Applied Economics

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/raec20

Environmental impact of 2011 Germany's nuclear shutdown: a synthetic control study

Bryanna Renuart & Jing Li

To cite this article: Bryanna Renuart & Jing Li (29 Jan 2024): Environmental impact of 2011 Germany's nuclear shutdown: a synthetic control study, Applied Economics, DOI: 10.1080/00036846.2024.2305623

To link to this article: https://doi.org/10.1080/00036846.2024.2305623

Published online: 29 Jan 2024.

APPLIED ECONOMICS
https://doi.org/10.1080/00036846.2024.2305623

Routledge
Taylor & Francis Group

Environmental impact of 2011 Germany's nuclear shutdown: a synthetic control study

Bryanna Renuart and Jing Li

Department of Economics, Miami University, Oxford, OH, USA

ABSTRACT

This article contrasts trajectories of Germany's nitrogen oxides, sulphur oxides, particulate matter 2.5, and carbon dioxide emissions with a data-driven weighted average of several European countries. 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 find a negative environmental impact of the nuclear shutdown. For instance, from 2010 to 2015, the normalized nitrogen oxides emission in Germany fell from 100 to 92.72, while the emission in the synthetic Germany dropped from 100 to 85.75. One mechanism for the treatment effect is that after the nuclear shutdown, Germany had to use more fossil fuel to generate electricity relative to other countries.

KEYWORDS

Nuclear energy; synthetic control; Germany; carbon dioxide; Air Pollution

JEL CLASSIFICATION

N54; Q48; Q53; Q54; Q58

I. 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 the Russian invasion of Ukraine, the closure of two of the last three nuclear power plants has been postponed.[2]

This article makes a contribution to the literature of energy economics by examining the direction and magnitude of the treatment effect of the 2011 nuclear shutdown on Germany's environment. Nuclear energy policy remains a politically divisive issue, and understanding its 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 reactor considered by the French government.[3]

From the econometric perspective, the random timing of the Fukushima 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 strategy takes advantage of the lack of reverse causation or simultaneity bias.

The abruptness of the 2011 nuclear shutdown also facilitates identification. 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 control group remained unchanged), then the observed post-2011 discrepancy between Germany and synthetic Germany can be attributed to the 2011 nuclear shutdown.

CONTACT Jing Li lij14@miamioh.edu Department of Economics, Miami University, 800 E. High Street, Oxford, OH 45056, USA

[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.

We apply the synthetic control method (SCM) proposed in Abadie and Gardeazabal (2003) 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 account for confounding factors such as improvement in vehicle fuel efficiency, enhanced agricultural technology, and ratification of the Kyoto Protocol. The SCM essentially compares the trajectory of a variety of measurements of Germany's environment to synthetic Germany. Another way to interpret the synthetic Germany is that it provides the counterfactual of what would have happened to Germany's environment had the 2011 shutdown not occurred.

We are able to demonstrate the pre-2011 'parallel trends' of Germany and synthetic Germany, and obtain an apple-to-apple comparison. To avoid the pitfall shown by Kaul et al. (2022), we use several covariates as the predictors. Furthermore, we report interval estimates of the treatment effect based on two specifications to mitigate the concern that one particular country may dominate the donor pool. Finally, we consider two alternative outcome variables when checking the robustness of our main results.

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 neighbouring countries; Grossi et al. (2017) emphasize the impact on prices based on a modified demand-supply framework; Ando (2015)dreams 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 adopting the synthetic control method and focusing on the environmental impact of the 2011 nuclear shutdown.

II. 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 to 2019; Carbon Dioxide Emissions (CO2) is obtained from World Bank, and ranges from 2000 to 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 micrometres or smaller that has an adverse health effect by travelling deep into the respiratory tract.

There are 11 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 COVID-19 Pandemic, which has substantial impact on economic activity, consumption of energy, and environment.

Consumption of energy depends on energy price and economy. Thus, the first two predictors used in this study are Consumer Price Index for household energy (CE for short) and purchasing power parity adjusted per capita GDP (GDP for short). A major contributor to air pollution is transportation sector, so the third predictor is the per capita car registration. The fourth and fifth predictors are electricity generation and electricity generation by fossil fuel. These two predictors can serve as proxies for the energy sector and composition of fuels. Finally, lag values of the outcome variables are included as additional predictors, which aim to capture the effect of confounding factors for which we do not have data. Examples of those unobserved factors are improvement in vehicle fuel efficiency, and increase in renewable energies incentivized by policies such as the Renewable Energy Sources Act or EEG.

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, 1 year before the German nuclear shutdown. It is evident that the NOx pollution in Germany (a blue line with circles) dominates other countries, which is not unexpected given the sizable manufacturing sector in Germany. 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 synthetic Germany if NNOx index other than NOx is used as the outcome variable. Finally and most importantly, despite the downward trends in each country's NNOx index after 2011, the German trend lies above all other countries, suggesting the negative impact of the 2011 nuclear shutdown on its environment. To summarize, Figure 2 shows that the NOx pollution in each country has dropped below its 2010 level. However, possibly because of the 2011 nuclear shutdown, Germany has seen the slowest improvement.

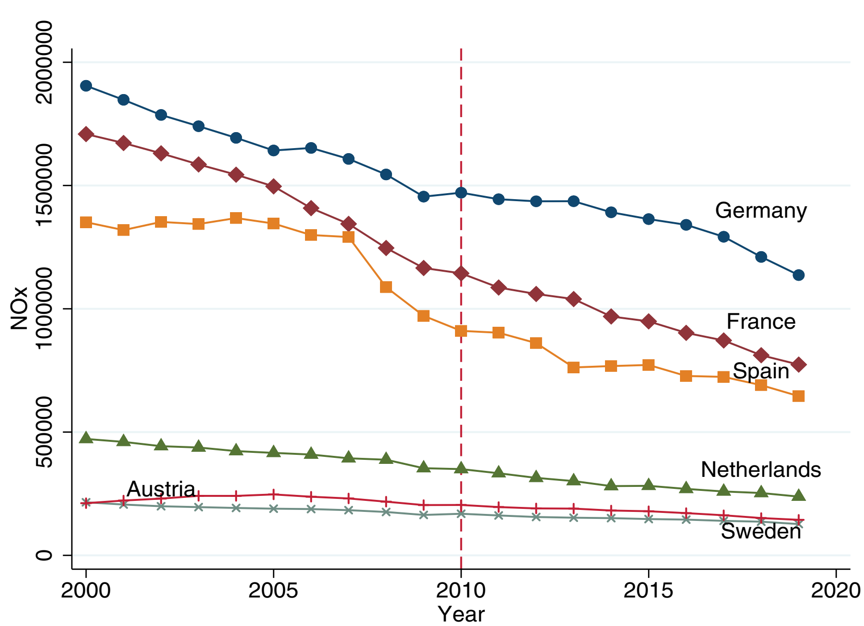

Figure 1. Time series plot of NOx.

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

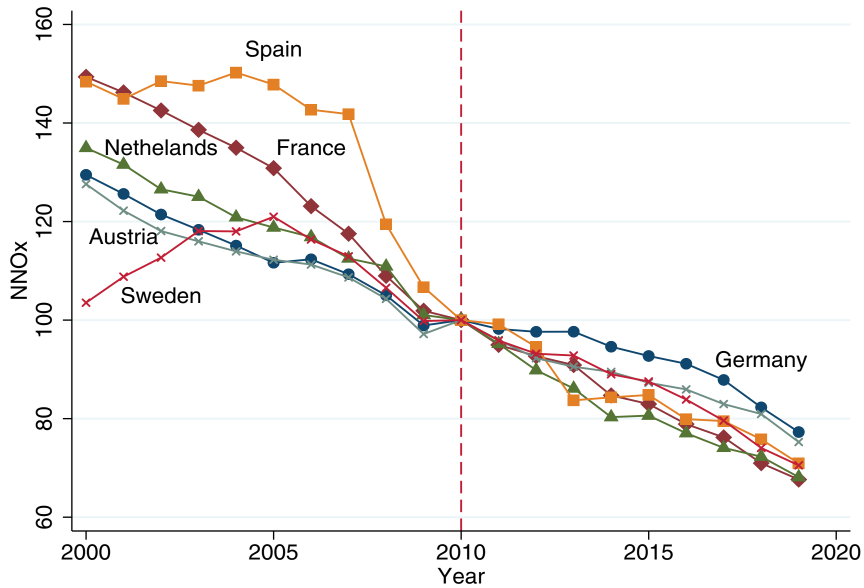

Figure 2. Time series plot of NOx normalized by 2010 value (NNOx).

Panels A and B of Table 1 quantify the pattern shown in Figures 1 and 2 by reporting sample means, before and after 2011, of NOx, CO2, SOx, PM2.5, and their normalized indexes. For instance, compare average NOx in Austria and Germany. Before 2011, the two countries are not comparable since the German average 1,667,804 and Austrian average 226,331 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 least reduction (from 113 to 90). In fact, Germany has the greatest post-2011 average NNOx of 90. The biggest drop of NNOx happens in Spain (from 136 to 82), which is consistent with the steepest downward line for that country in Figure 2.

A similar pattern is observed for CO2, SOx and PM 2.5—normalization makes Germany comparable to the donor pool before 2011, and more importantly, gaps emerge between Germany and the donor pool in terms of the change in the index after 2011. The synthetic control method is motivated by this finding.

Table 2 reports the sample means of predictors before 2011 for Germany, the synthetic Germany that is constructed based on a specification discussed later, France, and Sweden, two countries that receive the most weights in the synthetic

Table 1. Means of outcome variables before and after 2011.

	$\overline{NO_x}$	$\overline{NNO_x}$	$\overline{CO_2}$	$\overline{NCO_2}$	$\overline{SO_x}$	$\overline{NSO_x}$	$\overline{PM_{2.5}}$	$\overline{NPM_{2.5}}$
Panel A: Before 2011								
Austria	226,331	111	9	103	25,466	159	22,085	111
France	1,449,700	127	6	109	443,871	165	245,518	130
Germany	1,667,804	113	10	104	504,623	124	140,381	117
Netherlands	413,246	118	10	99	62,790	176	28,832	127
Spain	1,240,103	136	7	124	989,462	407	149,613	109
Sweden	188,964	112	6	108	36,224	126	29,926	114
Panel B: After 2011								
Austria	171,380	84	7	89	13,306	83	15,834	80
France	922,174	81	5	89	152,233	57	141,406	75
Germany	1,326,009	90	9	96	322,178	79	101,373	85
Netherlands	274,884	79	9	89	28,574	80	17,585	77
Spain	743,901	82	5	93	222,423	92	128,198	93
Sweden	144,458	86	4	78	19,653	68	20,216	77

$\bar{y}$ denotes the sample average of y.

Table 2. Means of predictors before 2011.

	Germany	Synthetic Germany	France	Sweden
GDP	32885.04	34123.37	31094.60	35783.10
CE	75.91	78.73	74.07	81.28
Car Registration	3.33	2.79	2.79	2.79
Normalized Electricity Generation	96.83	98.73	98.43	98.90
Normalized Electricity Generation by Fossil Fuel	100.72	79.12	92.89	71.58

Germany. We see that the sample means of GDP, CE, and Normalized Electricity Generation of Germany are comparable to those of France and Sweden. This suggests that those three predictors matter a lot when generating the synthetic Germany.

III. Methodology and model specification

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 the nuclear shutdown.[6] The synthetic control method assigns data-driven weights to the donor-pool countries, and the weights are determined by the predictive power. Intuitively, a country with characteristics similar to Germany should receive a greater weight than a country showing dissimilarity.

If the nuclear shutdown indeed has a treatment effect, we expect to observe a gap in trajectories of outcome variables between Germany and its synthetic counterpart after 2011. Our conjecture is that the nuclear shutdown would worsen Germany's environment, so the outcome time series of Germany would lie above the synthetic Germany after 2011.

In a nutshell, the objective of the synthetic control method is determining two sets of weights: the weights for donor pool countries, and the weights for predictors. More specifically, the method aims to solve the following nested optimization problems

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

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

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

Note that (1) is a restricted quadratic programming problem because the weight w_j is bounded between 0 and 1. The results are the optimal weights for untreated units for a given V. 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. More details about the synthetic control method can be found in Abadie et al. (2015).

Table 3 illustrates the process of model specifications to construct the synthetic Germany for NNOx. Each column represents a specification, with weights for donor pool countries and predictors reported in Panels A and B, respectively. In order to evaluate the predictive power of predictors, the pre-treatment periods are divided into training (in-sample) periods and validation (out-of-sample) periods. In this article, the validation set includes 2009 and 2010. The criterion for model selection is the root of mean squared prediction error (RMSPE) in the validation periods. The model with the least RMSPE is deemed the best one.

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

Table 3. Model specification for constructing synthetic Germany.

	Model 1	Model 2	Model 3	Model 4	Model 5
RMSPE	1.44	1.68	1.33	1.55	0.05
Panel A: Weights for Untreated Units					
Austria	0.223	0.449	0.222	0.504	0
France	0.572	0.481	0.642	0.442	0.354
Netherlands	0.042	0	0	0	0
Spain	0.035	0.07	0	0.054	0
Sweden	0.129	0	0.136	0	0.646
Panel B: Weights for Predictors					
GDP_{2008}	0.093	0.085	0.337	0.189	0.201
CE_{2008}	0.907	0.914	0.270	0.361	0.001
Car_{2008}	na	0.002	0.038	0.144	0.003
NEG_{2008}	na	na	0.355	0.032	0.197
$NEGFF_{2008}$	na	na	na	0.273	na
$\overline{NNOX}_{2006-2008}$	na	na	na	na	0.598

Outcome variable is NNOx. Each column represents a specification using the synthetic control method.

We follow the specific-to-general modelling strategy – we start with a simple model and then add predictors. Model 1 in Table 3 uses GDP and CE in 2008 as the predictors, and RMSPE equals 1.44. We get a worse fit (RMSPE rises to 1.68) in Model 2, which adds the predictor of car registration in 2008. Model 3 adds the normalized energy generation, and the RMSPE drops. By contrast, including the normalized energy generation by fossil fuel in Model 4 leads to a worse fit. Finally, Model 5 excludes the normalized energy generation by fossil fuel, but adds the average of NNOx between 2006 and 2008, which serves as a proxy for the unobserved factors.

The best fit is obtained in the Model 5 (RMSPE is 0.05), in which France and Sweden receive the weights of 0.354 and 0.646. Nevertheless, Kaul et al. (2022) demonstrate the pitfall of only using the lagged outcome variables as the predictors. In the light of that, we also consider the Model 3 (RMSPE is 1.33) without using the lagged outcome variable as predictor, and the weights for Austria, France, and Sweden are 0.222, 0.642 and 0.136. Note that rankings of France and Sweden switch in the Models 3 and 5. Later, we will show that our main findings are insensitive to the rankings of those two countries.

Alternatively, we can treat the two estimates from the Models 5 and 3 as an interval estimate that accounts for the uncertainty in modelling. Reporting the interval estimate can mitigate the concern that a particular country such as Sweden may dominate in the synthetic Germany. See Li et al. (2021) for another example of reporting interval estimates with the synthetic control method.

IV. Results

The best way to convey the results of a synthetic control analysis is visualizing Germany and synthetic Germany. The solid lines in Figure 3 represent the NNOx in Germany while the dash line in Panel A is synthetic Germany constructed with Model 5, and in Panel B with Model 3. Notably, the synthetic Germany is a satisfactory one as we observe 'parallel trends' – the solid and dash lines almost overlap from 2006 to 2010. Thanks to the parallel trends, the synthetic Germany is able to capture the impacts of unobservable factors, and therefore simulate the counterfactual if the nuclear shutdown had not happened.

We see in both panels that the downward NNOx trajectory of synthetic Germany lies below Germany throughout the post-treatment periods, implying that the NOx pollution in Austria, France, and Sweden had been reduced at a faster rate than Germany. This finding is consistent with the previous finding in Figure 2 that German NNOx time series is on the top after 2010. The widening gap from 2010 to 2014 is especially striking – 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 the German nuclear shutdown on the NOx pollution.

Next, we compare the numbers and check statistical significance. Focus on Panel A. From 2010

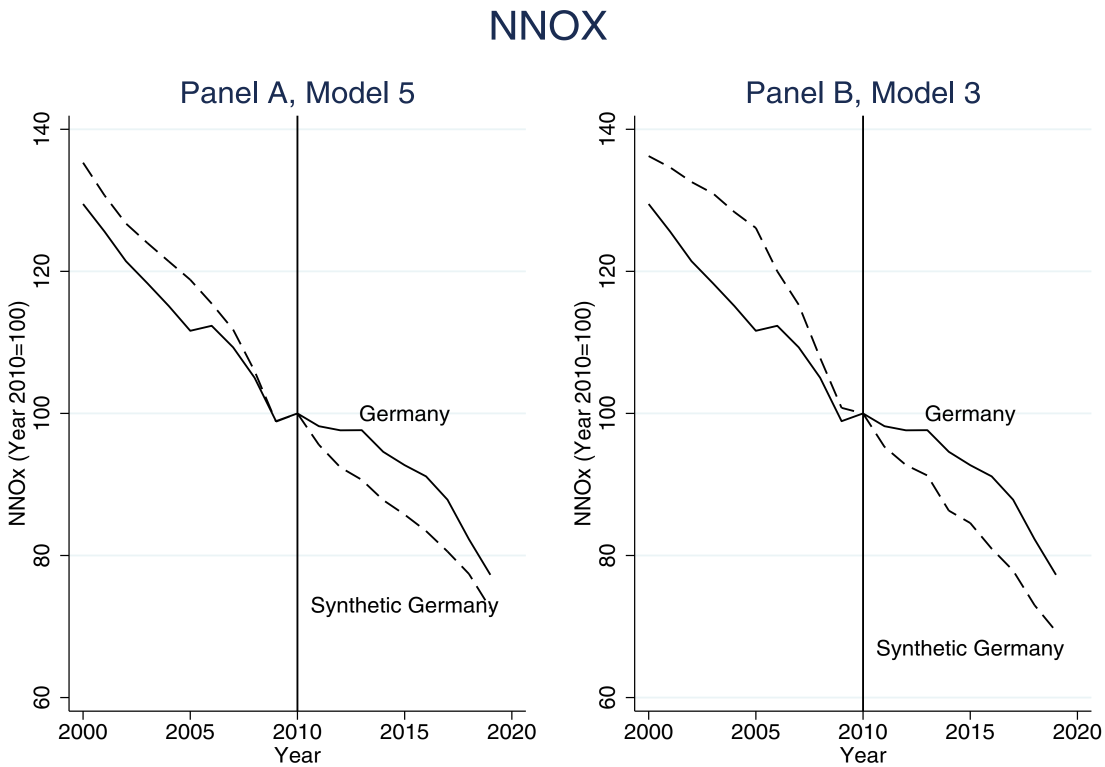

Figure 3. Time series plot of NNOx of Germany and synthetic Germany.

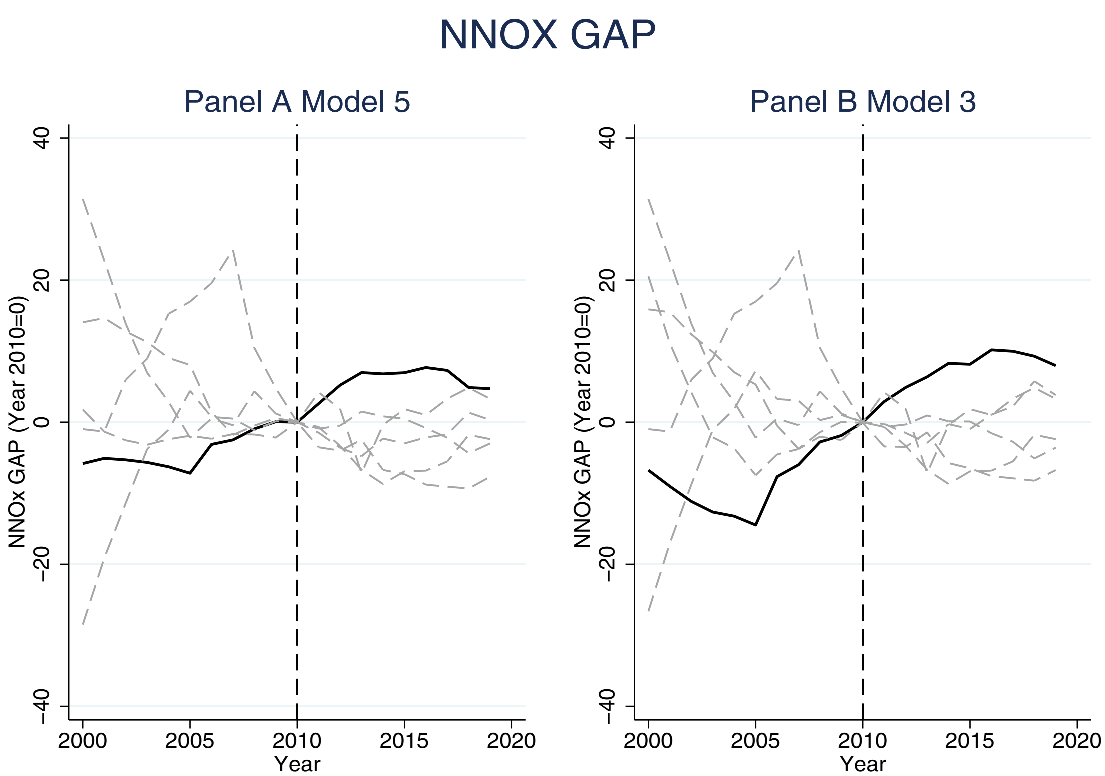

Figure 4. Time series plot of NNOx gap.

to 2014, NNOx in Germany fell from 100 to 94.60, while NNOx in synthetic Germany dropped from 100 to 87.80. The paired two-sample t-test applied to the two NNOx series is 3.24, rejecting the hypothesis of equal means at the 5% significance level. Within 10 years, from 2010 to 2019, Germany NNOx dropped from 100 to 77.28, and synthetic Germany NNOx dropped from 100 to 72.56, resulting in a two-sample t-test of 6.90. The equal-mean hypothesis is rejected again. By contrast, we find no significant difference between the NNOx series from 2006 to 2010—average NNOx of Germany is 104.41; average NNOx of synthetic Germany is 105.53; the two-sample t-test is −1.50.

Figure 4 provides more evidence for the significance of the post-treatment gap by plotting for each country the gap between NNOx series of that country and its synthetic counterpart. The solid line denotes the German NNOx gap, and dash lines for other countries in the donor pool. We see that no matter Model 5 or Model 3 is used, the post-2010 NNOx gap of Germany dominates other countries, which implies that the post-2010 gap shown in Figure 3 is unlikely to be there by chance.

The synthetic control analysis is then conducted for the normalized CO2 (NCO2), normalized SOx (NSOx) and normalized PM2.5 (NPM2.5), and results from the specifications with the least RMSPE are displayed in Figure 5, in which panels on the left show outcome time series, while panels on the right show outcome gaps. We see that the main findings are similar to NNOx – the outcome time series of synthetic Germany (dash line) traces Germany (solid line) before 2010, and after 2010 the outcome time series of Germany lies above the synthetic Germany.

To sum up, Figures 3–5 present evidences for the negative impact of the 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 faster rates.

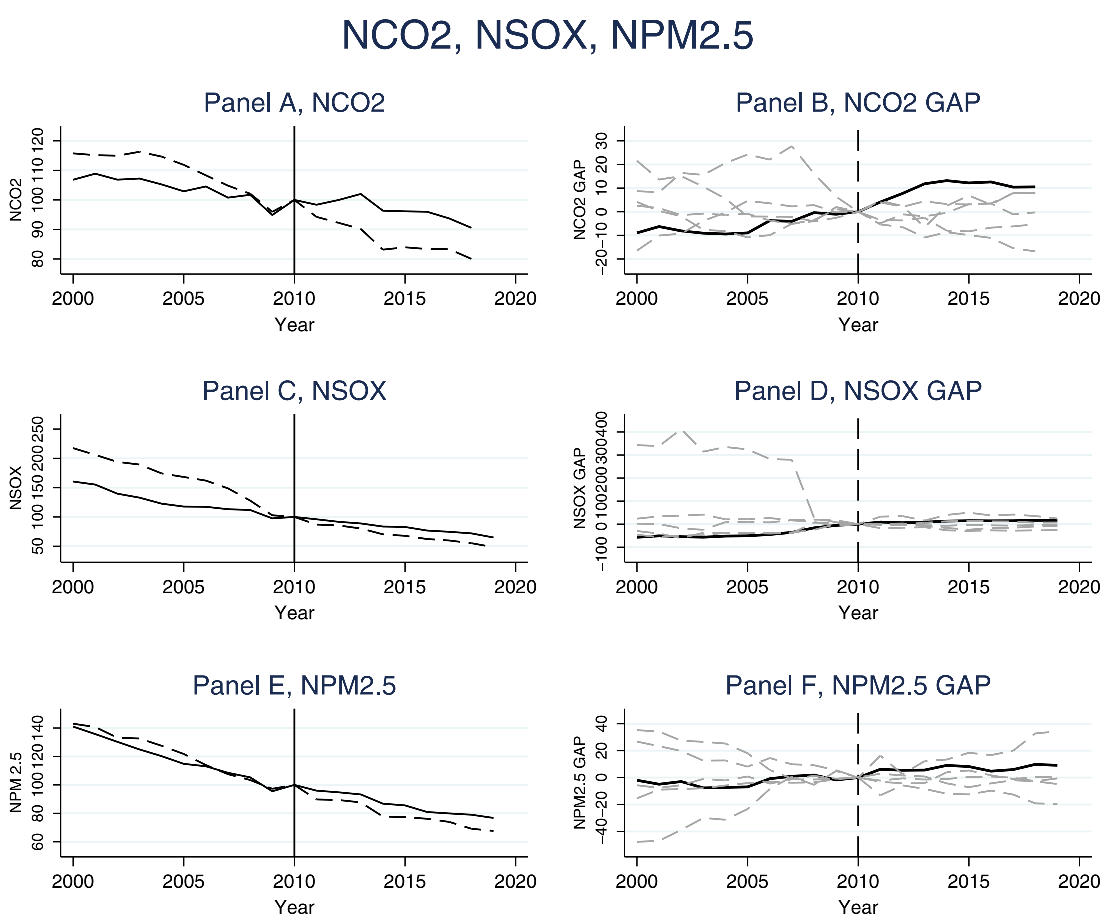

Figure 5. Time series plot of NCO2, NSOx, NPM2.5 and their gaps.

V. Mechanism and robustness check

It is questionable to attribute the post-2010 gaps seen in Figures 3–5 only to 2011 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 the best of our knowledge, we cannot think of another 2011 event in Germany that could have such a substantial and long-lasting impact on its environment.

Figure 6 demonstrates the mechanism through which the 2011 nuclear shutdown exerts its environmental influence by displaying in Panel A percentages of nuclear electricity production to total electricity production (normalized to 100 in 2010), and in Panel B percentages of fossil fuel electricity production to total electricity production. Both panels compare Germany to Sweden and France, the two countries that matter most in Model 5 and Model 3.

In panel A, there is a significant and enduring drop in German nuclear electricity percentage since 2010. For instance, the German nuclear electricity percentage fell from 22.35% in 2010 to 17.69% in 2011 (normalized index fell from 100 to 79). During the same period, there was no big drop in nuclear electricity percentages in Sweden and France.

On the other hand, we see in Panel B that the fossil fuel electricity percentage rose from 59.09% to 59.93% in Germany from 2010 to 2011. Later, during 2011–2014, there was a slight deduction in German fossil fuel electricity percentage, but the magnitude of reduction is less than Sweden and France. Notably, the post-2010 nuclear electricity percentage gap and fossil fuel electricity percentage gap between Germany and the other two countries in Figure 6 align with the post-2010 gaps seen in Figures 3–5. Behind this alignment is the well-known fact that combustion of fossil fuels in power plants is the main source of NOx, SOx, PM2.5 and CO2 emission. To sum up, Figure 6 illustrates that the air pollution gaps observed in Figures 3–5 are in large part rooted in the gaps in the production of nuclear and fossil fuel electricity.

Finally, we report two robustness checks of using alternative outcome variables. First, we try normalizing NOx pollution by dividing its level in 2000 (NNOxNEW), as opposed to 2010. As shown by Panel A of Figure 7, Germany (solid line) and its

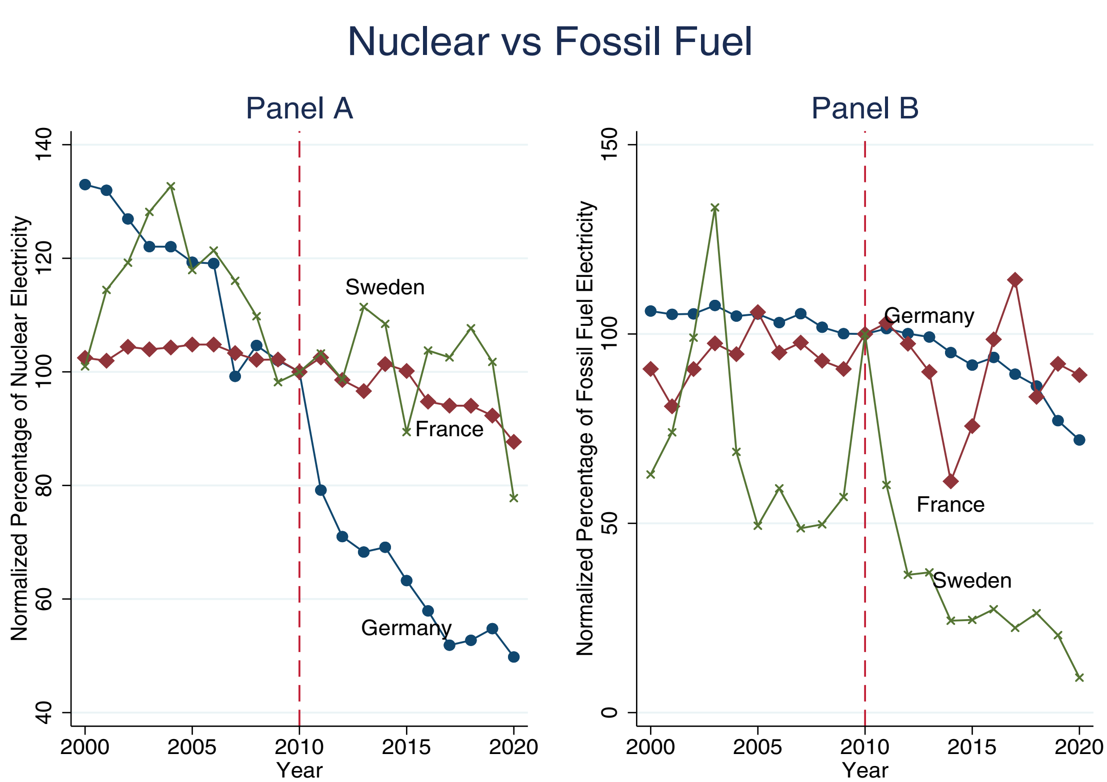

Figure 6. Mechanism for treatment effect.

synthetic one (dash line) now have the same starting point at the begging of sample. Despite using different normalizing methods, the post-2010 gaps in Panel A of Figures 7 and 3 are very much alike. This finding implies that the observed post-2010 gap in Figure 3 is not a technical artefact of using a particular year for the normalization.

Second, we try using the NOx emission per capita (NOxPC) as the outcome variable, and we do not normalize it to 100 in 2010. Once again, Panel B of Figures 7 and 3 look similar.

VI. Discussion

It is instructive to provide a broad picture of the impact of the 2011 nuclear shutdown.[7] The blue line with circles in Panel A of Figure 8 displays the times series of total energy production (Quad British Thermal Unit) in Germany. The green line with triangles shows nuclear energy production, the yellow line with squares shows renewable energy production, and the red line with diamonds shows fossil fuel energy production (including coal, natural gas, petroleum, and others).

It is evident that there was no remarkable change in total energy production from 2010 to 2011. However, we see a noticeable drop in the nuclear energy production during that period. This finding is in line with Panel A of Figure 6.

The loss of nuclear energy production was partially compensated by usage of fossil fuels. Panel B of Figure 8 plots the ratio of fossil fuel energy production to total energy production (per cent, blue line with squares), and the ratio of energy generated by coal to total energy production (red line with diamonds). Despite the downward trends, we see an increase in both ratios during 2010–2011 —the percentage of fossil fuel energy production rose from 49.87% to 51.65%, and the percentage of coal energy production rose from 38.12% to 39.71%. The combustion of fossil fuels releases a variety of pollutants into the atmosphere, leading to the divergence between Germany and synthetic Germany in terms of outcome variables.

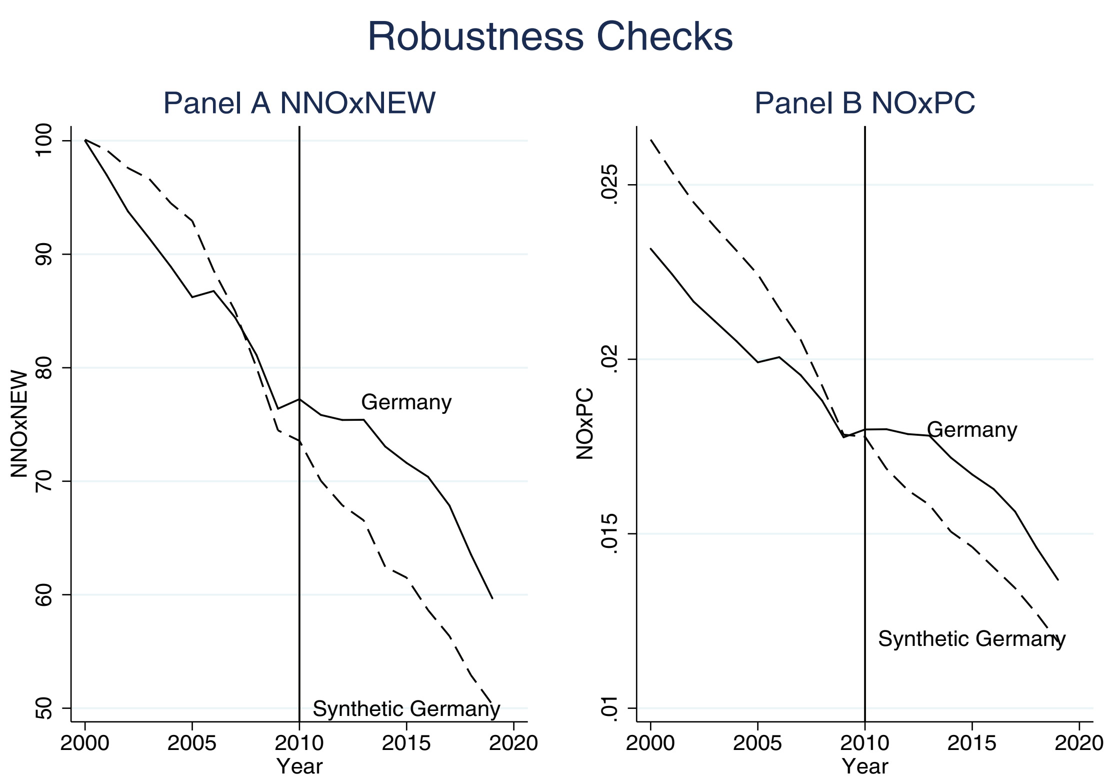

Figure 7. Robustness check.

[7]The data of energy production and electricity imports are from www.eia.gov; data of fuel intensity are from www.iea.org; data of CPI Energy are from FRED.

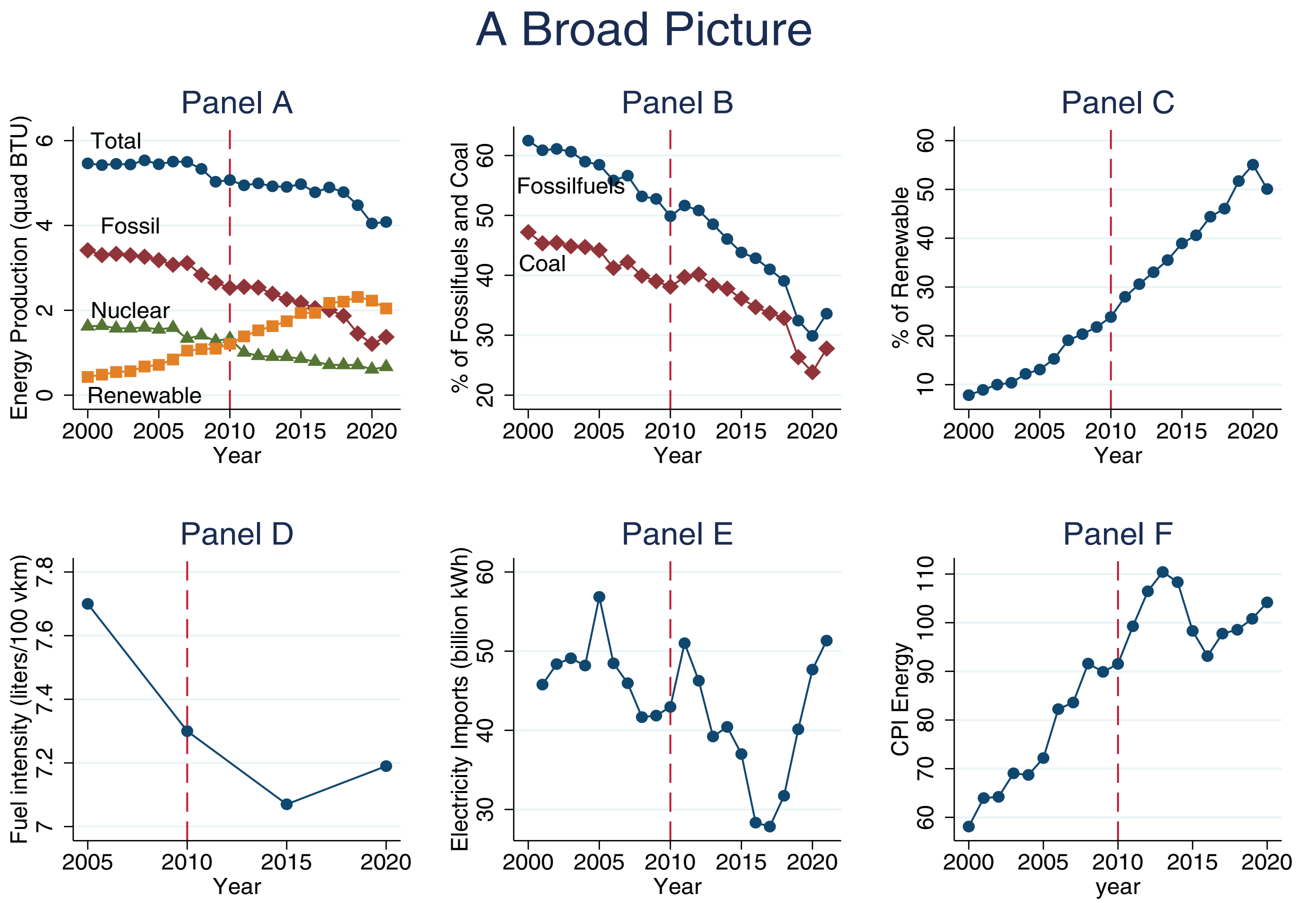

Figure 8. A broad picture.

Renewable energy sources also help mitigate the energy shortage created by the nuclear shutdown. Panel C of Figure 8 plots the ratio of energy generated by renewable sources to total energy production. The rising ratio is largely driven by 'Energiewende', the programme aiming to transition Germany to an environmentally friendly energy supply. In particular, there was an acceleration during 2010–2011—the percentage of renewable energy production rose from 23.86% to 28.00%, the biggest change since 2007.

Meanwhile, there was technical advancement that contributes to improving fuel efficiency. For instance, we see in Panel D of Figure 8 that between 2010 and 2015 there was a downward trend in fuel intensity (in terms of litres per 100 vehicle kilometres), which signifies better fuel economy of vehicles that can help reduce overall energy demand in Germany.

Importing electricity is another viable option for stabilizing energy system. Panel E of Figure 8 shows that Germany's electricity imports jumped from 43 billion kWh in 2010 to 51 in 2011. There are other steps. For instance, in May 2012 Germany revealed its plans to upgrade its electricity grid. This initiative aimed to facilitate the integration of renewable energy sources, compensating for the void created by the withdrawal from nuclear power.

It is worth noting that in addition to its environmental impact, the 2011 nuclear shutdown has ripple effects on economy such as the loss of jobs associated with the nuclear power plant and a decline in tax revenues of local governments. Panel F of Figure 8 focuses on energy affordability, and it shows that Germany's CPI Energy index rose from 91.53 in 2010 to 99.26 in 2011. By contrast, the index only rose by 1.64 from 2009 to 2010.

Due to data availability and space limit, this study cannot cover all issues related to the 2011 nuclear shutdown. For instance, readers who are interested in Germany's emission targets may refer to https://www.oecd.org/climate-action/ipac/practices/germany-s-annual-sectoral-emissions-targets

-2148cd0e/. We expect that the environmental impact may vary across regions within Germany due to factors such as local energy infrastructure. For instance, the locations of coal power plants in Germany can be obtained from https://www.carbonbrief.org/how-germany-generates-its-electricity/. Regions close to those coal power plants obviously absorb more of the environmental impact than other regions.

VII. Conclusion

The goal of this article 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 parallel trends between Germany and synthetic Germany. Those parallel trends enable us to obtain the counterfactual outcome of what would have happened to the German environment in the absence of the 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 manufacturing sector. Therefore, a direct comparison of air pollutants across countries is an apple-to-orange one. In order to increase the comparability, we normalize each country's air pollutant by the level in 2010. 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 the normalized nitrogen oxides emission fell from 100 to 92.72, while the normalized nitrogen oxides emission dropped from 100 to 85.75 in the synthetic Germany constructed with Model 5. With Model 3, the normalized nitrogen oxides emission in the synthetic Germany dropped from 100 to 84.57. Similar results are obtained for Carbon Dioxide, Sulphur Oxides, and Particulate Matter 2.5. These findings imply that, had the 2011 nuclear shutdown not happened, Germany's air pollution would have been reduced at a faster rate.

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

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Abadie, A., A. Diamond, and J. Hainmueller. 2015. "Comparative Politics and the Synthetic Control Method." *American Journal of Political Science* 59 (2): 495–510. https://doi.org/10.1111/ajps.12116.

Abadie, A., and J. Gardeazabal. 2003. "The Economic Costs of Conflict: A Case Study of the Basque Country." *American Economic Review* 93 (1): 112–132. https://doi.org/10.1257/000282803321455188.

Ando, M. 2015. "Dreams of Urbanization: Quantitative Case Studies on the Local Impacts of Nuclear Power Facilities Using the Synthetic Control Method." *Journal of Urban Economics* 85:68–85. https://doi.org/10.1016/j.jue.2014.10.005.

Bruninx, K., D. Madzharov, E. Delarue, and W. D'haeseleer. 2013. "Impact of the German Nuclear Phase-Out on Europe's Electricity Generation—A Comprehensive Study." *Energy Policy* 60:251–261. https://doi.org/10.1016/j.enpol.2013.05.026.

Davis, L., and C. Hausman. 2016. "Market Impacts of a Nuclear Power Plant Closure." *American Economic Journal: Applied Economics* 8 (2): 92–122. https://doi.org/10.1257/app.20140473.

Deschenes, O., M. Greenstone, and J. S. Shapiro. 2017. "Defensive Investments and the Demand for Air Quality: Evidence from the NOx Budget Program." *American Economic Review* 107 (10): 2958–2989. https://doi.org/10.1257/aer.20131002.

Goebel, J., C. Krekel, T. Tiefenbach, and N. R. Ziebarth. 2015. "How Natural Disasters Can Affect Environmental Concerns, Risk Aversion, and Even Politics: Evidence from Fukushima and Three European Countries." *Journal of Population Economics* 28 (4): 1137–1180. https://doi.org/10.1007/s00148-015-0558-8.

Grossi, L., S. Heim, K. Hüschelrath, and M. Waterson. 2018. "Electricity Market Integration and the Impact of Unilateral Policy Reforms." *Oxford Economic Papers* 70 (3): 799–820. https://doi.org/10.1093/oep/gpy005.

Grossi, L., S. Heim, and M. Waterson. 2017. "The Impact of the German Response to the Fukushima Earthquake." *Energy Economics* 66:450–465. https://doi.org/10.1016/j.eneco.2017.07.010.

Jacobs, D. 2012. "The German Energiewende–History, Targets, Policies and Challenges." *Renewable Energy Law and Policy Review* 3 (4): 223–233. https://www.jstor.org/stable/24324660.

Jarvis, S., O. Deschenes, and A. Jha. 2022. "The Private and External Costs of Germany's Nuclear Phase-Out." *Journal of the European Economic Association* 20 (3): 1311–1346. https://doi.org/10.1093/jeea/jvac007.

Kaul, A., S. Klößner, G. Pfeifer, and M. Schieler. 2022. "Standard Synthetic Control Methods: The Case of Using All Preintervention Outcomes Together with Covariates." *Journal of Business & Economic Statistics* 40 (3): 1362–1376. https://doi.org/10.1080/07350015.2021.1930012.

Knopf, B., M. Pahle, H. Kondziella, F. Joas, O. Edenhofer, and T. Bruckner. 2014. "Germany's Nuclear Phase-Out: Sensitivities and Impacts on Electricity Prices and CO2 Emissions." *Economics of Energy & Environmental Policy* 3 (1): 89–106. https://doi.org/10.5547/2160-5890.3.1.bkno.

Li, J., S. Sangal, and L. Shao. 2021. "Assessing Economic Impact of Sovereignty Transfer Over Hong Kong: A Synthetic Control Approach." *Applied Economics* 53 (30): 3499–3514. https://doi.org/10.1080/00036846.2021.1883529.

Neidell, M., S. Uchida, and M. Veronesi. 2021. "The Unintended Effects from Halting Nuclear Power Production: Evidence from Fukushima Daiichi Accident." *Journal of Health Economics* 79:102507. https://doi.org/10.1016/j.jhealeco.2021.102507.

Wheatley, S., B. Sovacool, and D. Sornette. 2017. "Of Disasters and Dragon Kings: A Statistical Analysis of Nuclear Power Incidents and Accidents." *Risk Analysis* 37 (1): 99–115. https://doi.org/10.1111/risa.12587.