Research Proposal:
Effects of Germany’s Nuclear Phase Out

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Abstract

In 2023, Germany solidified a monumental energy policy pivot (German Atomausstieg) by closing its final three plants of their nuclear phase out. The original Atomic Energy Act was amended in 2011- after the Fukushima accident- reinforcing German fears of the catastrophic risks associated with nuclear energy. This resulted in an immediate shutdown of 8 out of 17 reactors in the first year. This proposal assesses the potential for an accelerated reliance on coal, lignite, and gas by 2023 due to the phase-out and unintended consequences of events like Russian invasion of Ukraine. A shocking event that caused Germany to resolve its own energy goals and shortcomings. With an increase in fossil fuel generation, the consequences of increased combustion have potential to increase particles in the air, thus diminishing air quality. Although German Atomausstieg was not an impromptu policy action, impacts for high-caliber policy have a resounding impact. Since nuclear power generation is a zero-carbon energy source, its completed phase out raises concerns whether its generation loss will result in increased reliance on fossil fuels, generation substitutes like natural gas and coal, leading to higher concentrations of air pollutants. If proven, increased reliance on fossil fuels will lead to increased concentrations of PM, NO_2, and SO_2 linked to decreased air quality and increased respiratory morbidity. It is shown that escalation of these combustion emissions have adverse effects on respiratory health and is particularly prominent in vulnerable areas. The overall change in the systemic structural generation in Germany prompts the question to discover: What are the effects of Germany's 2023 nuclear phase-out on respiratory and cardiovascular hospitalization outcomes attributable to air pollution? In this proposal, we consider Germany's policy landscape and potential co-benefits of the Atomic Energy Act amendment if done efficiently in alignment with public health goals.

This study will be conducted using a differences-in-differences research method to compare the respiratory and cardiovascular hospitalization rates between Niedersachsen, a German federal state that hosted one of the three nuclear plants still open in 2022, and Schleswig-Holstein, a German federal state neighboring Niedersachsen, which is not reliant on nuclear power. The results will stem from the hospitalization rate differences before and after the shutdown of the nuclear power plant, Emsland.

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Historical context

Public Value Failures

Political opposition to nuclear power in Germany predates the 21st century. In 1975, the "anti-nuclear movement" showed cross-party support when 28,000 protestors occupied a nuclear construction site and effectively halted the project. After the Three Mile Island accident (1979), demonstrations against nuclear power reached over 200,000 people. Public fears continued to escalate as catastrophic nuclear events continued. The disastrous Chernobyl event (1986) gained political attention, steering politicians' support toward the impracticality of nuclear power for the future. This encouraged continued public opposition into the 1990s toward all nuclear projects, including the transportation of nuclear waste to holding sites and the development of permanent waste repositories

Political Response

Before legislative policy intervention was finalized, the Green Party entered alongside the Social Democrats in the government of Gerhard Schroeder. Together, they reached a "nuclear consensus"(Atomkonsens) with major utility companies. Under this consensus, they agreed to a long-term phase-out timeline that allocated each plant a specific amount of nuclear generation before it would be shut down. There were no specified dates for plant shutdowns, but the overall plan was to have a completed phase-out by 2022. The Atomic Energy Act Amendment of 2002 formalized the nuclear consensus into law. It banned the construction of new plants and set an official cap on the amount of electricity nuclear plants could generate, limiting their life span to 32 years. This was later revised in 2010 by the opposition chairwoman Angela Merkel of the Christian Democratic Union Party. The revocation of this amendment extended the operating timeline by eight years for seven nuclear plants and a ten-year extension for the other ten. Known as "Ausstieg aus dem Ausstieg" (phase-out of the phase-out).

The Catalyst

The Fukushima accident prompted immediate action from the Atomic Energy Act through the 13th Amendment which set fixed shutdown dates for all nuclear plants. Leading to an immediate shutdown of 8 of Germany's 17 reactors following an emergency safety review by the Reactor Safety Commission (RSK, 2011). Following this review, the federal government ordered an immediate shutdown of eight reactors and mandated an accelerated nuclear phase-out mechanism. This not only expedited the decline of nuclear generation but also ensured a dependence on other energy sources to maintain grid reliability.

Motivation for Research

Nuclear Replacement

When nuclear generation is shut down, the energy demand it was supporting must be replaced with a substitute. Fossil fuel is often selected for replacement to manage excess grid demand. In 2000, nuclear power made up 29.5 percent of the generation mix, and by 2020, in the midst of the phase out, that percentage dropped to 11.4 percent. (Clean Energy Wire, 2021) Now, at the phase-outs' completion, Germany does not cite nuclear power in their generation mix. Since nearly 30 percent of Germany's energy supply was supported by nuclear, they exposed the loss of a major low-carbon baseload generation source, marking a sizable gap to be filled.

In Kaariaho's *Unintended Effects of Germany's Nuclear phase out (2025)*, he finds that nuclear generation gaps like the one outlined in this shutdown lead to increased fossil fuel generation, and create a reliance on lignite and coal to compensate for the loss. Kaariaho uses a synthetic control Germany to model what emissions would have looked had had nuclear power not been phased out. His overall findings show that shutting down nuclear power increased mortality rates related to pollution.

This study realizes the trade-off between eliminating nuclear-associated risks and increasing risks associated with fossil fuels. Overall, the evidence provides a strong foundation to defend the long-term effects of the nuclear exit and increased fossil fuel reliance in Germany.

Fossil Fuel Operations/Combustions

Fossil fuel generation substitutes consist of coal, lignite, or gas. Lignite (or Brown Coal) is a cheap coal substitute mainly produced in Germany at a 35.3 percent power share with hard coal and used all over the world (Clean Energy Wire, 2023). Despite its cost efficiency, lignite is also high-carbon and health-damaging, making it a significantly more damaging environmental replacement for nuclear power. Coal plant emissions are closely correlated to the release of particulate matter (PM), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). In the final phase of Energiewende's completion, the energy market went through a period of uncertainty and volatility due to the Ukraine Gas Crisis. Before the Russian war with Ukraine, Germany received 55 percent of its gas from Russia and relied heavily on the imports for electricity. After the Russian invasion, this supply dropped by 80 percent, calling for an emergency winter extension of the nuclear phase-out policy. Although the extension was granted, Germany still suffered a surmountable loss in gas supply and was now increasing substitutions for this loss in conjunction with the nuclear phase-out. The increased energy system stressors, accompanied by loss of generation, further complicated the effects of the phase-out.

Pollutant Health Impact

Air pollution from fossil fuel combustion correlates with significant environmental risks affecting respiratory and cardiovascular health. When inhaled, these pollutants penetrate the lungs and can trigger oxidative stress, which leads to inflammation and impaired immune function. This process can facilitate an environment that worsens or promotes chronic respiratory diseases such as asthma, chronic obstructive pulmonary disease, pulmonary fibrosis, pneumonia, acute respiratory distress syndrome, or lung cancer.

Epidemiological evidence supports the relationship between air pollution and health outcomes, showing strong relationships between NO_2 and PM2.5 with respiratory and cardiovascular mortality (Hamanaka & Mutlu, 2022). In a time series analysis of Hong Kong, Wong et al. (1999) found that daily concentration rates of SO_2, NO_2, PM10, and O_3 (Ozone) were associated with hospitalizations for respiratory and cardiovascular diseases. They found that elderly populations were regularly most impacted by the change in pollutants, proving relative risks across all four pollutants than any other age group.

Causal Chain

During systemic shifts like Energiewende, change exposure levels to air pollutants and emphasize that health implications are typically an afterthought in grander policy implementations. DPSEEA (Driving forces- Pressure- State - Exposure - Effect - Action) is an environmental causal chain framework that can be used to propose the connection between energy policy, fossil fuel combustion, pollutant emissions, and health effects. (Sutcliffe et al., 2016) This framework can justify the placement of the nuclear phase-out as the driving force that increases pressure to substitute fossil fuel generation for nuclear power. This increased exposure to combustion emissions thereby changes the air quality and, inherently, the respiratory and cardiovascular hospitalizations in affected regions.

Findings suggest a strong relationship between respiratory and cardiovascular morbidity responses to air quality fluctuation. It is a predictable response to increases in fossil fuel generation, which elevate SO_2, $NO_{2,}$ and PM.

Policy Background

Nuclear Phase Out

Germany's nuclear phase-out is structured through subsequent amendments to the Atomic Energy Act. Each amendment had the goal of refining and reducing the lifetime of nuclear power in Germany. The initial phase-out decision in 2002 was accelerated after Fukushima (2011), with the goal to end nuclear power as soon as possible. The federal government ordered a safety review by the Reactor Safety Commission and passed the 13th Amendment to the Atomic Energy Act, ordering the immediate shutdown of eight of the existing seventeen reactors (Reactor Safety Commission, 2011). This effectively canceled previous nuclear extension efforts in 2010 by Angela Merkel. Nuclear Plants were shut down on a pre-determined schedule, while most plants were shut down depending on age; some were phased out based on pre-set electricity quotas.

Russia's invasion of Ukraine incited political negotiations to extend reactor lifetime to provide grid security into the winter. The (19th Act, 2022) allowed the final three reactors to remain in operation until April 15, 2023.

Coal Phase Out

The Coal Exit Law (Kohleausstiegsgesetz) was adopted in July 2020 and mandates a phase-out of coal and lignite by 2038. While the purpose of this phase-out is to reduce carbon emissions, the coal phase-out creates a prolonged transition period where coal and lignite will remain in the energy system for almost 20 years post-nuclear phase-out. This creates an opportunity for coal to scale in the lifetime of its slow exit; meanwhile, nuclear power was phased out at a more rapid pace through 2038. *(Clean Energy Wire, 2019) (Clean Energy Wire 2020)*

Analysts state this proposed phase-out timeline will not start to reduce CO2 emissions until after 2030 and conflicts with the EU deadline for coal phase-out. They also warn that this long-term phase-out may place an increased reliance on coal in times of supply shocks.(Kaariaho, 2025) This points to the dynamic that this proposal currently attempts to observe in the case of nuclear shutdowns.

Air Quality Policy

The Industrial Emissions Directive (IED) outlines emission limits for large combustion plants requiring the use of "best available techniques" (BAT) to limit SO_2, NO_2, and PM. *(EC-JRC, 2017).* These standards should mitigate pollutant emission increases from coal and lignite combustion if enforced correctly.

Germany, once a leader in low emissions, was found responsible for 19 premature deaths in 2013 according to the European Environmental Bureau (EEB, 2021). German implementation of IED raises concerns over compliance and public health as reports show their coal and lignite plants continue to emit pollutants at the upper bounds of IED. This raises concerns that fossil fuel substitutions still have degradation effects even while operating under EU regulatory constraints.

Hypotheses

This report formulates three hypotheses about the effect of the 2023 nuclear phase-out on respiratory and cardiovascular hospitalizations. Each hypothesis relies on existing literature pertaining to Germany's energy transition (Energiewende), fossil fuels as a substitute, and the health impacts of air pollution.

Null Hypothesis (H_0)

H0: The 2023 nuclear phase-out has no effect on respiratory and cardiovascular hospitalizations in Niedersachsen.

There is potential for a neutral health effect of the 2023 shutdown if renewables are deployed and air quality regulations can offset the increased fossil fuel generation. Energiewende is structured to replace nuclear and fossil fuels with renewables and energy-efficient practices. Sutcliffe et al. (2016) highlight the framing of this transition and its potential to improve population health if properly implemented.

Throughout the EU, the European Environmental Agency documents overall declines in pollutants (NO_2, SO_2, and PM)(EEA, 2023) and thus reductions in air pollution health burdens. So while air pollution causes most preventable cases of respiratory and cardiovascular diseases, if emission standards in Germany inhibit deterioration of air quality, then the impact of the nuclear phase-out on hospitalizations could be cut short or indistinguishable from before phase-out finalization.

Main Hypothesis (H_1)

H1: The 2023 nuclear phase-out increases respiratory and cardiovascular hospitalizations in Niedersachsen

The main hypothesis focuses on fossil fuel substitution as the fallback solution to the nuclear phase-out. Kaariaho (2025) notes that earlier plant closures in Germany resulted in increased fossil fuel generation. This correlated with a higher mortality rate on a national scale, relating this outcome to air pollution from the capacity the fossil fuels had to replace. Loiacono et al (2025) conclude that nuclear phase-out policies are highly associated with increased CO_2 emissions when low-carbon electricity is replaced with fossil fuel electricity. Together, these studies closely assert that nuclear exit practices are met with coal, lignite, or gas replacements rather than immediately substituted with other zero-carbon sources.

This hypothesis proposes that the 2023 shutdown of the remaining German nuclear reactors will prompt increased usage of coal, lignite, or gas in Germany's energy generation mix; this will inherently raise concentrations of NO_2, SO_2, and PM. Epidemiological literature links these pollutants with respiratory and cardiovascular morbidity. Wong et al. (1999) conducted a short-term time series trend study with findings that daily concentrations of these pollutants are associated with daily counts of emergency hospitalizations. Brunekreef et al. perform a study of eight cohorts from six European countries that shows the relationship between low-level air pollution and the increase in both natural and cause respiratory and cardiovascular mortality even at the lower bound levels of European air quality standards. Hamanaka & Mutlu (2022) review biomedical literature evidence that places PM exposure as a leading cause of respiratory morbidity and mortality in many lung diseases. They conclude there is no safe level of air pollution exposure and call for air pollution production to be met with mitigation methods.

Combined, these studies support the causal chain where increased fossil fuel generation after nuclear exit, elevates air pollutant levels and increases respiratory and cardiovascular hospitalizations. We expect a positive treatment effect under this methodology to correlate the 2023 nuclear phase-out to hospital admissions in Niedersachsen.

Counter Hypothesis (H_1a)

H1a: The 2023 nuclear phase-out decreases respiratory and cardiovascular hospitalizations in Niedersachsen

A counter possibility we consider is that the Energiewende's renewable expansion and efficiency precautions will produce health co-benefits that negate fossil fuel substitution effects. Sutcliffe et al. (2016) argue that if Energiewende aligns with public health goals, it could produce unintended health effects by reducing air pollution, but considering health impact in their energy plans. EEA's air quality status (2023) shows the relationship between prolonged reductions in regulated pollutants and declines in premature deaths due to cardiovascular and respiratory causes in regions with stringent air quality and climate standards(EEA, 2023).

Germany shows no current documentation for an accelerated deployment of renewables or plans to tighten emission standards for fossil fuels. If amendments to Energiewende are made and if pollution standards become more stringent, there is potential for the net effect of the 2023 nuclear phase-out to be a decrease in cardiovascular and respiratory hospitalizations.

Methodology

Differences-in-Differences

This study will be a quasi-experiment using the differences-in-differences (DiD) research design to look into the effects of Germany's 2023 nuclear phase-out on cardiovascular, alternatively called circulatory, and respiratory hospitalizations due to air pollution exposure. The DiD approach is best suited for this research, as there is a very clear treatment event taking place, the shutdown of Emsland, Germany's last nuclear power plant in the north. This policy-driven action impacted the energy mix in the designated region, Niedersachsen, whereas the federal state without a nuclear power plant, Schleswig-Holstein, remained unaffected.

This isolated treatment, the nuclear power plant shutdown, provides a clear treatment and control group necessary to test for parallel trends. Niedersachsen, where Emsland was located, would be the treatment. Schleswig-Holstein, a neighboring federal state without nuclear power in its energy mix, would be the control.

Measurements for this design will focus on the annual levels of air pollutant concentrations (PM10, NO_2, SO_2) in each state, as well as the number of circulatory and respiratory-related hospitalizations. The spatial coverage at the federal state level of Germany will align with publicly available datasets.

The results of this research will stem from comparing the differences in average respiratory and circulatory hospitalization rates between Niedersachsen and Schleswig-Holstein after the 2023 nuclear shutdown to the differences before. From our hypothesis, we expect there to be a greater difference after the shutdown.

Population of Interest

The population of interest consists of residents of Niedersachsen (treatment) and Schleswig-Holstein (control) between the years of 2019 and 2024, or until the end of data collection. This period will capture both pre- and post-data associated with the closure of Emsland, the nuclear power plant located in the treatment region. Appendix A shows a visualization of the treatment and control areas, as well as the location of Emsland.

To improve measurement validity and limitations of a cross-sectional analysis, the population of interest will be observed in age-based cohorts over time. This will allow for results across different vulnerable populations to be examined. Cohorts include children (0-14), working-aged adults (15-64), and older adults (65+). Cohort data recognizes for the fact that health effects differ by age group, and cardiovascular and respiratory hospitalization risks from air pollution will vary. Tracking the cohorts over time will account for demographic shifts and external shocks to the data, such as the increase in COVID-19 hospitalizations among the elderly.

Treated population: Age cohorts living in Niedersachsen between the years 2019 and 2024.

Control population: Age cohorts living in Schleswig-Holstein between the years 2019 and 2024.

Counterfactual

In order to completely isolate the effects of the nuclear power plant closure in northern Germany, the only difference between the treatment and control group should be that the former experiences the nuclear power plant shutdown and the latter does not. Appendix B offers the same visualization of the treatment and counterfactual areas, with the addition of other fossil fuel-producing power plants overlaid. This tells that there is at least one fossil fuel-burning power plant in each group.

The next step to ensure a strong counterfactual is to look at the level of nuclear power reliance between the two to ensure that the control group does not have any nuclear power in its energy mix. Out of the last three remaining federal states in Germany to use nuclear power, Niedersachsen was the most reliant in 2022, just before closures, and the control group did not rely on nuclear energy at all (see Appendix C).

Another covariate important to this study would be the smoking rates of both federal states. At least one fourth of Germany's adult population smokes, and smoking habits lead to increased hospitalizations, so it is necessary to ensure that the smoking prevalence is similar in both the treatment and the control (Zeiher et al., 2017). Other covariates include disposable household income and urbanization rates. Most importantly, the variable of interest, hospitalization rates, should be similar pre-intervention to adhere to the parallel trend assumption of a DiD design. Below, in Figure 1, the covariates of 2022 are shown for both the treatment and the control variables.

Variable	Treated	Control	P-value
PM10	13.6	14.4	0.178
Respiratory per 100k	590.0	543.0	0.274
Circulatory per 100k	1,481	1,398	0.0920
Total Population	16,008,933	5,848,109	7.26e-09
Pop 65+	0.113	0.117	0.0025
Pop (15-64)	0.811	0.815	0.056
Disposable Household Income	23,160	22,540	NA*
Smoking Rate	23%	24%	NA*
Urbanization Rate	0.51	0.48	NA*

Figure 1- Covariate Table for Treatment and Control in 2022

**represents data given at the state level*

From the figure, it is seen that Niedersachsen and Schleswig-Holstein are a suitable treatment-counterfactual pair when looking at pollution levels, respiratory hospitalizations, and circulatory hospitalizations. The parallel trends of each of these can be seen in Appendix D-F. The population on average is slightly older in the control group than in the treatment group; getting separate DiD estimates for each age cohort will counteract this imbalance.

Lastly, the reason why two northern federal states were chosen was because of Germany's geographic location of its coal density. Germany has the majority of their coal in the north (Renn & Marshall, 2016). This ties into the idea that both federal states have access to coal if they choose to burn it for energy.

Data Sources

The data necessary for this research comes from several publicly accessible sources, including both EU datasets and German datasets. All data sets will be pulled from Destatis, Germany's Federal Statistical Office's database (Statistisches Bundesamt).

Health outcome data are needed to get annual measures of respiratory and cardiovascular hospitalizations. This will come from the German Federal Health Monitoring System (Gesundheitsberichterstattung des Bundes). Specifically, the study will use the annual federal state-level hospitalization counts for both respiratory diseases (Table ICD-10 J00-J99) and circulatory diseases (Table ICD-10 I00-I99). The rates should be adjusted using the corresponding populations of that year.

Air pollution data will showcase the PM10, PM2.5, NO_2, and SO_2 annual mean concentrations across all measuring stations in Germany. These measurements are pooled together by Germany's Federal Environmental Agency (Umweltbundesamt, UBA) and will show to which federal state each measuring station belongs.

Demographic and socioeconomic data, necessary for measuring population, age structure ("Bevölkerung nach Altersgruppen"), dependency ratios, disposable income ("Verfügbares Einkommen der privaten Haushalte je Einwohner"), smoking rates ("Rauchen in Deutschland - Anteil der Rauchenden"), and urbanization levels ("Bevölkerung nach Siedlungsstruktur"), will come from Destatis. These variables are used to run a baseline comparability test to assess the strength of Schleswig-Holstein being the counterfactual to Niedersachsen.

Limitations

This study faces several limitations and threats to internal validity. Each of these limitations must be considered when interpreting the results of the paper. For each limitation, there will be a proposed counterargument that can be made during the execution of the research; this is done as a mitigation strategy to strengthen causal inference.

The first concern in this study is a potential violation of the stable unit treatment value assumption (SUTVA). A key assumption of a DiD research method is that the treatment will only affect one group and not the control group with regard to outcome measures. However, air pollution is not stationary; where it is produced is not always where it stays. There is a chance that if there were to be an increase in fossil fuel consumption in Niedersachsen, the resulting increased pollution may move into Schleswig-Holstein, its neighboring federal state. This would then void the measured treatment effect as the control group was contaminated. To address this threat, instead of looking at all air pollutants and particles, the study should focus on PM10, as it has smaller dispersion rates than other smaller particles (Prasetia et al., 2021).

Another limitation stems from the idea that for the concept of this study, there is a long causal chain established between nuclear power plant shutdowns and an increase in related hospitalizations. From a decrease in nuclear power, it is expected that Niedersachsen will increase its fossil fuel burning to make up for the lost energy, which will lead to increased levels of particle matter in the air, which will then lead to an increase in respiratory and cardiovascular hospitalizations. However, there may be reasons for changes in hospitalization rates unrelated to air quality that cannot be quantitatively measured, such as behavioral changes, health-care access issues, or changes in underlying disease trends. To mitigate this concern, the design uses the DiD methods with yearly federal-state level fixed effects, age-ranged cohorts, and observable covariates. It is relatively challenging to eliminate the effects of all unobservable covariates, but by measuring all that can be observed, there is a smaller set of alternative explanations for the results.

Naturally, when measuring pollution data, there is a sensitivity to how the data is collected. As each station might have different precision levels of accuracy, levels of pollutants may appear higher in some areas than others, even if they are truly the same. This is addressed by relying on the formal procedures and methods of the UBA and trusting their standardized estimates of pollutant exposure. Robustness checks can be performed using multiple pollutants (PM10, PM2.5, NO_2, and SO_2) to ensure similar patterns.

Germany's nuclear phase-out was a planned policy action, opening doors for possible anticipatory effects. Anticipatory effects occur when the treatment and/or control group changes their behavior before the intervention is implemented. In this case, energy utilities in Niedersachsen could have acknowledged that they soon couldn't rely on nuclear power and increase energy production from fossil fuels before the 2023 shutdown of Emsland. We can mitigate this effect by making sure that there is no unusual shift in PM trends before the 2023 intervention. This can be done by closely analyzing the time immediately before closure in smaller time increments.

External events have the potential to threaten internal validity. German national policies, such as the Industrial Emission Directive (IED), have the ability to change the emission levels and air pollutants independent of the nuclear shutdown (Drotloff, 2014). This should not bias the validity of this study, as national policies and initiatives impact all federal states. Therefore, both the treatment and the control should experience the same effects of these policy changes. The challenge lies in the timeline of implementation or the seriousness of enforcement in each federal state, which may lead to uneven effects, complicating the interpretation of the study's results.

Expected Outcomes/Impacts

As the Emsland nuclear power plant phase-out changed the energy mix of Niedersachsen, there is an expected increase in fossil fuel consumption, leading to an increase in the concentration of particulate matter in the atmosphere in that region. This increase in air pollutants may be associated with increased hospitalizations for respiratory and cardiovascular concerns. This increase will be measured against the counterfactual federal state, Schleswig-Holstein, which will not experience the same increase in hospitalizations. This effect will vary across the age-group cohorts, as different ages come with different vulnerabilities. If a pattern arises where there was an increase in air pollution and related hospitalizations in Niedersachsen, and a pattern of stable air pollution and related hospitalizations in Schleswig-Holstein, then this would suggest that the nuclear power plant shutdown did have health effects on its population.

Contributions

The results of this study can be used as a reference for when nations or smaller acting states prepare for a change in their energy mix. The research contributes to the policy landscape by looking into how energy transitions impact the health of residents in areas that burn fossil fuels, and how these effects are dispersed across age groups. It is important for countries to understand how using fossil fuel consumption as a substitute for the loss of another energy source may lead to unexpected health burdens.

The state-level analysis of this study showcases inequality in exposure to energy transitions. Targeted interventions should consider federal compensation or mitigation programs for the local region of impact. Overall, this study looks into the causal chain of tradeoffs in the energy sector.

Future Research

Future studies should consider implementing the ideas and methods of this study, but on a smaller scale. Instead of looking at federal states, look at an area directly next to a fossil fuel-burning plant to see localized health impacts. Collecting more detailed air pollution data and hospital-level information, such as whether the hospital visit is pollution-related or not, would help strengthen the hypothesized causal relationship. Finally, it would be beneficial to the generalizability of the study to look into nuclear power plant closure events outside of Germany.

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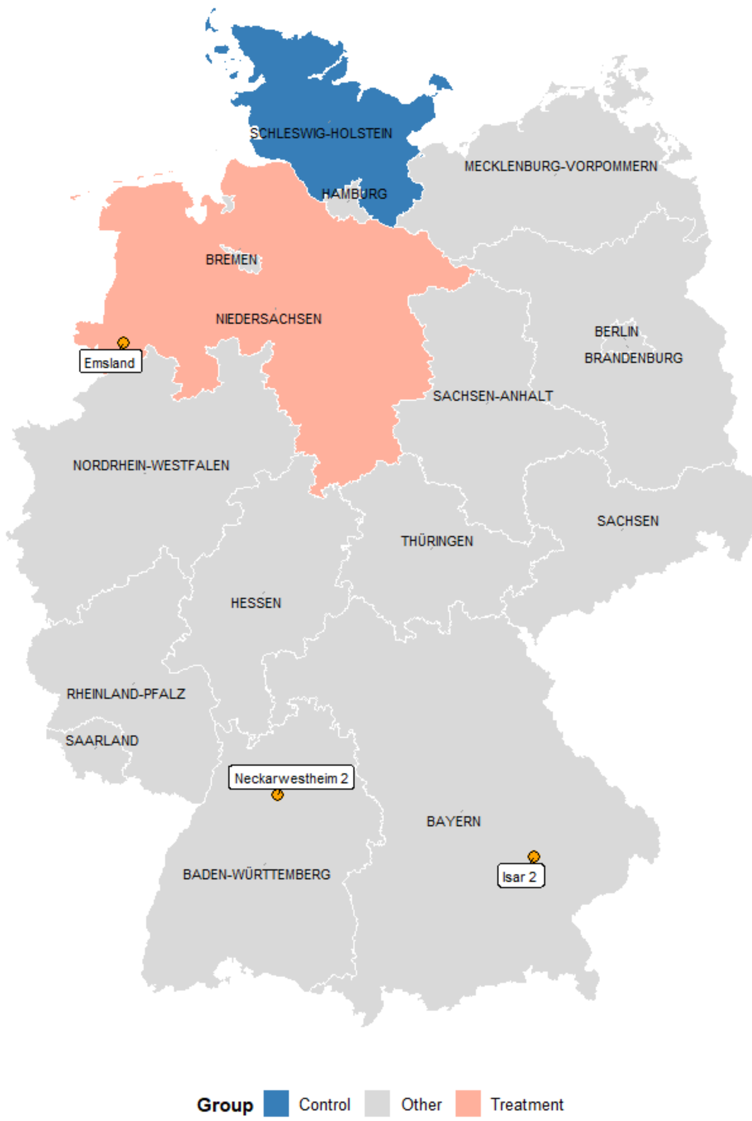
Appendices

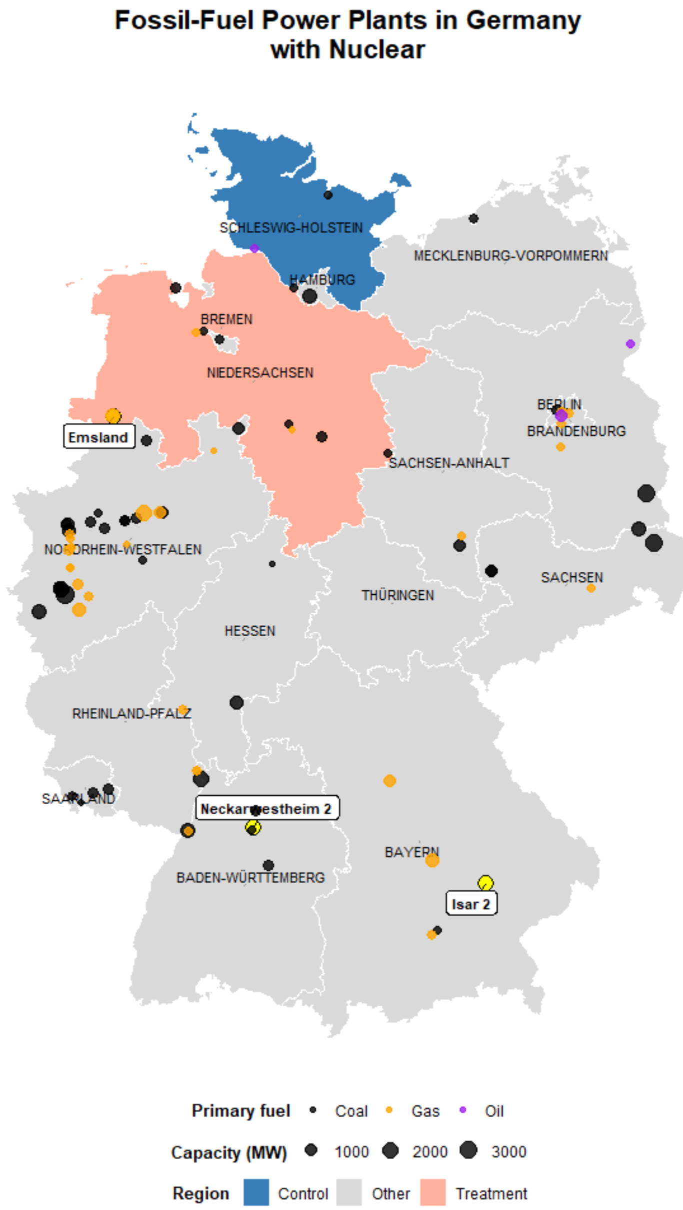
Appendix A

Germany Nuclear Power Plants



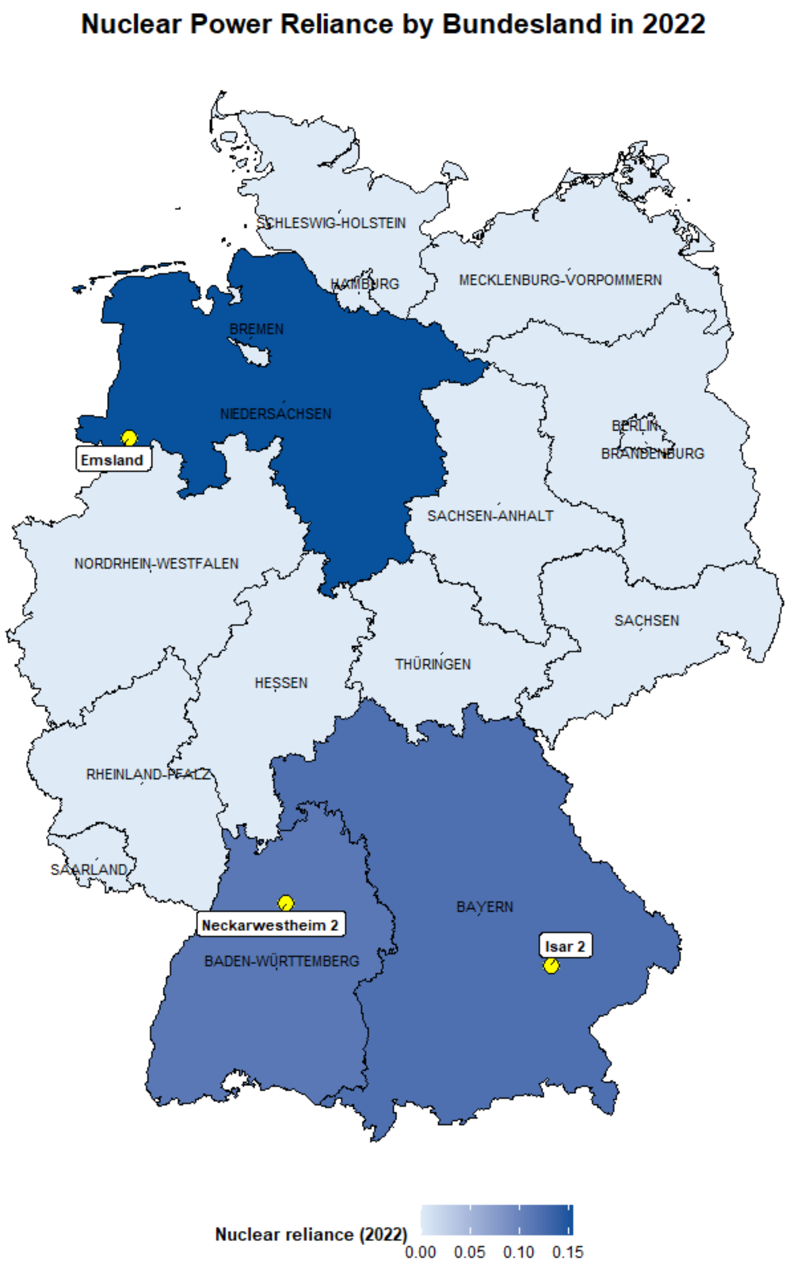
Shows the treatment and control groups as Bundesländer in Germany, as well as the last remaining nuclear power plants at the beginning of 2023.

Appendix B



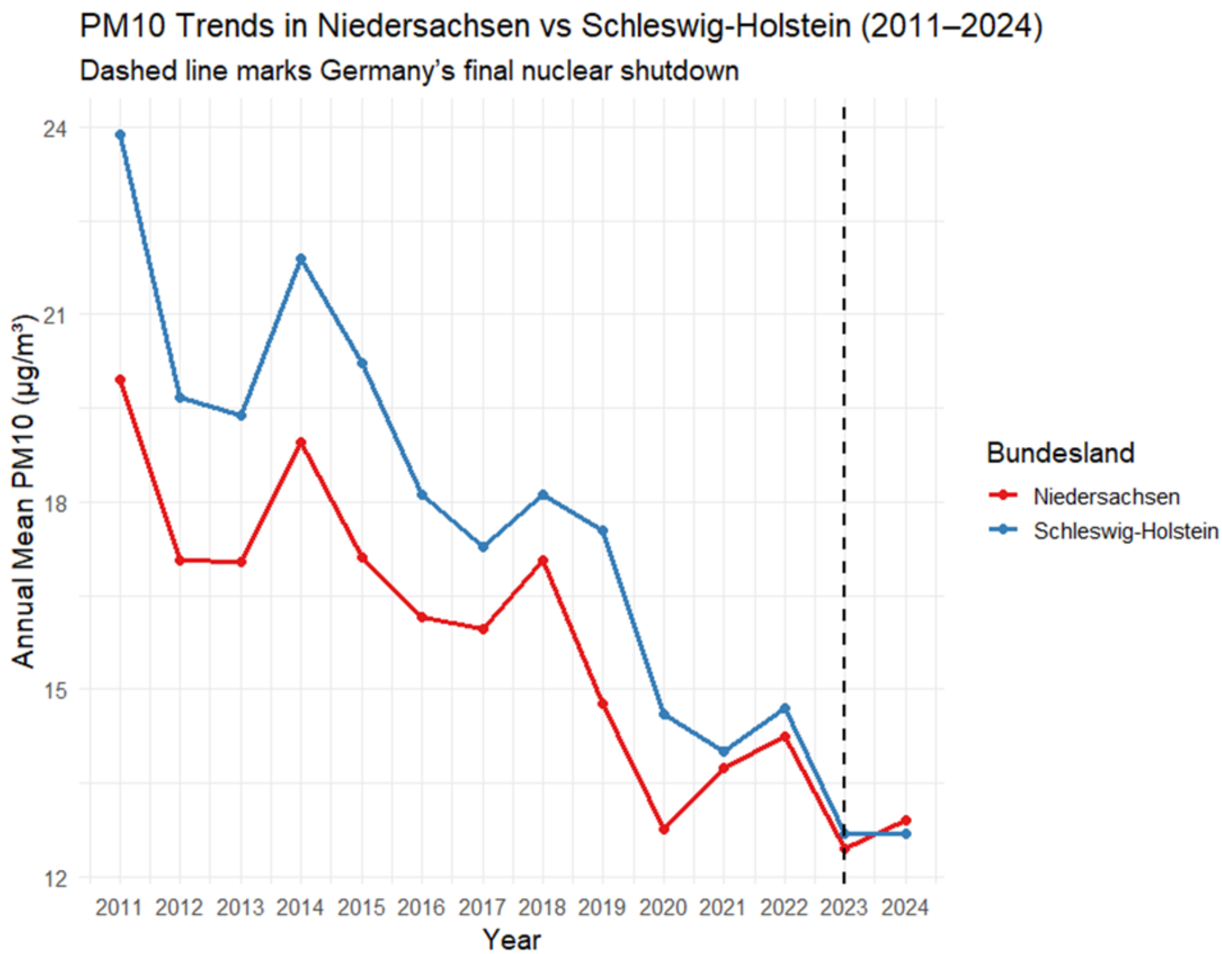
Shows the treatment and control groups as Bundesländer in Germany, with he location of nuclear power plants and fossil fuel-burning power plants at the beginning of 2023.

Appendix C



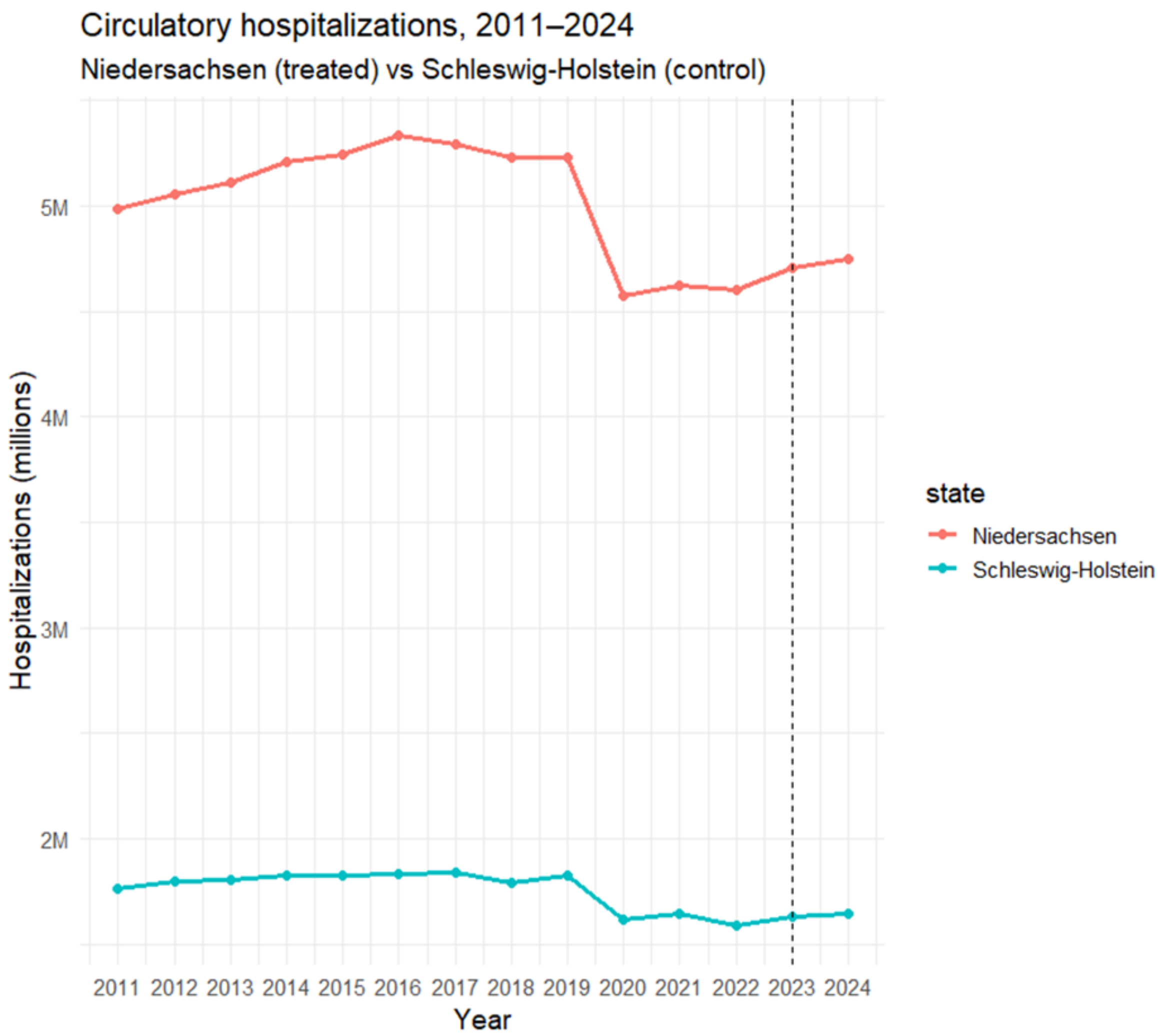
Shows the nuclear power reliance of each Bundesland in Germany in 2022, the year before the final phase of nuclear power shutdown.

Appendix D



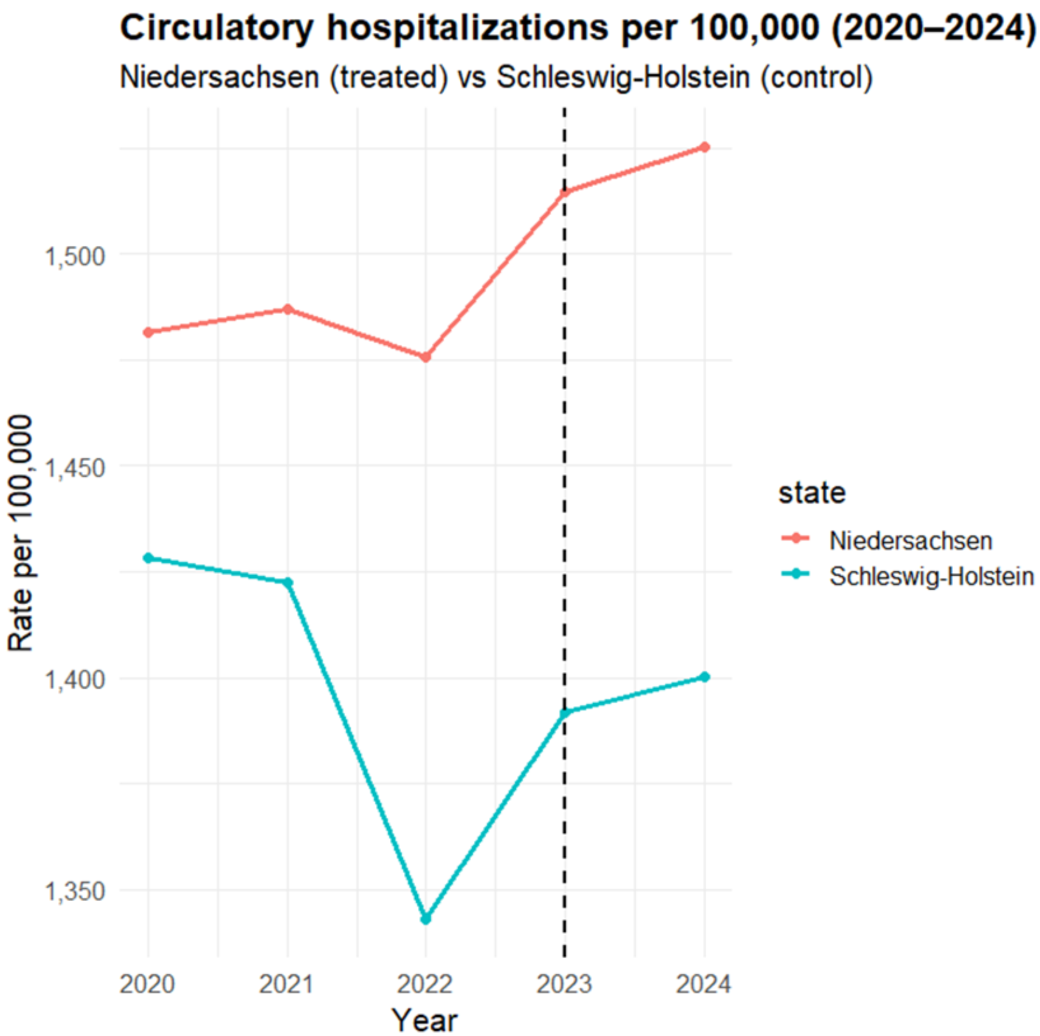
Particle matter trends over timein the treatment and control.

Appendix E.1



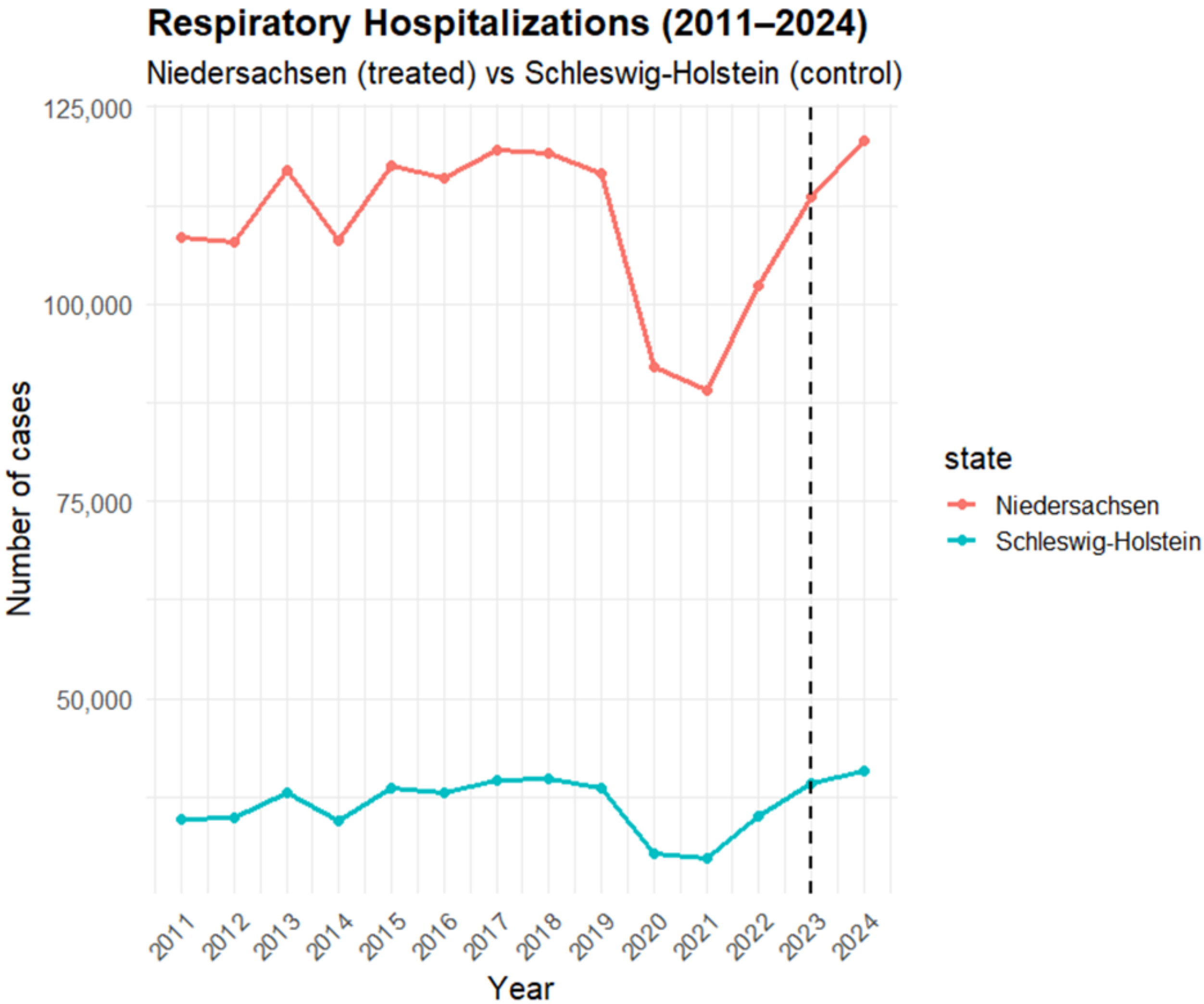
Circulatory hospitalizations in both the treatment and control groups over time.

Appendix E.2



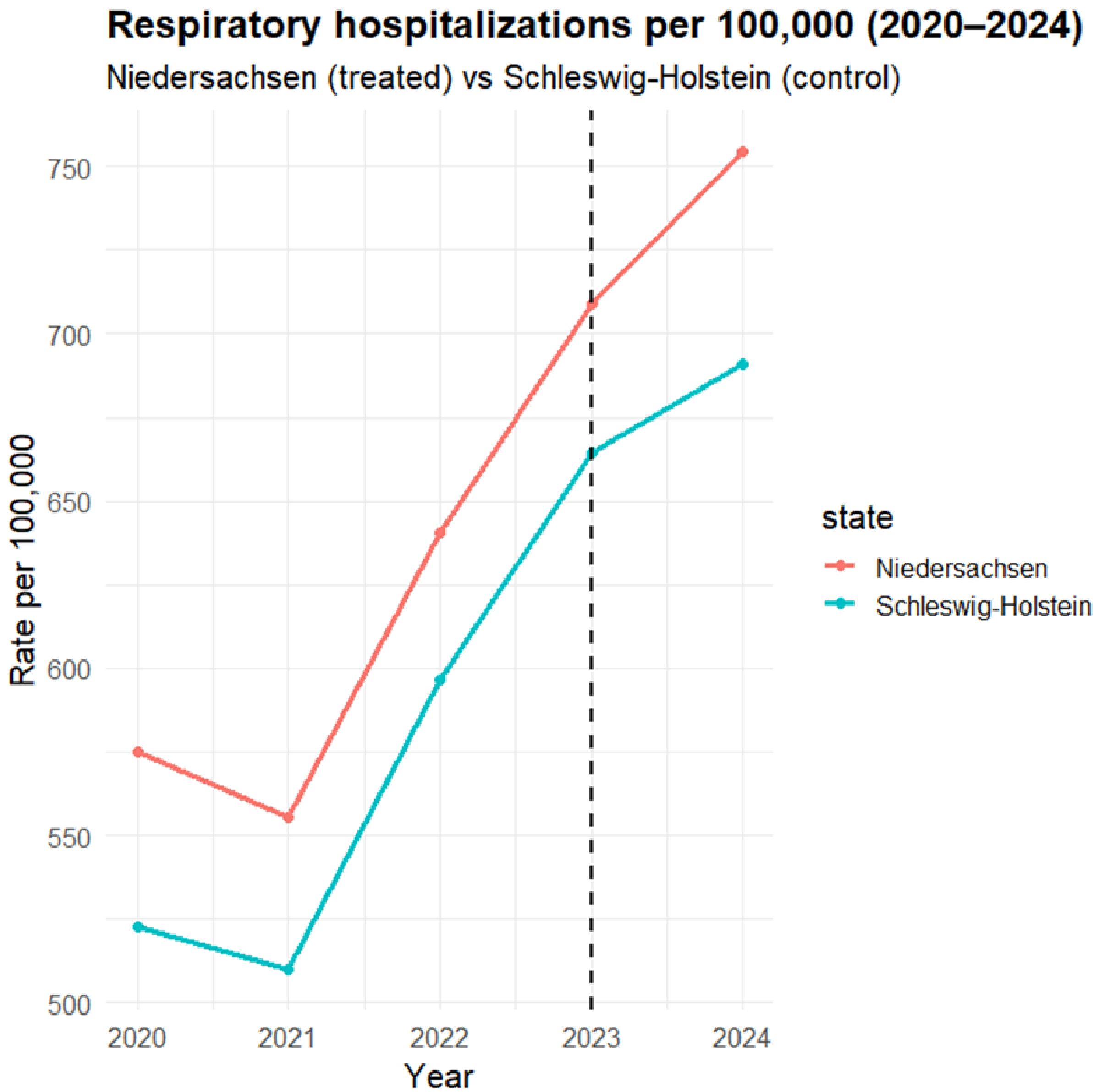
Circulatory hospitalizations in both the treatment and control groups over time, adjusted for population.

Appendix F.1



Respiratory hospitalizations in both the treatment and control groups over time.

Appendix F.2



Respiratory hospitalizations in both the treatment and control groups over time, adjusted for population.