	357,666

Table 7: NPP Operation and AOD in Adjacent Circles

	(1)	(2)	(3)
	AOD 40km	AOD 20km	AOD 80km
NPP Oper	-48.937***	-35.190***	-40.300***
	(12.399)	(13.085)	(14.395)
Other Energy DPI*Year FE		YES	YES
Lagged Population/Nighttime Lights		YES	YES
(Latitude,Border,Coast)×Year FE		YES	YES
Mean Temperature, Temperature Range		YES	YES
Unit FE	YES	YES	YES
Year FE	YES	YES	YES
Dep. Var. Mean	260.7	260.6	260.4
Dep. Var. SD	129.9	129.1	128.3
R2	0.86	0.87	0.88
Sample	all	all	all
Observations	187,060	165,951	166,005

4.3 Back of the Envelope Calculations (Preliminary)

Leveraging our estimates, we can calculate the potential aggregate health impacts caused by the Chernobyl-induced slow down of NPP construction. The calculation involves three main steps. First, following the estimates provided by NASA, we convert our estimated NPP-AOD relationship into an NPP-PM2.5 relationship.[15] Second, following the estimates provided by the Air Quality Life Index (AQLI), we convert the estimated PM2.5 reductions to the potential increases in life expectancies in each region.[16] Third, linking the estimated gains in life expectancies to grid-level population data, we calculate the total life years that are lost due to the global slowdown of NPP construction.[17]

According to our calculations, the construction of an additional NPP, by reducing the total total suspended particles (TSP) in the ambient environment, could on average save 816,058 additional life years. According to our baseline estimates, over the past 45 years, Chernobyl reduced the total number of NPPs worldwide by 469, which is almost entirely driven by the slowdown of new construction in democracies. Our calculations thus suggest that, globally, more than 380 million expected life years have been lost due to the democracies' changing attitudes toward NPP development.

5 Preliminary Conclusion

The results of this paper provide novel and rigorous empirical evidence that the decline in nuclear energy investment is largely driven by political factors. Our evidence supports the belief that fossil fuel interest groups play an important role in hindering nuclear investment in democracies.

This is a work-in-progress. We are in the process of collecting micro data from the Italian 1987 and 2011 referendums, congressional voting data from the U.S., as well as parliamentary minutes from the U.K.

[15]Source: https://appliedsciences.nasa.gov/sites/default/files/D2P3_AODPMEx.pdf

[16]Source: https://aqli.epic.uchicago.edu/

[17]Here we are assuming that the NPPs that were not constructed due to Chernobyl would have been located in regions at least as populated as the existing NPP locations.

Figure A.1: Map of Nuclear Reactors in the World, 1985

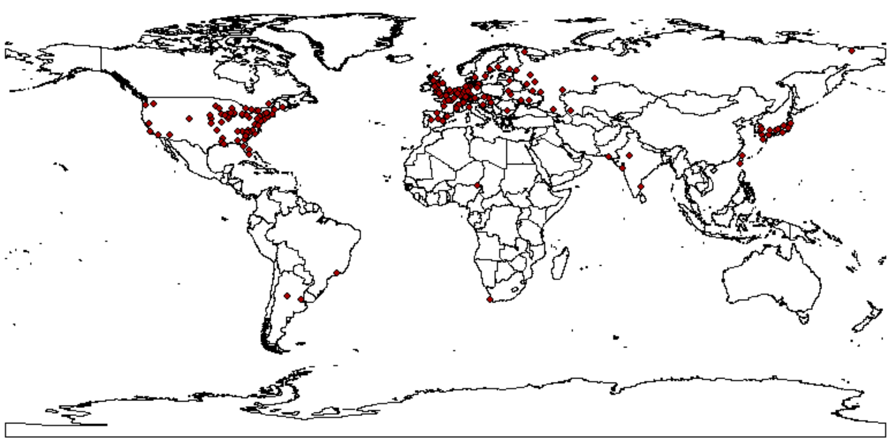

Figure A.2: Map of Nuclear Reactors in the World, 2020

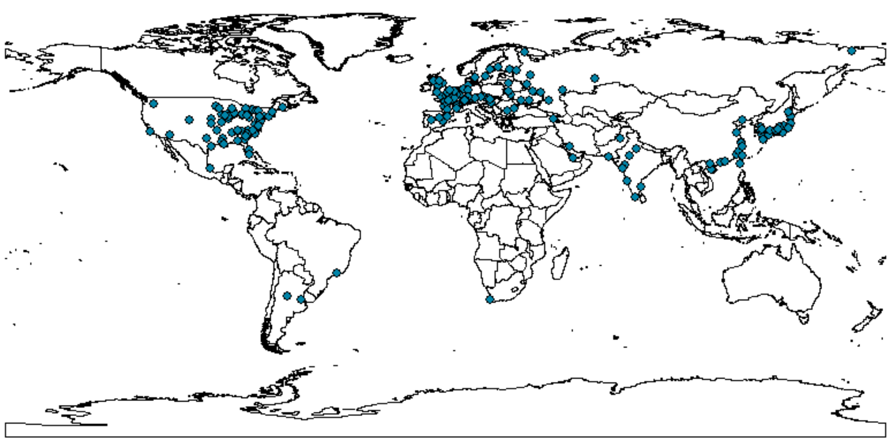

Table A.1: List of All Countries that Ever Built a Nuclear Power Plant with Democracy Scores in 1985

Country	Polity IV Democracy Score in 1985
Argentina	8
Armenia	0
Belgium	10
Brazil	7
Bulgaria	0
Canada	10
China	0
Czech Republic	0
Finland	10
France	8
Germany	10
Hungary	0
India	8
Iran, Islamic Rep.	0
Italy	10
Japan	10
Kazakhstan	0
Korea, Rep.	0
Lithuania	0
Mexico	1
Netherlands	10
Pakistan	0
Romania	0
Russian Federation	0
Slovak Republic	0
Slovenia	1
South Africa	7
Spain	10
Sweden	10
Switzerland	10
Taiwan	0
United Kingdom	10
Ukraine	0
United States	10

Table A.2: List of Variables Used in Pollution Regressions

Variable	description	source
AOD	Aerosol Optical Depth Land Mean from product MOD08_M3 (2001-2020)	https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD08_M3
SO2	Total Column Amount SO2 from product OMSO2e (2005-2020)	https://disc.gsfc.nasa.gov/datasets/OMSO2e_003/summary
Coal Power Units	Units (>30MW) from coal power plants around the world	https://globalenergymonitor.org/projects/global-coal-plant-tracker/tracker/
NPP Oper	Becomes 1 when nuclear reactors operate on the site	https://en.wikipedia.org/wiki/List_of_commercial_nuclear_reactors
LST mean	Land Surface Temperature day mean from product MOD11C3 , monthly data (2001-2020)	https://lpdaac.usgs.gov/products/mod11c3v006/
LST range	Range of monthly LST day mean from product MOD11C3 (2001-2020)	https://lpdaac.usgs.gov/products/mod11c3v006/
LST diurnal range	Average day and night difference of the monthly LST from product MOD11C3 (2001-2020)	https://lpdaac.usgs.gov/products/mod11c3v006/
Border	Whether the city is on the border of its country	
Coast	Whether it's a coastal city	
NTL	harmonized global nighttime light (1992-2020)	https://www.nature.com/articles/s41597-020-0510-y#Sec8
Population density	UN WPP-Adjusted Population Density (2000, 2005, 2010, 2015, 2020), interpolated	https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-adjusted-to-2015-unwpp-country-totals-rev11
Hydropower	Global Development Potential Indices for hydropower (2016)	https://sedac.ciesin.columbia.edu/data/set/lulc-development-potential-indices/data-download
Concentrated Solar Power	Global Development Potential Indices for concentrated solar power (2016)	https://sedac.ciesin.columbia.edu/data/set/lulc-development-potential-indices/data-download
Photovoltaic Solar Power	Global Development Potential Indices for photovoltaic solar power (2016)	https://sedac.ciesin.columbia.edu/data/set/lulc-development-potential-indices/data-download
Oil	Global Development Potential Indices for oil (2016)	https://sedac.ciesin.columbia.edu/data/set/lulc-development-potential-indices/data-download
Gas	Global Development Potential Indices for gas (2016)	https://sedac.ciesin.columbia.edu/data/set/lulc-development-potential-indices/data-download
Coal	Global Development Potential Indices for coal (2016)	https://sedac.ciesin.columbia.edu/data/set/lulc-development-potential-indices/data-download
Wind	Global Development Potential Indices for wind (2016)	https://sedac.ciesin.columbia.edu/data/set/lulc-development-potential-indices/data-download