Environmental Impact of 2011 Germany's Nuclear Shutdown: A Synthetic Control Study

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Environmental Impact of 2011 Germany's Nuclear Shutdown: A Synthetic Control Study

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Abstract

This paper contrasts the trajectory of Germany's nitrogen oxides, sulphur oxides, particulate matter 2.5, and carbon dioxide emissions with the trajectory of a data-driven weighted average of similar economies. The synthetic Germany is constructed to reveal the counterfactual of what would have happened to Germany's environment in the absence of shutting down eight nuclear reactors in 2011. We report a negative environmental impact. For instance, the energy-supply nitrogen oxides increased by 3.28% in Germany within five years of nuclear shutdown, whereas they dropped by 13.11% in synthetic Germany. The difference, 16.39%, is the estimated treatment effect of 2011 nuclear shutdown on energy-supply nitrogen oxides.

Keywords: Nuclear Energy, Synthetic Control, Germany, Nitrogen Oxides, Sulphur Oxides, Carbon Dioxide, PM2.5

JEL Classification: N54, Q53, Q54, Q58

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Introduction

Prompted by the Fukushima nuclear accident and public concerns about safety, the formerly pro-nuclear German government led by Chancellor Angela Merkel changed stance and decided to close eight nuclear reactors in August 2011. Furthermore, it was announced that Germany would phase out the remaining nine reactors by 2022. The 2011 German nuclear shutdown was exceptional in scale—nuclear energy in 2010 comprised 28% of energy supply in that country, but by 2020, it had dropped to 10%[1]. Most recently, in the wake of energy shortage caused by Russian invasion of Ukraine, the closure of two of the last three nuclear power plants has been postponed[2].

This paper makes contribution to the literature of energy by examining the direction and magnitude of the treatment effect of 2011 nuclear shutdown on Germany's environment. Nuclear energy policy remains a politically divisive issue, and understanding the environmental impact can be used to guide public policy in the ongoing climate and environment crisis. The topic of this study is highly relevant because our findings could shed light on the environmental costs of closing the remaining nuclear reactors in Germany, as well as the environmental benefits of building the new-generation reactors considered by the French government[3].

From econometric perspective, the random timing of the Fukushima nuclear accident combined with the political motivation behind the 2011 shutdown suggests that this policy shock was in large part independent of Germany's environmental circumstances, and therefore can be treated as a quasi-natural experiment[4]. Our identification of the treatment effect takes advantage of the lack of reverse causation, which enables us to rule out simultaneity

[1]https://world-nuclear.org/information-library/country-profiles/countries-g-n/germany.aspx

[2]https://www.dw.com/en/germany-plans-to-keep-2-nuclear-power-plants-in-operation/a-63258734

[3]https://www.energylivenews.com/2022/09/28/france-to-speed-up-new-nuclear-buildup/

[4]The shutdown decision was driven by concerns about the safety of nuclear power plants and the potential for similar disasters to occur in Germany. It was also influenced by widespread public opposition to nuclear power in the country, as well as the growing availability of renewable energy sources.

bias.

The abruptness of 2011 nuclear shutdown also aids in identification of the treatment effect. If we cannot conceive another sudden event of similar scale in 2011 that could push Germany away from its pre-2011 environmental trend (meanwhile trends of other countries in the comparison group remained unchanged), then the observed post-2011 discrepancy between Germany and synthetic Germany must be attributed to the 2011 nuclear shutdown.

We apply the synthetic control method (SCM) of Abadie and Gardeazabal (2003) and Abadie et al. (2015) to create the synthetic Germany—a weighted average of several European countries that did not shut down nuclear reactors in 2011. The synthetic Germany is used to control for confounding factors such as improvement in vehicle fuel efficiency, enhanced agricultural technology, and Germany's ratifying the Kyoto Protocol in 2002. The SCM essentially compares the trajectory of a variety of measurements of Germany's environment to synthetic Germany.

In light of the pre-2011 "common trend" shared by Germany and synthetic Germany, we are able to obtain an apple-to-apple comparison, and more importantly, isolate the effect of 2011 shutdown from factors that affect all countries. Another way to interpret the synthetic Germany is that it provides the potential outcome or counterfactual of what would have happened to Germany's environment had the 2011 shutdown not occurred—a post-2011 gap or divergence between Germany and synthetic Germany can be seen as evidence for the treatment effect of 2011 shutdown.

Our research is related to following studies: Jarvis et al. (2022) adopt a machine learning approach to estimate the social cost of 2011 shutdown; Grossi et al. (2018) show how an energy policy shock in Germany affects neighboring countries; Grossi et al. (2017) emphasize the impact on prices based on a modified demand-supply framework; Ando (2015) applies the synthetic control method to estimate how the establishment of nuclear power facilities in Japan in the 1970s and 1980s affects local economy; Knopf et al. (2014) examine the effect of nuclear phase-out on electricity price and CO2 emissions; Bruninx et al. (2013) conduct a scenario analysis of 2011 shutdown with an electricity generation simulation model; Jacobs (2012) discusses the historical background of 2011 shutdown. Other related works include Goebel et al. (2015), Davis and Hausman (2016), Deschenes et al. (2017), Wheatley et al. (2017) and Neidell et al. (2021). Our research differs from existing studies by applying the synthetic control method and focusing on the environmental impact of 2011 nuclear shutdown.

2 Data

We consider four environmental outcome variables: Nitrogen Oxides (NOx), Sulphur Oxides (SOx), and Particulate Matter 2.5 (PM2.5) are downloaded from Eurostat, and the sample ranges from 2000-2019; Carbon Dioxide Emissions (CO2) is obtained from World Bank, and ranges from 2000-2018. The reasons of choosing those four variables are as follows: nitrogen oxides and sulphur oxides are two of the most prevalent pollutants released from coal and general fossil fuel consumption; carbon dioxide emission is a primary factor contributing to climate change; particulate matter 2.5 is fine inhalable particle 2.5 micrometers or smaller that has an adverse health effect by traveling deep into the respiratory tract.

There are eleven annual observations from 2000 to 2010, and that subsample is long enough for the purpose of capturing the pre-treatment trend. Meanwhile, our sample ends before the 2020 covid19 pandemic, which has substantial impact on economic activity, consumption of energy, and environment.

Consumption of energy depends on energy price and economy. Thus the predictors used in this study are Consumer Price Index for household energy (CE for short) and purchasing power parity adjusted per capital GDP (GDP for short). Predictors also include lag values of the outcome variables, which serve as proxies for persistent confounding factors.

The basic idea of the synthetic control method is constructing a synthetic Germany—a weighted average of a group of nuclear-energy-producing countries (called donor pool) that are akin to Germany but not subject to the treatment of nuclear shutdown. Our donor pool consists of France, Netherlands, Spain, Sweden, and Austria. We focus on these European nations because of their economic and environmental similarities to Germany. During our sample span there were commercially operable nuclear reactors in France, Netherlands, Spain and Sweden. While there is no nuclear plant in Austria, it is included in the donor pool thanks to its close proximity to Germany. Countries such as Japan, Belgium and Switzerland are excluded because there were nuclear phaseouts in those countries (i.e., they cannot be considered as untreated or control group). Our preliminary study also adds United States into the donor pool, and we find no qualitative change in the results.

The success of synthetic control method hinges on an apple-to-apple, not apple-to-orange, comparison. As a starting point, Figure 1 plots the time series of nitrogen oxides in each country, with a vertical dash line representing 2010, one year before the shutdown treatment. It is evident that the NOx pollution in Germany (a blue line with circles) dominates other countries, which is not unexpected given its sizeable manufacturing sector. An imminent failure of SCM is implied by this finding as any weighted average of the donor pool would lie below Germany throughout the whole sample[5]. Put differently, we are not able to construct a satisfactory synthetic Germany that matches Germany in the pre-treatment periods. In short, Figure 1 illustrates an apple-to-orange comparison.

In order to achieve the apple-to-apple comparison, we *normalize* each outcome variable in each country by dividing its value in 2010, then multiplying by 100. The normalized nitrogen oxides (NNOx) *index* is shown in Figure 2. There are three findings: first, for each country NNOx index equals 100 in 2010, the base period. So this normalizing transformation puts all countries on an equal footing. Second, unlike Figure 1, NNOx in Germany does not dominate other countries before 2011, indicative of the possibility of obtaining a successful

[5]Consider $x < z, y < z$. For any $0 \leq w \leq 1$, it is impossible to find a w so that $wx + (1 - w)y = z$.

synthetic Germany if NNOx index other than NOx is used as the outcome variable[6]. Finally and most importantly, despite the downward trends in each country's NNOx after 2011, the German trend lies above all other countries, implying the possible negative impact of its nuclear shutdown on environment. To summarize, NOx pollution in each country has dropped below its 2010 level. However, possibly because of the nuclear shutdown, Germany has seen the slowest improvement (in terms of percentages).

Panels A and B of Table 1 quantify the pattern shown in Figures 1 and 2 by reporting sample means, before and after 2011, for the environmental variables, normalized indexes of those variables, and predictors. For instance, let's compare average NOx in Austria and Germany. Before 2011, the two countries are not comparable since German average 1667804 and Austrian average 226331 differ by almost one order of magnitude. Nevertheless, the two countries become comparable after normalizing—the average German NNOx index is 113 and Australian one is 111.

The downward trend in NOx pollution can be seen by comparing Panel B to Panel A. The average NNOx index declines in each country (e.g, it changes from 111 to 84 in Austria), but Germany shows the smallest reduction (from 113 to 90). In fact, German has the highest post-2011 average NNox of 90. The greatest drop of NNOx happens in Spain (from 136 to 82), which is consistent with the steepest downward line we see in Figure 2 for that country.

Similar pattern is observed for CO2, SOx and PM 2.5—normalization makes Germany comparable to the donor pool before 2011, and more importantly, a gap emerges between Germany and the donor pool after 2011. The synthetic control method is motivated by those findings.

Notice that we do not normalize the predictor since the average pre-2011 GDP and CE in Germany are already in line with other countries. Such comparability in predictive characteristics supports our selection of the donor pool.

[6]Consider $x < z, y > z$. Now it is possible to find a w so that $wx + (1 - w)y = z$.

3 Methodology and Model Specification

Recall that the synthetic Germany is a weighted average of countries in the donor pool. We hope the synthetic Germany is as similar to Germany as possible in the pre-treatment periods (i.e., before 2011), so that the synthetic Germany can simulate what would have happened to Germany in the absence of nuclear shutdown[7]. Intuitively, a country with outcome variable or characteristics similar to Germany should receive a greater weight than a country showing dissimilarity. In the end, the synthetic control method assigns data-driven weights to the donor pool countries, and the weights are determined endogenously by the predictive power.

If there is indeed a treatment effect of nuclear shutdown, we expect to observe a gap in the outcome trajectories between Germany and its synthetic counterpart after 2011. Since the treatment of nuclear shutdown is applied only to Germany, that gap can be seen as evidence for the treatment effect. Our conjecture is that the nuclear shutdown would slow down the environmental improvement, so the outcome trajectory of Germany would lie *above* the synthetic Germany after 2011.

In a nutshell, the goal of the synthetic control method is to determine two sets of weights: the weights for donor pool countries, and the weights for predictors. More specifically, constructing the synthetic Germany amounts to solving the following two nested optimization problems

$$W(V) = \texttt{argmin}_W (A_1 - A_0 W)' V (A_1 - A_0 W), \qquad (0 \le w_j \le 1, j = 1, \ldots, J) \quad (1)$$

$$V^{optimal} = \texttt{argmin}_V (B_1 - B_0 W(V))'(B_1 - B_0 W(V)) \quad (2)$$

where V is a diagonal matrix of weights for predictors; W is a vector of weights for countries in the donor poole (untreated units); A_1 is a vector of predictors for the Germany (treated

[7] According to the Rubin causal model, contrasting the potential outcome with actual outcome provides evidence for causation.

unit) in training set; A_0 is a matrix of values of predictors for control units in the training set; B_1 is the vector of outcome variables of the treated unit in validation set, and B_0 is the matrix of outcome variables of control units in the validation set.

Minimizing the quadratic form in (1) is a restricted quadratic programming problem because the weight is bounded between 0 and 1. The results are the optimal weights for controlled units for given V, and the optimal V is obtained by cross-validation. Finally the synthetic control estimate for the treatment effect is given by

$$C_1 - C_0 W(V^{optimal}) \tag{3}$$

where C_1 and C_0 contain values of outcome variables in the post-treatment periods for the Germany and donor pool, respectively. For more details about SCM, see Abadie et al. (2015).

Table 2 illustrates the process of finding the optimal synthetic Germany for NNOx from a variety of model specifications. Each column represents a specification, with weights for donor pool countries and predictors reported in Panels A and B, respectively[8]. The criterion for comparing models is root of mean squared prediction error (RMSPE):

$$\sqrt{\frac{\sum_{t=1}^{T}(y_t - \hat{y}_t)^2}{T}} \tag{4}$$

where T is the number of pre-treatment periods; y is NNOx in Germany and $\hat{y}$ is synthetic Germany. In order to evaluate the predictive power of predictors, the pre-treatment periods are divided into training (in-sample) set and validation (out-of-sample) set. In this paper the validation set includes 2009 and 2010. The model with the smallest RMSPE is deemed the best one.

To avoid overfitting we follow the principle of parsimony or specific-to-general modeling

[8] In the preliminary study we try numerous specifications. To save space only some of them are shown in Table 2.

strategy in the forecasting literature—we start with a simple model and keeps adding predictors until RMSPE is minimized. Model 1 in Table 2 uses the sole predictor of GDP in 2008 (so its weight is 1), and RMSPE equals 5.97. We get a much better fit (RMSPE falls to 1.60) with Model 2 that uses the lag value of NNOx in 2008 as the sole predictor. Even better results are obtained as Model 3 adds the lag value of NNOx in 2007, and Model 4 adds the lag value of NNOx in 2006 and GDP in 2008. The most general specification is Model 4, which includes CE in 2008 as an additional predictor. However, there are two signals that CE does not contribute much predictor power—first, the data-driven weight for CE is 0; second, RMSPE rises from 1.04 in Model 4 to 2.40 in Model 5. In light of that, Model 4 is chosen to construct the optimal synthetic Germany for NNOx. Notice that according to Model 4 the synthetic Germany is a weighted average of Sweden and France, whose weights are 0.887 and 0.113, respectively. Also notice that the weights for Austria, Netherlands, and Spain are close to zero in all specifications except the worst Model 1. Therefore using Sweden and France to generate the synthetic Germany is robust.

4 Results

The best way to deliver SCM results is visualizing Germany and synthetic Germany. The solid line in Figure 3 represents the NNOx in Germany while the dash line is synthetic Germany constructed with Model 4 in Table 2. Notably, the synthetic Germany is a satisfactory one as it matches Germany very well before 2010—the dash line closely traces the solid line up to 2010. Thanks to those "common pre-2010 trends", the synthetic Germany is able to capture impacts of observable and unobservable factors, and therefore simulate the counterfactual outcome faced by Germany if the nuclear shutdown had not happened.

More importantly, there is a noticeable gap between the solid and dash lines after 2010, and that gap is indicative of the treatment effect of nuclear shutdown. We see that the downward NNOx trajectory of synthetic Germany lies below Germany throughout the post-treatment periods, implying that the NOx pollution in Sweden and France has been reduced at a faster rate than Germany. This finding is consistent with the previous finding in Figure 2 that German NOx time series is on the top after 2010. The widening gap between 2010 and 2014 is especially striking—if we cannot come up with another possible reason for those remarkable differences in NOx pollution of the three countries, then the observed post-2010 discrepancy must demonstrate the treatment effect of the 2011 German nuclear shutdown on NOx pollution.

Let's look at the numbers behind Figure 3 and check statistical significance. From 2010 to 2014, NNOx in Germany falls from 100 to 94.60, while NNOx in synthetic Germany falls from 100 to 88.95. The paired two-sample t test applied to the two NNOx series is 3.20, rejecting the null hypothesis of equal means at the 5% level. Within ten years, from 2010 to 2019, Germany NNOx drops from 100 to 77.28, and synthetic Germany NNOx drops from 100 to 74.40, resulting in a two-sample t test of 6.10. The equal-mean hypothesis is rejected again. By contrast, we find no significant difference in the two NNOx series before 2010—average NNOx of Germany is 114.72; average NNOx of synthetic Germany is 114.98; the two-sample t test is -0.76.

Figure 4 provides more evidence for the significance of that post-treatment gap shown in Figure 3. Panel A just duplicates Figure 3 to facilitate comparison. In Panel B we report the so called "in-time placebo" or permutation test. That is, we pretend that the German nuclear shutdown happened in 2009, two years before the actual date. Then we redo the synthetic control analysis, but in this case, we fail to see a widening gap immediately after 2009. We also try using 2008 and 2007 as the treatment dates and find no instant gap either. Those findings imply that the post-2010 gap in Figure 3 is unlikely to appear by chance.

Panel C reports the "in-place placebo" that still uses 2011 as the treatment year but applies SCM to Austria, a country in the donor pool (not subject to the nuclear shutdown). The synthetic Austria matches Austria very well between 2005 and 2010. However, unlike

Germany, the two Austrian NNOx series do not part until 2013, suggesting no treatment effect. Moreover, the post 2013 Austrian gap is less noticeable than the German one, and in fact is statistically insignificant (two-sample t statistic is -0.27).

Finally we conduct the in-place placebo analysis for all countries, and Panel D plots the gap between NNOx series of a country and its synthetic counterpart. The solid line denotes the German NNOx gap, and dash lines for countries in the donor pool. There are two main findings. First, the German gap is almost flat and close to zero before 2010, a signal for a successful matching job done by the synthetic Germany. Second, after 2010, the German gap stands out conspicuously among the gaps of donor-pool countries, and lies above them. Thus, the observed post-2010 German gap shows the expected sign, and is substantial. Together, Panels B, C and D rule out the possibility that the observed post-2010 gap in German NNOx trajectories is due to chance[9].

We repeat all those analyses for normalized CO2 emissions, and Figure 5 displays the results. Panel A is the most important one, in which we see an expansive gap after 2010, and NCO2 of Germany (solid line) lies above the synthetic German. This implies that the CO2 emission in synthetic Germany (in this case the weights are 0.495 for France; 0.463 for Netherlands; 0.042 for Spain) fell at a faster rate than Germany. Again, given the sheer size of post-2010 gap, if we cannot think of another possible reason *as drastic as* the 2011 German nuclear shutdown, then that gap is the evidence for the negative impact of German nuclear shutdown on environment.

Compared to NOx, CO2 series is more volatile, and therefore it is hard to find a smooth and close pre-treatment match between Germany and synthetic Germany. Nevertheless, the pre-2010 common trends are still obvious. Another difference between Figure 4 panel A and Figure 5 panel A is, after 2011, NCO2 in Germany *rose* and reached a peak in 2013. By

[9]Panel D shows that SCM cannot guarantee satisfactory matching. For instance, it is impossible to construct a good synthetic Spain since the NNOx of Spain is on the top before 2010 in Figure 2. No linear combination of other countries can match the one on the top (or bottom).

contrast, NNOx in Germany largely maintained a downward trend after 2010.

Panel B of Figure 5 duplicates the in-time placebo (using 2009 as the treatment date), and Panel C reports the in-place placebo applied to Austria. Panel D shows the NCO2 gaps for all countries (solid line is Germany). They all imply that the observed post-2010 gap in panel A is unlikely to emerge by chance.

Figure 6 shows the results of synthetic control method applied to normalized SOx. We see that in Panel A NSOx of Germany (solid line) lies above synthetic Germany after 2010, that in Panel B there is no widening gap immediately after 2009 (in-time placebo), and that in Panel C no post-2010 gap appears for Austria (in-place placebo).

The dominance of German NSOx gap in Panel D is less evident than the Panels D in Figures 4 and 5, mainly because the synthetic control method fails for Spain. The SOx pollution in Spain is unusually high even after normalization—in Table 1 the average Spanish NSOx indexes are 407 before 2011 and 92 after 2011, both much greater than other countries. Consequently, the synthetic Spain lies way below Spain, and the Spanish NSOx gap is well above the horizontal axis in Panel D, dwarfing the German NSOx gap.

Results of synthetic control method applied to normalized PM2.5 are shown in Figure 7. Compared to NOx pollution (Figure 4), Panels A, B and C of Figure 7 show no qualitative change. In Panel D, however, the post-2010 Spanish NPM2.5 gap is greater than the German gap (solid line). This finding is consistent with Table 1: average normalized PM2.5 index reduces from 117 to 85 in Germany, and from 109 to only 93 in Spain. In other words, we see an unusual case here as Spain has a slower improvement in PM2.5 pollution than Germany.

To sum up, Figures 4, 5, 6 and 7 all provide evidence for the negative impact of 2011 German nuclear shutdown on its environment. In the absence of the nuclear shutdown, the air pollution and carbon dioxide emission in Germany should have been improved at a faster rate.

5 Mechanism

It is questionable to attribute the post-2010 gaps seen in Panels A of Figures 4, 5, 6 and 7 only to 2011 German nuclear shutdown. Those gaps could partially be driven by other factors. Nevertheless, our claim is that, had the shutdown not happened, those gaps, if still existing, could be smaller and less persistent. To our best knowledge, we can not think of another 2011 event in Germany that could have such substantial and long-lasting impact on its environment.

Figure 8 demonstrates the mechanism through which the German 2011 nuclear shutdown exerts its environmental influence by displaying percentages of nuclear electricity production to total electricity production (normalized to 100 in 2010) in Panel A, and percentages of fossil fuel electricity production to total electricity production in Panel B. Both panels compare German percentages to Sweden and France, two countries receiving nonzero weights in Model 4 of Table 2[10].

In panel A there is a significant and enduring drop in German nuclear electricity percentage after 2010. For instance, the German nuclear electricity percentage fell from 22.35% in 2010 to 17.69% in 2011 (normalized percentage fell from 100 to 79). During the same period, the nuclear electricity percentages rose in Sweden and France.

On the other hand, in Panel B, we see the fossil fuel electricity percentage rose from 59.09% to 59.93% in Germany. Later, during 2011-2014, there is a slight deduction in German fossil fuel electricity percentage, but the magnitude of reduction is much smaller than Sweden and France. Notably, both the post-2010 nuclear electricity percentage gap and fossil fuel electricity percentage gap between Germany and other two countries in Figure 8 align with the post-2010 gaps seen in Panels A of Figures 4, 5, 6 and 7. Behind this alignment is the well-known fact that combustion of fossil fuels in power plants is a main source of NOx, SOx, PM2.5 and CO2 emission.

[10]Energy data are from https://www.eia.gov/.

Overall, the key message of Figure 8 is that the air pollution gaps observed in Figures 4, 5, 6 and 7 between Germany and other countries are in large part rooted in the gaps in production of nuclear and fossil fuel electricity.

6 Robustness Check

We run four robustness checks. First, we try the alternative approach of using the NOx emission per capita (NOxPC) as the outcome variable. We do not normalize it to 100 in 2010. Panel A in Figure 9 shows that we fail to obtain an apple-to-apple comparison—thanks to the large German population, the German NOxPC (blue line with circles) is dominated by other countries prior to 2010. Sweden is the country with NOxPC close to Germany before 2010, and therefore is the only country that receives nonzero weight in the synthetic Germany. In Panel B of Figure 9 we see the new synthetic Germany does not trace Germany as closely as Figure 3. Notwithstanding, the post-2010 gap between Germany and synthetic Germany shown in Panel B looks similar to the post-2010 gap shown in Figure 3 (variables on the vertical axes are different though).

Second, we try normalizing NOx pollution by dividing its level in 2000 (NNOxNEW), as opposed to 2010. As shown by Panel A of Figure 10, all countries now have the same starting point at the begging of sample. Despite of different normalizing methods, the post-2010 gaps in Panel B of Figure 10 and Figure 3 are very much alike. This finding implies that the observed post-2010 gap in Figure 3 is not a technical artifact of using a particular year for the normalizing transformation.

Third, we still use NOx normalized by 2010 level as the outcome variable, but the predictors include per capita car registration in 2006-2008[11], GDP in 2008, and CE in 2008. The rationale is that vehicles are a major contributor to air pollution, and our goal is to see if using car registration can lead to a better fit of the model. The results are shown in

[11] Car registration data are from Fred.

Figure 11. Comparing to Figure 3, it is obvious that using car registration produces a less satisfactory synthetic Germany in terms of matching pre-2010 Germany. This finding is not unexpected since the predictors used by Figure 3 include the lagged outcome variables, which can serve as proxy for observed and unobserved factors including the pollution produced by car. For our purpose, it is reassuring to see the post-2010 gap in Figure 11 looks similar to Figure 3.

Finally, we redo the synthetic control analysis using the energy-supply NOx, SOx and PM2.5 normalized by the 2010 level as the outcome variables[12]. Comparing the Panel A of Figure 12 to Figure 3, it is interesting to see that the downward trend in the energy-supply NNOx did not appear until 2013. In light of this finding, we deduce that the declining NOx emission observed in Figure 3 stems partially from other factors. We should stress that what matters for this study is not the downward trend, but a post-2010 gap between Germany (solid line) and synthetic Germany (dash line). That post-2010 gap is evident in Panel A of Figure 12. More importantly, that gap is only related to production of electricity and therefore cannot be attributed to confounding factors such as enhanced fuel efficiency of vehicles or agricultural technology.

Panel B of Figure 12 plots the energy-supply SOx, for which a downward trend reappears, indicating that the energy industry in Germany and other countries had been lowering SOx emission. The new post-2010 gap shows no qualitative difference from the gap shown in Panel A of Figure 6. For the energy-supply PM2.5, the post-2010 gap in Panel C of Figure 12 looks similar to the Panel A of Figure 7. Overall, Figure 12 indicates the robustness of our previous findings regarding the post-2010 gap between Germany and synthetic Germany.

[12]data are from https://www.eea.europa.eu/data-and-maps/dashboards/national-air-pollutant-emissions-data. The energy-supply CO2 data are unavailable.

7 Conclusion

The goal of this paper is estimating the treatment effect of 2011 German nuclear shutdown on environment. Our identification strategy is contrasting the trajectory of air pollutants in Germany with similar European countries that did not shut down nuclear reactors in 2011. By combining those donor-pool countries into a synthetic Germany, with weights determined endogenously by data, we are able to capture the pre-treatment common trends between Germany and synthetic Germany. Those common trends enable us to obtain the counterfactual outcome of what would have happened to German environment in the absence of nuclear shutdown. The treatment effect can be visualized as a post-treatment gap between Germany and synthetic Germany.

Germany dominates other European countries thanks to the size of its economy and leading manufacturing sector. Therefore, a direct across-country comparison of air pollutants is an apple-to-orange comparison. In order to increase the comparability and likelihood of obtaining a successful synthetic Germany, we normalize each country's air pollutant by the level one year before 2011. When interpreting our results, readers should keep in mind that the outcome variable is an *index* of air pollutant that is specific to each country (index=100 in 2010).

We report a persistent post-2010 gap between the air pollutant trajectory of Germany and synthetic Germany. For instance, from 2010 to 2015, in Germany there is 7.28% reduction in total amount of nitrogen oxides. By contrast, in synthetic Germany the reduction of nitrogen oxides is 13.21%. The difference between those two values implies that, had the 2011 nuclear shutdown not happened, German nitrogen oxide emission would have improved at a faster rate.

A more direct estimate of the treatment effect is from using the energy-supply air pollutants that exclude the influence of other sectors such as agriculture and transportation. From 2010 to 2015, the energy-supply nitrogen oxides rise by 3.28% in Germany, whereas they fall by 13.11% in synthetic Germany. The difference, 16.39%, is the estimated five-year treatment effect of 2011 nuclear shutdown on energy-supply nitrogen oxides.

For energy-supply sulphur oxides, they drop by 8.58 % in Germany from 2010 to 2015, and by 64.09% in Synthetic Germany. The estimated five-year treatment effect is 55.51%; for energy-supply PM2.5, it drops by 17.98 % in Germany, and by 33.49% in Synthetic Germany. The estimated five-year treatment effect is 15.51%.

In short, our study demonstrates that the 2011 German nuclear shutdown has adverse impact on its environment by slowing down the declining trend in air pollutants. One mechanism for this negative treatment effect is that in the wake of nuclear shutdown Germany had to rely more on using fossil fuel to generate electricity than other countries.

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Table 1: Mean of Outcome Variables and Predictors

	$\overline{NO_x}$	$\overline{NNO_x}$	$\overline{CO_2}$	$\overline{NCO_2}$	$\overline{SO_x}$	$\overline{NSO_x}$	$\overline{PM_{2.5}}$	$\overline{NPM_{2.5}}$	$\overline{GDP}$	$\overline{CE}$
Panel A: Before 2011										
Austria	226331	111	9	103	25466	159	22085	111	35678	78
France	1449700	127	6	109	443871	165	245518	130	31095	74
Germany	1667804	113	10	104	504623	124	140381	117	32885	76
Netherlands	413246	118	10	99	62790	176	28832	127	38907	79
Spain	1240103	136	7	124	989462	407	149613	109	27988	68
Sweden	188964	112	6	108	36224	126	29926	114	35783	81
Synthetic Germany		114		105		126		120		
Panel B: After 2011										
Austria	171380	84	7	89	13306	83	15834	80	52300	103
France	922174	81	5	89	152233	57	141406	75	43097	106
Germany	1326009	90	9	96	322178	79	101373	85	50116	102
Netherlands	274884	79	9	89	28574	80	17585	77	53335	104
Spain	743901	82	5	93	222423	92	128198	93	36738	103
Sweden	144458	86	4	78	19653	68	20216	77	50400	110
Synthetic Germany		85		89		68		78		

Note: $\overline{y}$ denotes the sample average of y.

Table 2: Model Specification for Constructing Synthetic Germany

	Model 1	Model 2	Model 3	Model 4	Model 5
RMSPE	5.97	1.60	1.23	1.04	2.40
Panel A: Weight for Untreated Unit					
Austria	0.157	0.08	0.025	0	0
France	0.252	0.045	0.016	0.113	0.327
Netherlands	0.113	0.032	0.083	0	0
Spain	0.329	0.007	0.002	0	0
Sweden	0.149	0.836	0.874	0.887	0.673
Panel B: Weight for Predictor					
GDP_{2008}	1	na	na	0.01	0.113
$NNOx_{2008}$	na	1	0.821	0.219	0.441
$NNOx_{2007}$	na	na	0.179	0.370	0.015
$NNOx_{2006}$	na	na	na	0.400	0.310
CE_{2008}	na	na	na	na	0

Note: Outcome variable is NNOX. Each column represents a specification using the synthetic control method.

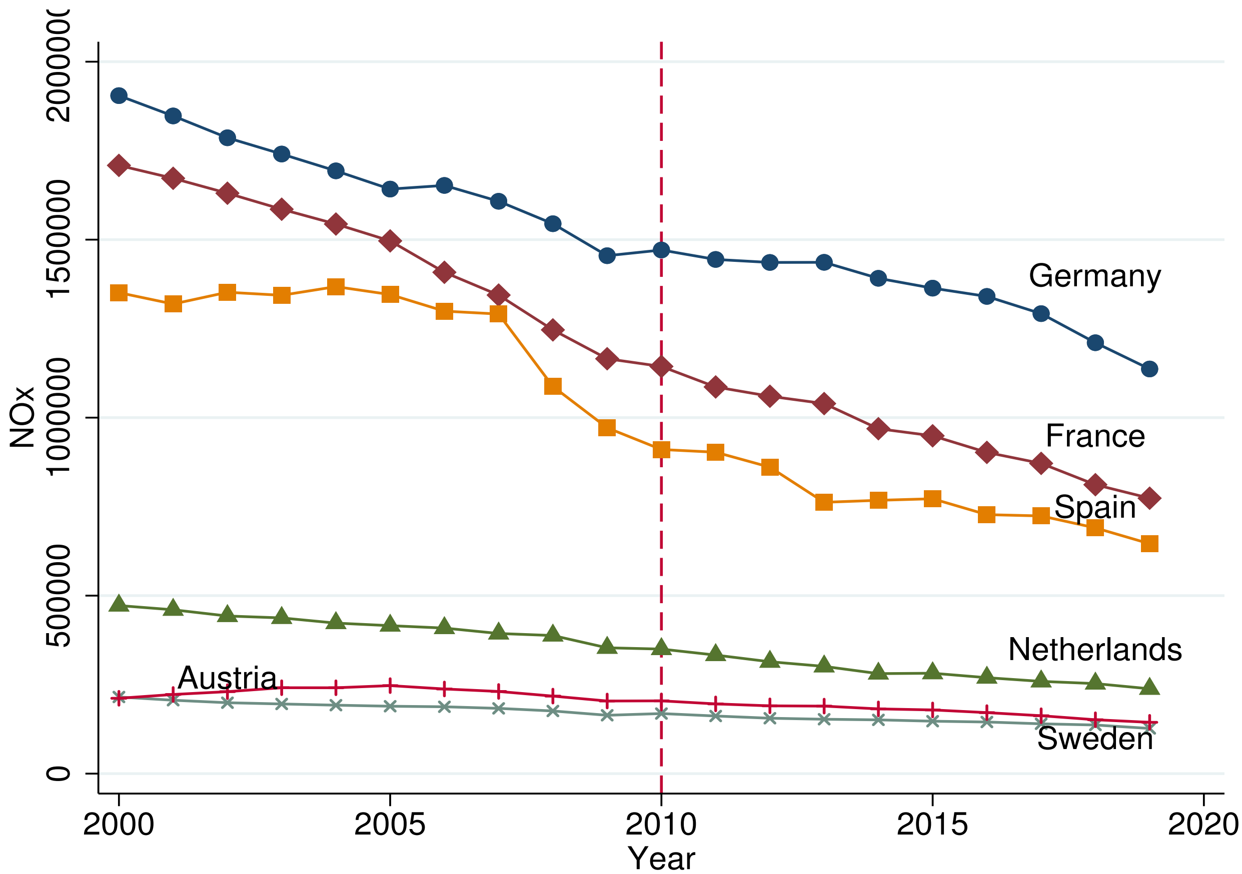

Figure 1: Time Series Plot of NOx

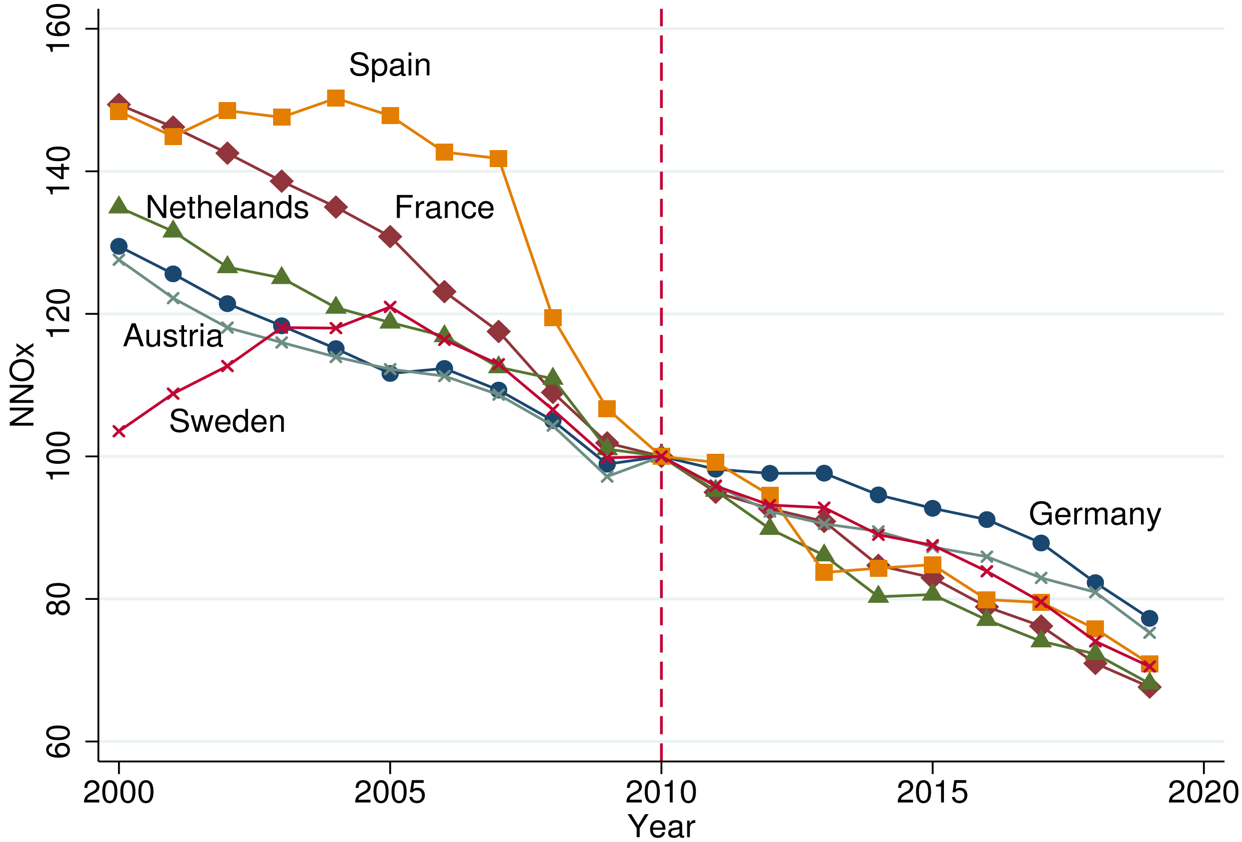

Figure 2: Time Series Plot of NOx Normalized by 2010 Value (NNOX)

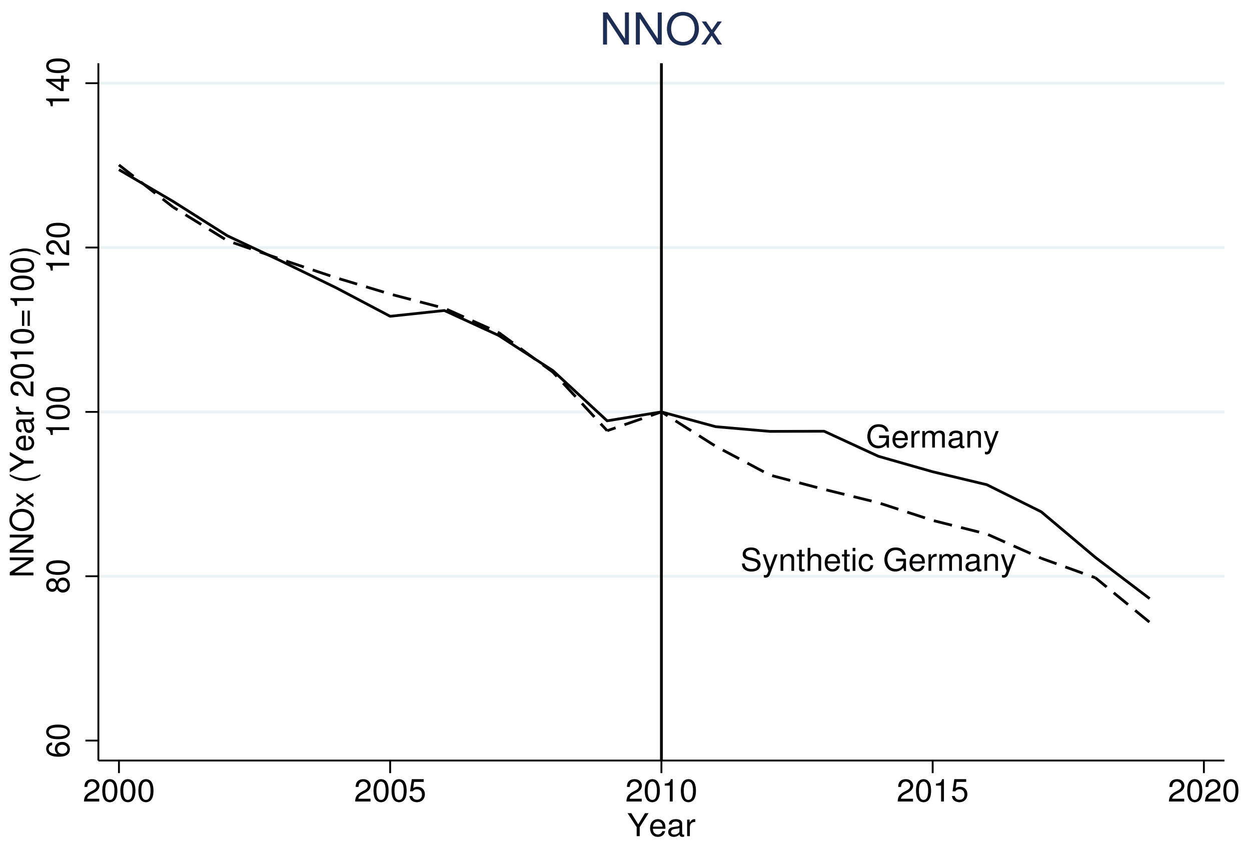

Figure 3: Time Series Plot of NNOx of Germany and Synthetic Germany

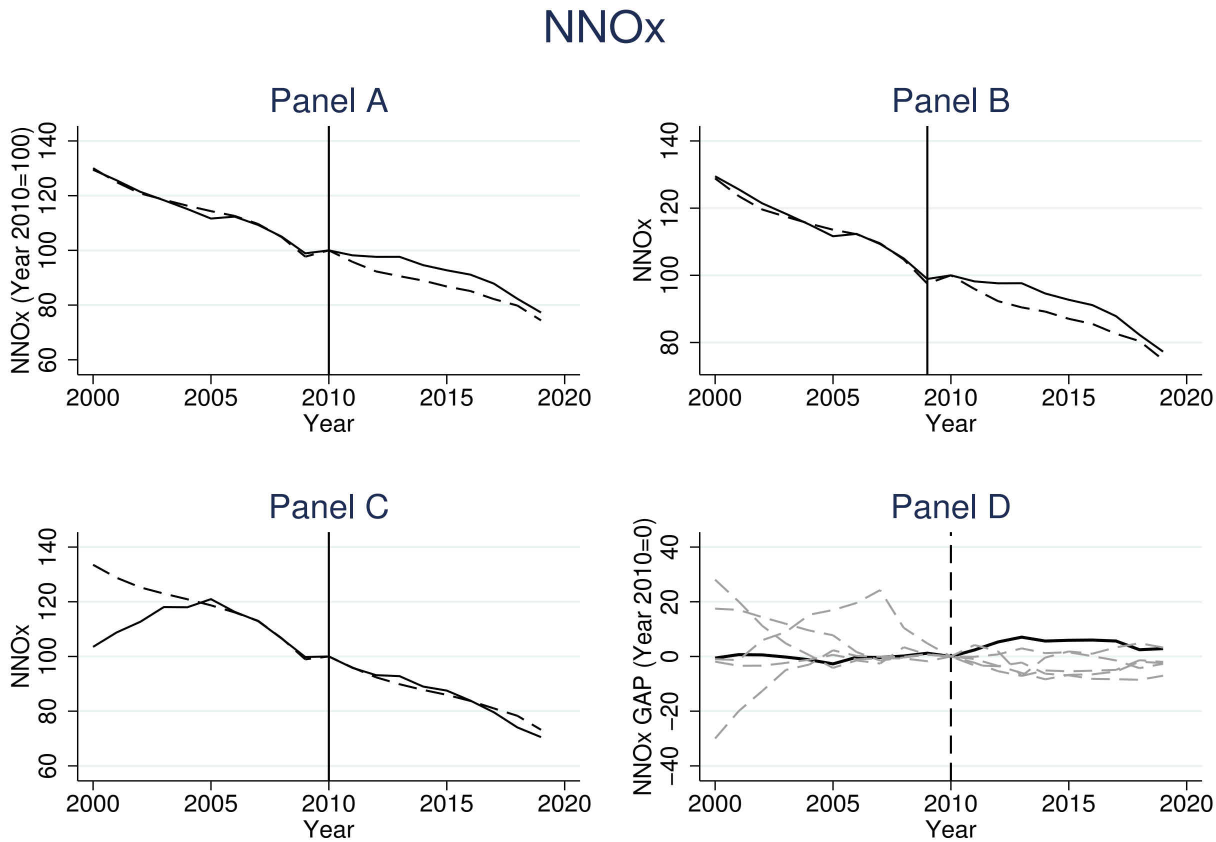

Figure 4: Synthetic Control Analysis of NNOx

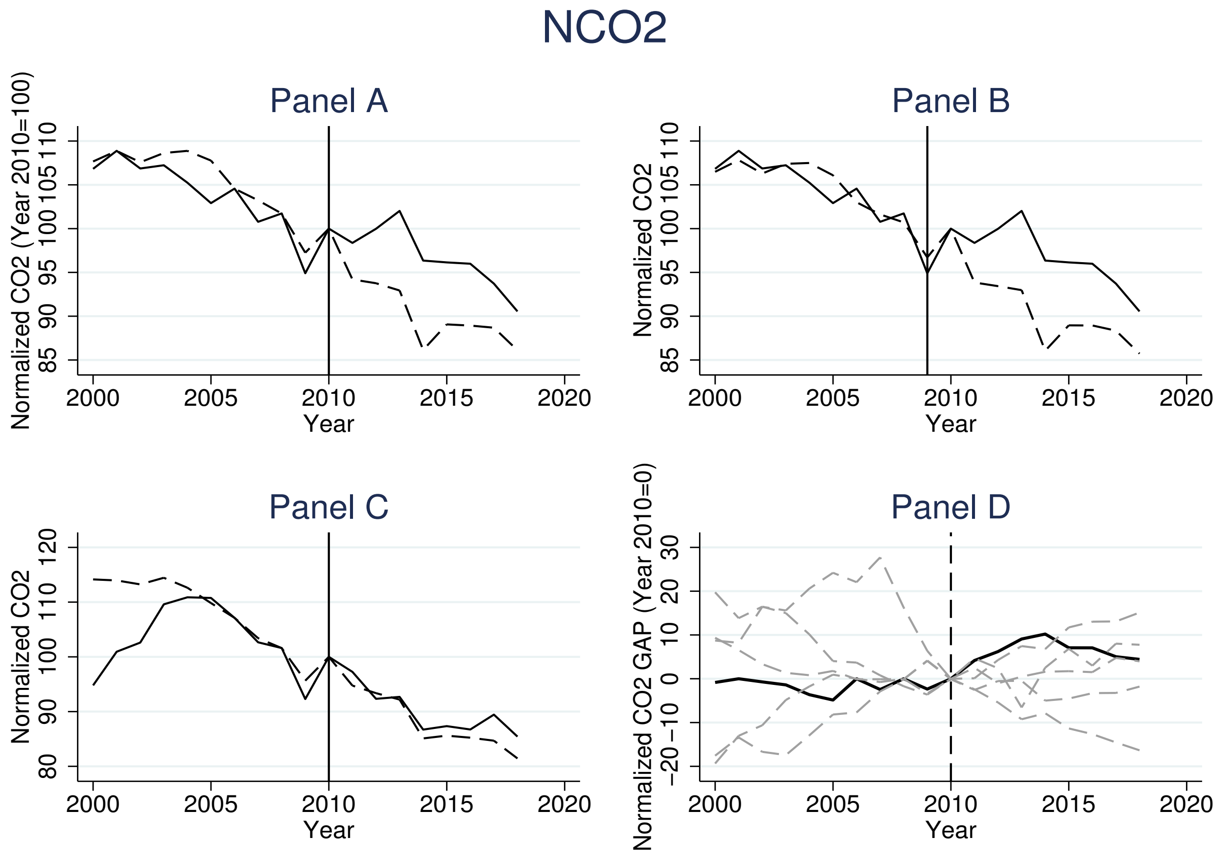

Figure 5: Synthetic Control Analysis of NCO2

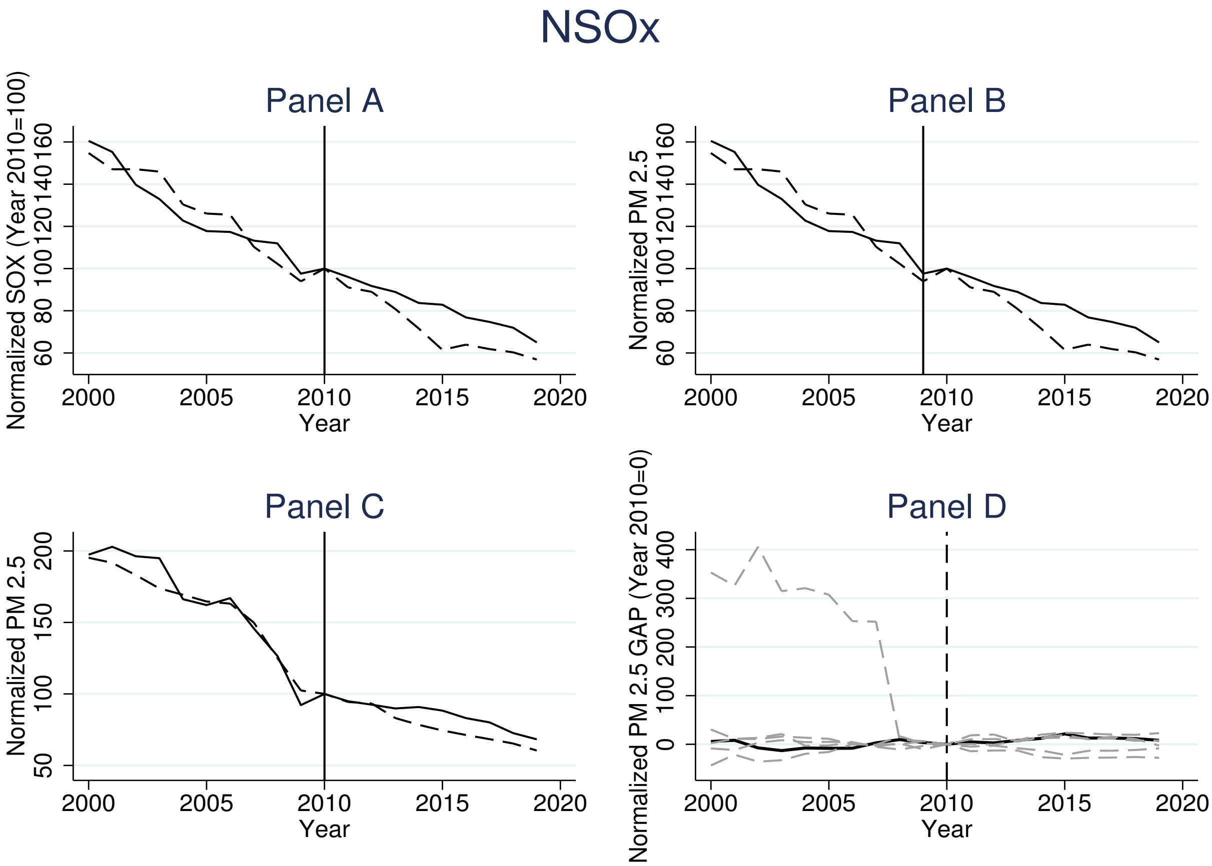

Figure 6: Synthetic Control Analysis of NSOx

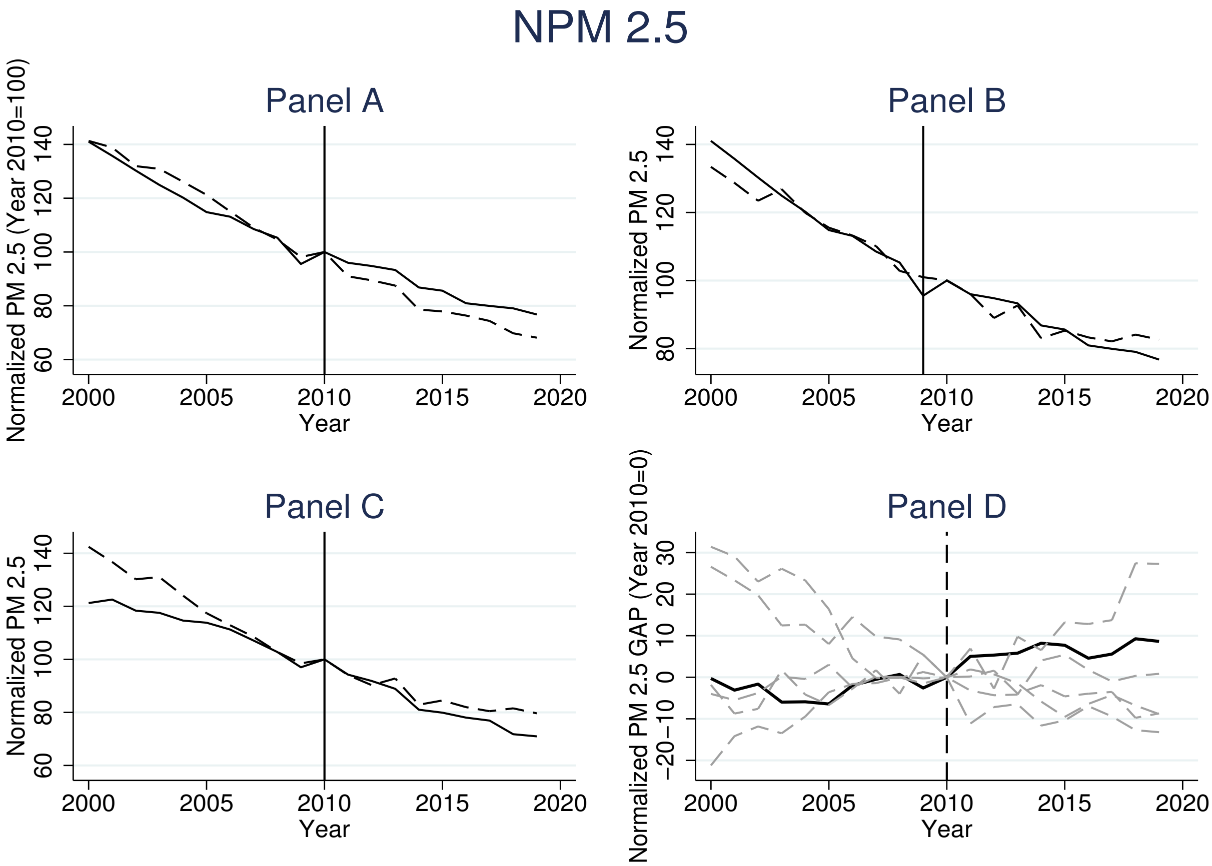

Figure 7: Synthetic Control Analysis of NPM2.5

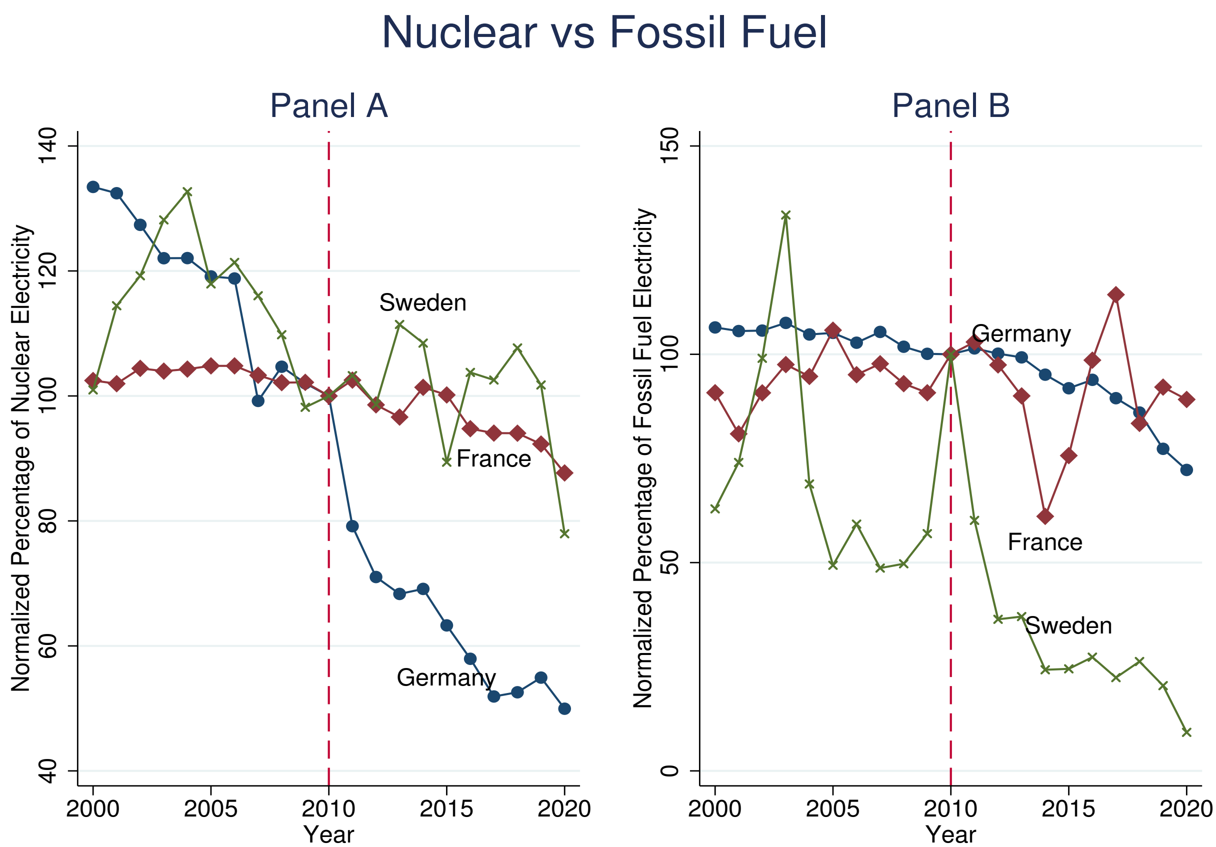

Figure 8: Mechanism for Treatment Effect

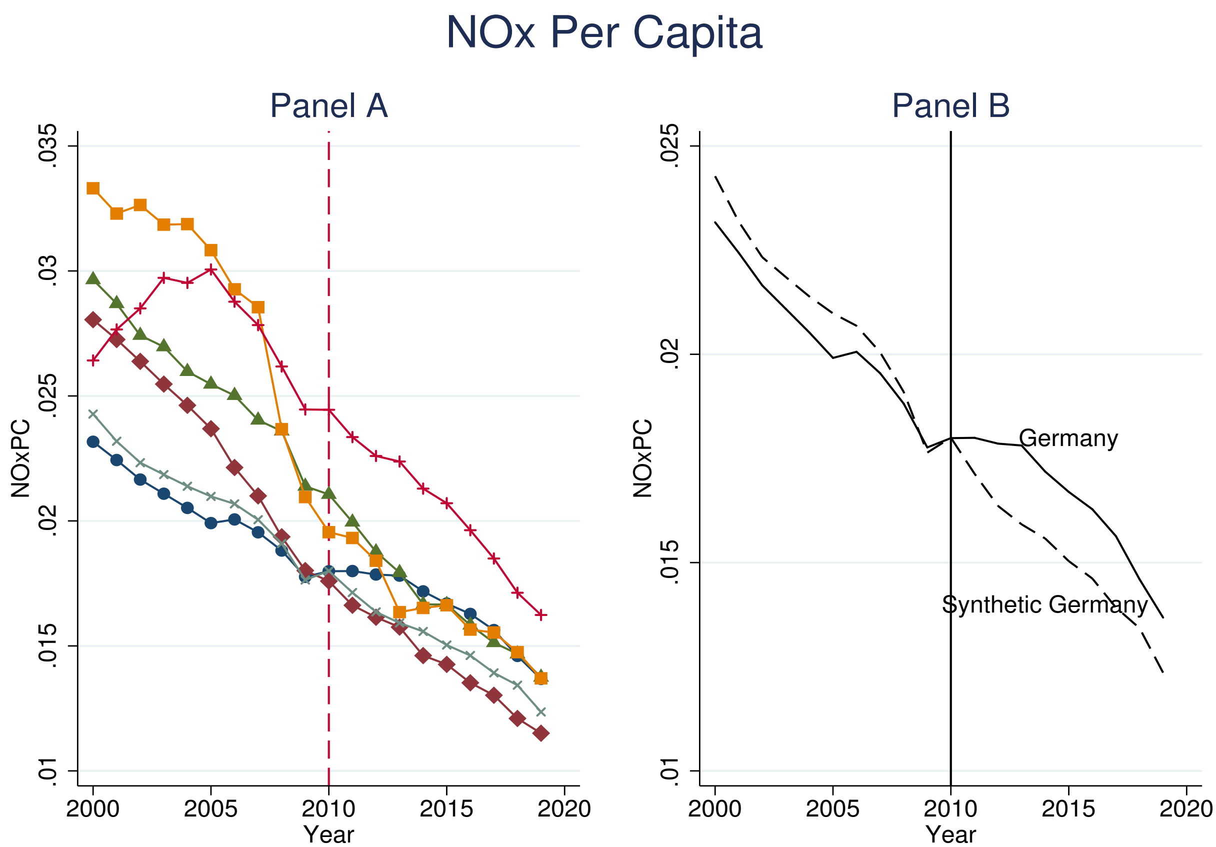

Figure 9: Synthetic Control Analysis of NOx Per Capita (NOxPC)

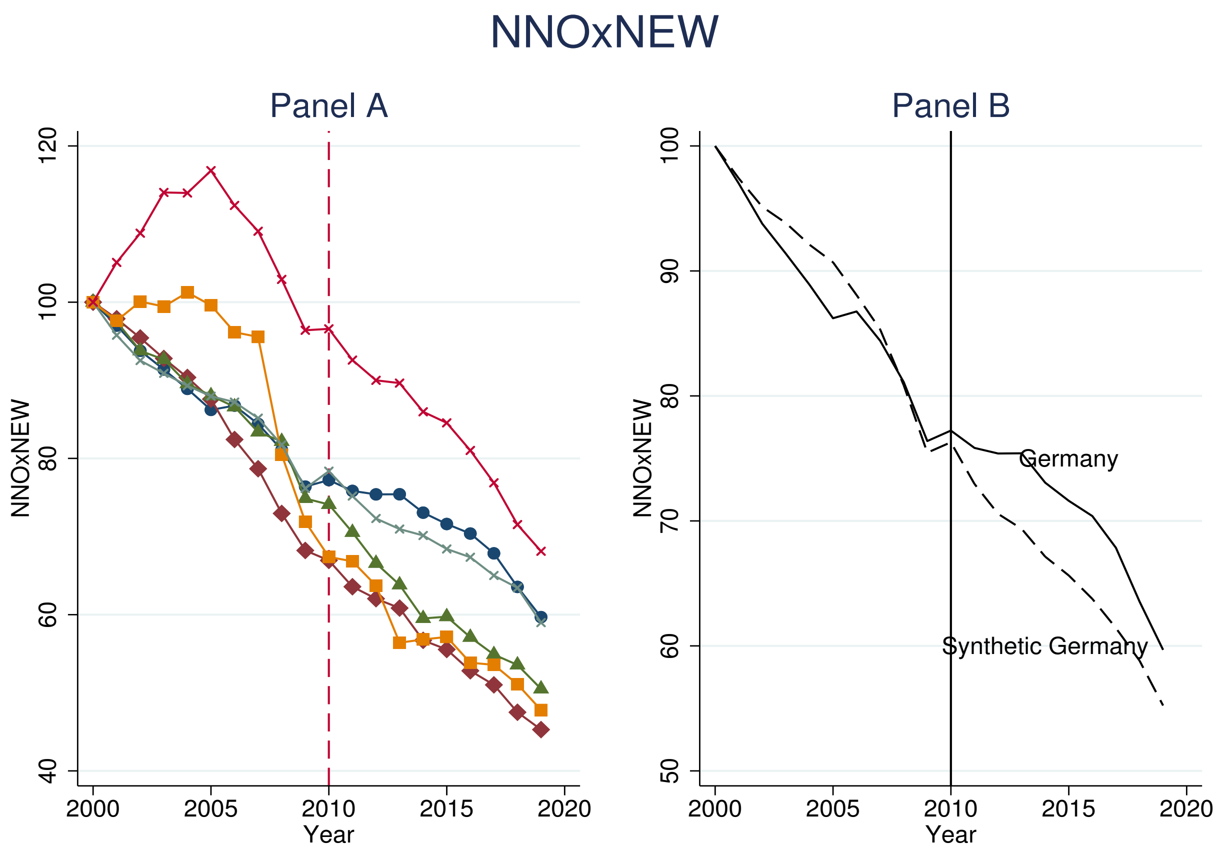

Figure 10: Synthetic Control Analysis of NOx Normalized by 2000 Value (NNOxNEW)

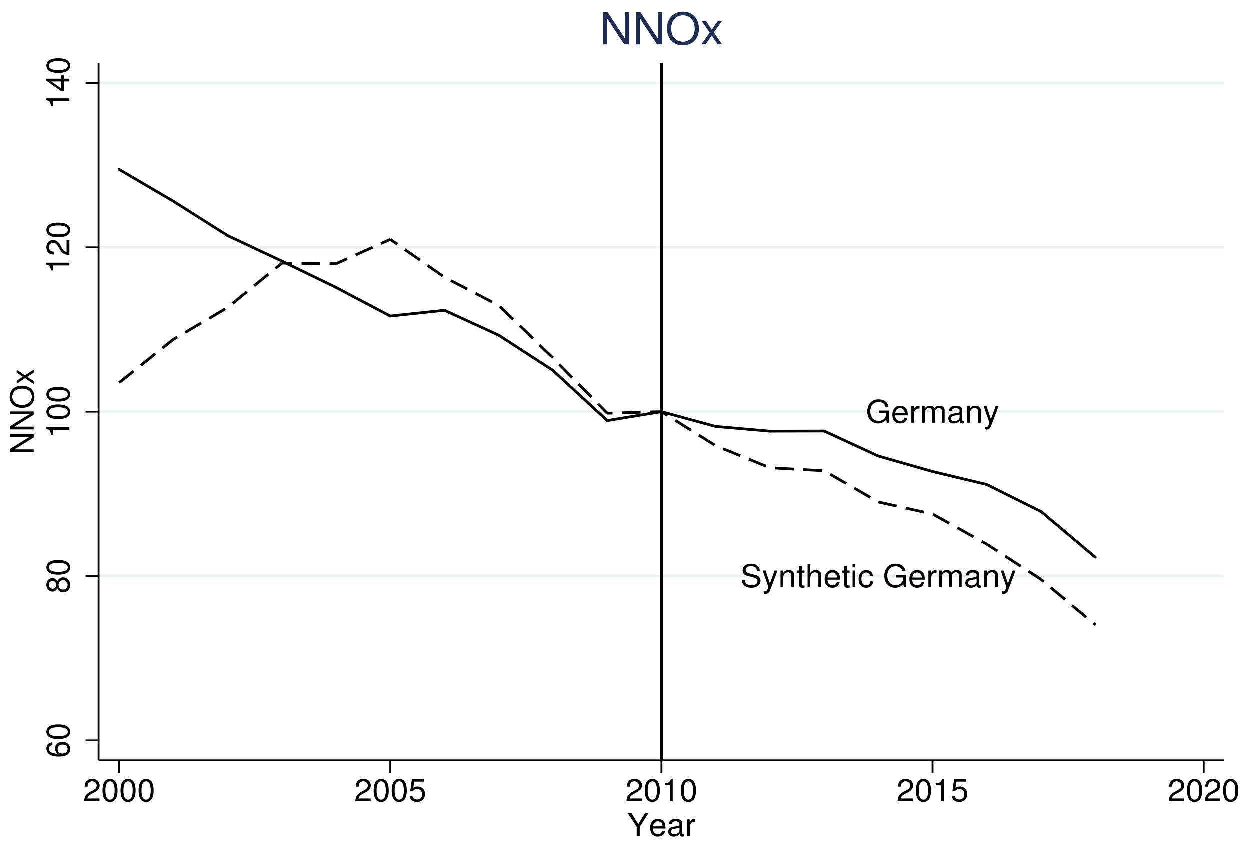

Figure 11: Synthetic Control Analysis of NNOx Using Car Registration as Predictor

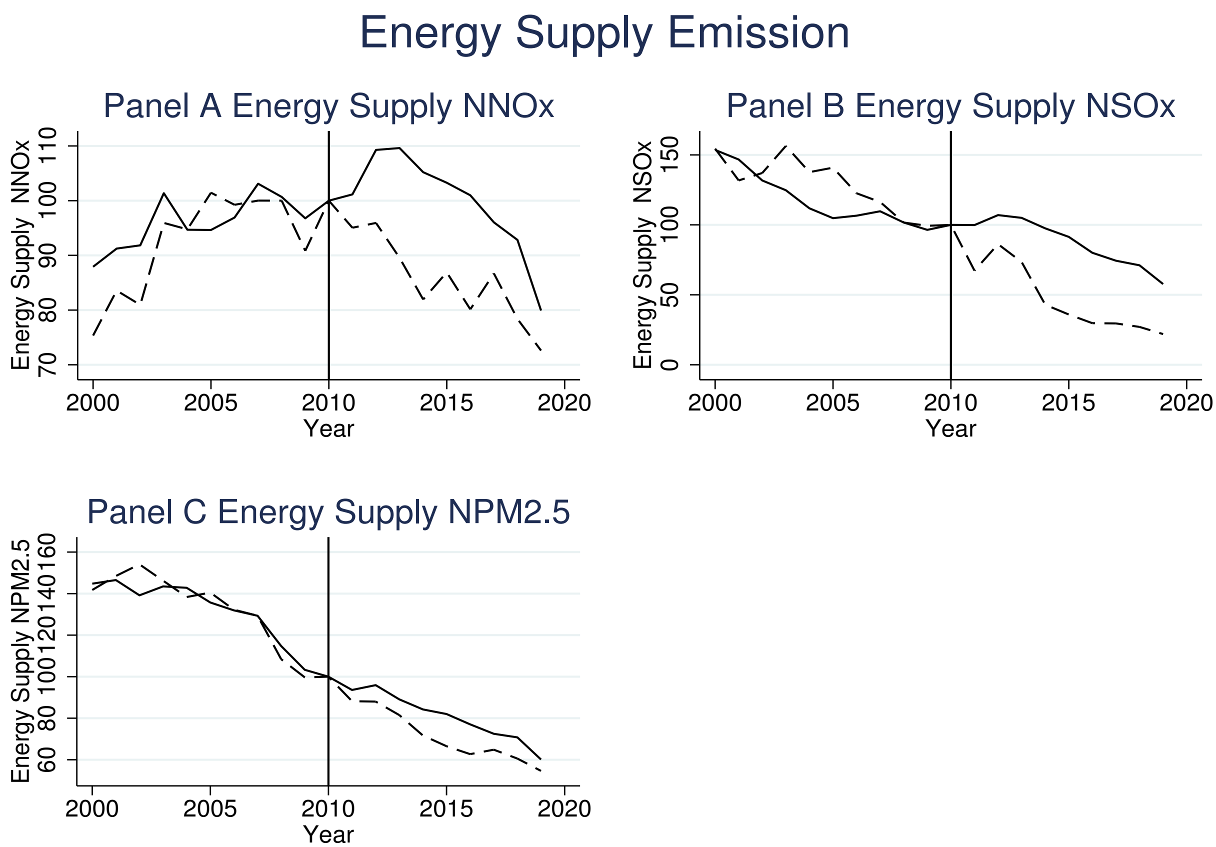

Figure 12: Synthetic Control Analysis of Energy Supply Pollutants