



Nuclear power: a risky endeavor or an opportunity for the future?

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Dissertation written under the supervision of Professor Joana Silva

Dissertation submitted in partial fulfilment of the requirements for the MSc in
Economics, at the Universidade Católica Portuguesa, January 2023.

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Abstract

In an age where a worldwide climate strategy is needed to mitigate the effects of climate change and global warming, the use of nuclear power as a source of electricity generation is currently a topic of discussion, amidst debates over energy decarbonization and security. This dissertation examines, theoretically and empirically, the effects of the closures of nuclear power plants on electricity prices and mortality. Using state-level monthly data on temperature, mortality, demographics, and the electricity market, I perform an event study that quantifies the impact of the closure of five nuclear power plants that were nearby and stopped operating at roughly the same time. Following the shutdown of nuclear power plants, it is anticipated that energy prices will rise, making access to temperature-regulating devices less affordable and exposing more people to extreme temperatures, which is anticipated to increase mortality rates. Results show that in almost all regions, residential electricity expenditure and prices decreased and exogenously increased after the nuclear plants' closure. As predicted, electricity demand is inelastic, particularly in the summer months, and increased following the nuclear plant shutdowns. Importantly, extreme temperatures positively affect mortality, and I estimate that the coinciding exposure to them and the lower level of electricity expenditure have caused up to additional 2776 deaths per year. This evidence has important implications for the assessment of the effects of the USA's decision to partially move away from nuclear power and the design of accompanying measures.

Keywords: Nuclear energy, temperature-mortality relationship, decarbonization, green energy, energy security, energy crisis, perceived risk.

Energia nuclear: uma missão arriscada ou uma oportunidade para o futuro?

Pedro Cruz

Resumo

Numa época em que uma política climática mundial é necessária para mitigar os efeitos das alterações climáticas e do aquecimento global, a utilização da energia nuclear como mecanismo para a produção de eletricidade é, atualmente, um tema em discussão, inserido nos debates sobre a descarbonização da produção de eletricidade e a independência energética. A presente dissertação examina, em termos teóricos e empíricos, o efeito do encerramento de centrais nucleares na mortalidade e no preço e consumo de energia elétrica. Usando dados mensais, ao nível estadual, relativos a temperatura, mortalidade, demografia e ao mercado da eletricidade, desenvolvo um *event study* que quantifica o impacto do encerramento de cinco centrais nucleares geograficamente próximas, cujas operações cessaram aproximadamente na mesma altura. Na sequência deste evento, espera-se que a energia se torne mais dispendiosa, expondo mais pessoas a temperaturas extremas, com potenciais consequências para a mortalidade. Os resultados indicam que, em quase todas as regiões, o preço e consumo de eletricidade no mercado residencial respetivamente aumentaram de forma exógena e diminuíram, após o encerramento das centrais nucleares. A elasticidade da procura de eletricidade é inelástica, particularmente nos meses de verão, tendo aumentado aquando do encerramento das centrais nucleares. Finalmente, mostro que temperaturas extremas fazem a mortalidade subir, e estimo que a exposição às mesmas, coincidindo com um menor consumo de eletricidade, tenham causado 2776 óbitos adicionais anualmente. Esta evidência tem implicações importantes para a avaliação dos efeitos da decisão dos EUA sobre a continuidade da energia nuclear e para o desenho de políticas públicas.

Palavras-chave: Energia nuclear, relação temperatura-mortalidade, descarbonização, energia verde, segurança energética, crise energética, risco percecionado.

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Acknowledgments

I am very thankful to my advisor, Professor Joana Silva, for her valuable guidance and mentorship over this journey. It was a true privilege to write this dissertation under her supervision, and a pleasure to have the opportunity to learn that much from an outstanding scholar.

I also appreciate the constructive input in the framing of the research path provided by Professor Jorge Abrantes, as well as his helpful comments in the review process. I also thank Professor Valentina Bosetti, whose classes on Climate Change Economics inspired the topic choice for my thesis.

Furthermore, I am very grateful to my friends, especially Mafalda Gouveia, for their inestimable help, particularly in the review process.

Finally, and most importantly, I want to thank my family, namely my parents, aunt and uncle, for their continued, unconditional support, and for setting me up for success.

List of Abbreviations

AC - Air Conditioning
AQI - Air Quality Index
BWR - boiling water reactor
C° or degrees - degrees Celsius
CO₂ - carbon dioxide
€ - Euro
EC – European Commission
EEA – European Environment Agency
EPA - Environmental Protection Agency
EU - European Union
GHG - Greenhouse Gas
kWh - kilowatt-hour
IAEA – International Atomic Energy Agency
IEA – International Energy Agency
IPCC - Intergovernmental Panel on Climate Change
LCOE – Levelized Cost of Electricity
MWh - megawatt-hour
PSID - Panel Study of Income Dynamics
PWR - pressurized water reactor
Solar PV – Solar photovoltaic
\$ - US dollar
TWh - terawatt-hour
US or USA - United States of America

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1. Introduction

The August 2022 gas crisis reignited the discussion about energy independence and security. Germany's government and citizens began to reconsider a political decision made eleven years ago based on significant public hostility to nuclear energy. Nearly three years prior, in December 2019, the European Union (EU) updated the taxonomy to include nuclear energy as green: a contentious move for some member states. Thirteen EU nations currently operate nuclear power facilities for commercial purposes¹. The debate over nuclear energy is a subset of a larger discussion about carbon pollution amid the urgent need to decarbonize the world's energy mix given that electricity and heat generation account for 25% of the planet's emissions (IPCC, 2014). Nuclear energy has one of the lowest death rates per terawatt-hour produced, even though it is perceived to be very dangerous by many². This dissertation distinguishes between perceived and actual risks associated with nuclear energy and focuses on how the former are often used to inform policy choices.

This thesis contributes to the literature by studying, theoretically and empirically, the effects of the closures of nuclear power plants on electricity prices and mortality. In the theoretical section, I review the literature on the justifications for considering nuclear energy in the context of the decarbonization debate, the benefits and drawbacks of classifying it as a green energy source, and how a shift towards cleaner energy generation sources may affect the dynamics of global electricity markets. Using an event study, the empirical analysis quantifies the impact of the closure of five nuclear power plants, that were in close proximity and stopped operating at roughly the same time, on electrical energy prices and human mortality. Based on the literature, it is expected that energy prices will rise, making access to temperature-regulating devices less affordable and exposing more people to extreme temperatures, which is anticipated to increase mortality rates.

Estimation of the price elasticity of electricity demand relies on the fact that the residential electricity market is regulated and price changes in that market are brought on by changes in supply. This enables the estimation of the elasticity in conjunction with the inclusion of fixed

¹ Belgium, Bulgaria, Czechia, Finland, France, Germany, Hungary, The Netherlands, Romania, Slovakia, Slovenia, Spain, Sweden

² Gallup's 2019 poll, for example, finds half of surveyed Americans see nuclear plants as not safe (Reinhart, 2019). For a comprehensive review of the evolution of public opinion, see for example Rosa & Dunlap (1994)

effects in the model, which account for constant heterogeneity across states. Effects on mortality are estimates incorporating state-level fixed effects, which take into account state-level characteristics that do not change over time, and on strong, random variation in the temperature distribution across states and over time.

The thesis has three main findings. First, demand is inelastic (-0.264), with prices and customers' sensitivity to them increasing after the shutdown of the nuclear power plants. Second, there is a U-shaped relationship between temperature and mortality — the more extreme temperatures, the higher the death rate. Women of all ages, as well as adult men, particularly those aged 45 to 64, are most vulnerable to extreme temperatures. Exposure to very low temperatures is also strongly linked to an increase in the prevalence of cardiovascular diseases. The data indicate that, compared to exposure to temperatures between 15 and 19 degrees, being exposed to negative temperatures for one day would raise the mortality rate for people aged 45 to 64 by about 2%. For the whole population, that percentage drops to 1.5%. Third, the rise in electricity prices, which followed the closure of the five nuclear power plants, contributed to an additional 2776 deaths annually. Lower electricity affordability increases low-income customers' exposure to extreme temperatures and is associated with a higher mortality rate.

This paper contributes to three strands of the literature. First, on the literature on the effects of a decrease of nuclear power generating capacity on electricity prices and expenditure. While most of the literature, such as Neidell et al. (2019) focuses on a shutdown of a country's complete nuclear power generating capacity, I study the consequences of partially moving away from this electricity generation mechanism. I also enrich the analysis of the residential electricity market by considering one of its main substitutes – natural gas. The analysis of the substitutability between natural gas and electricity is a less explored branch of the literature. Quantifying the degree to which consumers will react to changes in electricity prices seems quite relevant, given that many temperature-regulating devices are gas-powered. Their consumption can be affected by higher electricity prices. Linn and Muehlenbachs (2018) document, for the USA, a consumer reaction to a change in gas prices that is heterogeneous across regions. However, consistently throughout the country, lower wholesale gas prices significantly decrease residential electricity prices, with additional benefits in terms of GHG emissions and mitigating the negative effects of nuclear plant closures by making electricity more affordable.

Second, it contributes to the literature on the determinants of health outcomes and, specifically, mortality. While most of the literature focuses on how the death rate is influenced by socio-economic factors, such as pre-existing health conditions, social status or education level, I focus on the branch of existing research that analyses the link between extreme temperatures and mortality. Extensive literature has documented the different magnitude of the consequences of exposure to extreme temperatures, according to country, period and demographic characteristics. In my study, I contemplate the cause of death, building on Barreca et al. (2016), and disaggregate the population by other groups than those previously studied in the literature. The same study is among those that assert the heterogeneous reaction to extreme temperatures to be caused by several factors, including local climate differences, divergent levels of exposure to extreme temperatures, dissimilar extents of preparation to deal with abnormal weather conditions, and specific endemic health conditions of the population. Breaking down the analysis by demographic traits is relevant to better identify which individuals are most at risk of adverse health outcomes when exposed to extreme temperatures. Such information may be valuable for policymakers to take steps to protect this group of people.

Third, it contributes to the literature on whether the exposure to extreme temperatures could have differential effects on mortality in different economic contexts. In the event of an increase in electricity prices, access to temperature-regulating devices such as heaters or AC units will be less affordable. This will cause people to be more exposed to the weather conditions, and if there is a prevalence of extreme temperatures, there might be an increase in mortality. The magnitude of this effect depends on several socio-economic factors that extend beyond demographic characteristics, such as cheapness of access to electricity (Chirakijja et al., 2019), the country's balance of trade in electricity generation (Celasun et al., 2022; Zakhari et al., 2022) or people's living conditions³. Distinguishing the effect of extreme temperatures on mortality by considering the socio-economic dimension carries with it significant policy implications, as it can help to quantify and narrow down the members of the population that are most vulnerable to such situations - Cohen and Dechezleprêtre (2022) show how a health care program provided by the Mexican state has avoided more than 1500 cold-related deaths each year since 2004.

³ The US Department of Energy estimates that almost half of the electricity expenditure in a household is related to temperature regulation, namely heaters and AC units (Residential Program Guide, 2022)

The remainder of this dissertation is structured as follows: section 2 discusses the economic and social effects of a change in the role of nuclear energy in the energy mix, as well as how it can affect the energy market, in particular its price. It also analyzes the literature on the determinants of mortality, with a particular focus on temperature, and highlights how this relationship could be altered by a change in the price of energy. Section 3 presents the empirical strategy, describing the data and methods used. Section 4 reviews the results. Section 5 concludes.

2. Literature review

In this section, I review the literature that addresses the potential future role of nuclear-generated electricity in the global energy mix and its consequences for the electricity market. Finally, I examine existing research on the determinants of mortality, focusing on how the climate and the electricity market influence the death rate.

Moving towards a greener energy mix

A widely disseminated albeit inaccurate position describes renewable and nuclear energy as substitutes. Nuclear energy is a baseload power source, which implies that, as stated by Suna and Resch (2016), its substitutes are the fossil fuels currently dominating the global energy mix – oil (33.1%), coal (27%) and natural gas (24.3%)^{4 5} (Our World in Data, 2022). Because baseload power sources are responsible for meeting the fixed, constant portion of the demand, it is difficult to quickly change their output or capacity in the short term. Renewable energy sources like wind and solar power are inherently intermittent, meaning they only generate energy when the wind is blowing or when it is daylight, respectively. Their intermittent nature prevents them from replacing all polluting energy sources, especially the coal plants, which emit the most CO₂ (equivalent). These could only be replaced by an energy source that is assured to be continuous, such as nuclear power or renewable energy sources with a storage system. According to Shaner et al. (2018), a third option, for geographically and climatically diverse countries, is to use renewable energy, but "overbuild" it by installing more capacity than is necessary. This would ensure that even if some installed plants are not producing energy (for example, because the wind is not blowing in that area), there will be enough others to make up for it and therefore satisfy demand.

Ending the use of fossil fuels to generate electricity in the USA would reduce CO₂ emissions by two billion tons annually. This would result in savings of \$250 billion until 2050, assuming an underestimated social cost of carbon of \$100. Heal (2022) asserts that the elimination of emissions of other pollutants, such as particulate matter or SO₂, would have additional

⁴ Hydropower is a renewable baseload energy source, but its diffusion is quite small (6.4%), also given its strong dependence on geographic conditions.

⁵ The data also show a strong West-East divide, with most nations in Asia, Oceania and the Middle East having only minor shares of electricity generated by low-carbon sources. The Middle Eastern countries' energy mix has an average 3.99% of low-carbon electricity generation, while for Europe that value is 57.37%, and in the case of Southern America, that figure reaches more than two thirds (70.75%) of total electricity generation.

advantages and result in cost savings of between 361 and 888 billion dollars by mid-century.

The advantages of reducing pollution go beyond mere economic gain.

Tanaka et al. (2021) analyze a change in environmental regulation in the United States. The battery recycling industry relocated to Mexico because of stricter air quality regulations (measured by the concentration of lead). While most papers focus on displacement effects with a nation, this study adds to the literature by documenting the displacement of polluting activities from the US to Mexico, a country with less strict environmental regulation. The authors demonstrate how this change had a detrimental effect on Mexican residents who lived close to the recently opened recycling plants in terms of birth outcomes and health.

They enrich existing literature, by showing how more stringent regulation tends to shift polluting activities to developing nations, whose norms are less strict. The majority of studies concentrate on displacement effects within a country, which some researchers even claim to be uncommon.

To identify an environmental production externality between the two countries and highlight the significance of collaborative, coordinated environmental policymaking, the relocation of recycling activities is geographically tracked in this study.

Additionally, low-income families are more likely to live farther from city centers (i.e., where factories are most likely to be built) and experience greater financial hardships when moving away, which makes the health effects of plant relocation more noticeable for them. This is consistent with environmental justice literature, which notes that the burden of environmental damage is disproportionately carried by the people in the lower part of the income distribution.

Another example of the non-monetary benefits of pollution reduction is presented by Hanna and Oliva (2015), who study the effect of pollution (as measured by the concentration of sulfur dioxide - SO₂) on labor supply in Mexico City, taking advantage of a natural experiment – the closure of a large refinery.

Theoretically, the expected impact of pollution on work hours is indeterminate – reduced exposure to pollution is likely to have beneficial health effects, which may result in more hours of work supplied, but better health may also, for example, translate into a higher preference for leisure, thereby reducing labor supply.

Using panel data for pollution, climate, and the labor market, and relying on regressions and treatment effects to use a triple-difference approach – which allows the findings to not be

susceptible to bias from changes in the labor market - the authors find a positive impact of the refinery closure on labor supply. It led to a weekly increase of 3.5%, i.e., 1.3 hours in labor supplied, which would translate to an average yearly gain of around 126\$ per worker, for people living in a 5km radius of the closed plant. Overall, “the economic gains from increased work helped offset the costs of the refinery closure, (...) [and] demonstrate the importance of accounting for work effort gains when calculating the economic benefits of environmental regulations” (Hanna and Oliva, 2015). This has an important policy implication for developing countries, since, as the authors point out, some economic losses caused by stricter environmental regulation seem to be offset by an increase in labor supply. The potential for future research lies in finding who effectively is impacted by the benefits.

Electricity Market: dynamics and development

A change in a nation's energy mix is likely to result in new electricity market dynamics, including price changes and shifts in demand and consumption. To better anticipate the effects of the decarbonization of electricity generation, which is after all one of the objectives of my study, it is crucial to understand how this market functions.

Reiss and White (2005) estimate, through Method of Moments estimators, a model to analyze the effect of non-linear electricity pricing policies on the behavior of consumers, developing a model whose effectiveness is not limited by consumer self-selection, tailored tariffs (such as those offered specifically to low-income consumers) or heterogeneity in customers' price sensitivity. The authors underline the unique characteristics of the electricity market, where the product is consumed indirectly by aggregating the energy requirements of various appliances, which is how they model electricity demand. This study also supports previous findings that low-income households are more price sensitive.

Reiss and White base their study's elasticity of demand calculation on the actual marginal price that customers must pay. Ito (2014) contends that because non-linear tariffs place a disproportionately high cognitive load on most customers and hinder them from making decisions based on the margin, consumers tend to base their decisions on average price. Ito exposes the fallacies of various arguments made by policymakers when arguing for a change in power tariffs, using panel data from the beginning of this century. Pricing decisions based on marginal prices may have the opposite effect of what was intended and induce more consumption. The US Cap-and-Trade mechanism for carbon emissions started by giving out 30% of licenses for free to

electricity companies, for them to be given to each consumer as a fixed credit, thereby changing their marginal price of consumption. If consumers react to the average price, keeping consumption constant, the credit reduces the price they face – incentivizing an increase in demand.

The author identifies two key causes for the lack of influence of marginal pricing on consumer demand decisions. First, there are random demand shocks that occur without regard to the final price that must be paid. The lack of real-time data on electricity consumption is another problem; households only obtain data on this when they receive their bills and only in aggregate form (rather than at the appliance level). The author contends that customers would begin to base their decisions on the marginal price if such information were to be made available as consumption took place.

In their 2014 study, Jessoe and Rapson used a field experiment to support this assertion by assessing how information about power costs and use affected home electricity demand. 437 families in Connecticut were split into a control group and a treatment group during the course of the summer of 2011, with the latter receiving exogenous electricity price shocks. Some of these participants also got real-time access to information about their current electricity usage; for example, if they turned on a lamp, they immediately received information on the cost and the new electricity consumption level.

The main finding of the authors is that the elasticity of demand rises as more information is available. There is evidence of learning: better-informed households tend to adopt more energy-efficient behaviors, even after the experiment ended, when they no longer had access to real-time consumption data. This is in addition to the fact that informed households reduced their electricity consumption by 11 to 14% when faced with a price increase and that their price sensitivity is three standard deviations higher compared to uninformed households. This has an important policy implication since lowering the cost of acquiring data on electricity consumption will improve household energy efficiency over the long term. The authors point out that this persistent improvement in the way electricity is consumed can reduce global GHG emissions from the energy sector by up to 2%, not accounting for indirect benefits and savings that arise – one example would be that there would not be a need for such a large investment in electricity grids, since the amount of electricity demanded (and hence transported) would be smaller.

Most economic models assume that agents have perfect information, but in reality, information acquisition is expensive because it requires significant cognitive effort, costs money,

and faces technological barriers. Making data easily understandable and affordable will assist consumers in overcoming these barriers and encourage them to make more effective decisions. The authors use the example of a driver of a car who can easily find out how much it costs to travel one kilometer in terms of fuel but finds it very difficult to determine how much it would cost in terms of electricity to cool their home by one degree. Asymmetrical, imperfect cost information can result in inefficient decision-making.

The liberalization of electricity markets is a trend that has become prevalent in the 21st century. Around the world, an estimated 70 nations had liberalized their energy markets as of 1998 or were moving in that direction (Bacon and Besant-Jones, 2002). This led Cicala (2022) to evaluate how such choices would affect the price of producing electricity. The author analyzes how this policy change affected the cost of meeting electricity demand in each region using a variety of techniques, including regressions and difference-in-difference analysis.

A direct consequence of a liberalized market is the decentralization of grid management. In the case of the USA, decisions regarding the management of supply beyond baseload are currently made in each power control area (PCA), which is intuitive given that locally produced electricity will be more competitive, i.e. less expensive, than energy produced elsewhere.

According to the author, inter-PCA electricity trade profits increase by 55% when power is managed locally, which results in a three to five billion US dollar drop in electricity production costs.

More trade can reduce market dominance from state electricity providers and force them to be more efficient, which gains even more relevance considering that due to their size, nuclear power plant operators usually have some market power. However, this efficiency improvement requires a modernization of the US power grid because the existing infrastructure is not set up for electricity trade or transmission across the nation. Long-term potential for inter-PCA trade can be amplified even more by a more advanced power grid.

The economics of nuclear energy and its positive and normative share in the energy mix

In his 2019 paper, Murray's main goal is to critically assess Germany's decision to step away from nuclear power. In the last decades, nuclear power in Germany has always been a controversial issue, as is described in Summary 2.1 in the Appendix.

The Chancellor of Germany was compelled to personally decide to extend the lifespan of the remaining nuclear plants until April 2023, due to the extent of the controversy within the German government.

Critics of the extension argue Germany to rather have a gas problem, and even an electricity problem would not be solved by extending the lifecycle of nuclear power plants, as they only represent 6% of total electricity production. Proponents of the measure point out that shutting down the nuclear power plants would likely require an increase in fossil fuel use to replace any lost electricity.

In light of the fact that natural gas is used to generate electricity for most German households (BMWK, 2022), advocates of nuclear energy also question the existence of complaints about a gas shortage. According to the *Bundesverband der Energie- und Wasserwirtschaft*, the proportion of natural gas in German power production has remained at 15% since last year, despite the outbreak of war in Europe, which resulted in gas shortages. Shutting down nuclear power would mean that the generation of more electricity would be needed, eliminating the margin to reduce gas usage in power production. It is also noteworthy that, also due to design of the European electricity market, natural gas maintained its share in power production. Due to issues with the French power grid, there was a greater need for imported German electricity, which resulted in higher electricity costs in both France and Germany. Higher production of electricity by gas plants means that it is not being used for purposes such as heating, and implies, by market design, a higher electricity price.

While currently member states are trying to find short-term alternatives to Russian gas, the EU Green Deal, announced at the end of 2019, aims to provide a roadmap for the Union to fulfill its pledge to become the first-climate neutral continent by 2050.

Alternatives to Russian gas have also been found in the extension of nuclear energy – several countries postponed or completely reversed the closure of nuclear power plants, such as Belgium, the Czech Republic, and Slovakia. Others, like France, are expanding the share of nuclear electricity in their energy mix. The interconnection of the European power grid explains why they view with skepticism a looming shutdown of German nuclear power.

Thierry Breton, the EU commissioner for the single market, expressed a similar opinion when he emphasized the necessity of maintaining the operation of the last two German nuclear power plants "at least for some months past the end of this year and ensuring their operation is

safe" (Koch, 2022). He argued that doing this would be best for Europe because keeping nuclear energy in Germany can help the country meet one of the Green Deal's goals, which is to reduce greenhouse gas emissions by at least 55% by 2030 compared to pre-industrial levels. Other goals include increasing the proportion of renewable energy sources and enhancing energy efficiency.

In 2022, the Russian Federation's invasion of Ukraine underscored Benea's 2014 thesis that energy is a strategic aspect for every state. It highlighted the importance of energy security, "the ability of (...) households, businesses, and governments to accommodate disruptions of supply in energy markets" (Metcalf, 2013). The German example is compelling, with their excessive reliance on Russian gas having led to reactive policymaking to ensure energy security.

"The policy focus on energy security stems from society's inability to find ready substitutes for energy in the production of goods and services. (...) The elasticity of energy demand is low." (Metcalf, 2013)

Metcalf argues that, particularly for energy-intensive economies - defined by the EEA as economies that consume relatively more energy to generate their GDP (Tomescu, 2021) - a diversified energy mix is not only important in geopolitical terms but also vital for the stability of the economy, a point illustrated with the extreme increase in electricity prices following the Fukushima nuclear accident and the government's subsequent decision to shut down nuclear power, that represented 24.62% of the electricity generation in 2010⁶ (IEA, 2022). A nationwide strike by transporters of dangerous goods that brought the economy to a standstill in 2019 exposed Portugal's weaknesses associated with its dependency on oil, which is at the origin of 43.49% of all consumed energy (Ritchie et al., 2022). The lack of fuel transportation had an impact on many sectors and industries, including refueling airplanes at airports, stocking supermarkets, and running emergency medical and fire services, leading the government to declare an energy crisis (RTP, 2019).

The diversification of the energy mix can only be accomplished by combining a number of instruments, some of which have already been mentioned, such as taxes on the use of fossil fuels to reduce consumer demand, a decrease in reliance on oil to increase energy independence, and subsidies for renewable energy sources (and generally green energy sources) to promote their uptake.

⁶ This percentage dropped to 0.89% in 2015, according to the same source

If the energy mix needs to be reevaluated, the question is: what is or should be the place of nuclear power in it? The main justifications for and against a greater proportion of electricity produced by nuclear power are compiled in Table 2.2. With increased efficiency, public trust, and waste management options, nuclear power can become more appealing. Its advantages include the lowering of emissions (EPA, 2019) and the stabilization of electricity prices.

Its main issue is the economics of the plants and their impact on the electricity market: the LCOE is higher for nuclear than for fossil fuels, and the size of nuclear power plants, which often also operate at a loss, makes the energy system vulnerable, in case a disruption occurs.

The determinants of mortality

The present dissertation also concerns the determinants of mortality, with a particular focus on the temperature and the electricity market. The literature in this area is very rich, with studies performed in several regions and periods.

Yu et al. (2019) use panel data for China, from 2004 to 2012, to confirm the established hypothesis of a U-shaped relationship between temperature and mortality – as expected, more extreme temperatures increase the number of deaths, which is particularly prevalent for people at risk, notably elderly citizens – the authors highlight the significant dominance of cardiovascular diseases as the cause of death. This study is particularly pertinent because it not only concentrates on a developing nation, which turns out to experience much more severe effects than the USA, the most popular choice for this type of research, but also distinguishes for the first time between rural and urban areas, raising with it a salient policy implication: households are adapting to the higher frequency of extreme temperatures by consuming more energy towards temperature-regulating mechanisms for their homes. This raises inequality issues because the lower-income segment of the population, which in this study turns out to be concentrated in rural areas, might not be able to afford the higher minimal energy needs.

Gouveia et al. (2003) focus on the Brazilian city of São Paulo to evaluate the effect of temperature on mortality between 1991 and 1994, finding that the U-relationship also holds in a sub-tropical climate – in this study, very cold temperatures, affect mortality twice as much as hotter weather, which suggest local established adaptation to warmer conditions. Again, cardiovascular disease is responsible for most of the increased number of deaths.

A paper by Barreca et al. (2016) is one that forms the basis of my research. In an effort to infer conclusions for the present, they examine the temperature-mortality relationship in the US

over the past century. One of their main findings, in addition to confirming the U-shaped relationship, is that since the second half of the 20th century, the higher mortality rate associated with exposure to extreme temperatures has not been as evident in the data (the effect of a hot day became 80% less strong). The authors conclude that this is because residential air conditioning has become more widely available, as opposed to their other two hypotheses that it is because of increased access to electricity or healthcare. Three thousand fewer fatalities than anticipated were caused by residential AC between 1960 and 2004.

A vicious circle is discovered. For most people, especially those who reside in climate-sensitive areas, adapting to climate change means using more energy to power climate-controlling appliances like air conditioners and heaters. However, given the current high proportion of fossil fuels in the energy mix, increasing energy consumption is probably going to result in higher GHG emissions, which will exacerbate the effects of climate change and require more energy for community adaptation efforts, not to mention the likely rise in illnesses and mortality that will go along with it. According to Yu et al. (2019), the Chinese mortality rate would rise by 14.2% if GHG emissions kept rising through the end of the century, a scenario known as "business as usual" among climate scientists.

Chirakijja et al. (2019) focus on the winter months to perform a similar analysis. They calculate the impact on US mortality of a change in the price of temperature-regulating devices, namely heating, looking at both the electricity and natural gas markets. Their study examines the impact across states, over the first decade of the present century.

The authors point out the two dimensions under which the impact an increase in the cost of home heating on mortality must be analyzed. There is a direct effect, with a predictable decrease in heating consumption that induces greater exposure to the climate and hence increases the risk of diseases, with the study pointing to respiratory and cardiovascular problems as the most prevalent in this setting. However, considering that households will be forced to increase their expenditure for heating, given the higher prices but the need to keep their consumption as constant as possible, this will presumably lead to a decrease "in other expenditures that affect health, such as food and health care".

This study was the first to analyze the causal link between the cost of heating and health outcomes, specifically, mortality. The model that is estimated includes controls for air quality (i.e. pollution), the share of households whose heating is provided by natural gas, the relative price of

gas and electricity, demographic characteristics, and controls for significant macroeconomic events such as the Great Recession or the bursting of the housing bubble, as well as fixed effects.

The findings support the hypothesis that lower heating costs reduce wintertime mortality. Natural gas prices fell by more than 40% in the second half of the studied decade, which led to a 1.6% reduction in the mortality rate for gas consumers, more than 11000 deaths *per annum*.

A third paper whose reasoning is close to the one I adopt in my study is Neidell et al. (2019). In it, the authors analyze the aftermath of the 2011 Fukushima nuclear accident. The disaster caused 1362 deaths, victims of radiation exposure and fatalities occurring during the evacuation from the area. The authors then quantify the deaths that resulted from the Japanese government's decision to shut down all nuclear power plants in the aftermath of the accident. They show that, in the absence of nuclear energy, electricity prices increased, mostly due to additional imports of fossil fuels. This price growth reduced electricity consumption, which left more people, particularly those at the bottom of the income distribution, vulnerable to the weather conditions, and it has been shown, for example by Barreca et al. (2016), that extreme temperatures positively affect mortality, since climate control mechanisms such as heating are no longer affordable. Using regressions estimated through Generalized Least Squares, that relate electricity prices and demand, temperature and mortality, accounting for fixed effects by region, the authors conclude that, in the period from 2011 to 2014, the higher electricity prices caused additional 1280 deaths, for data that only covers 28% of the population. This hints at the conclusion that shutting down nuclear power caused more harm (as measured by the toll on human lives and on the Japanese energy mix and its increased dependency on foreign countries) than the actual consequences of the Fukushima nuclear accident.

Gohlke et al. (2011) explore the relationship between electricity use, coal consumption, and health and mortality outcomes (as measured by life expectancy and infant mortality), focusing on 41 countries and the period between 1965 and 2005. With the help of an autoregressive model, they confirm the theoretical expectations that increased access to electricity reduces infant mortality, particularly in developing countries (where the marginal impact of more population having access to electricity is higher). Furthermore, a higher level of coal usage decreases life expectancy and increases infant mortality, after controlling for electricity access and consumption.

Research is consistent in finding that fossil fuels have the highest death rate per unit of electricity production⁷ (Our World in Data, 2022; Conca, 2012; Casey, 2019). Brown coal causes almost 33 deaths per TWh of generated electricity, followed by coal (24.6 deaths), and oil (18.4). On the other end are solar, nuclear, and wind power, all of them causing the death of less than 0.05 people per terawatt-hour.

Reaffirming the difference between perceived and actual risk, and the conclusion made by Neidell et al. (2019) in their examination of the outcomes of the Fukushima nuclear accident, statistics show nuclear to be the second safest electricity generation form, possibly due to factors such as strict(er) regulation, public scrutiny, its large scale and the higher government accountability in case of issues.

The figures are particularly remarkable considering that in the 2019 global energy mix, coal and oil generate around 14 times more electricity than nuclear power⁸, but are responsible for 10795 times more deaths⁹. It is also worth pointing out that the share of fossil fuels in the energy mix does not reflect their efficiency in generating electricity and hence does not quantify the GHG emissions or perfectly reflect a change in their level.

⁷ Death causes contemplated in this analysis refer to either accidents in operation or air pollution

⁸ Global energy mix 2019: 33.1% oil, 27% coal, 4.3% nuclear (Our World in Data, 2022)

⁹ 2019 electricity generation in TWh: Oil – 53620, Coal – 43849, Nuclear – 6923; multiplying these values by the death rates yield the following estimated deaths for 2019: Coal – 1257150, Oil – 988217, Nuclear - 208 (author's calculations based on information from Our World in Data, 2022)

3. Estimation strategy

In this section, I describe the empirical strategy used. I describe the data and the identification strategy employed. The analysis has three parts. The focus is on the effect of electricity prices on the temperature-mortality relationship, to then quantify the number of deaths that are linked to the closure of the nuclear power plants. I complement the analysis by verifying if the relationships between temperature and mortality and electricity price and expenditure, which have been identified by existing literature, hold in this setting.

a. Temperature, electricity prices and mortality

The main relationship I evaluate is the joint effect of temperature and electricity prices on mortality. For that, the model assessing the temperature-mortality relationship is extended by adding the price of electricity and its interaction with temperature in a multiplicative way.

$$\log(M_{st}) = \sum_i \alpha'_i T_{sti} + \delta' \log(P_{st-k}) + \sum_i \lambda_i T_{sti} * \log(P_{st-k}) + \theta' X_{st} + \gamma'_{st} + v_{st}$$

The prime in the parameters is used to reinforce the distinction between all three models.

The dependent variable of this regression is the mortality rate (out of 100,000 people), in state s and month t .

T_{sti} indicates the temperature over the previous couple of months, to reflect lagged physiological effects of weather conditions – persistent cold temperatures, for example, can have negative repercussions on health, as is demonstrated by several studies including Barreca et al. (2016). Following that study, these temperatures are divided into seven bins – negative temperatures, 0-4, 5-9, 10-14, 20-24, 25-29 and 30 or more degrees Celsius. I, therefore, exclude the bin that corresponds to temperatures between 15 and 19 degrees. Hourly temperatures are chosen to avoid having to distinguish between minimum, maximum and mean temperatures, as opposed to several climate models such as those presented in the quoted paper).

The variable P corresponds to the average electricity price in state s and month $t-k$, with $k \in \{0,1,2\}$. Including a lag of the price accounts for what the literature describes as rational inattention – a theory initially proposed in 2003, and built on by several papers, such as Sallee (2013), Auffhammer and Rubin (2018), which document that consumers are not capable of processing all available information, at least immediately, and may hence take some time until noticing (or becoming sensitive to) a price change. The price change between months takes some time to be reflected in the electricity invoice - according to Neidell et al. (2019), the electricity

invoice in the USA arrives about one and a half months after the consumption period, which is when the price might have changed - and therefore to be noticed by the consumer, hence, the reaction to a price change may only be reflected in the data up to two months later. The choice of the average price, rather than the marginal one, is based on the recognition that customers tend to be more responsive to the average price as it minimizes the cognitive burden of understanding the tariff, as discussed in Section 2.

γ_{st} includes fixed effects of two types: state-by-month fixed effects reflect seasonal characteristics that are expected to influence mortality (such as seasonal weather conditions that are specific to a state) and year-by-month fixed effects account for factors whose effect is experienced in the same way across the country (such as macroeconomic shocks).

X_{st} accounts for unexpectedly high or low precipitation (which I define as dummy variables for when the precipitation in a month is in the first or fourth quartile of the average over the entire period under analysis).

Standard errors are clustered at the state level, with regressions being weighted by the population of each state.

The parameter of interest is λ , reflecting the effect on mortality of the interaction between temperature and price. Neidell et al. (2019) point out that this parameter should indicate “whether price moderates the effect of temperature on mortality”. I expect that in a period of extreme temperatures, mortality should increase with a rise in electricity prices. The intuition for this expectation is that, in the presence of extreme temperatures, a price increase will reduce the purchasing power and the ability to use temperature control devices (such as AC units or heaters), which leaves people more exposed to the weather conditions, hence, mortality is expected to increase.

This intuition implies that λ should not be significant in the absence of extreme temperatures. In that scenario, and given an increase in electricity prices, its consumption should decrease, however, mild temperatures are not expected to influence mortality. The definition of what is a mild or extreme temperature follows from the second equation, considering which bins were significant at explaining changes in mortality.

The subject of my analysis is a quantification of the number of deaths resulting from exposure to each of the relevant temperature bins, and out of that number, how many people died

because of the change in the electricity price, following the nuclear plant shutdowns. I therefore focus on the period between 1996 and 1999.

The number of deaths from exposure to any temperature bin is calculated by multiplying the relevant coefficient $\hat{\alpha}$ from the second model, by age group j for the bin in question, the number of hours where temperatures in that bin were registered, the mortality rate by month, state and age group, and the population by month, state and age group. I sum across states, age groups, and years and divide to find the annual average number of deaths.

$$\text{Number of deaths from exposure to a temperature bin} = \sum_j \sum_t \hat{\alpha}_j * T_{st} * M_{stj} * Pop_{stj}$$

As for deaths that are attributable to exposure to temperatures in the bin in question and to the change in the electricity price, I calculate the same product of temperature, mortality and population, multiplying it also by the year-to-year percentage change in electricity prices in each state ΔP_{sy} and by the relevant coefficient $\hat{\lambda}$ that was estimated in the first model for each age group. I sum across states, age groups and years and divide to find the number of annual deaths that is expected to be due to the change in electricity prices.

$$\begin{aligned} &\text{Number of deaths from exposure to a temperature bin and the change in electricity prices} \\ &= \sum_j \sum_t \hat{\lambda}_j * T_{st} * M_{stj} * Pop_{stj} * \Delta P_{sy} \end{aligned}$$

b. Temperature and Mortality

The previous analysis relies on evaluating the relationship between temperature and mortality. In the spirit of Barreca et al. (2016), I estimate the following regression.

$$\log(M_{st}) = \sum_i \alpha_i T_{sti} + \theta X_{st} + \gamma_{st} + \mu_{st}$$

All variables are defined above.

The expectation is that, as discussed in Section 2, extreme temperatures increase mortality, the parameter of interest, α , is therefore only expected to be significant for the first and last one or two temperature bins.

In this model, the identification strategy for the impact of temperatures on mortality relies heavily on the incorporation of fixed effects, associated with the existence of significant, aleatory, exogenous variations in each state's monthly recorded temperatures.

Standard errors are once again clustered at the state level, with regressions being weighted by the population of each state.

I extend the model developed by Barreca et al. (2016) by performing separate estimations by gender (male or female), age (0-4, 5-19, 20-44, 45-64 or above 64 years of age), ethnic background (white, black or neither), population density of residence area¹⁰, and cause of death (focusing on cardiovascular, chronic respiratory and non-communicable diseases).

c. Electricity Prices and Demand

Building on Auffhammer and Rubin (2018), I also evaluate the effect of electricity prices on electricity expenditure by estimating the following regression.

$$\log(EXP_{st}) = \delta \log(P_{st-k}) + \beta X_{st} + \rho_{st} + \varepsilon_{st}$$

In this equation, the dependent variable is the average household electricity expenditure in state s and month t . As a proxy, I divide the revenue from each state provider's electricity sales by the number of customers.

X_{st} includes several other time-varying, state-level controls that are expected to help to explain the variation in electricity expenditure. They include a vector of household and demographic characteristics of each state (the averages of the number of household members, of the share of children in the household, of the percentage of employment, of the age of the head of the household, and the percentage of home ownership). Also included, in the same way as in the first model, are controls for unexpectedly high or low precipitation, as well as the absolute frequency of registered hourly temperatures in each month.

ρ_{st} designates the fixed effects that I include in the model, to reflect the seasonality dimension of electricity consumption in each state (in the form of state-by-month fixed effects) and to account for time-varying events that affect all states at once, such as economic shocks or public policy (in the form of year-by-month fixed effects).

ε_{st} designates the error term. Standard errors are clustered at the state level. Regressions are weighted by the number of households in each state.

The key condition for the successful identification of the parameter of interest is the non-liberalization of the residential electricity market. Consumers are unable to choose between electricity suppliers, and, crucially, tariffs, meaning that a change in pricing is attributable to the supply side and is independent from demand. In addition to that, the usage of fixed effects ensures that the heterogeneity across states that derives from constant characteristics is properly accounted for and does not bias the results.

¹⁰ A proxy for Yu et al. (2019)'s considerations on the relevance of a rural or urban environment.

The parameter of interest is $\delta - 1$, which designates the elasticity of electricity demand, measuring how reactive consumers are to a change in the price. As electricity is assumed to be an ordinary good, this value is expected to be negative, following the law of demand, which expresses that, for such goods, higher prices decrease the demanded quantity.

In a separate analysis, I evaluate the dynamics of the gas market, using the same model, although replacing the electricity price and expenditure by the respective values in the residential gas market. The parameter of interest remains the same, as is the theoretical expectation for its sign and magnitude.

Finally, I calculate the cross-price elasticity between electricity expenditure and gas prices, to evaluate whether the two are complements or substitutes, discriminating further by season, since the theory leads to the expectation that in the summer, a change in gas prices should not affect electricity consumption significantly, as few heating devices work with gas.

Data and Methods

In this section, I review my data sources, the way through which I treated them, and I go through some relevant descriptive statistics.

My analysis concerns the period between 1993 and 1999, focusing on the effect of the closures of the nuclear power plants Millstone 1, Maine Yankee, Zion 1, Zion 2, and Big Rock Point. A summary of the pertinent data about these plants is shown in Table 3.1; it is important for my analysis to note that they are concentrated in an area of very close proximity and that, except for one plant, the electricity they produced was significant, indicating that they had a significant impact on the local energy market. The year 1993 was chosen as the analysis's starting point to allow for data variability and reflect the status quo just before the first nuclear power plant under study was shut down. The decision to stop the analysis in 1999 stems from the explicit intention to calculate the short-term response to the closure of the nuclear power plants, in line with Reiss and White's (2005) reasoning, as well as Neidell et al. (2019), who analyze the consequences of Japan's nuclear power plants for the three years after the implementation of the measure. I extend the analysis through the end of 1999 because Zion 1 ceased operations in 1997.

I do not include 2000 because of the global macroeconomic environment, which saw the start of a recession in Europe before spreading to the USA as the "dot-com crisis" and might have impacted the findings of my analysis.

By focusing on a number of closing plants rather than the total demise of nuclear power in the United States, my research stands out from similar studies in the literature. The nuclear power plants I selected all shut down within a relatively short period—less than two years—with the first shutting down without any prior closures for three years. Further, while Zion 1 shut down in 1997, Crystal River 3, the following nuclear power plant to close didn't do so until 2009. Therefore, there are no closures of additional plants that might bias the results.

Based on Neidell et al. (2019), most of the plants on my list are located in the same region, serving as a good proxy for Japan, where the most severe effects of the end of nuclear energy were felt in the regions where electricity production was most nuclear-intensive. Additionally, these nuclear power plants were selected with consideration for the fact that the states in which they were situated at the time of the analysis had electricity markets that were regulated. This is a crucial requirement for my study because it means that price changes are due to the supply side of the

market - customers do not have access to a variety of suppliers - this enables the identification of the coefficient from which the elasticity is derived.

The data for average monthly residential electricity prices were taken from the U.S. Energy Information Administration, from a database that includes information on prices (cents/kWh), electricity sales to residential customers (MWh), and sales revenue (\$). The latter can be identified as a proxy for electricity expenditure since it is the result of the product of prices and electricity sales. The required variable is per-customer expenditure. Hence, I divide sales revenue by the number of electricity customers, data that is provided yearly (except for 1993, where I assume the same values as for 1994) by the same entity. As for population, I do not believe that the monthly changes in the number of electricity customers in each state will be large enough to bias the results. Considering the regulated nature of the electricity market, electricity prices are uniform within each state.

For the analysis I conduct on the gas market, I use monthly, state-level data for residential gas prices and expenditure, also sourced from the Energy Information Administration database, with the dataset including information on the two variables I indicated.

The monthly data for state-level mortality are retrieved from the Center for Disease Control's Multiple Cause of Death Files. This dataset lists all deaths together with several additional data, such as cause of death, sex, race, age or population density of the place of residence, which I take advantage of in my analysis to extend the models developed in papers such as Barreca et al. (2016). For the second and third models, which use mortality as the dependent variable, I estimate them using the total mortality rate, but also the mortality rate from cardiovascular diseases, non-communicable diseases and chronic respiratory diseases. Cardiovascular diseases were the leading cause of increased mortality due to exposure to cold temperatures, chronic respiratory diseases turned out not to be relevant in the analysis in Japan (which prompts me to want to see if that conclusion holds in my study), and there are several studies - such as Bunker et al. (2017) - that associate exposure to extreme temperatures to a risk of developing non-communicable diseases.

For information regarding population by state, I use the U.S. National Cancer Institute's data.

Hourly temperature and wind data are sourced from Iowa State University's Iowa Environmental Mesonet. To improve precision and the state-level validity of the results, as well as

to minimize the impact of possible missing or faulty data, the values used for each state in my analysis are an average of the measurement of five stations, except in the cases of Delaware and Rhode Island, where data was only available for, respectively, three and four stations. The choice of these stations is random, constrained by both the availability of data for the period under analysis, and the avoidance of using two weather stations in the same vicinity. For wind, I apply the same reasoning as for precipitation, using a dummy variable to signal wind speed that is in the bottom or top quartile of the entire sample for the state in the period under analysis. In the case of temperature, following the literature, I sort the temperature by bins, counting the hourly frequency of measurements for each of them.

The hourly state-level precipitation dataset comes from the National Oceanic and Atmospheric Administration. As for other climate metrics, the measurement used is also an average for five randomly selected weather stations, respecting the constraints previously highlighted. For the states of Delaware and Rhode Island, only two weather stations gathered this data for the period under analysis.

Hourly pollution data are gathered through EPA's Air Quality Index (AQI), a composite indicator that evaluates air quality, contemplating the concentration of ground-level ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide. Similarly to temperature data, I work with AQI data by calculating the frequency of hours where the registered measurement falls into each of the six bins defined by the EPA ("good", "satisfactory", "moderate", "poor", "very poor", "severe"). The first category is excluded. The last category is also excluded, given that in all states and the period under analysis, the recorded AQI never reached that level. To enhance precision, the AQI used for a state is the average measurement across all available stations within that state, which are usually five.

As for the household characteristics, I use the Panel Study of Income Dynamics (PSID) to gather state-level, annual data. The PSID is conducted by the University of Michigan and comprises, in the period I am studying, around twenty to thirty thousand individuals. The panel is kept up to date and ensured to be representative at the state level. The survey was not conducted in 1998; in that year, lacking better information, I use the same data that had been gathered for 1997. Since I adopt this procedure for all states, this should not significantly impact the results of my analysis.

Seasonally adjusted, state-level, monthly unemployment rates are taken from the FRED database.

In terms of the methodology to treat and analyze the data, some important aspects should be highlighted.

My analysis, over the three models, covers 48 out of the 50 US States. Both the District of Columbia and US territories such as Puerto Rico or the Virgin Islands are excluded from my analysis, considering missing information and a different operation of electricity markets. Maryland and Rhode Island are not considered, because in these states the liberalization of the electricity market occurred before 1999. I categorize a state's energy market as regulated until three criteria are met: The enactment of the legislation liberalizing the market, customer choice is extended to most of the customer base, and more than 10% of the consumers must have left the regulated market and entered a contract with one of the possible suppliers. Nevertheless, in Section 4 I show that my study's results are robust to a looser definition of a regulated market, whereby a market is liberalized after the corresponding bill is enacted. In that case, three additional states are excluded from the analysis: Massachusetts, New York, and Pennsylvania.

In a separate analysis of the gas market, which I perform in the context of the first model, I contemplate 41 out of the 50 states. Besides the two I exclude from the analysis of the electricity market, I also do not include data from California, Georgia, Massachusetts, Montana, Nebraska, New Mexico, and Ohio, since all these states liberalized their gas market before 1999¹¹. This notion of liberalization fulfills both the stricter and the looser criteria I applied for the selection in the analysis of the electricity market.

For PSID data, I remove from the dataset all entries that have any missing or inconsistent information (such as negative values for age). I also redefine the variable that describes the age of the head of the household, for it to be coherent across years – 97 years old becomes at least 97 years old; this top-coding was already done for some of the survey years.

Descriptive Statistics

My main dataset is composed of 4032 observations, corresponding to monthly data during seven years for 48 states. I use separate datasets for the analysis in the second model, whose size depends on the characteristic under analysis (demographic background, cause of death, etc.) and

¹¹ It should be highlighted that these states are geographically dispersed, meaning that their exclusion should not significantly bias the results or the estimates for the elasticity of a particular region.

the number of deaths per state-month. Hence, in both datasets, an observation corresponds to a month in a state. Table 5.2 summarizes the main dataset and contains basic data for the entire nation.

The mean nationwide monthly electricity expenditure per customer over the seven years was 67.7\$ but ranging from 24.93\$ to 152.85\$. The electricity price has demonstrated a smaller variation, averaging at 8.36 cents/kWh, and peaking at 16.13 cents/kWh. During the seven years and over the fifty states, the fourth quartile of the recorded electricity prices was 9.65 cents/kWh.

The data indicates heterogeneous weather conditions across the country over the period. On average, there were 371 logged instances of extreme wind, but range between 24 and 1084 hours.

Analyzing AQI data, it is noticeable that the pollution levels have been low, according to EPA's standards. Nationwide, air quality levels only reached "very unhealthy" levels for a total of eight hours over the 7 years, in Connecticut, Delaware, and Maine. Unhealthy levels were recorded for 199 hours, and moderate air quality was registered for 925 hours in that period.

The average electricity price had an increasing trend until 1997, with an average growth of 6.5 cents per year. From 1997 to 1999, the mean nationwide price decreased by 17 cents, returning to 1994 levels. Midwestern states experienced a minor variation in the mean price, 6 cents above and below the average of 7.66 cents/kWh. The biggest variation happens in the region of the Northeast, which is also the region where, in the period under analysis, most nuclear power plants closed. It should also be pointed out that in this region, the average price increased by more than one cent between 1993 and 1997. In comparison to the other regions, the Northeast was also the region with the highest average electricity price in all years under analysis.

Over the seven years, the states with the highest average electricity price are New York (13.66 cents/kWh), Hawaii (13.6 cents/kWh), and New Hampshire (13.37 cents/kWh). The lowest mean price in that period was recorded in Washington – 4.92 cents/kWh.

The heterogeneity in electricity prices across the USA is underlined if looking at Figures 3.3 and 3.4, that not only show a strong difference in prices by region but also across time. The graphs show a cyclical pattern in prices, particularly in the gas market. In the electricity market, the cyclicity is less present in the Middle Atlantic and West regions, which display, respectively, higher and lower deviations than expected. However, the magnitude of the changes in the electricity price was also similar across all regions.

4. Results

In the following section, I present and briefly comment on the results that come from the estimation of the three models.

The first model looks at the effect of electricity prices on the temperature-mortality relationship, with the results reported in Table 4.1. With exception of the seventh temperature bin, temperatures are no longer significant on their own in explaining mortality. Their interaction with prices, however, is particularly significant for temperatures in the 0-4 and 5-9 C° range, for both the current period and lagged electricity prices.

Figure 4.2 shows that the parallel trend assumption holds in this event study. As expected, the effect of the closure of the nuclear power plants becomes noticeable in 1996, with a similar trend than the one observed prior to the shock.

Following Neidell et al. (2019), the calculation of the number of deaths from exposure to extreme weather conditions is based on logged temperatures between 0 and 4 degrees, because it was the most significant bin in the second model. The data predict around 16.652 annual deaths due to exposure to temperatures in that range. When accounting for the joint effect of temperature and the electricity price, the number of annual deaths averages 2.776.

The second model aims to confirm a widely established U-shaped relationship between temperature and mortality. I repeat my analysis changing, successively, the mortality rate. I distinguish between total mortality, and mortality rate due to cardiovascular disease, chronic respiratory disease, and non-communicable disease.

Starting with the total mortality rate, the coefficients associated with high temperatures are not significant, which may suggest a high penetration of non-electricity-powered cooling devices. Contemporaneously, the first and second bin are the only significant negative is 0.000397, which means that one-hour exposure to temperatures in that range is predicted to increase mortality by about 0.0397% versus one hour exposed to temperatures in the 15-19 C° range, *ceteris paribus*.

As opposed to literature, no coefficients associated with lagged temperatures are significant in explaining mortality, which may be due to local regional climate differences, health characteristics, or more advanced infrastructure to deal with extreme temperatures, such as better insulated houses.

Looking at the three causes of death under analysis, I find that for the US, in the period in question, people suffering from chronic respiratory diseases are more susceptible to death from exposure to extreme temperatures in the present or the two previous months. People suffering from non-communicable diseases see a higher mortality rate be related to exposure to medium temperatures, which goes against the general expectation, while cardiovascular diseases, which yielded the anticipated effect in Neidell et al. (2019), only display a significant coefficient for a current-period exposure to negative temperatures. The full tables are presented in the Appendix under the references 4.2 and 4.3.

I also look at how several demographic characteristics influence total mortality. Looking at the effect of age, it's noticeable that for any gender and almost all age groups, exposure to low temperatures is significant in explaining a change in mortality. In the case of negative temperatures, for almost any ethnic background and illness causing death, this relationship holds as well in the case of low temperatures. The graphs show that older and black people are among the groups where the exposure to negative temperatures is most significant in explaining a variation in the mortality rate. For better visualization, the results are reported in Figures 4.4 and 4.5.

As for the third model, the correlation coefficient between electricity prices and expenditure is, on average, 0.2175, with the coefficients by year listed in Table 4.6. This very low, albeit positive value, leads to the hypothesis that the electricity demand seems to be inelastic.

This possibility is confirmed by previous literature, which has consistently, over time, found (residential) electricity demand in the USA to be inelastic. Some of the studies reaching that conclusion include Burke and Abayasekara (2018), as well as Bernstein and Griffin (2006). Using different methods, and for different periods, these studies find short-run elasticity values of -0.1 to -0.2 and long-run elasticities between -0.3 and -1.

The nature of the energy market in the U.S. is underscored by studies such as the Energy Information Administration's 1997 Residential Energy Consumption Survey, which indicates electricity and natural gas to both be dominant, suggesting that electricity consumers should be more sensitive to price changes, given the wide diffusion of a substitute product. The study found more households use electricity than natural gas (101.4 versus 61.9 million). The dominance of these two power sources is highlighted by the fact that the third-ranking energy source, fuel oil, is only used by around ten million households.

Despite having fewer customers than electricity, natural gas dominates in the number of households that use it for space (54.5 versus 42 million) and water heating (52.8 versus 40.5 million). A possible explanation for the low price sensitivity of electricity consumers is that some appliances, including temperature regulation mechanisms like AC units, do not work with any other power source except for electricity.

To recall, the first model aims to evaluate the nature of the relationship between electricity price and expenditure. The parameter of interest will help to confirm or discard the established hypothesis.

Table 4.7 presents the estimates for the price elasticity of residential electricity demand, by subtracting one unit from the coefficient associated with the main regressor. The key independent variable, the logarithm of electricity prices, is successively the price in the same in the previous two periods. The coefficients associated with the logarithm of price, regardless of the lag, are all statistically significant at the 1% level. As expected, following the law of demand, the elasticities are negative, and broadly consistent with estimates from the literature, showing signs that demand is inelastic. The slightly higher elasticity for the current period, if compared with previous research, may be due to the shorter period of analysis.

With this baseline specification, I also estimate the price elasticities for winter and summer periods. Winter is defined as the months from October to March, while summer is defined from June until August, although the results are robust to alternative definitions of these seasons. This analysis will help to find whether consumers are most price sensitive to electricity prices if they are using it for heating or cooling purposes. One might expect price sensitivity to be lower in the summer months, since, as previously discussed, there are no easily accessible substitutes to air conditioning units that function with a power source different from electricity. The same cannot be said for heating mechanisms, for which there is a significant number that work based on oil, and, as previously highlighted, oil has a significant market share in the US. While in both cases the seasonal elasticities are higher than the values estimated for the entire period under analysis, the results turn out to match the theoretical expectation, in that the consumers' electricity price sensitivity is much higher in winter periods, except for a slightly higher value for the 2-period elasticity, which is marginally higher in the summer.

Table 4.8 shows the results of robustness checks to the main specification of the model, which deals with the electricity market. They show the estimates to be robust to different

specifications, as long as these include the fixed effects¹². All coefficients associated with the logarithm of electricity prices are statistically significant at the 1% level. I also find that a more narrow, strict definition of states with regulated electricity markets, as discussed in Section 3, still yields a similarly estimated elasticity of electricity demand.

Table 4.9 presents the calculation of the price elasticity of electricity demand broken down by two periods, which are built following two criteria: first, only in the second period are the effects of the closure of the nuclear plants expected to be noticeable, and second, the periods are also meant to be of similar length. Only the contemporaneous elasticity increases with the period change, and by a smaller magnitude than the decreases in price sensitivity for one and two lags.

The latter are somewhat surprising results since the theoretical expectation was to observe a higher price sensitivity faced with an increase in prices following the closure of the nuclear power plants. Consumers might have become less sensitive to the prices of the previous period since they were lower than the contemporaneous prices.

Breaking down the estimated contemporaneous elasticities by region and period, one can see in Table 4.10 that for all regions except the Midwest, customers become more price-sensitive towards the end of the century. The two regions where nuclear power plants were shut off, display contrasting effects. While in the Northeast the elasticity increases, the opposite, albeit mild, effect is observed in the Midwest. A possible explanation may reside in the fact that at the beginning of 1997, prices increased much more in the Northeast region than in the Midwest. It should be noted that this analysis is somewhat limited considering the small, uneven number of states per region.

To gain a better understanding of the energy market, I analyze the dynamics of residential gas consumption, with the estimation of similar parameters to those I calculated for the electricity market.

Table 4.11 shows the estimated price elasticity of gas demand over the 7-year period and additionally by season. The conclusions one can reach are somewhat restricted due to the different nature of the industry and consumption habits. In the gas market, the customers' price sensitivity is much higher than in the electricity market, also if we disaggregate the estimation by season. As expected, the elasticity is higher during summer months, possibly reflecting the lower demand during that period. Overall, the higher customer sensitivity observed in the gas market, if compared

¹² The significant difference in the estimated elasticity in the absence of fixed effects underlines their importance in the identification strategy.

with the electricity market, can be related to the more specific use of gas – as discussed above, electricity can power more temperature-regulating devices, while gas is mostly associated with heat-generating appliances. Also noteworthy is the non-significance, at a 5% level, of the lagged gas prices on the current period consumption.

Looking at the development of the elasticity by period and region, one notices in Table 4.12 that in all regions of the USA, the customer sensitivity to gas prices increases. The theoretical expectation was ambiguous since on the one hand, the closure of nuclear power plants stimulated an increase of electricity supply by gas plants, which would imply a decrease in gas prices assuming constant demand, but the latter effect turns out to dominate this relationship.

Finally, I also perform the estimation of the Cross-Price Elasticity of Demand, and find, as is shown in Table 4.13, that, as expected, natural gas and electricity are substitutes, although this relationship is only statistically meaningful for the two lagged periods.

Discussion

The first model's results bring significant differences if compared with the theoretical expectations, since some values of λ are not insignificant for what the second model defines as mild temperatures. Nevertheless, the results are consistent across the two models for temperatures between five and nine degrees, for both the contemporaneous period and the two lags. This is an additional indicator of regional differences, like climate or preparedness for dealing with low temperatures, if we compare my study with other papers in this area.

The results of the last two models are generally consistent with the literature:

In the case of low temperatures, I confirm the U-shaped relationship between temperature and mortality, which holds regardless of age, gender, or race. Specifically, my results are consistent with studies such as Yu et al. (2019), who found patients with cardiovascular diseases to be most vulnerable to the temperature-mortality relationship, particularly when exposed to low temperatures. I also confirm that, as anticipated, the price elasticity of demand for residential electricity is negative but close to zero, which makes sense, considering it is a necessity good. Given the greater availability of alternatives to electricity-powered temperature-regulating mechanisms, the elasticity is higher in the winter.

In-depth, there are some differences, though. One somewhat unexpected outcome of the first model was the observation of a price decline in one of the regions where nuclear power plants were shut down, with the elasticity also moving towards zero. In the second model, I do not find that exposure to high temperatures significantly explains mortality. This is consistent with some existing studies such as Cohen and Dechezleprêtre (2022), who also find cold temperatures to have a more pronounced impact on mortality than warm weather conditions. Possible causes are variations in local weather patterns, or customers' homes that are better equipped to withstand higher temperatures, as argued by Barreca et al. (2016).

Limitations

As for limitations of the empirical part of my study, some issues should be highlighted.

The primary point is that it is impossible to guarantee the external validity of my conclusions. When determining whether nuclear power will continue to be used in a European state, policymakers should not assume similar results to occur if nuclear power were to be shut down in their country. Not only are all EU member states smaller than the US (which also means fewer regional differences within the nation, for example in terms of electricity prices, but also

demographics), but they also have a different climate from the US, a much higher interconnection to other countries' electricity grids, a liberalized energy market, and diverse endemic health situations.

However, the urgency of decarbonizing the energy mix and the methods for doing so (increasing the penetration of renewables, modernizing the electrical infrastructure, and adequately replacing baseload power sources with renewables and storage technologies or less polluting baseload energy sources like nuclear energy) are shared. The goal of this dissertation is to inform policymakers about a previous instance in which another country took a similar step, rather than trying to forecast the changes that will occur after a country shuts down its nuclear energy.

The conflicting results of some studies in the literature, such as whether electricity prices are reduced by the presence of nuclear energy in the electricity mix, also hint at the inexistence of a “one-size-fits-all” solution, with nuclear energy being more adequate in some regions than in others.

Furthermore, my study, by design, only focuses on the short-to-medium-term reaction to the closure of the nuclear power plants. As Reiss and White (2005) make clear, there are two types of reactions to a change in electricity price. The consumer might change how they use the device in the short term, but they might decide to buy an energy-efficient product in the long run.

In terms of data, some issues might slightly bias the results, among them the fact that the PSID was not conducted in 1998, or the risk that the five weather stations used for each state do not adequately represent its climate diversity, which might be at the origin of the non-significance of extremely warm temperatures in explaining mortality.

The body of knowledge regarding the financial and non-financial effects of a nation's nuclear energy program may be further enhanced by additional research, conducted in a different context and/or period. Analyzing the opening of nuclear power plants in a country to see if the outcomes are the opposite of those in the present thesis—a decrease in mortality and electricity prices—would be an unexplored branch in this field.

Future research in this area might also examine the sensitivity to different pollutants. It can also relax the assumption that the effect on mortality is equal for temperatures inside the same 5-degree bin.

5. Conclusion

Amidst a debate in Germany, that extends to the EU and to most of the world, over which role nuclear energy should have in the energy mix, this dissertation aimed to evaluate the effect, in monetary and non-monetary terms, of shutting down nuclear power plants in the US, and thus provide insights that a policymaker in any country should consider before deciding on this topic. Decarbonizing electricity production would mean reducing GHG emissions from the most polluting activity, and at the global scale, is one of the keys to achieving the target of limiting the global temperature increase to two degrees relative to preindustrial levels.

In the empirical section of my work, using regressions that contemplate controls for demographics, climate, and pollution, I reach results that are generally consistent with previous, existing studies – I partially confirm the expected U-shaped relationship between temperature and mortality, demonstrating that when people are exposed to extremely low temperatures, an increase in mortality can be observed, particularly related to chronic respiratory diseases. In terms of how the price of electricity affects spending (and subsequently demand), I find that, as anticipated, the demand for electricity in the US during the relevant period is inelastic. Customers are significantly more price sensitive in the gas market.

The elasticity increases in most regions following the closure of the nuclear power plants, as it does in winter months, given the wider availability of substitutes powered with fuels other than electricity. Herein lies one of the factors limiting the external validity of this study: the diffusion of non-electric temperature control devices varies to varying degrees across different nations. This influences the sensitivity to electricity price changes. For the case of the USA, I estimate that the closure of the five nuclear power plants in the last decade of the previous century caused up to additional 8.725 deaths per year.

In the theoretical section of the current dissertation, I begin by highlighting the importance of decarbonizing the energy mix, given that the activity that emits the most GHGs is the production of electricity and heat. Reviewing the literature, I find that nuclear and renewable energy are complementary. Because of two problems—their intermittency and the need for an improved power grid that is equipped for a longer transmission of the generated power—renewables do not replace baseload power sources like coal plants, even though they frequently replenish gas plants. Given that electricity is a necessity, policymakers ought to exercise extreme care when causing or managing supply shocks because these can reduce the availability of electricity. This may increase the risk of diseases brought on by increased

exposure to extreme temperatures, which has implications for both the demand for electricity and the demographics.

Politicians seem to make decisions regarding nuclear energy based on perceived risk rather than fully considering the safety of this electricity generation form (both in absolute terms and relative to other power generation sources), which is largely ensured by a regulation standard that is much higher than for any other element of the energy mix.

Despite having one of the safest records among all electricity generation methods, nuclear energy is currently not required to be a part of a future decarbonized energy mix due to economic reasons. However, the other options currently available are either not yet commercially developed (storage mechanisms) or are deemed unacceptable by society (e.g., fully relying on renewable energy sources, which run the risk of leaving no power if production conditions are unfavorable).

As long as there is a viable and acceptable alternative, such as one of those mentioned, or progress in the field (in the form of the commercial development of fusion technology, which is predicted to be safer and not produce waste - Videmšek, 2022), societal opposition to nuclear energy seems a legitimate justification for its end in a nation. This is true regardless of whether the opposition is based on precedent, such as in Germany, or concerns about economics, non-competitiveness, market dominance, excessive vulnerability due to dependence on individual plants, security, nuclear waste storage, or other of the drawbacks discussed in this study. I contend that until such an alternative exists, nations that already use this power source shouldn't abandon it because, in addition to the concerns about energy security, experience with other countries suggests that doing so would have detrimental effects on mortality and the cost of electricity. Furthermore, if there are no viable alternatives, nuclear energy will be replaced by fossil fuels. With the well-known effects that continued global warming and failure to meet the 2-degree warming threshold would have on the human race (McCarthy, 2021), these are not only less safe but also more harmful to the environment.

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Appendix

Summary 2.1 - Key notes on nuclear energy in Germany

Protests against nuclear energy in Germany date back to the 1970s and they influenced the decision of no new plants being built since 1989. In 1998, the Government led by Gerhard Schröder put in to law the *Atomgesetz*, legislation that stipulated the end of nuclear power in Germany by 2022. Chancellor Angela Merkel's government partially reversed the measure once she took office in 2009. Public protests followed the decision of an extension of the plants' operating licenses for eight to fourteen years. However, the pro-nuclear government soon walked back on what became known as the phase-out of the nuclear phase-out: in 2011, following the Fukushima accident, the *Bundestag* overwhelmingly voted (513:79) in favor of a measure proposing the immediate permanent shutdown of half of the nuclear power plants, with the other half due to close by the end of this year.

The decision to close all remaining nuclear plants by the end of 2022 seems thus to have been politically motivated and justified with the security risks that were demonstrated by the Fukushima accident, but, besides the point made by Neidell et al. (2019) in their paper – shutting down nuclear power in Japan following the Fukushima accident caused more deaths than the accident itself - Murray (2019) points out that Germany's geographical and geological conditions are very different than those encountered by Japanese nuclear power plants: the small coast line decreases significantly the danger of a tsunami, and being on the center of the European tectonic plate makes the earthquake risk negligible.

As of August 2022, and amidst a gas shortage, Germany started rethinking its decision and has begun reconsidering the future of nuclear power in the country (Girschick and Gill, 2022; Reisin, 2022). The long-term plan for the Germany energy sector relied on a combination of renewable energy – which requires a still pending upgrade of the power grid – and Russian gas (Bundesministerium Klimaschutz, 2022; Bundeszentrale für politische Bildung, 2022), whose supply to the EU is steadily decreasing. The public perspective changed, with an estimated four fifths of the population now supporting an extension of the nuclear power plants licenses (ARD, 2022a; ARD, 2022b), as opposed to a strong divide in the government, with the anti-nuclear green party opposing such a step, having reportedly expressed a preference to rather reactivate coal plants, which would strongly go against IPCC research and EU's policy. This deadlock in the German government forced Chancellor Scholz to personally intervene, deciding an extension of the remaining nuclear plants' lifetime until April 2023.

Table 2.2

Expanding the role of nuclear energy

- Benefits in GHG emission reductions (Mari 2014)
- Public perception regarding climate change is increasing (Lake 2002)
- Mitigation of price volatility that results from fossil fuels (where there are market-based emission control initiatives such as the European Emissions Trading System and where fuel, whose price is inherently volatile, represents a significant portion of the electricity generation costs - 75% for gas versus 8% for nuclear energy) and the higher penetration of intermittent electricity generation sources (Mari 2014)
- Contract responsibility is a way to help keep projects under budget (Mari 2014)
- Development of the industry can make it more attractive: operation efficiency (high concentration uranium, use heat from nuclear power plant to provide residential heating, etc.), ending nuclear insecurity by designing reactors that can't melt, solving the waste (Pearce 2012), recycling cooling water or develop fusion-based plants, which don't produce waste), regaining of the public trust in the industry (which is key to build closer to residential areas) (Pearce 2012)
- Construction times and costs can be reduced building smaller reactors closer to residential areas, but it requires full public trust (Pearce 2002)

Reducing the role of nuclear energy

- The key factor preventing a more widespread diffusion is of economic nature - calculating the LCOE for coal, gas and nuclear, even without the risk premium of nuclear energy and with a carbon tax, nuclear energy is still the most expensive (Davis 2012)
- Nuclear power plants often operate at a loss, mostly caused by a high penetration of gas and renewables, which drive down the price of electricity; regardless of the gas price, (only) multi-reactor - hence large - plants avoid CO₂ emissions at a cost lower than the social cost of carbon, which puts the idea of smaller nuclear plants into question (Roth and Jaramillo 2017)
- Building nuclear power plants is unattractive - uncertainty over future economic scenario (e.g. decrease in fossil fuel prices), shortage of professionals/suppliers during the construction period, technological and financing risk, regulatory process (Davis 2012)
- From the policy-making side, there is modest evidence of learning-by-doing or economies of scale, and no evidence these benefit the whole industry; other electricity generation mechanisms such as wind also have these benefits. This means subsidizing nuclear energy doesn't have economic ground, and the existence of subsidies would also encourage standardization (which disincentivizes the development of more powerful, efficient and safe units) (Davis 2012)
- Their large size and hence non-negligible market share means the existence of nuclear power plants sustains a non-competitive energy market, making it easier to keep prices at a higher value. In Germany there is also no correlation between the diffusion of nuclear power and lower electricity prices. (Nestle 2012)
- The large size of nuclear plants makes the energy system vulnerable. There was an exogenous shutdown for five months, short notice, of plants generating one fifth of the total French nuclear power, for an inspection of reactors that were potentially compromised with a security fault. Electricity prices rose by 27% in France and due to cross-border trade by 11% in Germany (respectively 17.41€ and 4.58€/MWh) (Rimec 2019)

Table 3.1

Nuclear power plant	Type of reactor*	Location	Gross capacity	Lifetime electricity supplied**	Years in operation	Periods without electricity production
Millstone 1	BWR	Connecticut - Northeast	684 MW	101.37 TWh	1970-1998	before 1971 and after 1995
Maine Yankee	PWR	Maine - Northeast	900 MW	118.72 TWh	1972-1997	in 1972 and 1997
Zion 1	PWR	Illinois - Midwest	1085 MW	124.41 TWh	1973-1998	in 1998
Zion 2			1085 MW	124.5 TWh	1973-1998	in 1973 and after 1996
Big Rock Point	BWR	Michigan - Midwest	71 MW	12.74 TWh	1962-1997	before 1971

*BWR – boiling water reactor; PWR – pressurized water reactor
 **For reference, in 2000, Chicago, the state capital of Illinois, consumed 113.98 TWh of electricity (ACEEE, 2017)

Table 3.2– Descriptive Statistics

VARIABLES	(1) N	(2) Mean	(3) St. Dev.	(4) Minimum	(5) Maximum
Freq. of temperatures in bin 1	4,032	25.06	54.84	0	216
Freq. of temperatures in bin 2	4,032	17.78	31.50	0	167
Freq. of temperatures in bin 3	4,032	18.46	28.59	0	158
Freq. of temperatures in bin 4	4,032	21.90	30.38	0	175
Freq. of temperatures in bin 5	4,032	27.95	36.92	0	204
Freq. of temperatures in bin 6	4,032	17.44	29.01	0	178
Freq. of temperatures in bin 7	4,032	6.492	16.85	0	109
Electricity Price	4,032	8.36	2.33	4.34	16.13
Electricity Expenditure	4,032	67.7	19.57	24.93	152.85
Total Mortality Rate	4,032	0.000276	7.02e-05	0.000135	0.000688
Extreme Precipitation	4,032	0.498	0.500	0	1
Frequency of extreme wind	4,032	370.9	82.07	24	1,084
Freq. of AQI in level 2	4,032	3.493	6.418	0	31
Freq. of AQI in level 3	4,032	0.765	1.950	0	17
Freq. of AQI in level 4	4,032	0.0667	0.398	0	8
Freq. of AQI in level 5	4,032	0.00124	0.0417	0	2

Frequencies in hours

Figure 3.3

Residential electricity price development by Region, in cents/kWh

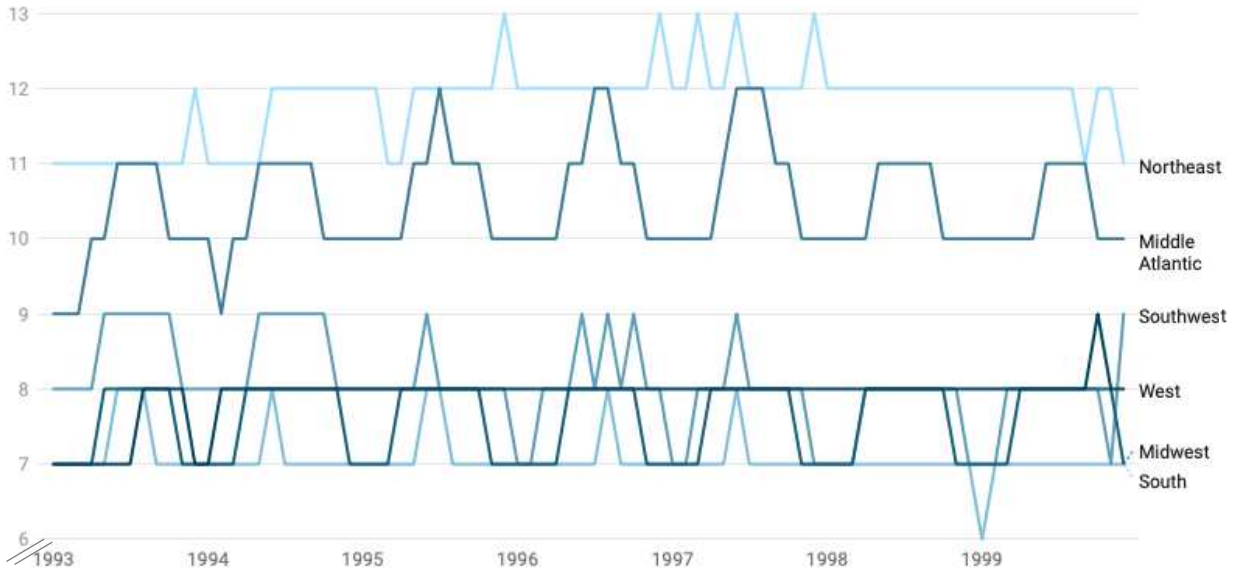
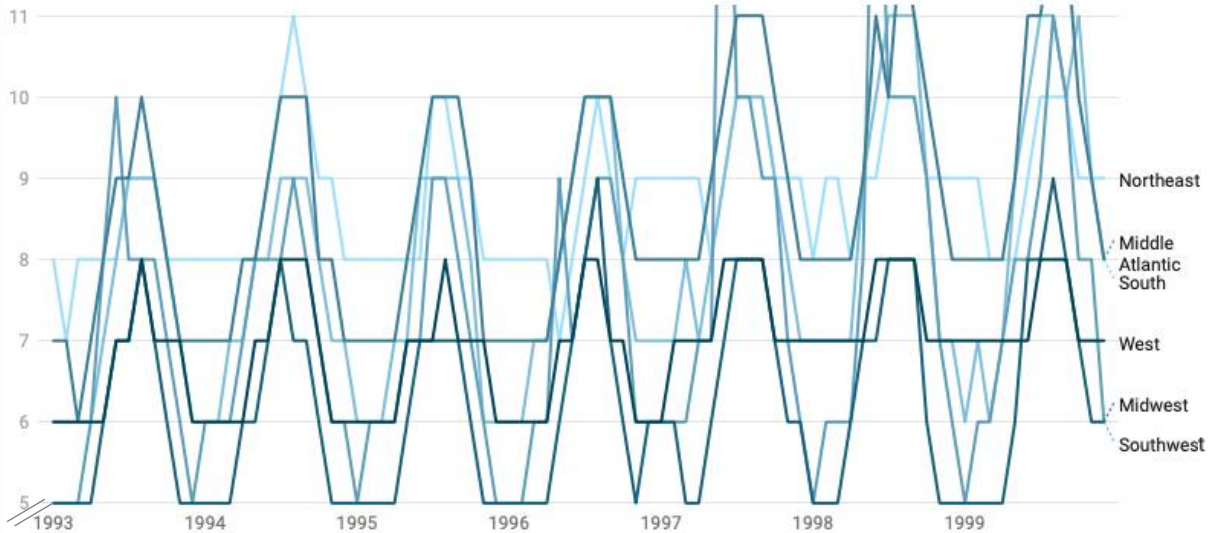


Figure 3.4

Residential electricity gas price development by Region, in \$/cubic feet



1 cubic feet is equivalent to about 0.29kWh

Table 4.1 – Effect of electricity on the temperature-mortality relationship

Temperature bins	(1)
7	-0.00137* (0.000743)
3 x contemp. price	-0.00390** (0.00151)
5 x contemp. price	-0.00193* (0.00107)
3 x price with lag 1	0.00392** (0.00186)
5 x price with lag 1	0.00387*** (0.00112)

Robust standard errors in parentheses
 *** p<0.01, ** p<0.05, * p<0.1
 Only significant coefficients are reported

Figure 4.2

Parallel trend analysis

Development of the number of deaths caused by exposure to cold temperature

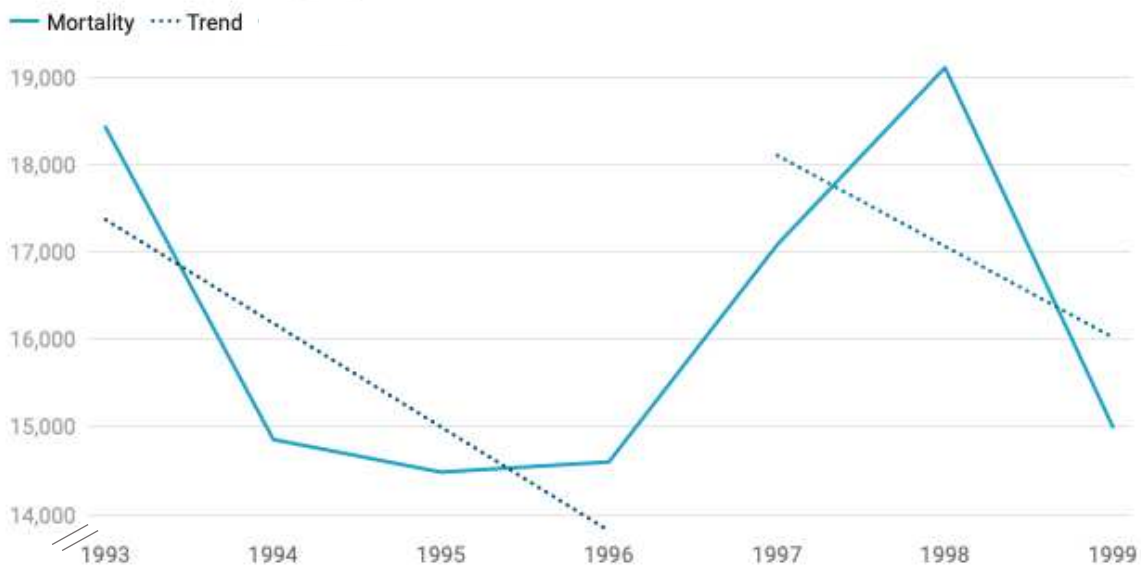


Table 4.3 – Analysis of the temperature-mortality relationship

Temperature bin	(1) Total mortality	(2) Cardiovascular diseases	(3) Chronic respiratory diseases	(4) Non-communicable diseases
1	0.000397*** (0.000113)	4.20e-05** (2.00e-05)	-9.11e-06 (2.76e-05)	2.34e-05 (1.64e-05)
2	0.000370*** (9.54e-05)	1.28e-05 (2.36e-05)	-4.65e-05** (2.29e-05)	6.39e-06 (2.14e-05)
3	7.25e-05 (9.86e-05)	-4.33e-05 (2.87e-05)	-5.80e-05** (2.33e-05)	-4.41e-05** (2.08e-05)
4	0.000138 (0.000125)	-2.26e-05 (1.95e-05)	-3.21e-06 (2.42e-05)	-2.25e-05 (1.48e-05)
5	3.67e-05 (0.000114)	-3.68e-05 (2.67e-05)	3.11e-05 (3.20e-05)	-2.16e-05 (2.06e-05)
6	7.18e-05 (0.000156)	-3.75e-05 (3.32e-05)	-2.11e-05 (2.97e-05)	-3.49e-05 (2.50e-05)
7	0.000110 (0.000169)	-1.02e-05 (4.06e-05)	0.000181** (6.94e-05)	2.58e-05 (2.79e-05)
1, with 1 lag	-0.000141 (0.000143)	3.17e-05 (2.01e-05)	-5.51e-05** (2.44e-05)	1.45e-05 (1.81e-05)
2, with 1 lag	-8.27e-05 (0.000209)	-1.03e-05 (1.97e-05)	-7.87e-05*** (2.25e-05)	-1.34e-05 (1.67e-05)
3, with 1 lag	-6.23e-05 (0.000137)	-3.72e-05 (3.62e-05)	-7.51e-05*** (2.60e-05)	-4.72e-05* (2.70e-05)
4, with 1 lag	-5.52e-05 (0.000181)	-1.39e-05 (2.36e-05)	7.08e-07 (2.39e-05)	-1.60e-05 (1.62e-05)
5, with 1 lag	-8.87e-05 (0.000129)	-3.03e-05 (2.81e-05)	3.64e-05 (2.85e-05)	-1.52e-05 (2.29e-05)
6, with 1 lag	-7.48e-05 (0.000149)	-1.83e-05 (2.72e-05)	-1.16e-05 (2.64e-05)	-1.96e-05 (2.01e-05)
7, with 1 lag	-3.18e-05 (0.000186)	-1.76e-05 (4.11e-05)	0.000123*** (3.23e-05)	1.06e-05 (2.80e-05)
1, with 2 lags	-0.000161 (0.000136)	-2.12e-05 (2.09e-05)	-9.69e-05*** (2.90e-05)	-2.90e-05* (1.72e-05)
2, with 2 lags	3.39e-05 (0.000106)	-3.38e-05 (2.45e-05)	-9.89e-05*** (3.41e-05)	-3.54e-05 (2.15e-05)
3, with 2 lags	-0.000119 (0.000112)	-6.43e-05* (3.66e-05)	-9.07e-05*** (3.07e-05)	-6.79e-05** (2.91e-05)
4, with 2 lags	9.92e-05 (0.000114)	-3.79e-05* (2.12e-05)	-1.79e-05 (2.92e-05)	-3.88e-05** (1.49e-05)
5, with 2 lags	-2.90e-05 (0.000115)	-3.64e-05 (2.31e-05)	3.38e-05 (2.46e-05)	-1.93e-05 (1.94e-05)
6, with 2 lags	-0.000175 (0.000141)	-3.62e-05 (2.75e-05)	-3.51e-05 (3.44e-05)	-4.00e-05** (1.97e-05)
7, with 2 lags	0.000105 (0.000127)	1.20e-05 (3.35e-05)	0.000158*** (3.65e-05)	3.78e-05 (2.36e-05)

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.4 – The temperature-mortality relationship by US region

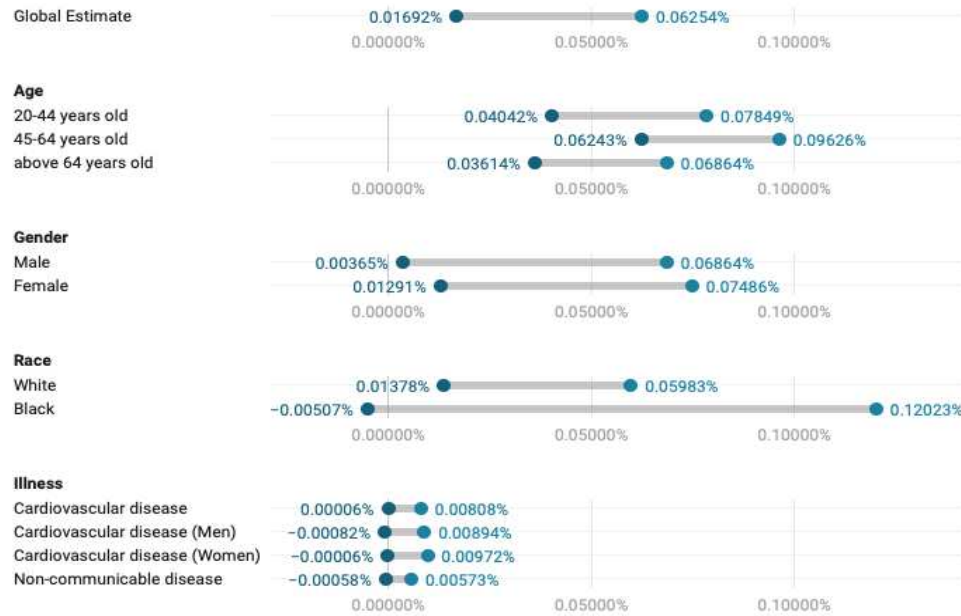
VARIABLES	(1) Northeast	(2) Middle Atlantic	(3) South	(4) Midwest	(5) Southwest	(6) West
1	6.98e-05 (0.000976)	-0.00228 (0.00121)	0.000299 (0.000347)	-6.23e-05 (0.000256)	-4.38e-05 (0.000364)	0.000474 (0.000491)
2	0.000574 (0.000437)	-0.00201* (0.000659)	0.000467 (0.000286)	-0.000192 (0.000366)	-0.000258 (0.000301)	0.000449 (0.000523)
3	6.88e-06 (0.00117)	-0.000409 (0.000332)	0.000257 (0.000249)	-0.000247 (0.000273)	0.000133 (0.000213)	-0.000119 (0.000322)
4	0.000495 (0.000255)	-0.000674 (0.000582)	0.000222 (0.000152)	1.30e-05 (0.000254)	-0.000134 (0.000474)	0.000358 (0.000531)
5	-0.000590 (0.000569)	0.000417 (0.000922)	0.000170 (0.000181)	-0.000228 (0.000208)	2.89e-05 (0.000118)	3.58e-05 (0.000556)
6	-0.000604 (0.000387)	0.000865 (0.000448)	0.000259 (0.000250)	0.000152 (0.000384)	-0.000359 (0.000576)	4.30e-05 (0.000538)
7	-0.00305 (0.00367)	0.00123 (0.00129)	-5.92e-05 (0.000190)	-0.000859 (0.000503)	-0.000193 (0.000241)	0.00108*** (0.000251)
1, with 1 lag	0.000788 (0.00104)	0.00111** (0.000330)	0.000320 (0.000300)	-0.000183 (0.000297)	-0.000250 (0.000493)	5.24e-05 (0.000341)
2, with 1 lag	0.000239 (0.000962)	0.00101** (0.000174)	0.000175 (0.000245)	8.80e-05 (0.000298)	0.000742 (0.000532)	-0.000322 (0.000458)
3, with 1 lag	0.000902 (0.000743)	0.000238 (0.000223)	8.87e-06 (0.000292)	-0.000548 (0.000330)	-0.000275 (0.000213)	0.000368*** (9.52e-05)
4, with 1 lag	-0.000853 (0.000576)	0.00128** (0.000356)	0.000118 (0.000264)	-6.80e-05 (0.000180)	-1.74e-05 (0.000553)	-0.000403 (0.000295)
5, with 1 lag	-0.000867 (0.00140)	-0.00136* (0.000468)	-0.000113 (9.55e-05)	-8.16e-05 (0.000168)	0.000319 (0.000791)	1.33e-05 (0.000366)
6, with 1 lag	-6.26e-05 (0.00105)	-0.00160** (0.000335)	1.15e-05 (0.000228)	-1.78e-05 (0.000504)	-0.000658 (0.000344)	0.000487* (0.000236)
7, with 1 lag	-0.00231** (0.000565)	-0.000838 (0.000695)	-0.000187 (0.000133)	-4.80e-06 (0.000610)	0.000202 (0.000255)	-0.000653** (0.000267)
1, with 2 lags	0.000875 (0.000530)	-0.000959 (0.000883)	-0.000322 (0.000320)	-0.000131 (0.000290)	0.000387 (0.000532)	0.000245 (0.000397)
2, with 2 lags	0.000653 (0.000941)	-0.000123 (0.00102)	-0.000119 (0.000247)	0.000219 (0.000282)	0.000140 (0.000439)	0.000723** (0.000238)
3, with 2 lags	0.000273 (0.000454)	-0.000119 (0.000305)	-0.000183 (0.000281)	-0.000464* (0.000256)	-0.000318 (0.000477)	0.000558 (0.000311)
4, with 2 lags	0.00104 (0.000517)	0.000255 (0.000177)	0.000186 (0.000202)	2.94e-05 (0.000267)	0.00119 (0.00124)	0.000520 (0.000440)
5, with 2 lags	0.000198 (0.000660)	-0.000826** (0.000148)	5.14e-05 (0.000156)	-0.000228 (0.000248)	-0.000521 (0.000766)	0.000841* (0.000428)
6, with 2 lags	-0.000472 (0.000463)	-0.00219** (0.000467)	-0.000244 (0.000159)	-0.000139 (0.000299)	-0.000189 (0.00125)	-0.000145 (0.000419)
7, with 2 lags	0.00150 (0.00275)	0.000289 (0.00106)	1.23e-06 (0.000196)	5.73e-06 (0.000792)	7.63e-05 (0.000504)	0.000742 (0.000599)

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Figure 4.5

Estimated effect of an additional hour of exposure to negative temperatures on mortality, relative to one hour exposed to temperatures between 15 and 19C°



The 95% Confidence Interval range is displayed.

Figure 4.6

Estimated effect of an additional hour of exposure to temperatures in the 0-4 C° range on mortality, relative to one hour exposure to temperatures between 15 and 19C°



The 95% Confidence Interval range is displayed.

Table 4.7

Year	Correlation coefficient between Electricity Price and Expenditure
1993	0,235
1994	0,214
1995	0,225
1996	0,211
1997	0,252
1998	0,171
1999	0,212

Table 4.8 – Elasticity Estimates			
	(1)	(2)	(3)
	Contemporaneous Period	1 Lag	2 Lags
Price Elasticity of Electricity Demand	-0.264*** (0.0625)	-0.520*** (0.0602)	-0.645*** (0.0476)
Winter Price Elasticity of Electricity Demand	-0.252*** (0.0872)	-0.557*** (0.110)	-0.673*** (0.0951)
Summer Price Elasticity of Electricity Demand	-0.240*** (0.123)	-0.398*** (0.0967)	-0.713*** (0.0980)
Number of States	48	48	48

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.9 – Robustness Checks							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Price Elasticity of Electricity Demand							
Current Period	-0.264*** (0.0625)	-0.277*** (0.0654)	-0.276*** (0.0648)	-0.263*** (0.0623)	-0.278*** (0.0667)	-0.0583*** (0.115)	0.0890*** (0.133)
1 Lag	-0.520*** (0.0602)	-0.525*** (0.0621)	-0.524*** (0.0609)	-0.520*** (0.0594)	-0.509*** (0.0655)	-0.311*** (0.0825)	-0.172*** (0.0955)
2 Lags	-0.645*** (0.0476)	-0.647*** (0.0473)	-0.645*** (0.0473)	-0.644*** (0.0474)	-0.625*** (0.0468)	-0.593*** (0.0735)	-0.496*** (0.0747)
Observations	3,936	3,936	3,936	3,936	3,690	3,936	3,936
Number of States	48	48	48	48	45	48	48
Precipitation and Wind	Yes	Yes	No	No	Yes	Yes	Yes
Household Characteristics	Yes	No	No	Yes	Yes	Yes	Yes
Narrower definition of 'regulated market'	No	No	No	No	Yes	Yes	Yes
Year-Month Fixed Effects	Yes	Yes	Yes	Yes	Yes	No	Yes
State-Month Fixed Effects	Yes	Yes	Yes	Yes	Yes	No	No

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.10 – Elasticity by Period		
Price Elasticity of Electricity Demand	(1) Price elasticity 1993-1996	(2) Price elasticity 1997-1999
Contemporaneous	-0.268*** (0.0936)	-0.312*** (0.0649)
1 Lag	-0.708*** (0.0775)	-0.488*** (0.0779)
2 Lags	-0.738*** (0.0566)	-0.667*** (0.0872)
Observations	2,304	1,632
Number of States	48	48

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.11 – Elasticity by Period and Region						
Price elasticity of residential electricity demand	(1) Northeast	(2) Middle Atlantic	(3) South	(4) Midwest	(5) Southwest	(6) West
1993-1996	-0.261*** (0.0848)	-0.221*** (0.0870)	-0.266*** (0.0750)	-0.230*** (0.0688)	-0.269*** (0.0863)	-0.298*** (0.0815)
1997-1999	-0.300*** (0.0611)	-0.276*** (0.0726)	-0.316*** (0.0505)	-0.212*** (0.0643)	-0.301*** (0.0537)	-0.304*** (0.0627)
Observations	2,474	2,440	2,746	2,678	2,440	2,678

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.12– Gas Elasticity Estimates

	(1) Contemporaneous Period	(2) 1 Lag	(3) 2 Lags
Price Elasticity of Residential Gas Demand	-1.437*** (0.0662)	-0.991 (0.0812)	-0.976 (0.0760)
Winter Price Elasticity of Residential Gas Demand	-1.299*** (0.0638)	-1.083 (0.0748)	-0.998 (0.0873)
Summer Price Elasticity of Residential Gas Demand	-1.480*** (0.0981)	-0.935 (0.110)	-0.958 (0.0848)
Observations	3,357	3,357	3,357
Number of States	41	41	41

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.13 – Gas Elasticity by Period and Region

Price elasticity of residential gas demand	(1) Northeast	(2) Middle Atlantic	(3) South	(4) Midwest	(5) Southwest	(6) West
1993-1996	-1.407*** (0.0566)	-1.464*** (0.0613)	-1.416*** (0.0532)	-1.362*** (0.0621)	-1.345*** (0.0621)	-1.485*** (0.0767)
1997-1999	-1.493*** (0.0893)	-1.520*** (0.0823)	-1.464*** (0.0817)	-1.407*** (0.0920)	-1.434*** (0.106)	-1.515*** (0.0822)

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.14 – Substitutability of Electricity and Gas

	(1) Contemporaneous Period	(2) 1 Lag	(3) 2 Lags
Cross-Price Elasticity of Electricity Demand	-0.00612 (0.0315)	0.485*** (0.0629)	0.347*** (0.0494)
Winter Cross-Price Elasticity of Electricity Demand	-0.0120 (0.0565)	0.497*** (0.120)	0.344*** (0.121)
Summer Cross-Price Elasticity of Electricity Demand	0.0108 (0.0431)	0.498*** (0.0682)	0.247*** (0.0808)
Number of States	41	41	41

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1