Nuclear Shutdown, Coal Power Generation, and Infant Health: Evidence from the Tennessee Valley Authority (TVA) in the 1980s*

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Abstract

When environmental regulations focus on a subset of power plants, the ultimate goal of human health protection may not be reached. Because power plants are interconnected through the electrical grid, excessive scrutiny of a group of facilities may generate more pollution out of another group, with potential deleterious effects to public health. I study the impact of the shutdown of nuclear power plants in the Tennessee Valley Authority (TVA) in the 1980s, on health outcomes at birth. After the Three Mile Island accident in 1979, the Nuclear Regulatory Commission (NRC) intensified inspections in nuclear facilities leading to the shutdown of many of them, including Browns Ferry and Sequoyah in the TVA area. I first show that, in response to the shutdown, electricity generation shifts one-for-one to coal-fired power plants within TVA, increasing air pollution in counties where they are located. Second, I find that babies born after the shutdown have both lower birth weight and lower gestational age in the counties most affected by the shutdown. Third, I highlight the presence of substantial heterogeneity in those effects depending on how much more electricity those coal-powered facilities are

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generating in response to the shutdown. Lastly, I use the heterogeneity in response to the shutdown to provide suggestive evidence on the "safe" threshold of exposure to total suspended particles (TSP), which may help the Environmental Protection Agency (EPA) to set the National Ambient Air Quality Standards (NAAQS) for particulate matters (PM). It may also help regulators to incentivize power companies to respond optimally to unexpected energy shortages.

Keywords: Nuclear Shutdown, Power Grid, Coal Power, Air Pollution, Birth Weight, Gestational Age

1 Introduction

Nuclear accidents usually generate a tremendous drop in support for nuclear energy. The Fukushima nuclear disaster in March 2011, for example, gave rise to a public backlash against the nuclear power industry around the world. As a result of such a pressure, some countries/states reacted promptly by enacting new regulations or by shutting down nuclear facilities. Germany, for instance, started a nuclear phase-out right away[1], permanently shutting down eight of its seventeen reactors by August 2011, and pledging to close the rest by the end of 2022. California followed suit by retiring the San Onofre Nuclear Generating Station (SONGS) in June 2013. Although media outlets focus attention on damages to public health potentially caused by exposure to high levels of radioactivity, news coverage misses important aspects of the debate. Exceptionally, a recent New York Times editorial clearly points out some of those missing elements: *"Only Germany succumbed to panic after the Fukushima disaster and began to phase out all nuclear power in favor of huge investments in renewable sources like wind and sun. One consequence has been at least a temporary increase in greenhouse emissions as Germany has been forced to fire up old coal- and gas-powered plants. The dangers of nuclear power are real, but the accidents that have occurred, even Chernobyl, do not compare to the damage to the earth being inflicted by the burning of fossil fuels - coal, gas and oil."* (May 1, 2014).

[1]According to Goebel et al. (2013), support to nuclear energy dropped 20 percent in Germany after the Fukushima disaster.

In this paper, I document the shift in electricity generation from nuclear to coal-fired power plants after the shutdown of the nuclear facilities of the Tennessee Valley Authority (TVA) in the 1980s, following the Three Mile Island accident in 1979, and provide evidence of the resulting increase in air pollution and reduction in birth weight and gestational age in the most affected counties. I show that these empirical findings are consistent with a simple model where consumers value electricity, air quality and health, but power generation damages air quality and health through emissions of pollutants and radioactivity. Also, I use the heterogeneity in response to the nuclear shutdown by coal-powered plants within the TVA power grid to shed light on the "safe" threshold of exposure to total suspended particles (TSP), which may help the Environmental Protection Agency (EPA) to set the National Ambient Air Quality Standards (NAAQS) for particulate matters (PM). It may also help regulators to incentivize power companies to respond optimally to unexpected energy shortages.

The Three Mile Island accident was a partial nuclear meltdown that occurred on March 28, 1979, in one of the two Three Mile Island nuclear reactors in Pennsylvania. Being the worst accident in U.S. commercial nuclear power plant history, the accident crystallized anti-nuclear safety concerns among activists and the general public. Following the public backlash, the Nuclear Regulatory Comission (NRC) started cracking down on nuclear facilities, leading to new regulations and the shutdown of several nuclear plants around the nation in the 1980s, including Browns Ferry and Sequoyah in the TVA area in 1985. I exploit this setting to study the substitution among energy sources in electricity generation, and potential consequences of the use of non-renewable sources on air quality and public health. I focus on the TVA because it has a diverse portfolio of power sources which are connected through the electrical grid - hydroelectric dams, coal- and gas-fired plants, and nuclear facilities -, and is self-sufficient in power generation. Hence, when an energy source faces a temporary shock, responses are likely to occur within the area. Besides, the TVA was operating the nation's largest electric power system in 1985, the year of the nuclear shutdown.

I first investigate whether environmental regulations targeted at a subset of power plants in a network of energy production are effective at protecting public health. Chain reactions within the power grid may completely offset the perceived health benefits of the nuclear shutdown when the response is an increase in electricity generation through the burning of fossil fuels. By plotting monthly electricity generation data at the plant-fuel level from the Historic EIA-906 Form in figure 1, we can see that such pattern indeed emerges after the shutdown of the TVA nuclear plants. By employing an empirical strategy similar to the dynamic reduced-form approach advanced by Cullen (2013), I estimate those responses and find out that the substitution between nuclear and coal seems to be one-for-one. That is, each megawatt-hour not produced by nuclear power plants due to the shutdown appears to be generated by coal-powered plants. Furthermore, summary statistics presented in the last row of table 1 show that the nuclear shutdown leads to not only a shift in power generation to coal-fired plants, but also an increase in TSP concentration, and a decrease in birth weight. Monthly measures of TSP concentration were constructed by aggregating daily readings from the network of monitoring stations provided by EPA. Natality data come from the National Vital Statistics System of the National Center for Health Statistics (NCHS's). Estimates from the econometric analysis corroborate the broad picture just described, and I conclude that targeted environmental regulations in network do not seem to protect public health.

Although the general results arising from the nuclear shutdown are already illuminating, a more detailed analysis reveals a rich pattern of heterogeneity in the responses of interest. By splitting the power generation response of coal-fired power plants into four groups - high, medium, low, and negligible -, the right-hand side of table 1 indicates that TSP and birth weight responses also differ across groups. To the best of my knowledge, this heterogeneity driven by responses within the power grid has not been exploited in studies of air pollution, but has the potential to enrich the analysis. In fact, a single shock can generate multiple sources of variation in terms of pollution intensity and geographic areas. I take advantage of such heterogeneity by employing a difference-in-differences approach to estimate the impact of air pollution on birth weight and gestational age. I define the control group as the set of counties whose coal-fired power plants were not affected by the nuclear shutdown - the ones with negligible variation, and three treatment groups according to their pollution intensity.

The difference-in-differences approach exploiting the network heterogeneity allows me to address my second research question: are there levels of TSP concentration that are "safe" to infants? In a recent review of the literature on the impact of pollution on health outcomes, Currie et al. (2014) point out the preponderance of evidence of harmful effects of high levels of pollution, but emphasize the need to identify "safe" thresholds. This is a particularly important question for policy because it could guide EPA in the process of setting the NAAQS, for instance. It may also give regulators tools to incentivize power companies to respond optimally to unexpected energy shortages.

In this attempt to recover the dose response function of pollution motivated by Currie et al. (2014), notice that TSP concentrations displayed in the right-hand side of table 1 do not appear to respond proportionally to power generation. Although the high group generates around 30 percent more electricity than the medium group on average, TSP responses seem to be very similar. In fact, the patterns depicted in figure 3 look a lot alike, with the only difference being the level of pollution that they begin with. The medium group starts in the 30s and jumps to the 40s $\mu g/m^3$, while the high group moves from the 40s to the 50s $\mu g/m^3$. Just for reference, the EPA annual standard for TSP is 75 $\mu g/m^3$ from 1971 to 1987. Difference-in-differences estimates reveal that even though TSP concentrations are below EPA standards in 1985, they are not at "safe" levels. Air pollution seems to decrease birth weight by roughly 134 grams, or 5.5 log points, when TSP concentration is above 50 $\mu g/m^3$. No statistically significant effects are found for TSP levels below 50 $\mu g/m^3$. Indeed, these effects are evident even in the raw data as depicted by figure 3. Therefore, 50 $\mu g/m^3$ appears to be a "safe" threshold. When translating these TSP concentrations into particulate matter (PM) concentrations[2], my findings suggest that the EPA may have set the TSP and TSP-equivalent standards right only from 1997 onwards, as shown in table 2.

In summary, this study makes four contributions to the literature. First, it points out that environmental regulations focused on one node of an extensive network of energy production may trigger unanticipated chain reactions that go against the ultimate goal of protecting public health. Networks should be taken into account in the design of those regulations. Second, it shows that a curve relating effects of pollution on health and intensity of pollution exposure may be estimable through the use of networks. When shocks in one node produce different responses over other nodes, quasi-experimental variation in pollution exposure may arise. Third, it provides evidence that suspending nuclear energy production might not generate as much benefits as the public perceives. Lastly, it corroborates recent findings by Lavaine and Neidell (2013) that pollution externalities from energy production are also prominent, and should be seriously considered in the design of environmental policies.

The remainder of this paper is organized as follows. Section 2 provides a simple conceptual framework that guides the empirical analysis. Section 3 presents a brief historical background of the nuclear shutdown in the TVA area in the 1980s, and introduces the research design. Section 4 describes the data used in this study, and presents some descriptive statistics. Section 5 outlines the methodology for the empirical analysis. Section 6 reports and discusses results regarding the impact of the shutdown on coal-burning generation, air pollution, and health outcomes at birth. Finally, Section 7 provides some concluding remarks.

2 Conceptual Framework

To elucidate the trade-off between nuclear and coal power, and motivate the empirical analysis, I briefly examine the social planner's problem regarding electricity generation. The

[2] In 1987, EPA stops setting TSP standards, and starts focusing on PM_{10} and $PM_{2.5}$. They provide correspondences between measures of those three elements.

social planner maximizes the utility of a representative consumer over electricity, air quality, and health, taking into account potential damages to air quality and health due to emissions of pollutants and radioactivity arising from power generation.

2.1 Set-up

The social planner maximizes a concave utility function $U(E, A, H)$ of a representative consumer over electricity E, air quality A, and health H. Electricity is generated by a concave production function $E(C, N, R)$ separable in coal C, uranium N, and river water R[3]. That is, electricity is generated by coal-fired power plants, nuc

lear facilities, and hydroelectric dams. Because coal-fired power plants emit lots of pollutants, I assume that air quality is a nonincreasing function of coal. That is, $A(C)$, with $A_C \leq 0$. Finally, I assume that health is a nonincreasing function of air pollution and radioactivity released from nuclear reactors, i.e., $H(A, N)$, with $H_A \geq 0$ and $H_N \leq 0$. The social planner's problem can be expressed as

$$\begin{aligned} &\text{Max}_{C,N,R \in \mathbb{R}^3_+} U(E, A, H) \\ &\qquad \text{s.t. } E = E(C, N, R) \\ &\qquad\qquad A = A(C) \\ &\qquad\qquad H = H(A, N), \end{aligned}$$

which is equivalent to

$$\text{Max}_{C,N,R \in \mathbb{R}^3_+} U(E(C, N, R),\ A(C),\ H(A(C), N)).$$

[3]One can also treat R as another source of renewable energy such as wind and solar.

The first order conditions (FOCs) for such a problem can be written as

$$\begin{aligned} U_E E_C + (U_A + U_H H_A) A_C &= 0 \\ U_E E_N + U_H H_N &= 0 \\ U_E E_R &> 0. \end{aligned}$$

2.2 Model Predictions

This simple model provides three main predictions. First, the social planner operates power plants with renewable sources of energy at full capacity before turning to coal and nuclear power. In this context, hydroelectric dams should generate an important part of the baseload. Second, once renewables are fully exploited, the trade-off between nuclear and coal power could emerge. If environmental regulations are targeted at nuclear power plants, we should expect a shift in electricity generation to coal-powered plants. The trade-off exists only if the additional coal power generation deteriorates air quality. In the FOCs, only if A_C is not zero. If that is the case, the reduction in the risk of exposure to radioactivity through H_N could be offset by the increase in the exposure to air pollution. If regulations also constrain emissions of existing coal-fired power plants such as the ones pushed by EPA recently, then perhaps air quality would not be affected, and the trade-off would not emerge. Third, the intensity of the trade-off depends on (i) potential nonlinearities in the effect of coal power generation on air quality (A_{CC}), (ii) the impact of air pollution on health (H_A), and (iii) potential nonlinearities in the relationship betwen pollution and health (H_{AA}).

Recent studies have provided strong evidence of deleterious health effects of radioactivity (Almond et al., 2009; Black et al., 2014). There is also plenty of evidence of the effects of air pollution on health (Stieb et al., 2012; Currie et al., 2014). However, to the best of my knowledge, there is no study linking the functioning of the electricity markets to non-market outcomes such as air quality and health. Also, nonlinearities in health responses to pollution, which would provide guidelines for policymaking such as setting the NAAQS by EPA, have yet to be credibly estimated. I exploit the quasi-experimental design associated with the nuclear shutdown in the TVA in the 1980s to shed light on those issues[4].

3 Historical Background and Research Design

In order to investigate the trade-off between coal and nuclear power empirically, it would be desirable to find exogenous variation in electricity generation by nuclear plants within a power grid with a diverse portfolio of power plants. As will be described in the data section, the TVA has a variety of large power plants, mainly hydroelectric dams, coal-powered plants, and nuclear facilities. Thus, in the empirical analysis, I exploit the shutdown of nuclear power plants in the TVA area in the 1980s as such an exogenous source of variation to identify substitution between energy sources and its consequences to air pollution and health outcomes. I now discuss some background information on such a nuclear shutdown in 1985. Figure 4 depicts a timeline with important events.

As mentioned before, the Three Mile Island Unit 2 reactor partially melted down on March 28, 1979, near Middletown, Pennsylvania. This was the most serious accident in U.S. commercial nuclear power plant operating history. It triggered the NRC to tighten and heighten its regulatory oversight, bringing about sweeping changes in many areas of nuclear power plant operations.

Two months before the 1979 Three Mile Island nuclear accident, the Union of Concerned Scientists (UCS) called upon the government to shut down the facility and 15 other nuclear reactors, based on analysis showing that the NRC had dramatically understated the probability of an accident[5]. The public backlash that followed the accident forced the NRC to crack down on nuclear facilities, leading to the shutdown of several nuclear reactors in the 1985 to 1990 time frame. The TVA Browns Ferry Units 1, 2 and 3, and Sequoyah Units 1

[4]Observe that the marginal utility of electricity enters every FOC directly. Although EPA designs and implements regulations based on evidence of harm to the environment or public health, a proper cost-benefit analysis should include the value of electricity to consumers. Indeed, Lewis and Severnini (2014) show that electricity is extremely valuable to farmers due to increases in productivity and household's well-being.

[5]Ever since the Three Mile Island accident, federal, state, and local officials have looked to UCS for unbiased information about the safety of nuclear power plants.

and 2, as well as Davis-Besse, Fort St. Vrain, Nine Mile Point Unit 1, Peach Bottom Units 2 and 3, Pilgrim, Rancho Seco, and Surry Unit 2, all had year-plus outages in this period (UCS, n.d.).

At Browns Ferry, NRC inspectors identified 652 violations between 1981 and 1984, and the agency imposed $413,000 in fines (USC, n.d.). In July 1984, the NRC issued an order requiring TVA to implement its Regulatory Performance Improvement Program (RPIP) and provide periodic status reports. In February 1985, reactor vessel water level instrumentation problems happened in Unit 3, leading TVA to cease operations in March 19 at all three Browns Ferry units to focus on programmatic improvements. By September 1985, NRC stated that the RPIP had been ineffective and required TVA to try again with another plan. The shutdown of Browns Ferry would last for approximately five years.

Regarding Sequoyah, the NRC induced its outage based on new regulations taking effect in March 1985. After the agency informed TVA that Sequoyah would be one of the first plants to be audited according to the new requirements, the company brought in a contractor to pre-audit the facility. That independent review indicated that reactors could not be safely shut down in the event of an accident. Hence, TVA voluntarily ceased operations at both reactors in August 22, 1985, before the NRC's inspectors got a chance to do so (USC, n.d.). That shutdown would last until November 1988.

The UCS clearly states that "*[t]hese back-to-back outages reflect a regulatory bias first identified by the various inquiries into the Three Mile Island Unit 2 accident and still not exorcised.*" (UCS, n.d., Report on Browns Ferry Unit 3 - p.2). Therefore, the Three Mile Island accident appears to have induced targeted environmental regulations. The nuclear facilities were under much more scrutiny than the coal- and gas-powered plants in those years. Furthermore, TVA annual reports indicate that the shutdown was unexpected. According to the reports, TVA had an extraordinary perfomance in 1985 due to "*unplanned reductions in nuclear and hydro generation*" (TVA, 1985, p.26).

The reductions in hydro mentioned in the TVA report resulted from an unusual drought in the area during the 1980s, which limited the supply of its only source of renewable energy. This short-run capacity constraint in renewables makes this setting even more appropriate to examine the potential trade-off between coal and nuclear power. To some extent, the operator may be forced to ramp up production in coal-fired power plants, which could increase air pollution in the area, and perhaps deterioration of public health.

4 Data

The data I use in this study come from three sources. To investigate the response of TVA hydro and coal-fired power plants to the shutdown of Browns Ferry and Sequoyah nuclear facilities in 1985, I utilize monthly electricity generation data at the plant-fuel level from the Historic EIA-906 Form. To obtain the impact of the nuclear shutdown on air pollution, I construct monthly measures of TSP at the county level. Daily TSP readings from the network of monitoring stations in the TVA area were provided by EPA under a Freedom of Information Act (FOIA) request. To aggregate these daily readings into monthly measures, I employ the same procedure used by EPA to produce its annual summaries. To estimate the effect of the pollution arising from coal-fired power plants in response to the nuclear shutdown on birthweight, I use natality data from the National Vital Statistics System of the National Center for Health Statistics (NCHS's). The NCHS's birth data provide rich demographic and health information of infants and their mothers. I focus my analysis in the period 1983-1987, which covers eighteen months before and after the shutdown. Eighteen months just represent two pregnancy cycles, which is a natural time frame when undertaking the birth weight analysis.

The TVA was operating the nation's largest electric power system, and had a pretty diverse portfolio of power generation in 1985, the year of the nuclear shutdown. Focusing on large plants - 100 megawatts of capacity or more -, the TVA had 15 hydroelectric dams, 11 coal-fired plants, and two nuclear facilities, as you can see in figure (5). The blue squares represent hydro, the red circles coal, and the yellow triangles nuclear plants. Since hydro dams do not seem to respond to the nuclear shutdown, I focus my analysis on coal-powered plants. Figure (6) plots only those plants together with the nuclear generating stations. The different symbols represent the heterogeneity in power generation responses to the nuclear shutdown, as pointed out previously based on the summary statistics of table (1). The red diamond represents the Paradise coal-fired plant, with the highest variation in power generation due to the shutdown ($H - \triangle PG$), the red square represents Cumberland, with a medium response ($M - \triangle PG$), the red circles represent coal-powered plants with low responses ($L - \triangle PG$), and the red hollow circles represents facilities with negligible responses ($N - \triangle PG$)[6].

With the exception of Allen Fossil Plant in the Memphis metropolitan area, all coal-fired plants are located in counties with low population density, as you can notice from the relatively small number of births in table (3). Observe that the high and medium groups are made of only one power plant each, so in my main analysis I compare these two distinctive counties with the group of counties with low responses, and with the control group. Recall that the control group is defined as the group of counties whose responses of their coal-powered plants to the nuclear shutdown are economically and statistically insignificant.

The sample for my birth weight analysis has almost 56,000 observations, as shown in table (3). The middle panel in the table contains the information of plants used in my analysis. I exclude Kingston and Bull Run coal-fired plants because they are located in neighboring counties, and I have not found reliable information on wind patterns for that area in that period of time, so I cannot control precisely for upwind pollution. The right-hand side panel of that table includes those two plants. Later on, I show that my results are not sensitive to the inclusion of those plants.

It is important to point out the difference in sample sizes for the counties hosting Paradise and Cumberland. Because the number of births around Cumberland is much smaller than

[6] In Appendix A, I provide evidence that most of the response in power generation can be explained by cost considerations within TVA.

around Paradise, one should expect less precision for estimates associated with the medium response group. A reweighting strategy based on number of births is used to check whether the results are robust to such heterogeneity.

5 Empirical Strategy

In this section, I present the methodology to provide empirical evidence on the consequences of the shutdown of the TVA nuclear facilities in the 1980s. Motivated by the predictions of the model discussed in section (2), I address three main topics: (i) how power generation changes after the shutdown both in hydro and coal-fired plants, (ii) how air pollution, measured as TSP concentration, respond to the shutdown because of additional emissions by coal-powered plants, and (iii) how birthweight is affected in counties where both power generation and air pollution increase after the shutdown. Throghout my analysis

5.1 Response of Power Generation

In order to estimate the response of coal and hydro power generation to the nuclear shutdown, I build on the approach advanced by Cullen (2013). Basically, I estimate the following equations for each power source - coal versus hydro:

$$PGen_{cm} = \beta_0 + \beta_{1c} DNucShut_m + Z_{cm}\delta + \gamma_c + \lambda_m + \theta_y + \varepsilon_{cm}, \tag{1}$$

$$\text{or } PGen_{cm} = \beta_0 + \beta_{1c} PGenNuc_m + \beta_{2c} PGenNuc_{m-1} + Z_{cm}\delta + \gamma_c + \lambda_m + \theta_y + \varepsilon_{cm}, \tag{2}$$

where c stands for county, m for month, and y for calendar year. $PGen$ represents power generation measured in megawatt-hours, $PGenNuc$ is power generated by nuclear plants, $DNucShut$ represents a dummy variable that takes value one from the shutdown onwards, and Z is a set control variables such as temperature and precipitation.

Notice that this approach accounts for dynamics in the production process. As discussed in Cullen (2011), the operating decision of a coal-powered plant is inherently dynamic due to costs associated with startup, shut down, and ramping up and down production. Therefore, in the estimation one must include not only contemporaneous covariates, but also elements of the information set which the electric utility - TVA, in this case - considers when adjusting its optimal production. At the end of the day, the estimating equation recovers the reduced-form optimal policy function coming from the dynamic programming problem of each generator, taking into account firm's expectations. For the sake of completeness, lagged variables are also included in Z. In fact, Z contains a quadratic function of contemporaneous and lagged precipitation and temperature.

The time frame of my analysis is eighteen months before and after the shutdown. It is equivalent to two full-term pregnancies, and is less than the typical two years to construct a coal-fired power plant. Because eighteen months are not enough for electric utilities to adjust production by increasing capacity, the responses captured in β_{1c}'s are in the intensive margin. In this sense, the nuclear shutdown represents an exogenous source of variation in power generation, since it can be seen as a shock to the other power plants.

Finally, I estimate equations (1) and (2) separately for counties with coal versus hydro power plants. My underlying assumption is that TVA's decision making may be different for coal and hydro generation. In any case, the variables of interest are interacted with counties so that responses can be obtained for each and every power plant.

5.2 Response of Air Pollution

Regarding the estimation of air pollution responses, I follow the approach developed for responses of power generation. I just substitute TSP concentration for power generation as the dependent variable in the estimating equations. That is,

$$TSP_{cm} = \beta_0 + \beta_{1c} DNucShut_m + Z_{cm}\delta + \gamma_c + \lambda_m + \theta_y + \varepsilon_m, \qquad (3)$$

$$\text{or } TSP_{cm} = \beta_0 + \beta_{1c} PGenNuc_m + \beta_{2c} PGenNuc_{m-1} + Z_{cm}\delta + \gamma_c + \lambda_m + \theta_y + \varepsilon_m. \quad (4)$$

On the one hand, coal-burning power plants are important sources of particle pollution - the tiny particles of fly ash and dust that are expelled from the combustion of coal. On the other hand, coal power generation involves essentially dynamic decisions. As explained before, it is costly to fire up coal-fired boilers, so electric utilities do so only when they expect to generate large amounts of electricity. Therefore, power generation and particle pollution are both dynamic processes. In fact, pollution data exhibit great temporal dependence. Hence, it is natural to employ a similar estimation strategy for both cases.

Again, the estimation is carried out separately for counties with coal plants and counties with hydro dams. Geographic conditions determining the installation of coal-powered plants and hydroelectric dams probably differ. Those same features may also affect TSP concentration in distinctive ways.

5.3 Response of Birth Weight

Lastly, I assess the impact of the nuclear shutdown on health outcomes at birth, proxied by birth weight. As well-known, low birth weight infants experience severe health and developmental difficulties that can impose large costs on society (Almond, Chay, and Lee, 2005; Black, Devereux and Salvanes, 2007). I estimate difference-in-differences models to exploit the heterogeneity in responses of power generation and TSP concentration. My treatment group consists of babies born in counties with coal-fired power plants affected by the shutdown, and my control group contains infants born in counties whose coal plants did not respond statistically or economically to the shutdown.

As with any difference-in-differences design, the key underlying assumption for identification is that the control group serves as a valid counterfactual for the treatment group with parallel trends. In my setting, this seems like a reasonable assumption because all women having babies in my sample are living near coal-powered plants. Thus, they might have similar preferences for pollution. In fact, all of them are being exposed to air pollution, with the only difference being in intensity, which is affected by the response of coal plants to the nuclear shutdown. Furthermore, I am focusing my analysis on a short period of time - eighteen months -, which limits migration in response to additional TSP concentration.

I implement this approach by estimating the following equation:

$$\begin{aligned} BWeight_{icm} = \beta_0 &+ \beta_1(DNucShut \times H\Delta PG)_{cm} \\ &+ \beta_2(DNucShut \times M\Delta PG)_{cm} \\ &+ \beta_3(DNucShut \times L\Delta PG)_{cm} \\ &+ X_{icm}\delta + \gamma_c + \phi_{my} + \varepsilon_{icm}, \end{aligned} \tag{5}$$

where i stands for infant, c for county, m for month, and y for calendar year. $DNucShut$ represents a dummy variable that takes value one from the nuclear shutdown onwards, the three dummy variables for ΔPG represent the intensity of the power generation response of coal plants to the shutdown - high, medium, low -, and X is a set control variables such as county temperature and precipitation, and characteristics of infants and their mothers. I also include county fixed effects (γ_c) to control for their time-invariant attributes, and control for seasonal and temporal patterns by including month-by-year dummies in ϕ_{my}. It is important to mention that the same approach is used to estimate the impact of the nuclear shutdown on incidence of very low birth weight (less than 1,500 grams), low birth weight (less than 2,500 grams), and weeks of gestation. In each case, I just replace the dependent variable with one of these outcomes.

Besides exploiting the variation in exposure to additional pollution at the county level, I use variation in exposure depending on months of gestation. If women are in early versus late months of pregnancy by the time of the nuclear shutdown, then their babies are exposed to different amounts of additional TSP. I make use of dummy variables for infants born in each trimester before and after the shutdown to incorporate that source of treatment heterogeneity into my econometric model. Babies born in the first trimester following the shutdown face less pollution in utero than those born in the third trimester, for instance. It is basically an event study analysis for each group of response to the shutdown in terms of power generation. The estimating equation can be expressed as

$$\begin{aligned} BWeight_{icm} = \beta_0 &+ \beta_1^{Trim}(DTrimBirth \times H\Delta PG)_{cm} \\ &+ \beta_2^{Trim}(DTrimBirth \times M\Delta PG)_{cm} \\ &+ \beta_3^{Trim}(DTrimBirth \times L\Delta PG)_{cm} \\ &+ X_{icm}\delta + \gamma_c + \phi_{my} + \varepsilon_{icm}, \end{aligned} \tag{6}$$

where the only difference relative to equation (5) is the replacement of $DNucShut$ with $DTrimBirth$, a dummy for each trimester of birth before and after the shutdown.

6 Results

6.1 Response of Power Generation and Air Pollution

I start by examining the responses of power generation and TSP concentration to the nuclear shutdown. Table 4 presents the estimates for coal-fired power plants, and table 5 for hydroelectric dams.

The first column of table 4 shows the average monthly amount of electricity generated due to the shutdown, whereas the second column provides similar information in log points. Paradise, for example, increases its production in approximately 431 gigawatt-hours (GWh) in a typical month, which is an increase of roughly 0.64 log points in its output. I classify Paradise coal plant as having a high response to the nuclear shutdown. The corresponding numbers for Cumberland, the plant with medium response, are 302 GWh and 0.39 log points. The low response group consists of Johnsonville, Shawnee, Widows Creek, and Colbert, and Kingston. Finally, the control group, or set of plants with negligible responses to the shutdown, is made of Bull Run, Allen, John Sevier, and Gallatin.

The third column of table 4 reveals where the electricity not produced by Browns Ferry and Sequoyah ended up being generated. Roughly a fourth of each megawatt-hour (MWh) not produced by the two TVA nuclear plants was generated by Paradise. The other three fourths were almost equally split among the other coal plants with non-negligible response to the shutdown. In fact, one cannot rule out that the substitution between nuclear and coal power is one to one, as shown at the bottom of that table. This means that electricity generation shifted completely from the nuclear facilities that were shut down to coal-powered plants. Similar conclusion can be reached for the total amount of nuclear power generation. One cannot rule out that the average monthly 1,800 GWh produced by Browns Ferry and Sequoyah before the shutdown were being generated by coal plants afterwards[7].

Concerning air pollution, the response of TSP concentration is similar in the counties where the coal plants with the highest responses are located. As noticeable from the fourth column of table 4, even though Paradise generates more electricity than Cumberland due to the nuclear shutdown, TSP responses in their host counties are statistically identical, as shown at the very bottom of column 4. This evidence corroborates the raw data plotted in figure 3. No statistically significant TSP effects are consistently found for the counties where the other power plants are situated. Nevertheless, observe that the point estimates seem to be strongly associated with the responses of coal-powered plants to the shutdown. Indeed, at the bottom of the fourth column, I present the correlation between the coefficients of columns 1 and 4, as well as the R-squared of a simple linear regression of TSP coefficients

[7]Price increases could have been another way to adjust to the nuclear shutdown. However, there appear to be a one-for-one substitution between nuclear and coal power generation, and coal prices adjusted for coal quality decreased roughly 11.5 percent after the shutdown, as shown in table A.3. Therefore, it is not suprising that "*[i]n its role as a major energy producer, TVA again in 1985 maintained stable electric rates, a key factor in industrial growth. (...) TVA power proved a real value for residential consumers, too, as residential rates remained stable for the third year in a row.*" (TVA, 1985, p.24). Nevertheless, the TVA report of the following year mentions that "*[a]fter four years of virtually flat rate levels, consumers' bills increased an average of about 6 percent.*" (TVA, 1986, p.20). But they explain that "*[o]ver the past five years, TVA power costs to consumers have been held below the level of general inflation.*" (TVA, 1986, p.20). Overall, prices do not seem to be a first-order margin of adjustment in the TVA after the nuclear shutdown.

on power generation responses, and they are both above 0.60.

I also examine the response of sulfur dioxide (SO_2) levels to the nuclear shutdown. SO_2 is another criteria pollutant with a good network of monitoring stations in the TVA area. The estimates are shown in the fifth and sixth columns of table 4. Although Paradise's excess power generation seems to affect this pollutant concentration as well, SO_2 levels appear to increase more in counties where coal plants do not respond to the shutdown. In fact, the correlation between the coefficients of columns 1 and 6 is virtually zero. In other words, variation in SO_2 concentration may be due to factors not related to the nuclear shutdown. This is the main reason why I focus my analysis on TSP.

When we turn to responses of hydroelectric dams in table 5, we can see that some changes also happen in their power generation. However, as a whole, the drop in electricity generated by those facilities is relatively small. Furthermore, one cannot rule out that such reduction was compensated by additional power generated in coal-fired power plants, as evident from the bottom of tables 4 and 5. This is also consistent with the high cost to adjust production in coal-powered plants. It may be the case that, in order to be profitable, coal plants might have had to generate more electricity than the foregone output from the nuclear facilities.

Reductions in hydropower generation in that period may also be attributed to a harsh drought in 1985. "*This year was one of the driest on record and this limited TVA's hydroelectric power production to about 13.6 billion kilowatthours, about 5 billion less than in a typical year and the second lowest annual amount since the 1950s.*" (TVA, 1985, p.26). Since I have controlled flexibly for climate variables in my regressions, the results discussed above are already conditional on temperature and precipitation. In any case, because hydro facilities do not produce air pollutants, TSP and SO_2 concentrations do not seem to increase systematically in counties with hydro dams after the shutdown[8].

It is encouraging to notice that my findings corroborate statements from TVA annual reports. The 1985 report, for instance, mentions that "*[t]he coal-fired plants, which represent*

[8]Observe that the network of monitoring stations for TSP and SO_2 does not cover counties with hydro dams very well. In general, air pollution monitors are closer to coal plants, which actually emit pollutants.

55 percent of TVA's installed generating capacity, supplied about 70 percent of TVA's generating requirements, or about 74 billion kilowatthours, during 1985. They did this with a budget and staff based on previous production estimates of only 65 billion kilowatthours. In May and June, the coal-fired plants supplied more than 80 percent of the system requirements. This extraordinary performance was a consequence of unplanned reductions in nuclear and hydro generation." (TVA, 1985, p.25-26).

6.2 Response of Birth Weight

Having found a relationship between the shutdown of the TVA nuclear power plants in 1985 and air pollution, I now turn to the effects of the shutdown on health at birth. Table 6 presents the main results of the impact of exposure to the shutdown anytime during pregnancy on birth weight. It shows my findings in levels (grams) and log points, overall and conditional on weeks of gestation, as well as levels (weeks) and log points of gestational age. Table 7 reports alternative measures of birth weight: incidence of low (less than 2,500 grams) and very low (less than 1,500) birth weight. For each dependent variable, I explore sensitivity to control variables such as county fixed effects, month-year dummies, infant and mother characteristics[9], a quadratic function in temperature and precipation in the month of birth, and per capita income and wages/salaries at the county level. Table 8 shows an example of those specifications adding covariates for birth weight. The last column in that table is the first one in the table with my main results. It is my preferred specification, which includes all controls at the same time.

Starting with birth weight in table 6, I find that it decreases by approximately 134 grams,

[9] *Infants*: indicator for gender of birth; racial indicators for black, and other birth; *not* a singleton indicator (twins or greater birth); birth order indicators for second, and third or more. *Mothers*: continuous age; continuous years of education; marital status indicator; quadratic function on total number of prenatal care visits; indicator for first prenatal care visit in months 1 or 2, indicator for first prenatal care visit in month 3, indicator for first prenatal care visit in months 4, 5, or 6, indicator for first prenatal care visit in months 7, 8, or 9; total number of children born dead to this mother; total number of children ever born to this mother; indicator for 1 previous termination before week 20 of gestation, indicator for 2 or more previous terminations before week 20 of gestation, indicator for 1 previous termination after week 20 of gestation, indicator for 2 or more previous terminations after week 20 of gestation; indicator for delivery in a hospital, indicator for physician present at delivery.

or 5.4 log points, after the nuclear shutdown. Keep in mind that the mean birth weight before the shutdown is roughly 3,267 grams. Notice, though, that the effect emerges only when coal power generation responds strongly to the shutdown, and TSP concentration jumps from the 40s to the 50s $\mu g/m^3$. In fact, the test of equality of the coefficients from the high response and the medium response in terms of power generation indicates that those estimates are statistically different at conventional levels. If we assume that the only pollutant affected by coal power generation in response to the shutdown is TSP, we can compute the impact of TSP on birth weight by dividing the effect of the shutdown on birth weight by the effect of the shutdown on TSP, as shown in table 4, akin to instrumental variables (IV). This procedure suggests that exposure to an additional 1 $\mu g/m^3$ of TSP during pregnancy after the shutdown decreases birth weight by approximately 11 grams. As discussed by Lavaine and Neidell (2013) in a similar context, one should be cautious in interpreting this last finding. Coal-fired power plants may have affected other pollutants in their response to the nuclear shutdown, and this would violate the exclusion restriction of a valid IV. Indeed, as mentioned before and shown in table 4, the shutdown might have increased SO_2 levels as well, even though such increase seems to be uncorrelated with responses from coal plants.

It is imperative to mention that my estimates are at least twice as larger as those effects found in epidemiological studies. In a systematic review and meta-analysis of the impact of ambient air pollution on birth weight, Stieb et al. (2012) find that an increase of 10 $\mu g/m^3$ in PM_{10} and $PM_{2.5}$ concentration reduces birth weight by 8.4 and 11.7 grams, respectively. Using the EPA correspondences between measures of TSP, PM_{10} and $PM_{2.5}$ [10], those effects could be translated into reductions of 17.5 and 42 grams, respectively, when TSP concentration increases by 10 $\mu g/m^3$.

One could be interested in disentangling the negative impact of the shutdown on birth weight into two components: (i) slower fetal growth, and (ii) shorter gestation. The reduction of 134 grams has not been conditioned on gestational age, another potential variable

[10]The TSP/PM_{10} ratio is 0.48 (Pace and Frank, 1986, Table 1), and the $PM_{10}/PM_{2.5}$ ratio is 0.58 (Parkhurst et al., 1999, Table 3).

affected by the shutdown. When I control flexibly for weeks of gestation - quartic function in gestational age -, the effect on birth weight reduces 35 percent to roughly 87 grams, as shown in the third column of table 6. Thus, growth retardation might explain 65 percent of the impact of the nuclear shutdown on birth weight. Therefore, it does appear that the nuclear shutdown induces deleterious effects on health at birth through both channels: growth retardation and shorter gestation[11]. Moreover, both effects seem to have economic significance. Taken together, these results differ from those of the impact of a recent strike in oil refineries in France, studied by Lavaine and Neidell (2013). They suggest that the increase in birth weight, driven likely by a decrease in SO_2 concentration, might be solely due to shorter gestation, rather than growth retardation.

Nevertheless, the role of prematurity is still non-negligible. Indeed, looking directly at gestational age, my estimates from columns 5 and 6 of table 6 indicate that the shutdown decreases weeks of gestation by roughly 0.54 weeks, or 3.8 days, or 1.5 log points. Here, though, the p-value of the test of equality of the coefficients from the high response and the medium response in terms of power generation is much higher. Keep in mind that the baseline mean is approximately 39 weeks. This yields an "IV" estimate of a reduction of 0.32 days of gestational length for each 1 $\mu g/m^3$ increase in TSP concentration driven by the shutdown. I follow Lavaine and Neidell (2013) to translate this effect in weeks into weight. Fetuses gain about 200 grams per week in the final month of pregnancy (Cunningham et al., 2010). Hence, the 0.54 week decrease in gestation translates into a reduction of 108 grams in weight. Given that the coefficients from the high response and the medium response in terms of power generation are statistically similar, though, one cannot rule out that the effect is as small as 60 grams, which is very close to the amount explained by shorter gestation in the birth weight regressions.

[11] Air pollution is hypothesized to affect the fetus directly through transplacental exposure or indirectly by adversely impacting maternal health during pregnancy. Although the mechanisms of toxicity of air pollution on the fetus are poorly understood, several have been proposed, particularly for PM effects, including oxidative stress, pulmonary and placental inflammation, blood coagulation, endothelial dysfunction and changes in diastolic and systolic blood pressure (Kannan et al., 2006).

Turning to the incidence of low birth weight - less than 2,500 grams -, my estimates from the first column of table 7 suggest that it increases by approximately 2 percent after the nuclear shutdown in the county where coal-fired power generation responded strongly to the shutdown. An impact of opposite sign but similar magnitude is found for the county that had a medium response in terms of power generation. Those effects are even stronger for the incidence of very low birth weight - less than 1,500 grams, as shown in the column 4. Keep in mind that low birth weight is a rare event in the TVA area. Indeed, even before the shutdown, the tenth percentile of birth weight was already above that threshold: 2,580 grams. Again, I control flexibly for weeks of gestation to check if these findings can be explained by shorter gestation. Estimates from column 2 indicate that prematurity may play a major role in this context, although not enough to explain the whole pattern. Thus, I consider the possibility that my estimates may also reflect the fact that the response to the shutdown may have improved the economic status of households by bringing more economic activity to locations with coal-powered plants. Even though I control for changes in per capita income and per capita wages/salaries at the county level, those variables might not capture well changes in earnings at the household level. In such a case, my estimates would reflect only the net effect of additional pollution and earnings. Hence, in the third column of table 7 I control directly by changes in the number of jobs and wage bills in those coal-fired power plants brought about by the response to the nuclear shutdown. It appears that such variables explain the overall pattern of the effects on the probability of low birth weight[12]. In fact, both coefficients are much smaller and no longer statistically significant. Furthermore, the test of equality of the coefficients from the high response and the medium response in terms of power generation indicates that those estimates are statistically identical to zero. A similar pattern is found for very low birth weight in columns 5 and 6.

It is important to say that all these results survive a number of robustness checks. First, they are robust to the time frame used in the estimation, as we can see in table 9, where

[12] As we will see in the next paragraph, this is not the case for my main birth weight results.

I present estimates for one to two year windows. Also, as shown in table 10, they are not very sensitive to (i) including changes in the number of jobs and wage bills in coal-fired power plants associated with the response to the nuclear shutdown, (ii) adding climate variables - average temperature and total precipitation - for each trimester during pregnancy (Currie and Schwandt, 2013), (iii) incorporating infants from two neighboring counties which both contain coal-powered plants (Kingston and Bull Run Coal Plants), which could share pollution and economic activity driven by the response to the shutdown (iv) excluding babies from the county where Allen Fossil Plant is located, which is in the control group but has the majority of observations in my sample, and because the plant was built in the 1950s by the Memphis Light, Gas, and Water Division, leased to TVA in 1965, and purchased outright by TVA in 1984, (v) weighting a few observations from states that reported only half of the births, and (vi) reweighting by the number of births in each county due to differences in sample sizes across counties.

In their review and meta-analysis, Stieb et al. (2012) find an enormous variation in the effects of air pollution by exposure period and recommend further exploration. Here, given that women are in different stages of pregnancy by the time of the shutdown, it is possible to determine whether the impact on health outcomes at birth depends on the length of the exposure to TSP. To exploit this source of variation, I interact the dummy of the nuclear shutdown with each trimester the baby was born before and after the shutdown. If the infant is born in the first quarter following the shutdown, for instance, that means that exposure to additional air pollution *in utero* was at most three months. Table 11 presents my results controlling for the same covariates mentioned previously for my preferred specification, and figure 7 present the event study graph.

Although babies born in the first trimester after the shutdown do not appear to be negatively affected, I find that most of the impact of the shutdown on birth weight comes from infants that are exposed to additional TSP for at least six months. Furthermore, the effects seem to be increasing in exposure to additional pollution. Indeed, the effect is

97 grams for infants born in the second trimester following the shutdown, 146 grams for babies born in the third trimester, and of similar magnitude thereafter. Beacuse there is no evidence of a decline in the impact on birth weight after three trimesters, migration responses to higher TSP concentration might be negligible. Nine months would be more than enough for households to find a location with lower levels of pollution. Again, the impact is found only for the group experiencing the highest coal power generation response. If anything, the effect for the medium response group would be positive, but the coefficients are generally statistically zero.

Figure 7 actually motivates the regression analysis for birth weight discussed previously. It plots coefficients for each group of response to the nuclear shutdown and their 95 percent confidence intervals. They provide an opportunity to judge the validity of the difference-in-differences-style approach that is based on the assumption of similar trends in advance of the shutdown. That figure does seem to support the validity of the design as there is little evidence of differential trends in birth weight for each of the treatment groups in the trimesters preceding the shutdown.

Because of strong seasonal patterns of pollution and other environmental confounders, I evaluate the validity of my research design by running a falsification test. Basically, I assign the date of the nuclear shutdown to have occured in March 1979, a few years before the actual one[13]. A severe recession happens in the early 1980s - July 1981 to November 1982 -, generating substantial variation in air pollution across sites, as exploited by Chay and Greenstone (2003) to study the impact of air pollution on infant mortality. If I had assigned the placebo shutdown to happen in March 1983, two years before the actual nuclear shutdown, the pre-placebo shutdown would have included a substantial period of the 1981-1982 recession. I end up using March 1979 instead. It still includes a recession from the early 1980s, but it is a much shorter one - January to July 1980. As shown in tables 12, 13

[13]Recall that my time frame for the estimation is eighteen months before and after the shutdown. This is the reason why I do not assign the placebo shutdown to have happened in the year immediately before the actual one.

and 13, I find that the placebo shutdown is broadly neither associated with TSP levels[14] nor measures of health at birth.

6.3 "Safe" Threshold for Exposure to TSP

Having found plenty of evidence that high levels of pollution are harmful, Currie et al. (2014) suggest that a *"particularly important question for policy is whether there is a safe level of these substances."* (p.20) for fetuses and young children. In other words, they urge recovering a curve of pollution effects as a function of pollution exposure. My attempt to infer such a dose response function in the context of my study is quite primitive, but might still shed some light on the safe threshold for TSP, and may inspire further research.

I begin by noticing that TSP concentrations displayed in the right-hand side of table 1 do not appear to respond proportionally to the coal power generation driven by the nuclear shutdown. Although the medium group generates only two thirds of the additional electricity produced by the high group, TSP responses seem to be very similar. Indeed, when I plot the smoothed data on TSP concentration in figure 3, the only difference in the observed patterns seems to be the level of pollution that each group starts with. The medium group jumps from the 30s to the 40s $\mu g/m^3$, whereas the high group moves from the 40s to the 50s $\mu g/m^3$. Just for reference, the EPA annual standard for TSP is 75 $\mu g/m^3$ from 1971 to 1987.

Proceeding with my difference-in-differences estimation approach, I find that, in 1985, even though TSP concentrations are below EPA standards, they are not at safe levels. When TSP concentration is above 50 $\mu g/m^3$, but still below the standard of 75 $\mu g/m^3$, air pollution seems to decrease birth weight by roughly 3.7 percent, and gestational age by 0.67 weeks, as discussed previously. However, no statistically significant effects are found for TSP levels

[14] Although some TSP effects seem to be statistically significant in a couple of counties after the placebo shutdown, notice that those effects are significant only where responses from coal-powered plants are not significant. The apparent spatially heterogeneous decrease in TSP might be related to emission reductions from other sectors, which may be facing a short recession in the post-placebo nuclear shutdown. In fact, if anything, coal-fired power generation may have increased in those counties where the negative TSP effects are statistically significant.

below 50 $\mu g/m^3$. From this comparison, I primitively infer that 50 $\mu g/m^3$ might be a safe threshold for exposure to TSP. I say "primitive" because I am not testing for any break around 50 $\mu g/m^3$. Furthermore, the difference of the coefficients from the high response and the medium response in terms of power generation is somewhat imprecisely estimated, even though the p-values are much lower than those found in the placebo tests.

In 1987, EPA replaces the earlier TSP air quality standard with a PM_{10} standard. A decade later, a $PM_{2.5}$ standard is added. The new standards focus on smaller particles that are likely responsible for adverse health effects because of their ability to reach the lower regions of the respiratory tract. I use EPA correspondences between measures of those three elements[15] to translate TSP to PM levels, and to evaluate the standards vis-à-vis the inferred threshold. My findings suggest that EPA might have set the TSP and PM standards right only from 1997 onwards, as shown in table 2. This illustrates that the research design used in this study might help EPA setting the NAAQS for other pollutants.

7 Concluding Remarks

When environmental regulations focus on a subset of power plants, the ultimate goal of human health protection may not be reached. Because power plants are interconnected through the electrical grid, excessive scrutiny of a group of facilities may generate more pollution out of another group, with potential deleterious effects to public health. In this study, I investigate the impact of the shutdown of nuclear power plants in the Tennessee Valley Authority (TVA), in 1985, on health outcomes at birth. After the Three Mile Island accident in 1979, the Nuclear Regulatory Commission (NRC) intensified inspections in nuclear facilities leading to shutdown of many of them, including Browns Ferry and Sequoyah in the TVA area.

I have four main findings. I first show that, in response to the shutdown, electricity

[15] The TSP/PM_{10} ratio is 0.48 (Pace and Frank, 1986, Table 1), and the $PM_{10}/PM_{2.5}$ ratio is 0.58 (Parkhurst et al., 1999, Table 3).

generation shifted mostly to coal-fired power plants within the TVA, increasing air pollution in counties where they were located. I provide evidence that the substitution of coal for nuclear power generation may be one to one. Also, that TSP concentration, my measure of pollution, responds only in counties hosting the coal-powered plants with the highest increases in coal-burning generation due to the shutdown.

Second, I find that babies born after the nuclear shutdown have both lower birth weight and lower gestational age in those counties with coal-fired power plants that do respond to the shutdown. This indicates that exposure to higher levels of TSP may deteriorate infant health via two channels: growth retardation and shorter gestation. Third, I highlight the presence of substantial heterogeneity in those effects depending on how much more electricity those coal-powered facilities were generating in response to the shutdown. For the group with the highest response in terms of both coal-burning generation and TSP concentration, it seems that exposure to an additional 1 $\mu g/m^3$ of TSP during pregnancy after the shutdown induces a reduction of roughly 11 grams in birth weight. Furthermore, both fetal growth and gestational length appear to be affected negatively by the shutdown. I find no statistically significant effects when coal generation responses to the shutdown are medium or low.

Summing the growth retardation and the shorter gestation effects, I estimate that birth weight reduces by approximately 134 grams, or 5.4 percent, in those counties with coal-fired power plants responding strongly to the nuclear shutdown. This effect is at least twice as larger as those found by Stieb et al. (2012) in their systematic review and meta-analysis of the impact of ambient air pollution on birth weight. To get a sense of the magnitude of my estimate, I consider the U.S. Special Supplemental Nutrition Program for Women, Infants, and Children (WIC) program, which among other things provides supplemental foods, health care referrals, and nutrition education for low-income pregnant women. Kowaleski-Jones and Duncan (2002) estimate that participation in the WIC by a pregnant woman increases child birth weight by 7.5 percent, which is almost the opposite effect induced by the nuclear shutdown. Using the impact of birth weight on adult outcomes from Black, Devereux and

Salvanes (2007), a 5.4 percent reduction in birth weight would lead to a 0.7 percent decrease in full-time earnings, a 0.4 centimeter decrease in height, a 0.04 stanine decrease in IQ, and a 0.8 percent decrease in the birth weight of their children[16]. Isen, Rossin-Slater and Walker (2015) calculate that the mean present value of lifetime earnings at age zero in the U.S. population is $434,000 (2008 dollars) using a real discount rate of 3 percent (i.e., a 5 percent discount rate with 2 percent wage growth). Thus, the financial value of being born into a county with a coal-fired power plant responding to the nuclear shutdown in the months after the shutdown is 0.7 percent of $434,000 or $3,038 per person.

Lastly, I use the heterogeneity in response to the nuclear shutdown to provide suggestive evidence on the "safe" threshold of exposure to TSP, which can potentially guide the Environmental Protection Agency (EPA) in setting the National Ambient Air Quality Standards (NAAQS) for particulate matters. Although I find no significant impact on health at birth associated with medium coal generation response to the shutdown, TSP levels do increase in those locations. The crucial difference among counties with high and medium responses is the level of TSP that they start with. In the high response group, it jumps from the 40s to the 50s $\mu g/m^3$, whereas in the medium response group it moves from the 30s to the 40s $\mu g/m^3$. Hence, the "safe" threshold for exposure to TSP might be 50 $\mu g/m^3$, which is close to the current EPA standards for PM when translated to the PM_{10} and $PM_{2.5}$ scales.

Taking together, these findings make four contributions to the literature and policymaking. First, they point out that environmental regulations focused on one node of an extensive network of energy production may trigger unanticipated chain reactions that go against the ultimate goal of protecting public health. Networks should be taken into account in the design of those regulations. Second, they show that a curve relating effects of pollution on health and intensity of pollution exposure may be estimable through the use of networks. When shocks in one node produce different responses over other nodes, quasi-experimental

[16] Black, Devereux and Salvanes (2007) estimate that each 1 percent decrease in birth weight decreases expected earnings by 0.13 percent, height by 0.07 centimeter, IQ stanine by 0.007, and birth weight of their children by 0.15 percent.

variation in pollution exposure may arise. As already discussed, this methodology has the potential to guide EPA when setting the NAAQS. Third, they provide evidence that suspending nuclear energy production might not generate as many net benefits as the public perceives. The retirement of the San Onofre Nuclear Generating Station in California, and the denuclearization Germany intensified after the Fukushima disaster, may actually bring about unintended net costs to society. Lastly, they corroborate recent findings by Lavaine and Neidell (2013) that pollution externalities from energy production are also prominent, and should be seriously considered in the design of environmental policies.

References

- Almond, Douglas, Kenneth Y. Chay, and David S. Lee. (2005). The Costs of Low Birth Weight, *Quarterly Journal of Economics* 120(3): 1031-1083.

- Almond, Douglas, Lena Edlund and Mårten Palme. (2009). Chernobyl's Subclinical Legacy: Prenatal Exposure to Radioactive Fallout and School Outcomes in Sweden, *Quarterly Journal of Economics* 124 (4): 1729-1772.

- Black, Sandra E., Paul J. Devereux, and Kjell G. Salvanes. (2007). From the Cradle to the Labor Market? The Effect of Birth Weight on Adult Outcomes, *Quarterly Journal of Economics* 122(1): 409-439.

- Black, Sandra E., Aline Bütikofer, Paul J. Devereux, and Kjell G. Salvanes. (2014). This Is Only a Test? Long-Run and Intergenerational Impacts of Prenatal Exposure to Radioactive Fallout, *Working Paper - University of Texas at Austin.*

- Cullen, Joseph. (2013). Measuring the Environmental Benefits of Wind-Generated Electricity, *American Economic Journal: Economic Policy* 5(4): 107-133.

- Cunningham FG, Leveno KJ, Bloom SL, et al. (2010). "Fetal growth and development." In: Cunnigham FG, Leveno KL, Bloom SL, Hauth, JC, Rouse DJ, Spong CY, eds. Williams Obstetrics. 23rd ed. New York, NY: McGraw-Hill; chap 4.

- Currie, Janet, and Hannes Schwandt. (2013). Within-Mother Analysis of Seasonal Patterns in Health at Birth, *Proceedings of the National Academy of Sciences* 110(30): 12265-12270.

- Currie, Janet, Joshua S. Graff Zivin, Jamie Mullins, and Matthew J. Neidell. (2014). What Do We Know About Short and Long Term Effects of Early Life Exposure to Pollution?, *Annual Review of Resource Economics* 6: 217-247.

- Goebel, Jan, Christian Krekel, Tim Tiefenbach, and Nicolas R. Ziebarth. (2013). Natural Disaster, Policy Action, and Mental Well-Being: The Case of Fukushima, *IZA DP No. 7691*.

- Isen, Adam, Maya Rossin-Slater, and W. Reed Walker. (2015). Every Breath You Take - Every Dollar You'll Make: The Long-Term Consequences of the Clean Air Act of 1970, *Working Paper, University of California, Berkeley.*

- Kannan S., D. Misra, J. Dvonch, and A. Krisnakamar. (2006). Exposures to Airborne Particulate Matter and Adverse Perinatal Outcomes: A Biologically Plausible Mechanistic Framework for Exploring Potential Effect Modification by Nutrition, *Environmental Health Perspectives* 114(11):1636-1642.

- Kowaleski-Jones, Lori, and Greg J. Duncan. (2002). Effects of Participation in the WIC Program on Birthweight: Evidence From the National Longitudinal Survey of Youth, *American Journal of Public Health* 92(5): 799-804.

- Lavaine, Emmanuelle, and Matthew J. Neidell. (2013). Energy Production and Health Externalities: Evidence From Oil Refinery Strikes in France, *NBER Working Paper* 18974.

- Lewis, Joshua, and Edson R. Severnini. (2014). The Value of Rural Electricity: Evidence from the Rollout of the U.S. Power Grid, *Working Paper - Carnegie Mellon University.*

- Pace, Thompson G., and Neil H. Frank. (1986). Procedures for Estimating Probability of Nonattainment of a PM_{10} NAAQS Using Total Suspended Particulate or PM_{10} data, *U.S. Environmental Protection Agency Report* EPA-450/4-86-017.

- Parkhurst, William J., Roger L. Tanner, Frances P. Weatherford, Ralph J. Valente, and James F. Meagher. (1999). Historic $PM_{10}/PM_{2.5}$ Concentrations in the Southeastern United States - Potential Implications of the Revised Particulate Matter Standard, *Journal of the Air & Waste Management Association* 49(9): 1060-1067.

- Stieb, David M., Li Chen, Maysoon Eshoul, and Stan Judek. (2012). Ambient air pollution, birth weight and preterm birth: A Systematic Review and Meta-Analysis, *Environmental Research* 117: 100-111.

- Tennessee Valley Authority (TVA). (1985). 1985 Annual Report. Available at *hathitrust.org*.

- Tennessee Valley Authority (TVA). (1986). 1986 Annual Report. Available at *hathitrust.org*.

Appendix A

The shutdown of the TVA nuclear power plants in 1985 triggered a response in terms of power generation by TVA coal-fired power plants. County fixed-effect regressions using annual data for all coal plants from 1982 until 1987 reveal that most of that response vanishes away when one controls for technology and cost variables. That is, the cost structure of coal plants can explain relatively well the observed power generation response, suggesting that society's pressure to avoid exposure to pollution might not have been the underlying force behind the heterogeneity in response across plants.

Tables A.1 and A.2 show the results. In the first column, only the dummy for the nuclear shutdown is included, and its coefficient is statistically significant. In the second column, efficiency - a proxy for plant technology - is added, and its coefficient is also significant, but it does not change the magnitude and significance of the effect of the nuclear shutdown. The third column incorporates the cost per kW of installed capacity, reflecting the sunk investment in those power plants. Its coefficient does not seem to be an important factor affecting the response to the nuclear shutdown. The fourth column adds the cost of coal by cents per million Btu, and its coefficient is significant and does affect the association between the nuclear shutdown and the dependent variables. Lastly, in the fifth column, the Clean Air Act non-attainment designation is included, without any impact on the coefficient of the other covariates. Therefore, it appears that variable costs in coal-fired power plants may be the driving force of the power generation response to the nuclear shutdown.

Table A.3 presents the summary statistics of all variables mentioned above. As we can see, the plant with the highest power generation response - Paradise - had the lowest coal costs before the nuclear shutdown. Similarly, Cumberland, the plant with the second highest response, had the largest reduction in coal costs after the shutdown. These pieces of information illustrate the underlying importance of cost considerations in the reaction to the shutdown. Indeed, the overall reduction in coal costs is the most noticeable feature of table A.3.

It is also interesting to see that the response to the nuclear shutdown did not happen through the Allen power plant, which is close to one of the largest urban centers in the TVA area, but did affect power generation at Paradise, situated in a county with small population density. Since both plants were in counties out of attainment under the Clean Air Act, it might be the case that TVA was trying to act like a social planner, although regression analysis did not corroborate this line of reasoning, and air pollution was never a front and center issue in TVA annual reports.

Table A.1: Reasons for the Power Generation Response

Dep. Var.: Power Generation (millions kWh)	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
Nuclear Shutdown: 1(Year ≥ 1985)	1,049.56***	1,093.00***	1,051.27***	546.95	538.27
	(301.28)	(334.25)	(300.45)	(388.90)	(402.83)
Efficiency		693.39***	719.39**	799.27**	796.61**
		(188.90)	(307.23)	(305.86)	(312.72)
Cost per kW of Installed Capacity			1.25	3.61	4.50
			(7.60)	(9.89)	(10.02)
Cents per Million BTU				-20.71*	-21.39*
				(10.29)	(10.86)
Clean Air Act - Non-Attainment Status					399.86
					(730.27)
Observations	66	66	66	66	66
R-squared	0.87	0.89	0.89	0.90	0.90

Notes: Standard errors clustered by plant in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table A.2: Reasons for the Capacity Factor Response

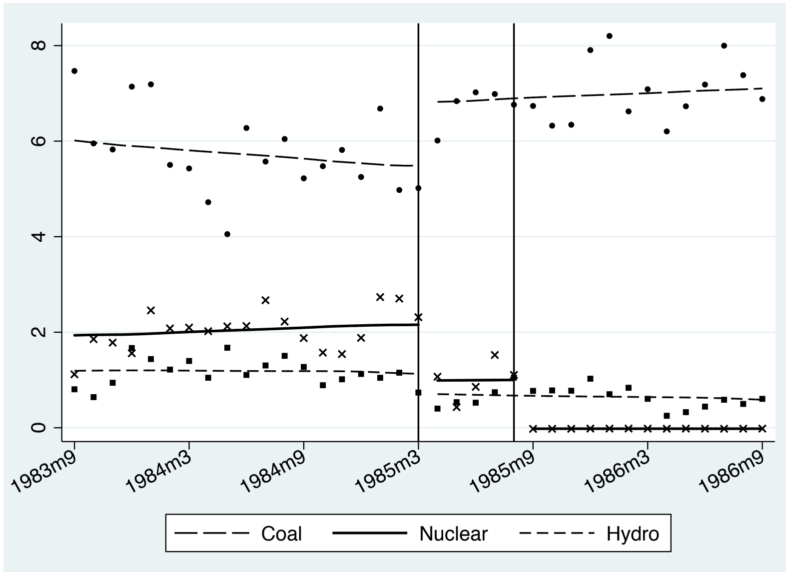
Dep. Var.: Capacity Factor (%)	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
Nuclear Shutdown: 1(Year ≥ 1985)	6.68***	6.93***	7.10***	4.35	4.33
	(1.78)	(1.87)	(1.93)	(2.44)	(2.48)
Efficiency		3.92***	3.81**	4.24**	4.24**
		(0.96)	(1.37)	(1.46)	(1.47)
Cost per kW of Installed Capacity			-0.01	0.01	0.01
			(0.04)	(0.05)	(0.05)
Cents per Million BTU				-0.11**	-0.11**
				(0.04)	(0.05)
Clean Air Act - Non-Attainment Status					0.77
					(3.13)
Observations	66	66	66	66	66
R-squared	0.84	0.86	0.86	0.87	0.87

Notes: Standard errors clustered by plant in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table A.3: Reasons for Response - Summary Statistics

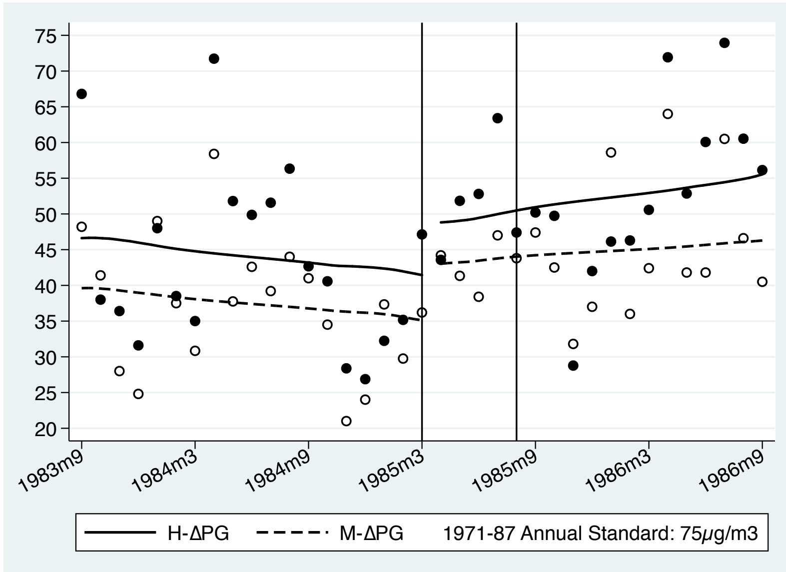
Plants	Groups	Power Gen. (millions kWh)	Capacity Factor (%)	First Year of Operation	Nameplate Capacity	Efficiency (%)	Cost per kW of Installed Capacity	Cents per Million BTU	Clean Air Act - Non-Attainment Status
1982-1984									
Paradise	H-ΔPG	8,067.07	36.00	1963	2,558	34.14	223.16	142.00	1
Cumberland	M-ΔPG	11,592.20	50.90	1973	2,600	33.93	245.85	196.33	0
Johnsonville	L-ΔPG	4,132.73	31.76	1951	1,485	31.29	210.77	160.33	0
Shawnee	L-ΔPG	5,698.33	37.17	1953	1,750	33.38	193.68	216.00	1
Widows Creek	L-ΔPG	4,235.67	24.56	1952	1,969	32.43	210.63	179.33	0.33
Colbert	L-ΔPG	5,967.17	50.46	1955	1,350	33.90	204.83	197.33	0
Kingston	L-ΔPG	7,667.37	51.49	1954	1,700	34.27	176.03	178.67	0
Bull Run	N-ΔPG (Control)	5,500.67	66.10	1967	950	37.95	207.57	182.33	0
Allen	N-ΔPG (Control)	3,654.70	42.14	1959	990	35.34	49.39	169.67	0.67
John Sevier	N-ΔPG (Control)	5,006.63	71.44	1955	800	36.00	164.32	172.67	0
Gallatin	N-ΔPG (Control)	6,081.47	55.31	1956	1,255	36.20	181.31	178.67	0
All		6,145.82	47.03	1958	1,582	34.44	187.96	179.39	0.27
1985-1987									
Paradise	H-ΔPG	10,256.57	45.77	1963	2,558	33.42	339.96	139.67	1
Cumberland	M-ΔPG	13,829.60	60.72	1973	2,600	34.17	259.84	151.33	0
Johnsonville	L-ΔPG	5,796.63	44.55	1951	1,485	31.00	212.04	137.00	0
Shawnee	L-ΔPG	5,710.27	37.25	1953	1,750	32.98	199.17	178.00	1
Widows Creek	L-ΔPG	5,588.83	32.41	1952	1,969	31.59	230.52	155.00	0
Colbert	L-ΔPG	7,700.57	65.12	1955	1,350	34.19	227.93	188.33	0
Kingston	L-ΔPG	9,334.70	62.68	1954	1,700	34.89	180.97	151.67	0
Bull Run	N-ΔPG (Control)	5,464.97	65.67	1967	950	38.28	237.99	208.00	0
Allen	N-ΔPG (Control)	3,781.33	43.60	1959	990	35.34	177.81	145.00	0
John Sevier	N-ΔPG (Control)	5,178.87	73.90	1955	800	35.78	182.76	139.00	0
Gallatin	N-ΔPG (Control)	6,506.80	59.18	1956	1,255	36.52	199.72	153.33	0
All		7,195.38	53.71	1958	1,582	34.38	222.61	158.76	0.18

Figure 1: TVA Power Generation (Terawatt Hours)



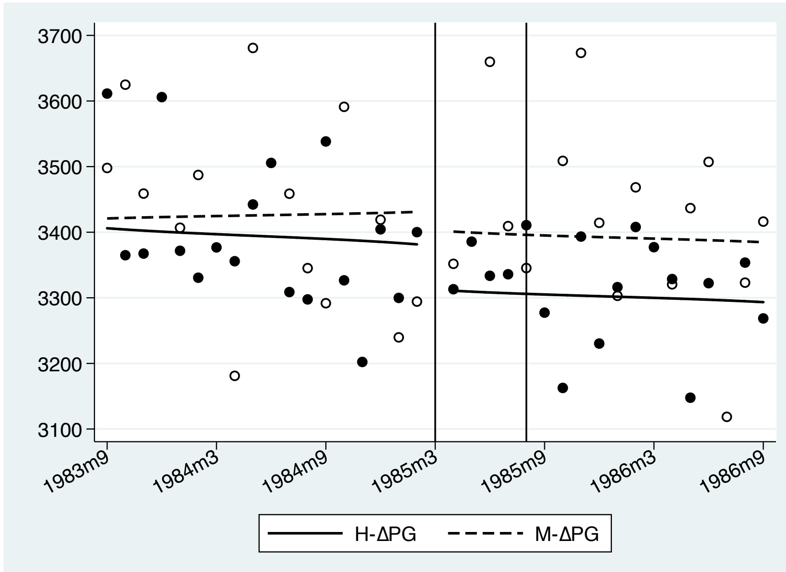
Notes: This figure plots monthly EIA electricity generation data at the plant-fuel level in the TVA area. Kernel-weighted local polynomial regressions of those monthly values on time provide the smoothed values graphed in the figure. (The kernel function used in the smoothing was Epanechnikov, the kernel bandwidth was six, and the degree of the polynomial smooth was zero.) The first solid vertical is at March 1985, when the first TVA nuclear power plant - Browns Ferry - was shut down. The second solid vertical is at August 1985, when the second and last TVA nuclear power plant - Sequoyah - was shut down.

Figure 2: TSP Concentration - >50 $\mu g/m^3$ vs. <50 $\mu g/m^3$



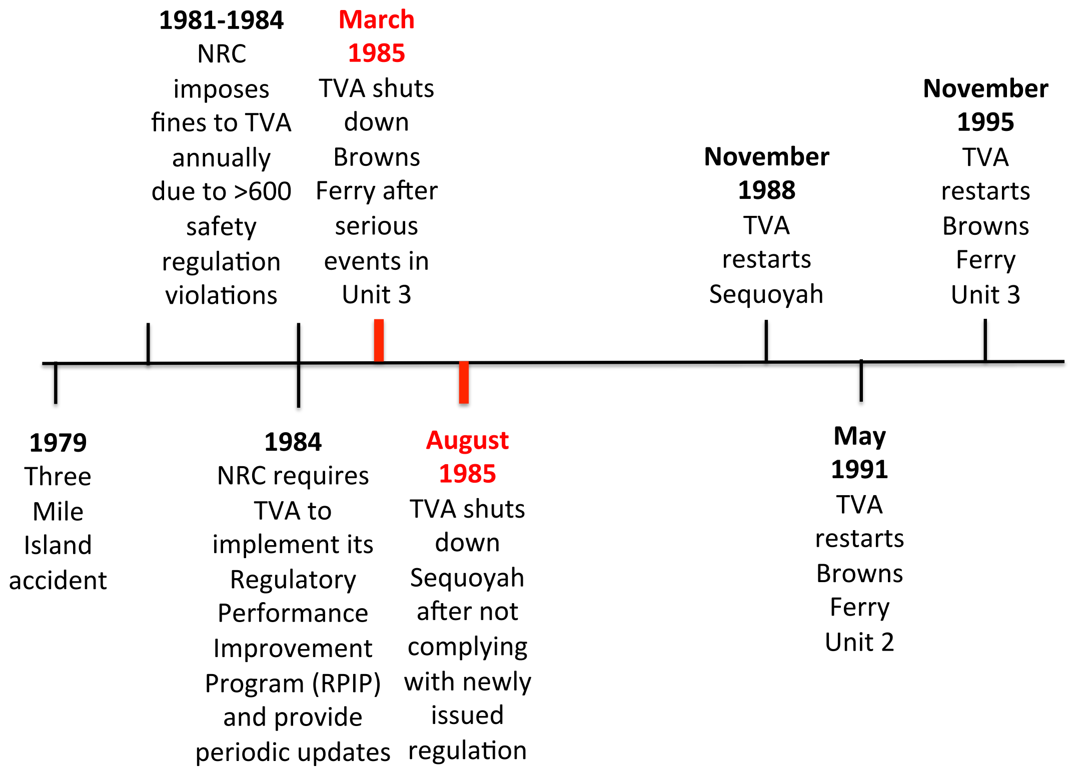
Notes: This figure plots monthly TSP data from EPA at the county level in the TVA area. Kernel-weighted local polynomial regressions of those monthly values on time provide the smoothed values graphed in the figure. (The kernel function used in the smoothing was Epanechnikov, the kernel bandwidth was six, and the degree of the polynomial smooth was zero.) The first solid vertical is at March 1985, when the first TVA nuclear power plant - Browns Ferry - was shut down. The second solid vertical is at August 1985, when the second and last TVA nuclear power plant - Sequoyah - was shut down. $H - \Delta PG$ represents the county with a coal-fired power plant with a high response to the nuclear shutdown in terms of power generation. $M - \Delta PG$ represents the county with a coal plant with a medium response to the nuclear shutdown. The "Annual Standard" refers to the National Ambient Air Quality Standards (NAAQS) for TSP set by EPA in 1971.

Figure 3: Birth Weight - >50 $\mu g/m^3$ vs. <50 $\mu g/m^3$



Notes: This figure plots birth weight data from the National Vital Statistics System at the county level in the TVA area. Each dot represents the average birth weight of all babies born in a month in a county in the TVA area. Only values between 3,100 and 3,700 grams are shown in the scatterplot to make it easier to see the changes in (smoothed) birth weight. Kernel-weighted local polynomial regressions of those monthly values on time provide the smoothed values graphed in the figure. (The kernel function used in the smoothing was Epanechnikov, the kernel bandwidth was nine, and the degree of the polynomial smooth was zero.) The first solid vertical is at March 1985, when the first TVA nuclear power plant - Browns Ferry - was shut down. The second solid vertical is at August 1985, when the second and last TVA nuclear power plant - Sequoyah - was shut down. $H - \Delta PG$ represents the county with a coal-fired power plant with a high response to the nuclear shutdown in terms of power generation. $M - \Delta PG$ represents the county with a coal plant with a medium response to the nuclear shutdown.

Figure 4: Timeline - TVA Nuclear Shutdown



Source: Documents from the Union of Concerned Scientists (UCS).
Note: "… outages reflect a regulatory bias first identified by the various inquiries into the Three Mile Island Unit 2 accident."

Figure 5: Map of TVA Power Plants - 1985

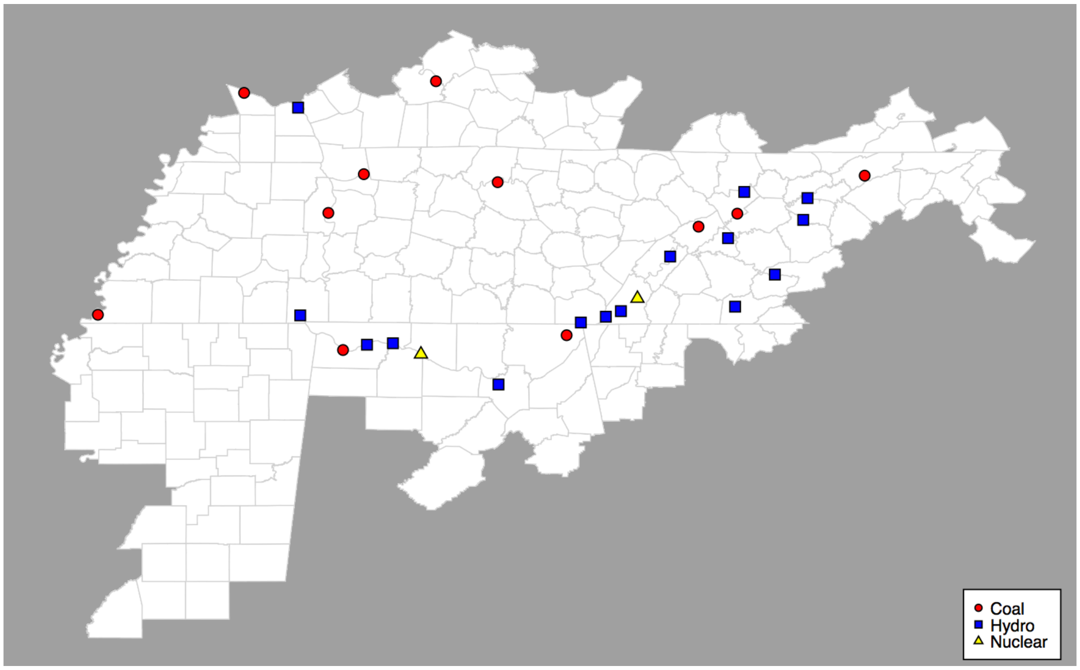


Figure 6: Map of TVA Coal and Nuclear Power Plants -1985

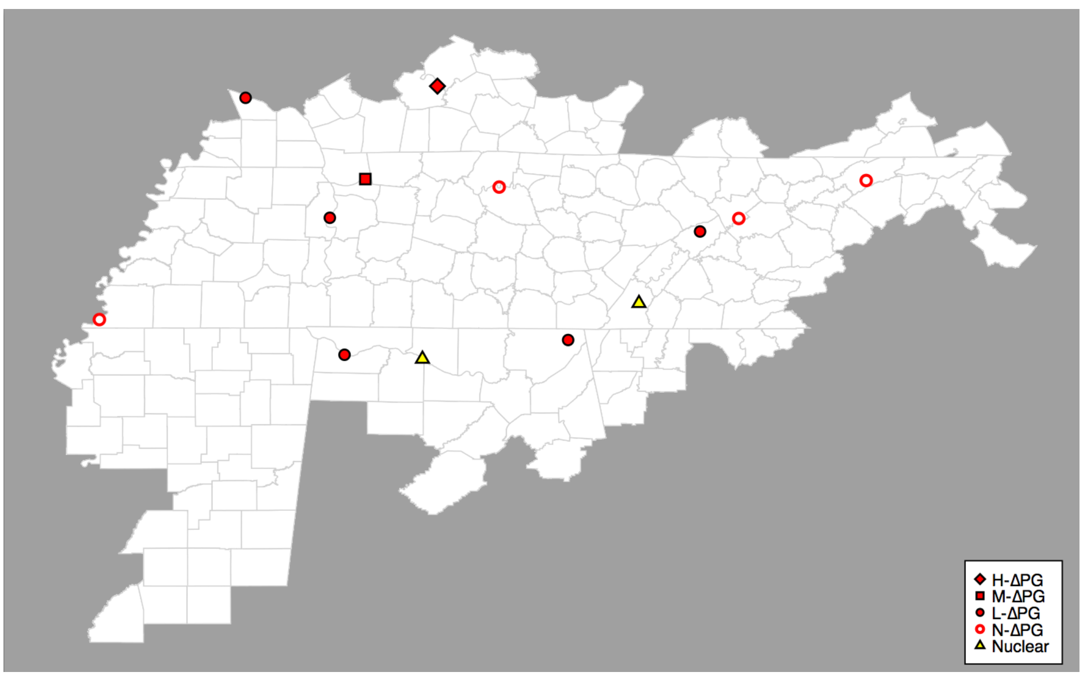
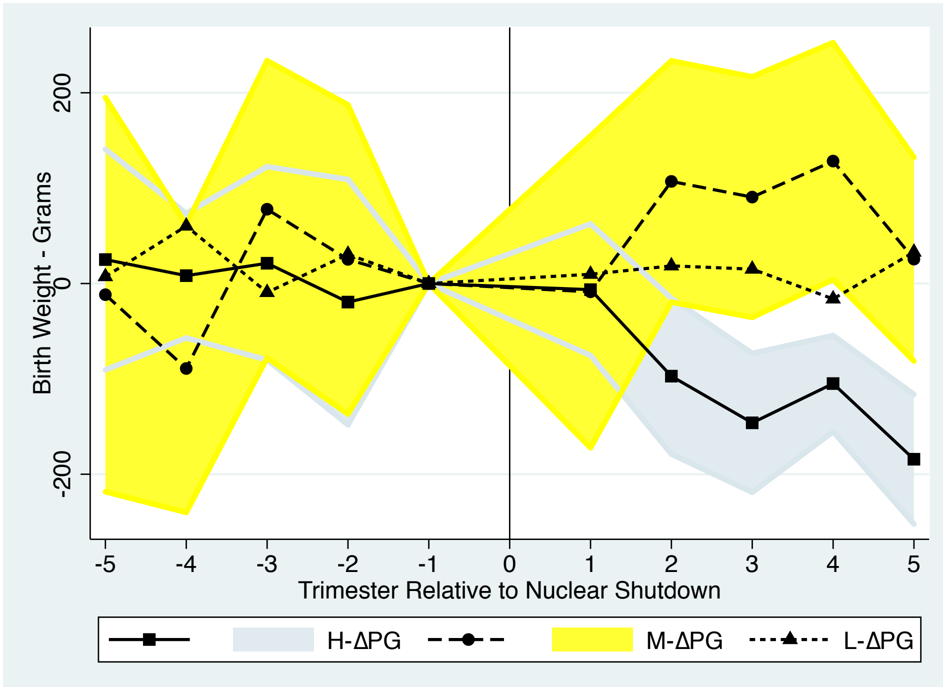


Figure 7: Birth Weight - Event Study of the Nuclear Shutdown



Notes: This figure plots the coefficients of an event study regression based on equation 11 for birth weight. The analysis spans five trimesters before and after the TVA nuclear shutdown in March 1985.

Table 1: Heterogeneity in response to nuclear shutdown

Groups - Coal Power Plants	Before Nuclear Shutdown			After Nuclear Shutdown		
	PG (GWh)	TSP ($\mu g/m^3$)	BWeight (grams)	ΔPG (GWh)	ΔTSP ($\mu g/m^3$)	ΔBWeight (grams)
H-ΔPG	280.26	43.61	3395.12	186.90	9.06	-93.34
M-ΔPG	511.44	37.13	3438.60	121.75	7.63	-49.53
L-ΔPG	218.77	43.94	3381.11	54.20	1.41	-15.89
N-ΔPG	183.14	48.44	3314.72	-4.15	-0.30	36.56
Total	**232.85**	**45.17**	**3360.27**	**46.88**	**1.83**	**-3.80**

Notes: This table presents some summary statistics for TVA counties classified in one of the groups based on intensity of the response to the nuclear shutdown: $H - \Delta PG$ (high response), $M - \Delta PG$ (medium response), $L - \Delta PG$ (low response), and $N - \Delta PG$ (negligible response). "PG" represents power generation, "TSP" total suspended particles, and "BWeight" birth weight.

Table 2: EPA Standards and "Safe" Threshold - TSP, PM_{10} and $PM_{2.5}$

Annual Standards	TSP	PM_{10}	$PM_{2.5}$
1971-87	75µg/m^3		
1987-97		50µg/m^3	
1997-06		50µg/m^3	15µg/m^3
2006-12			15µg/m^3
2012-...			12µg/m^3
Suggestive Threshold	50µg/m^3	24µg/m^3	14µg/m^3

Source: epa.gov/ttn/naaqs/standards/pm/s_pm_history.html

Table 3: Sample for Birth Weight Analysis

Coal Plants	Group	Obs - Main	Percentage	Obs	Percentage
Paradise	H-ΔPG	1,177	2.10	1,177	1.96
Cumberland	M-ΔPG	235	0.42	235	0.39
Johnsonville	L-ΔPG	511	0.91	511	0.85
Shawnee	L-ΔPG	2,437	4.36	2,437	4.06
Widows Creek	L-ΔPG	1,967	3.52	1,967	3.28
Colbert	L-ΔPG	2,096	3.75	2,096	3.50
Kingston	L-ΔPG	0	0.00	1,640	2.73
Bull Run	N-ΔPG (Control)	0	0.00	2,406	4.01
Allen	N-ΔPG (Control)	42,195	75.45	42,195	70.36
John Sevier	N-ΔPG (Control)	1,573	2.81	1,573	2.62
Gallatin	N-ΔPG (Control)	3,730	6.67	3,730	6.22
Total	**All**	55,921	100.00	59,967	100.00

Notes: This table presents some summary statistics for TVA counties classified in one of the groups based on intensity of the response to the nuclear shutdown: $H-\Delta PG$ (high response), $M-\Delta PG$ (medium response), $L-\Delta PG$ (low response), and $N-\Delta PG$ (negligible response). Each row shows the name of the coal-fired plant located in the county whose data are tabulated above. "Main" represents the sample used in the main analysis, and it refers to the first two columns of data in the table. The last two columns include information on two counties which have coal plants but are neighbors. They are excluded from the main analysis because of potential pollution spillovers. (Results are robust to their inclusion.)

Table 4: Response of Power Generation and Pollution - Coal

Dep Var RHS Var	Class of ΔPG	GenCoal DNucShut (1)	ln(GenCoal) DNucShut (2)	GenCoal GenNuc (3)	TSP DNucShut (4)	ln(TSP) DNucShut (5)	SO2 DNucShut (6)	ln(SO2) DNucShut (7)
Paradise	H-ΔPG	431,051***	0.6368***	-0.2307***	11.94***	0.28***	1.42*	0.21*
		(66,725)	(0.1069)	(0.0391)	(3.68)	(0.08)	(0.80)	(0.12)
Cumberland	M-ΔPG	302,085***	0.3906***	-0.1214**	8.90**	0.25***	-0.26	-0.07
		(115,219)	(0.1390)	(0.0584)	(3.53)	(0.08)	(0.70)	(0.10)
Johnsonville	L-ΔPG	219,876***	0.5387***	-0.1060***	4.31	0.13	0.95*	0.13
		(38,161)	(0.0901)	(0.0188)	(3.26)	(0.08)	(0.50)	(0.08)
Shawnee	L-ΔPG	192,411***	0.4953***	-0.1018***	5.72	0.14*	0.48	0.01
		(59,170)	(0.1314)	(0.0235)	(3.60)	(0.07)	(0.53)	(0.09)
Widows Creek	L-ΔPG	166,730**	0.6083**	-0.0878**	4.04	0.10	0.52	0.07
		(72,177)	(0.2928)	(0.0391)	(3.16)	(0.08)	(0.55)	(0.10)
Colbert	L-ΔPG	136,005***	0.2827***	-0.0758***	1.79	0.06	1.70***	0.29***
		(35,879)	(0.0842)	(0.0181)	(3.47)	(0.08)	(0.57)	(0.10)
Kingston	L-ΔPG	137,868**	0.2576***	-0.0814***	-2.40	-0.04	-0.47	-0.15**
		(56,189)	(0.0858)	(0.0230)	(3.94)	(0.09)	(0.48)	(0.07)
Bull Run	Control	65,555	0.1457	-0.0367	0.01	0.01	2.04***	0.24***
	(N-ΔPG)	(107,146)	(0.1431)	(0.0350)	(3.64)	(0.08)	(0.70)	(0.09)
Allen	Control	60,093	0.1641	-0.0262	-1.60	-0.00	2.60***	0.34***
	(N-ΔPG)	(42,238)	(0.1154)	(0.0220)	(3.14)	(0.06)	(0.60)	(0.09)
John Sevier	Control	49,758	0.1405	-0.0319	4.98	0.12	-0.51	-0.02
	(N-ΔPG)	(41,554)	(0.1029)	(0.0214)	(3.28)	(0.08)	(0.76)	(0.10)
Gallatin	Control	-12,279	0.0200	-0.0017	1.14	0.09	0.15	-0.00
	(N-ΔPG)	(44,484)	(0.1020)	(0.0253)	(6.96)	(0.14)	(0.97)	(0.11)
Pooled		166,384***	0.3301***	-0.0826***	3.23	0.10*	0.80*	0.10
		(51,390)	(0.0888)	(0.0259)	(2.44)	(0.06)	(0.45)	(0.06)
F-tests		Sum = 1800GWh		Sum = -1MWh	Corr((1),(4))		Corr((1),(6))	
F-stat		0.02		0.33	0.80		-0.01	
Prob > F-stat		0.8860		0.5658	R^2 LRM: 0.65		R^2 LRM: 0.00	
F-tests		Sum = 2100GWh		Sum = -1.15MWh	Parad=Cumb			
F-stat		0.98		2.1	0.65			
Prob > F-stat		0.3229		0.1477	0.4196			
Observations		444	403	444	408	408	402	402

Notes: Newey-West standard errors with three lags in parentheses. (ΔNucPG ≈ −1776.25GWh)
*** p<0.01, ** p<0.05, * p<0.1

Table 5: Response of Power Generation and Pollution - Hydro

Dep Var RHS Var	GenCoal DNucShut (1)	ln(GenCoal) DNucShut (2)	GenCoal GenNuc (3)	TSP DNucShut (4)	ln(TSP) DNucShut (5)	SO2 DNucShut (6)	ln(SO2) DNucShut (7)
Wilson	-106,570***	-0.2234	0.0538***	3.48	0.10	1.81	0.08
	(22,891)	(0.1859)	(0.0109)	(3.06)	(0.07)	(1.45)	(0.11)
Wheeler	-36,689***	-0.0367	0.0164**	0.52	0.06		
	(12,472)	(0.2098)	(0.0075)	(2.62)	(0.07)		
Guntersville	-20,790***	-0.1373	0.0091***	0.47	0.03		
	(4,735)	(0.1843)	(0.0026)	(2.01)	(0.04)		
Kentucky	-17,997***	0.1316	0.0099***	1.78	0.07		
	(5,634)	(0.1707)	(0.0031)	(4.48)	(0.08)		
Hiwassee	-11,069**	-0.2620	0.0045*				
	(4,511)	(0.2467)	(0.0023)				
Fontana	-32,886***	-0.2235	0.0165***				
	(8,985)	(0.1957)	(0.0054)				
Norris	-6,435**	-0.0700	0.0035**	-2.13	-0.03	3.97***	0.28**
	(3,211)	(0.2171)	(0.0016)	(4.06)	(0.08)	(1.50)	(0.13)
Raccoon Mountain	-8,495	0.0128	0.0042	-3.10	-0.05		
	(19,278)	(0.1784)	(0.0095)	(1.98)	(0.04)		
Pickwick Landing	-37,702***	-0.0157	0.0196***	0.67	0.04		
	(9,230)	(0.1616)	(0.0050)	(2.49)	(0.06)		
Cherokee	-3,899	-0.0436	0.0010				
	(3,558)	(0.2201)	(0.0018)				
Fort Loudoun	-9,320	0.0297	0.0042				
	(10,802)	(0.4293)	(0.0055)				
Nickajack	-15,106***	-0.0720	0.0075***	-1.34	-0.02		
	(3,189)	(0.1631)	(0.0018)	(3.21)	(0.08)		
Watts Bar Hydro	-25,396***	-0.0541	0.0122***				
	(4,973)	(0.1681)	(0.0029)				
Douglas	-10,812**	-0.1555	0.0059**				
	(4,476)	(0.2125)	(0.0023)				
Pooled	-1,336	0.0888	-0.0003	-5.34**	-0.08	-0.19	0.04
	(4,864)	(0.1980)	(0.0025)	(2.40)	(0.05)	(1.20)	(0.08)
F-tests	Sum = 0GWh		Sum = 0MWh	Corr((1),(4))			
F-stat	71.91		58.99	-0.79			
Prob > F-stat	0.0000		0.0000	R^2 LRM: 0.62			
F-tests	Sum = -300GWh		Sum = 0.15MWh				
F-stat	1.14		0.69				
Prob > F-stat	0.2863		0.4059				
Observations	1,147	1,058	1,147	609	609	302	302

Notes: Newey-West standard errors with three lags in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table 6: Response of Birth Weight - Main Results and Mechanisms

Dep Var	BWeight	ln(BWeight)	BWeight	ln(BWeight)	GWeeks	ln(GWeeks)
	(1)	(2)	(3)	(4)	(5)	(6)
H-ΔPG	-134.1341***	-0.0536***	-86.9686***	-0.0289***	-0.5405***	-0.0155***
	(18.5561)	(0.0096)	(20.4241)	(0.0084)	(0.1151)	(0.0033)
M-ΔPG	1.8190	0.0125	23.0019	0.0170	-0.2990*	-0.0075*
	(35.8650)	(0.0124)	(35.8860)	(0.0107)	(0.1668)	(0.0045)
L-ΔPG	-4.3670	0.0030	-11.1787	-0.0010	0.1313	0.0036
	(14.6924)	(0.0057)	(13.8475)	(0.0047)	(0.0925)	(0.0024)
All Controls - Pref Specification	Yes	Yes	Yes	Yes	Yes	Yes
Quartic in Weeks of Gestation	No	No	Yes	Yes	-	-
H-ΔPG = M-ΔPG: Prob > Chi2	0.0000	0.0000	0.0020	0.0001	0.2721	0.1938
Observations	55,921	55,921	55,921	55,921	55,921	55,921
R-squared	0.1791	0.1715	0.3588	0.4666	0.1097	0.1136

Notes: Standard errors clustered by county and month/year in parentheses. *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level. Control variables from my preferred specification are county fixed effects, month-year dummies, infant and mother characteristics, a quadratic function in temperature and precipation in the month of birth, and per capita income and wages/salaries at the county level.

Table 7: Response of Birth Weight - Low Birth Weight

Dep Var	BWeight<2500	BWeight<2500	BWeight<2500	BWeight<1500	BWeight<1500	BWeight<1500
	(1)	(2)	(3)	(4)	(5)	(6)
H-ΔPG	0.0183*	-0.0028	0.0046	0.0204***	0.0069	0.0016
	(0.0102)	(0.0101)	(0.0115)	(0.0070)	(0.0057)	(0.0097)
M-ΔPG	-0.0197*	-0.0260**	-0.0174	-0.0229***	-0.0194***	-0.0167**
	(0.0106)	(0.0103)	(0.0132)	(0.0062)	(0.0066)	(0.0072)
L-ΔPG	0.0040	0.0064	0.0027	-0.0060**	-0.0040	-0.0048
	(0.0077)	(0.0067)	(0.0080)	(0.0029)	(0.0027)	(0.0033)
All Controls - Pref Specification	Yes	Yes	Yes	Yes	Yes	Yes
Quartic in Weeks of Gestation	No	Yes	No	No	Yes	No
Jobs/Wage Bill in Power Plants	No	No	Yes	No	No	Yes
H-ΔPG = M-ΔPG: Prob > Chi2	0.0058	0.0656	0.3894	0.0000	0.0048	0.1944
Observations	55,921	55,921	55,921	55,921	55,921	55,921
R-squared	0.1186	0.2898	0.1186	0.0581	0.4341	0.0583

Notes: Standard errors clustered by county and month/year in parentheses. *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level. Control variables from my preferred specification are county fixed effects, month-year dummies, infant and mother characteristics, a quadratic function in temperature and precipation in the month of birth, and per capita income and wages/salaries at the county level.

Table 8: Response of Birth Weight - Preferred Specification

Dep Var: Birth Weight	(1)	(2)	(3)	(4)	(5)
H-ΔPG	-100.7955***	-111.7510***	-111.4839***	-111.6665***	-134.1341***
	(15.1302)	(16.4545)	(15.0273)	(15.8956)	(18.5561)
M-ΔPG	-6.4201	-13.9859	-36.1604	-36.7420	1.8190
	(24.7203)	(25.7608)	(34.2865)	(35.0907)	(35.8650)
L-ΔPG	-4.7234	-14.5492	1.0185	5.2950	-4.3670
	(29.7916)	(29.9847)	(19.3031)	(19.0561)	(14.6924)
County FE	Yes	Yes	Yes	Yes	Yes
Month-Year FE	No	Yes	Yes	Yes	Yes
Mother/Infant Characteristics	No	No	Yes	Yes	Yes
Quadratic in Temp/Prec at Birth	No	No	No	Yes	Yes
PCI and PCWages/Salaries	No	No	No	No	Yes
H-ΔPG = M-ΔPG: Prob > Chi2	0.0092	0.0083	0.0185	0.0357	0.0000
Observations	55,921	55,921	55,921	55,921	55,921
R-squared	0.0101	0.0110	0.1789	0.1790	0.1791

Notes: Standard errors clustered by county and month/year in parentheses. *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level. Control variables from my preferred specification are county fixed effects, month-year dummies, infant and mother characteristics, a quadratic function in temperature and precipation in the month of birth, and per capita income and wages/salaries at the county level.

Table 9: Response of Birth Weight - Robustness Checks in Time Frame

Dep Var: BWeight	NucShut ± 12m	NucShut ± 15m	NucShut ± 18m	NucShut ± 21m	NucShut ± 24m
	(1)	(2)	(3)	(4)	(5)
H-ΔPG	-63.2967**	-118.0406***	-134.1341***	-106.1130***	-83.9360***
	(30.3653)	(28.1921)	(18.5561)	(20.6754)	(17.1056)
M-ΔPG	-0.2046	56.1803	1.8190	-16.8052	-28.3878
	(49.9263)	(43.3363)	(35.8650)	(32.5150)	(27.9980)
L-ΔPG	-6.1159	-4.7276	-4.3670	-7.7775	-3.9815
	(21.4798)	(17.4063)	(14.6924)	(12.6721)	(15.2165)
All Controls - Pref Specification	Yes	Yes	Yes	Yes	Yes
H-ΔPG = M-ΔPG: Prob > Chi2	0.2839	0.0019	0.0000	0.0058	0.0791
Observations	38,215	47,002	55,921	65,885	74,708
R-squared	0.1792	0.1788	0.1791	0.1779	0.1802

Notes: Standard errors clustered by county and month/year in parentheses. *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level. Control variables from my preferred specification are county fixed effects, month-year dummies, infant and mother characteristics, a quadratic function in temperature and precipation in the month of birth, and per capita income and wages/salaries at the county level.

Table 10: Response of Birth Weight - Other Robustness Checks

Dep Var: BWeight	Job/WB PPlants	Temp/Prec Preg	W/ CoalNeigb	W/o Allen	W/ weights	Reweighting
	(1)	(2)	(3)	(4)	(5)	(6)
H-ΔPG	-134.3521***	-129.2601***	-122.4262***	-136.6759***	-134.3152***	-132.7703***
	(34.3627)	(27.1546)	(29.0158)	(40.2837)	(18.4287)	(22.2781)
M-ΔPG	8.7913	-1.5520	-22.1264	-25.0069	1.2754	9.3906
	(35.8609)	(43.6717)	(42.4918)	(52.4386)	(36.9627)	(36.8595)
L-ΔPG	-1.1635	-6.3954	-9.1643	-16.2679	-4.0642	-2.5451
	(19.5168)	(16.0046)	(15.0243)	(30.8777)	(14.4026)	(14.9242)
All Controls - Pref Specification	Yes	Yes	Yes	Yes	Yes	Yes
H-ΔPG = M-ΔPG: Prob > Chi2	0.0010	0.0017	0.0123	0.0173	0.0001	0.0000
Observations	55,921	55,921	60,688	13,726	55,921	55,921
R-squared	0.1791	0.1792	0.1806	0.1511	0.1791	0.1797

Notes: Standard errors clustered by county and month/year in parentheses. *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level. Control variables from my preferred specification are county fixed effects, month-year dummies, infant and mother characteristics, a quadratic function in temperature and precipation in the month of birth, and per capita income and wages/salaries at the county level.

Table 11: Response of Birth Weight - Event Study

Dep Variable: Birth Weight	**H-ΔPG (1)**	**M-ΔPG (2)**	**L-ΔPG (3)**
Birth in 6th Trim Before NucShut	39.8305	163.3557**	-11.2719
	(48.0943)	(72.7196)	(22.1446)
Birth in 5th Trim Before NucShut	25.0984	-11.7332	7.2304
	(59.0361)	(105.4326)	(27.4729)
Birth in 4th Trim Before NucShut	8.2076	-89.1711	60.2397
	(33.3092)	(76.9838)	(38.8237)
Birth in 3rd Trim Before NucShut	21.2238	77.8573	-9.4000
	(51.7052)	(79.5036)	(43.5396)
Birth in 2nd Trim Before NucShut	-19.5173	25.2760	30.6538
	(65.6190)	(82.7206)	(22.6833)
Birth in 1st Trim Before NucShut	0	0	0
Birth in 1st Trim After NucShut	-6.4558	-8.7118	9.6738
	(35.1905)	(83.4382)	(38.0388)
Birth in 2nd Trim After NucShut	-97.1999**	107.0312*	18.4863
	(41.7047)	(64.5444)	(24.0461)
Birth in 3rd Trim After NucShut	-146.1554***	90.6054	15.0754
	(37.1477)	(64.3648)	(36.1800)
Birth in 4th Trim After NucShut	-104.9641***	128.3572**	-16.1667
	(25.6917)	(63.3985)	(28.1728)
Birth in 5th Trim After NucShut	-184.3147***	25.5224	32.8948
	(34.6792)	(54.5197)	(28.9058)
Birth in 6th Trim After NucShut	-177.9129***	-89.1949	-33.3750
	(22.1823)	(55.8944)	(51.0436)
All Controls - Pref Specification		Yes	
Observations		55,921	
R-squared		0.1794	

Notes: Standard errors clustered by county and month/year in parentheses. *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level. Control variables from my preferred specification are county fixed effects, month-year dummies, infant and mother characteristics, a quadratic function in temperature and precipation in the month of birth, and per capita income and wages/salaries at the county level.

Table 12: Response of Power Generation and Pollution - Coal - Placebo

Dep Var RHS Var	Class of ΔPG	GenCoal DNucShut (1)	ln(GenCoal) DNucShut (2)	GenCoal GenNuc (3)	TSP DNucShut (4)	ln(TSP) DNucShut (5)
Paradise	H-ΔPG	33,374	0.1647	-0.1040	-0.99	-0.04
		(104,827)	(0.1779)	(0.1737)	(5.98)	(0.09)
Cumberland	M-ΔPG	49,428	0.2856	0.0402	-7.42**	-0.17**
		(99,118)	(0.1819)	(0.1424)	(3.17)	(0.07)
Johnsonville	L-ΔPG	-47,504	0.0054	-0.1638***	-0.95	-0.01
		(42,218)	(0.1270)	(0.0574)	(2.78)	(0.06)
Shawnee	L-ΔPG	-42,936	0.0533	-0.1816**	-3.83	-0.12
		(60,221)	(0.1336)	(0.0876)	(4.71)	(0.08)
Widows Creek	L-ΔPG	3,820	0.0951	-0.1119*	-4.42	-0.07
		(39,556)	(0.1179)	(0.0625)	(2.72)	(0.06)
Colbert	L-ΔPG	102,686**	0.3130***	-0.1536***	-1.05	-0.02
		(41,519)	(0.1156)	(0.0515)	(2.99)	(0.07)
Kingston	L-ΔPG	4,169	0.1403	-0.0997*	-11.88***	-0.21**
		(47,458)	(0.1197)	(0.0580)	(4.12)	(0.08)
Bull Run	Control	117,842	0.2004	-0.0021	-7.34**	-0.14*
	(N-ΔPG)	(81,779)	(0.1811)	(0.2014)	(3.73)	(0.08)
Allen	Control	37,133	0.2348*	-0.1449***	-3.66	-0.10*
	(N-ΔPG)	(35,415)	(0.1302)	(0.0486)	(3.64)	(0.06)
John Sevier	Control	-9,943	0.0541	-0.0369	-0.25	-0.06
	(N-ΔPG)	(39,513)	(0.1290)	(0.0530)	(5.10)	(0.08)
Gallatin	Control	53,533	0.2134	-0.1723***	-5.07	-0.09
	(N-ΔPG)	(58,815)	(0.1364)	(0.0564)	(4.34)	(0.09)
Pooled		5,116	-0.1096	-0.1205***	-6.43***	-0.12**
		(43,352)	(0.0950)	(0.0411)	(2.47)	(0.05)
F-tests		Sum = -200GWh		Sum = -1MWh	Corr((1),(4))	
F-stat		2.39		0.09	-0.18	
Prob > F-stat		0.1233		0.7677	R^2 LRM: 0.03	
Observations		444	439	444	432	432

Notes: Newey-West standard errors with three lags in parentheses. (ΔNucPG ≈ 221.13GWh vs. −1776.25GWh)
*** p<0.01, ** p<0.05, * p<0.1

Table 13: Response of Birth Weight and Weeks of Gestation - Placebo

Dep Var	BWeight (1)	ln(BWeight) (2)	BWeight<2500 (3)	BWeight<1500 (4)	GWeeks (5)	ln(GWeeks) (6)
H-ΔPG	6.4498	-0.0040	-0.0006	0.0072	0.1504	0.0022
	(36.4644)	(0.0125)	(0.0124)	(0.0059)	(0.1641)	(0.0045)
M-ΔPG	-49.4146	-0.0240	0.0466***	0.0027	-0.7289***	-0.0188***
	(52.0110)	(0.0173)	(0.0180)	(0.0073)	(0.1534)	(0.0040)
L-ΔPG	10.4231	-0.0032	0.0061	0.0066*	-0.1186	-0.0039
	(14.9860)	(0.0059)	(0.0081)	(0.0035)	(0.1082)	(0.0029)
All Controls - Pref Specification	Yes	Yes	Yes	Yes	Yes	Yes
H-ΔPG = M-ΔPG: Prob > Chi2	0.4300	0.3923	0.0059	0.6025	0.0000	0.0001
Observations	33,635	33,635	33,635	33,635	33,635	33,635
R-squared	0.2036	0.1995	0.1274	0.0770	0.1494	0.1473

Notes: Standard errors clustered by county and month/year in parentheses. *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level. Control variables from my preferred specification are county fixed effects, month-year dummies, infant and mother characteristics, a quadratic function in temperature and precipation in the month of birth, and per capita income and wages/salaries at the county level.