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THE MORTALITY EFFECTS OF WINTER HEATING PRICES*

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This paper examines how the price of home heating affects mortality in the United States. Exposure to cold is one reason that mortality peaks in winter, and a higher heating price increases exposure to cold by reducing heating use. Our empirical approach combines spatial variation in the energy source used for home heating and temporal variation in the national prices of natural gas and electricity. We find that a lower heating price reduces winter mortality, driven mostly by cardiovascular and respiratory causes. Our estimates imply that the 42% drop in the natural gas price in the late 2000s, mostly driven by the shale gas boom, averted 12,500 deaths per year in the United States. The effect appears to be especially large in high-poverty communities.

Many families worldwide struggle to heat their homes each winter. Their heating bills are so high relative to their income that they are considered to be living in 'fuel poverty'. In the European Union, 8% of households are unable to keep their homes adequately warm in winter (Eurostat, 2021). In the United States, 17% of households spend over 10% of their income on home energy; winter heating is the largest contributor (RECS, 2009). The problem becomes even more acute during energy crises. For example, when natural gas supply was disrupted after Russia's invasion of Ukraine in 2022, heating prices soared in many parts of the world, pushing millions of additional households into fuel poverty.

Households face a difficult trade-off when heating prices are high: they have to keep their home uncomfortably cold to save on heating, or they have to forgo other spending to afford their high heating bill. Either choice could be harmful to their health. Using less heating means exposure to lower ambient temperature, which has been linked to cardiovascular, respiratory and other health problems. But if families do not cut back heating usage one for one when the price rises, their energy bills will increase, leaving less money for other expenditures that affect health such as food and health care. For these reasons, morbidity and mortality are potentially important consequences of high heating prices.

This paper estimates the effect of heating prices on mortality in the United States. A large literature has documented that mortality peaks in winter (see Online Appendix Figure A1) and

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The data and codes for this paper are available on the Journal repository. They were checked for their ability to reproduce the results presented in the paper. The authors were granted an exemption to publish parts of their data because access to these data is restricted. However, the authors provided a simulated or synthetic dataset that allowed the Journal to run their codes. The synthetic/simulated data and the codes for the parts subject to exemption are also available on the Journal repository. They were checked for their ability to generate all tables and figures in the paper; however, the synthetic/simulated data are not designed to reproduce the same results. The replication package for this paper is available at the following address: https://doi.org/10.5281/zenodo.8206902.

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that cold weather is associated with higher mortality. Our contribution is to examine whether high home heating costs exacerbate this pattern of ‘excess winter mortality’.

Our empirical design uses spatial variation across the United States in the energy source used for home heating. Natural gas and electricity are used for heating by 58% and 30% of US households, respectively. Importantly, there is considerable variation across counties in whether natural gas versus electricity is mainly used. We combine this spatial variation with temporal variation in the national prices of natural gas and electricity. The price of natural gas varied substantially over the 2000 to 2010 study period, relative to the price of electricity; it first rose, partly due to supply disruption from Gulf of Mexico hurricanes, and then fell after 2005, mostly due to the supply influx from shale production of natural gas (Hausman and Kellogg, 2015). We use the fact that, when the price of natural gas rose or fell, households in areas that rely on natural gas for heating experienced a rise or fall in their home heating price, relative to households in areas reliant on electricity.

We find that lower heating prices reduce mortality in winter months.[1] The estimated effect size implies that the 42% drop in the price of natural gas in the late 2000s averted 12,500 winter deaths per year in the United States. Moreover, we find that this effect does not just represent a short-run postponement of mortality. We also show that the effect, which is driven mostly by cardiovascular and respiratory causes and is larger in high-poverty communities, is robust to several stress tests of the empirical specification.

Our findings have implications for policies that reduce households’ heating costs such as the federal Low Income Home Energy Assistance Program (LIHEAP) and state energy price subsidy programs in the United States (see, e.g., Hahn and Metcalfe, 2021) and analogous policies worldwide, and are also relevant for cost-benefit analysis of weatherization programs that reduce households’ need for heating. In addition, our findings highlight a health benefit of increases in US energy supply that has not received much prior attention.

Our paper contributes to the literature on the effects of cold weather on mortality (Eurowinter Group, 1997; Analitis *et al.*, 2008; Deschênes and Moretti, 2009) and other dimensions of well-being (Bhattacharya *et al.*, 2003; Cullen *et al.*, 2004; Ye *et al.*, 2012; Beatty *et al.*, 2014). To our knowledge, no prior study has estimated the causal effect of heating prices—an important and policy-relevant mediating factor—on health. Previous work has found that the winter spike in mortality is especially large for people living in older housing, which tends to be poorly insulated, which is suggestive, but not dispositive that indoor temperature is a mediating factor (Wilkinson *et al.*, 2007).

Another related line of research examines adaptations that mitigate the temperature-health relationship. Previous research has examined the role of technological and medical advances (Deschênes and Greenstone, 2011, Barreca *et al.*, 2016), migration (Deschênes and Moretti, 2009) and weatherization and energy-efficiency programs (Critchley *et al.*, 2007; Howden-Chapman *et al.*, 2007; El Ansari and El-Silimy, 2008; Green and Gilbertson, 2008). Increased heating use is another important household-level adaptation, and we contribute by analysing how high fuel prices stymie this adaptation. A study concurrent to ours analyses the aftermath of the Fukushima nuclear power plant accident in Japan and finds that higher electricity prices exacerbate the relationship between cold temperatures and mortality (Neidell *et al.*, 2021). An advantage of our research design is that we can directly identify changes in the price of heating

[1] We define ‘winter’ as November to March, the coldest months of the year in the United States (see Online Appendix Figure A1). We also show the results using December to March, similar to analyses of excess winter mortality in the UK and Europe where those are the coldest months (Wilkinson *et al.*, 2004).

(by incorporating geographic variation in the energy source used for heating) instead of energy prices more broadly, which might also affect health through other channels. Additionally, we shed light on the relative importance of the different mechanisms through which a higher heating price increases mortality.[2]

Our paper also contributes to the literature on the health effects of the shale gas (or 'fracking') boom by highlighting a national-level health benefit—the drop in energy prices reduced winter mortality. Prior work has highlighted the health benefit of fracking displacing pollutive coal in electricity generation (Knittel *et al.*, 2015; Cullen and Mansur, 2017; Holladay and LaRiviere, 2017; Fell and Kaffine, 2018; Linn and Muehlenbachs, 2018). Fracking has also been shown to be harmful because of local contamination from the chemicals used (Groundwater Protection Council and ALL Consulting, 2009; Jackson *et al.*, 2014; Muehlenbachs *et al.*, 2015; Casey *et al.*, 2016; Currie *et al.*, 2017; Hill, 2018). The health harm from the toxic chemicals is likely much larger per person affected than the health benefits from lower energy prices; however, the latter channel affects a much larger population. Thus, the net health effect of fracking aggregated for the whole US population is ambiguous. Finally, our empirical strategy is similar to that of Myers (2019), who compared households that use heating oil or natural gas in Massachusetts to study whether home energy costs are capitalised into home values.

1. Empirical Strategy

To identify the effect of heating prices on mortality, we combine information on whether a locality typically uses natural gas or electricity for heating with data on national energy prices. This approach enables us to control for average differences across localities and time.

1.1. *Estimating Equations*

In principle, we want to estimate the following equation:

$$\log(m_{jt}) = \alpha + \beta \log(p^H_{jt}) + \epsilon_{jt}. \tag{1}$$

Each observation is a county-month. The outcome $\log(m_{jt})$ is the log of age-adjusted mortality in county j in month t. (We use the log of the mortality rate following Stevens *et al.*, 2015, but also report the results in levels.) The key regressor is $\log(p^H_{jt})$, the log of the heating price for the county-month. The coefficient β measures the elasticity of mortality with respect to the heating price. The hypothesis is that $\beta > 0$: a higher heating price increases mortality.

There are no data on p^H_{jt} because utilities do not set a price specifically for heating, just for different energy sources. Instead, we construct a proxy for the heating price by interacting ShareGas_{jt}, the proportion of households in the area that used natural gas for heating in that year, with $\log(\text{RelPrice}_{jt})$, the ratio of the price of gas to electricity in the state-month. To see why this interacted variable tracks the heating price for households, note that when natural gas prices increase (high RelPrice), areas with high ShareGas face relatively higher heating prices. Conversely, when electricity prices increase (low RelPrice), areas with higher ShareGas face

[2] Other studies have focused on financial assistance for energy bills or heating subsidies for low-income families (Frank *et al.*, 2006; Grey *et al.*, 2017; Crossley and Zilio, 2018).

relatively low heating prices. In practice, most of the identifying variation comes from the natural gas price because it fluctuates more over the study period.[3]

Utilities markets within the United States vary considerably in terms of prices and regulations, which means that $\text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt})$ could be endogenous to local demand. To solve this problem, our empirical strategy relies on national-level energy prices combined with (pre-period) local variation in the energy source for heating. That is, we instrument for $\text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt})$ with $\text{ShareGas}_{j,2000} \times \log(\text{RelPrice}_{\text{US},t})$.[4]

We estimate the following equation with this instrumental variables approach:

$$\log(m_{jt}) = \alpha + \beta\, \text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt}) + \gamma_j + \tau_t + \boldsymbol{\theta} \cdot \mathbf{Z_j} \times \log(\text{RelPrice}_{\text{US},t}) + \boldsymbol{\delta} \cdot \mathbf{X_{jt}} + \epsilon_{jt} \tag{2}$$

with the first-stage equation given as

$$\text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt}) = \tilde{\alpha} + \tilde{\beta}\text{ShareGas}_{j,2000} \times \log(\text{RelPrice}_{\text{US},t}) + \tilde{\gamma}_j + \tilde{\tau}_t + \tilde{\boldsymbol{\theta}} \cdot \mathbf{Z_j} \times \log(\text{RelPrice}_{\text{US},t}) + \tilde{\boldsymbol{\delta}} \cdot \mathbf{X_{jt}} + \nu_{jt}.$$

In addition to replacing $\log(p^H_{jt})$ with $\text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt})$, we augment (1) by including county fixed effects, γ, and month-year fixed effects, τ. We also include several control variables, denoted by the vector **X**. Because the study period spans the housing market boom and bust as well as the Great Recession, we control for a housing price index, the unemployment rate and the manufacturing share of local employment income. Vector **X** also includes factors that might affect mortality, namely air pollution—particulate matter 2.5 and 10 microns, separately, and nitrogen dioxide—absolute humidity and the heating degree days (HDDs) of the area (a measure of coldness, described in Section 2). We additionally include nitrogen dioxide as a quadratic term to control for it more flexibly because we find that it is correlated with $\text{ShareGas}_{j,2000} \times \log(\text{RelPrice}_{\text{US},t})$. The humidity-mortality relationship is non-linear (Barreca and Shimshack, 2012), so we also control for a quadratic term in absolute humidity. Finally, we control for area characteristics **Z**, specifically pre-period log income (25th, 50th and 75th percentiles) and the share of the population over age 70, interacted with $\log(\text{RelPrice}_{\text{US},t})$; these controls help safeguard against a spurious correlation due to the Great Recession (or another phenomenon with a similar temporal pattern as $\log(\text{RelPrice}_{\text{US},t})$) having a differential impact on mortality across socioeconomic or demographic groups (Hoynes *et al.*, 2012).

The identification assumption is that, when natural gas prices are high relative to electricity, places with more natural gas usage for heating have higher mortality only because of the higher heating price they face, conditional on fixed effects and control variables. Throughout, we cluster SEs by state to allow for serial correlation plus spatial correlation among counties in a state.

For our baseline specification, we restrict the data to only winter months (when possible) when most of the year's heating is consumed. We also estimate a winter/non-winter specification that

[3] Our results are similar if we replace RelPrice with the price of natural gas, with or without controlling for ShareGas interacted with the electricity price.

[4] Formally, $\text{ShareGas}_{j,2000} \times \log(\text{RelPrice}_{\text{US},t}) = \text{ShareGas}_{j,2000} \log(p^G_{\text{US},t}) + \text{ShareElec}_{j,2000} \log(p^E_{\text{US},t}) - \log(P^E_{\text{US},t})$, where $\text{ShareElec}_{j,2000}$ is the proportion of households in 2000 that use electricity for heating, and $p^G_{\text{US},t}$ and $p^E_{\text{US},t}$ are the national prices of natural gas and electricity, respectively. Month-year fixed effects absorb $\log(p^E_{\text{US},t})$. The first two terms on the right capture the average proportional change in the heating price *across* households in a county (some use gas, while others use electricity as their main heating source), i.e., it is an exogenous proxy for $\log(p^H_{jt})$.

uses the non-winter months as an additional comparison group, testing the prediction that the price of heating affects mortality more in winter than in the remaining, warmer months:

$$\begin{aligned}\log(m_{jt}) = \alpha &+ \lambda_1 \text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt}) \times \text{Winter}_t \\ &+ \lambda_2 \text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt}) \\ &+ \lambda_3 \text{ShareGas}_{j,2000} \times \text{Winter}_t + \lambda_4 \log(\text{RelPrice}_{\text{US},t}) \times \text{Winter}_t \\ &+ \boldsymbol{\theta_1 \text{Z}_\text{j}} \times \log(\text{RelPrice}_{\text{US},t}) \times \text{Winter}_t + \boldsymbol{\theta_2 \text{Z}_\text{j}} \times \log(\text{RelPrice}_{\text{US},t}) \\ &+ \boldsymbol{\theta_3 \text{Z}_\text{j}} \times \text{Winter}_t + \gamma_j + \tau_t + \boldsymbol{\delta \text{X}_\text{jt}} + \epsilon_{jt}.\end{aligned}$$

Analogous to before, the first two regressors are instrumented using $\text{ShareGas}_{j,2000} \times \log(\text{RelPrice}_{\text{US},t})$ and $\text{ShareGas}_{j,2000} \times \log(\text{RelPrice}_{\text{US},t}) \times \text{Winter}_t$. The prediction is $\lambda_1 > 0$.

Some winters or particular months in winter are colder than others, so we can also replace Winter with HDD. In this specification, we control for the county's average HDDs in winter, $\overline{\text{HDD}}_j$, in parallel to HDD_{jt} to adjust for systematic differences (e.g., demographics) between colder regions such as the Midwest and warmer ones such as the South.

1.2. *Assessing the Heating and Non-Heating Consumption Channels*

Heating prices can affect mortality through two channels: a cutback in heating use ('heating channel') and a reduction in the income left over for other consumption after paying the heating bill ('non-heating channel'). To gauge the potential relevance of each channel, we analyse two additional outcomes.

The first one is the (log) quantity of home energy use. Here, the coefficient β from (2) can be interpreted as a price elasticity. We expect it to be negative: consumers substitute away from heating when it becomes more expensive. The data on home energy use do not disaggregate it by purpose (e.g., heating, lighting). Thus, while the variation in the price of natural gas is mainly measuring variation in a household's heating price, the outcome combines heating plus other energy uses, so the coefficient represents a lower bound magnitude for the price elasticity of heating demand. The use of natural gas in homes is mostly for heating (space heating and water heating), with an additional small contribution from kitchen ranges and clothes dryers. Non-heating home energy needs such as lighting, refrigeration and air conditioning predominantly use electricity throughout the United States. Home heating is the largest component of home energy use, accounting for 42% of annual home energy consumption, with water heating accounting for an additional 18% (RECS, 2009).

The second outcome is expenditures on home energy, again with the caveat that we cannot distinguish spending on heating from other energy uses (although in winter months, heating accounts for most energy use). If households are not cutting back one for one when the price rises then higher energy prices will lead to higher energy bills (and thus less income left for other consumption).

1.3. *Geographic Variation in Heating Source*

Natural gas and electricity are the two most common energy sources for home heating in the United States, with considerable geographic variation. In some communities, almost every household uses natural gas for heating, and in other communities, almost no one does.

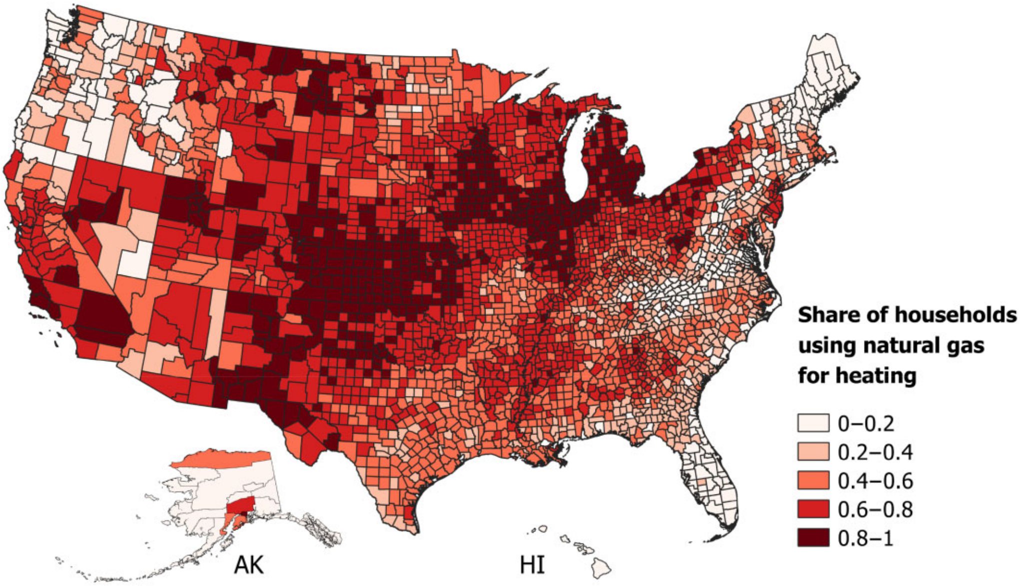

Fig. 1. *Share of Households Using Natural Gas for Heating, by US County.*
Notes: The figure shows the proportion of occupied housing units in each county that report using natural gas as their main heating source. Data are from the 2000 US census.

Figure 1 shows the share of households using natural gas as their heating source across counties, based on the 2000 US census data.

Whether a locality uses natural gas, electricity or another heating source is not random, and various factors explain the differences. Natural gas pipelines do not extend to some parts of the United States, such as Maine. Areas that are well suited for hydroelectric power generation have low electricity costs and thus rely more on electricity. For historical reasons, much of the Northeast uses heating oil, a petroleum product, instead of gas or electricity. Importantly, the geographic differences were determined long before the study period and are highly persistent. Being predetermined does not rule out that an area's heating source is correlated with other factors affecting mortality, so the analysis controls for other locality characteristics in parallel to the heating source. This guards against the endogeneity of shares emphasised by Goldsmith-Pinkham *et al.* (2020).[5]

1.4. *Temporal Variation in Energy Prices*

Figure 2 plots the national prices of natural gas and electricity over the 2000 to 2010 study period. The data source is the US Energy Information Administration (EIA). Natural gas is one of the fuel sources used in electricity generation, so the two prices co-move, but far from in lockstep. Electricity prices changed somewhat over the time period, while natural gas prices rose and then

[5] Users of natural gas can partially substitute to electric space heaters in the short run, but there is no low-cost short-run way to substitute in the other direction. In Online Appendix Table A1, we find little evidence of changes in heating source in response to changes in relative prices.

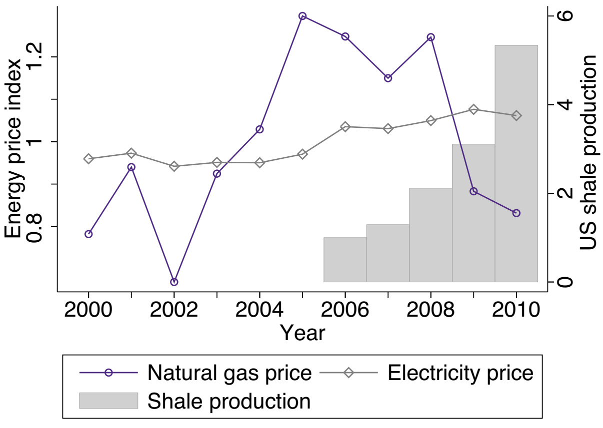

Fig. 2. *US Natural Gas and Electricity Prices, 2000 to 2010.*
Notes: The data series depicted with lines are the national prices of natural gas and electricity, normalised by their respective averages between 2000 and 2010 (left axis). National shale gas production in trillion cubic feet is shown as the bar chart (right axis). Data are from the US Energy Information Administration.

fell much more dramatically. As a result, the relative price of natural gas to electricity rose and then fell over the period.

Natural gas prices rose from 2004 to 2005 due in part to supply disruptions from major hurricanes along the Gulf coast (Hurricane Ivan in 2004 and Hurricanes Katrina and Rita in 2005) (Brown and Yücel, 2008). In addition, increased efficiency of producing electricity from natural gas boosted demand for natural gas during the early 2000s (Hartley *et al.*, 2008). A main cause of the natural gas price decline in the mid-2000s was the sharp increase in shale gas production (plotted in Figure 2); Hausman and Kellogg (2015) estimated that increased supply from shale gas explains 83% of the 2007–13 decline in the price of natural gas.[6]

1.5. *Home Heating versus Other Heating*

While we sometimes refer to our results as due to home heating, the analysis cannot isolate home heating from other indoor (e.g., workplace) heating. Some policy implications, such as whether to promote increased energy supply, are similar whether the channel is home heating or other indoor heating. For other policies, such as subsidies for consumer heating bills, it would be valuable to isolate heating costs at home, which our research design does not permit. A related, more minor limitation is that we cannot separate the effect of space heating from water heating; the energy source is the same in most households (RECS, 2014), and both types of heating likely affect health through similar mechanisms.

2. Data

Our analysis focuses on the contiguous United States between 2000 and 2010. This section describes our data sources, with further details in Online Appendix B.

[6] To investigate whether the price decline is also due to lower demand for natural gas during the Great Recession, we estimated the relationship between RelPrice_{jt} and the unemployment rate (a proxy for the Great Recession intensity). The regression coefficient is small and statistically insignificant (see Online Appendix Table A2).

2.1. *Mortality*

We construct the county-year-month age-adjusted mortality rate from restricted-use vital statistics microdata (National Center for Health Statistics, 2017). We exclude counties with a small population over age 50, specifically those in the bottom decile of counties, as they have few (often zero) deaths per month.[7]

We focus on causes of mortality that exhibit a high degree of excess winter mortality (EWM). Overall mortality is higher in winter than the rest of the year, but the pattern is more pronounced for some causes than others. We zoom in on these causes because it is most plausible that they are exacerbated by exposure to cold and also because doing so increases statistical power. We use a data-driven approach to determine these causes. Using monthly data, we estimate a regression of log age-adjusted mortality for the entire United States on a dummy for winter, separately for each of the 113 National Center for Health Statistics (NCHS) selected causes of death. Causes with a large positive winter coefficient have more excess mortality in winter. We also estimate the model in levels to exclude minor causes that might have spuriously large coefficients. We select the causes whose winter coefficients are in the top quartile in both levels and logs, excluding two causes where there is no clear direct physiological link to cold exposure ('deaths from smoke, fire, and flames' and the residual category, 'all other diseases'). The final 14 causes are within four alphabetic (i.e., broad) categories, and generally match the causes highlighted in the literature as exacerbated by cold (e.g., cardiovascular, respiratory). These high-EWM causes (hereafter, EWM causes) account for 61% of total mortality and 63% of total mortality in winter. Online Appendix Table A3 lists the 14 EWM causes, and Online Appendix Figure A2 shows the seasonality for EWM and non-EWM causes.

2.2. *Independent Variables*

We construct county-level $\text{ShareGas}_{j,2000}$ using the 2000 census summary files. For subsequent years, we use the American Community Survey (ACS), which is available starting in 2005, and linearly interpolate for years without data. (ShareGas is highly correlated over time—the correlation between ShareGas in 2000 and 2010 is 0.95.)

RelPrice, the ratio of the price of gas to electricity, is constructed using monthly state (for the endogenous heating price proxy) and national (for the instrument) price data from EIA. The appropriate specification depends on the timing of consumers' response to RelPrice. Similar to Auffhammer and Rubin (2018), we find that residential energy use responds to RelPrice with a lag of three months. Consumers seem to cut back on usage only after seeing their energy bill, which typically arrives a few weeks after the billing period ends. In addition, the health effects of cutbacks in heating use or paying higher bills might not be instantaneous. Hence, we use the average of the three- and four-month lagged price to construct RelPrice. We find similar results when we reduce the lag by one month or use annual prices. To investigate if the mortality effects materialise with a longer delay, we also estimate models that incorporate mortality effects in subsequent, post-winter months; the effect in subsequent months could also be negative if deaths are hastened by only a short duration ('harvesting').

The analysis also incorporates temperature data. We use daily average temperature (PRISM Climate Group, 2016) to compute the HDDs for each county-month. HDDs are a commonly

[7] These small counties constitute 0.37% of the total population and 0.45% of the total deaths in 2000. Among our retained counties, less than 0.03% of all county-month observations have zero deaths.

used measure of coldness—or need for heating—based on the idea that heating demand is linear in temperature when the temperature falls below 65 °F. That is, $\text{HDD}_{jt} = \sum_{x=1}^{T} \max\{65 - tmean_{jtx}, 0\}$, where $tmean$ is the mean temperature of area j on day x of month t, and T is the number of days in month t. Online Appendix B provides details on the data sources for our control variables.

2.3. *Other Dependent Variables*

An auxiliary outcome we examine is the average price of home energy that consumers face. Our specification uses $\text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt})$ as a proxy for the home *heating* price faced by households. We do not have household-level data on heating prices, but we can use aggregate administrative data on residential energy prices to verify that our regressor is a good proxy for household heating prices. The dependent variable we use for this is the weighted average of the local prices of natural gas and electricity, where weights are the local consumption levels of each energy source. Price and usage data are aggregated state-month-level data from EIA.

As discussed in Section 1.2, we also examine residential energy use. We sum natural gas and electricity usage from EIA data. To examine household spending on home energy, we combine 2000 census microdata and ACS data for 2005 to 2010, aggregated to the county-year level.

3. Results

We first present results on the intermediate outcomes of home energy prices, quantity of energy consumed and energy bills. We then present the mortality results.

3.1. *Effect of Heating Price on Energy Use and Spending*

We start by examining the usage-weighted average price of residential natural gas and electricity prices. Each observation is a state-month. As shown in Table 1, columns (1) and (2), home energy prices are strongly positively correlated with the heating price proxy. In column (1), we include only state and month-year fixed effects. In column (2), we add our other control variables. The coefficient on the heating price proxy is less than 1 because the outcome is the average *energy* price, while the regressor is a proxy for the average *heating* price. Heating comprises roughly 40% of annual home energy use, so we would expect a 10% change in the heating price to lead to a 4% change in the home energy price, or a coefficient of 0.4. The estimated coefficient of 0.36 is quite close to this.

We next quantify how heating prices affect households' energy use and energy bills. (In principle, once we know one of these numbers, we could calculate the other, but showing both is useful given that the data are available at different geographic levels and based on different samples.) First, we examine the impact on energy usage, shown in Table 1, columns (3) and (4). As expected, higher prices lead to less energy consumption.[8] Both the outcome and key regressor are in logs, so the coefficient represents an elasticity. The coefficient of −0.093 implies that households cut back usage quite a bit, but not one for one with price. To quantify the energy-use elasticity, one needs to scale the coefficient by the corresponding price-change coefficient from

[8] Online Appendix Table A4 shows that this cutback in usage occurs three months after the increase in the heating price, as stated in Section 2.2.

Table 1. *Effect of Heating Price on Energy Use and Energy Spending.*

	Dependent variable:							
	Log of average electricity and gas price		Log of total energy consumption		Log of total monthly energy bill		Total monthly energy bill	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Heating price proxy	0.351***	0.361***	−0.125***	−0.0932**	0.270***	0.246***	57.4***	50.9***
	[0.0671]	[0.0700]	[0.0391]	[0.0393]	[0.0369]	[0.0352]	[7.33]	[6.94]
Observations	2,695	2,695	2,695	2,695	21,665	21,665	21,665	21,665
Mean price/quantity	21.1	21.1	22.1	22.1	220.7	220.7	220.7	220.7
Basic fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
All other controls	No	Yes	No	Yes	No	Yes	No	Yes
Implied elasticity			−0.36	−0.26				

Notes: SEs clustered by state in brackets. Asterisks denote significance: ** $p < 0.05$, *** $p < 0.01$. Columns (1) to (4): the sample comprises state-year-month observations in the contiguous United States for winter months (November–March) between 2000 and 2010. Outcomes are constructed from EIA data. Columns (5) to (8): the sample comprises county-year observations in the contiguous United States, aggregated and crosswalked from microdata in the 2000 census and the ACS PUMS data between 2005 and 2010. *Heating price proxy* is $\text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt})$, where ShareGas_{jt} is the state-year (columns (1) to (4)) or county-year (columns (5) to (8)) proportion of occupied housing units with natural gas as their main heating source, and RelPrice_{jt} is the ratio of the citygate price of natural gas to the residential price of electricity. Prices are state-month prices averaged over the three- and four-month lag in columns (1) to (4), and state-year prices in columns (5) to (8). *Heating price proxy* is instrumented using $\text{ShareGas}_{j,2000} \times \log(\text{RelPrice}_{\text{US},t})$, i.e., the interaction of ShareGas_{jt} in 2000 with the US-level $\log(\text{RelPrice}_{jt})$. Average electricity and gas price is the state's consumption-weighted average of the residential prices of electricity and gas, in dollars per million British thermal units (BTUs). Total energy consumption is the state's total delivery of natural gas and electricity to residential consumers, in trillion BTUs. Total monthly energy bill is the mean monthly bill from electricity, gas and other fuels in the county. *Basic fixed effects* are state and year-month fixed effects for columns (1) to (4), and county and year fixed effects for columns (5) to (8). *All other controls* are the interactions of $\log(\text{RelPrice}_{\text{US},t})$ with the log state or county household income in 1999 (25th, 50th and 75th percentiles) and the share of people aged 70 and above in 2000, the state housing price index, the unemployment rate, the state's manufacturing sector share of total employee compensation, HDDs, a quadratic in absolute humidity, the air quality indices (AQIs) for $PM_{2.5}$, PM_{10} and No_2, and the AQI for No_2 squared. Implied elasticity is the ratio of the coefficient reported in that column to the corresponding coefficient from the first two columns. Monetary variables are in constant 2016 US dollars.

columns (1) and (2).[9] We report the implied elasticity, which is −0.26, at the bottom of the table. This elasticity is similar to the winter natural gas demand elasticity for California estimated by Auffhammer and Rubin (2018) and Hahn and Metcalfe (2021). In Online Appendix Table A5, we show that the estimates based on our winter/non-winter specification are similar.

The elasticity having a magnitude less than 1 implies that households are spending more money on energy expenses when the heating price increases. We verify this using census/ACS data. Columns (5) and (6) of Table 1 show that the heating price shock is associated with a 25 log point increase in energy expenses. If the result is driven by changes in winter expenses then the coefficient is an underestimate of the impact during winter months. (We cannot isolate spending in winter because the ACS does not release the survey month, and the Census asks about annual spending on energy bills.) Columns (7) and (8) examine the outcome in levels: a 10% increase in the price of heating is associated with a $5 (in 2016 USD) increase in the monthly home energy bill, averaged over the year. To help interpret these magnitudes, note that the relative price of natural gas fell by 42% (54 log points) between 2005 and 2010. This price decline led to a 13%

[9] The relevant scale factor to convert our mortality results into an elasticity of mortality with respect to the heating price is 1; $\text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt})$ incorporates information on heating sources and is hence a better proxy of the heating price than the average energy price.

or $330 annual decrease in energy bills for natural gas users, using the estimates in columns (6) and (8), respectively.

To summarise, we find that households meaningfully reduce their heating use in response to an increase in their heating price, and they also experience an increase in their energy bills.[10]

3.2. *Effect of Heating Price on Mortality*

We now turn to estimating the effect of heating prices on mortality. Table 2 shows that a higher (log) heating price increases the (log) mortality rate.[11] Column (1) reports results for all-cause mortality, controlling for all fixed effects and control variables listed earlier. The elasticity of all-cause mortality with respect to the heating price is 0.032 ($p < 0.05$).[12]

Column (2) presents results for EWM mortality. An increase in the heating price increases EWM mortality, with an elasticity of EWM mortality with respect to price of 0.059 ($p < 0.01$).[13] Given that EWM causes account for 63% of total mortality in winter, the implied elasticity of total mortality is 0.037, similar to the elasticity using all-cause mortality.

We next examine non-EWM mortality. As shown in column (3), the coefficient for the heating price proxy is very close to 0 and statistically insignificant. Non-EWM causes are, by and large, not exacerbated by exposure to cold, so the heating use channel is not applicable. However, this is not a placebo test because the non-heating consumption channel (less income to spend on non-heating expenditures) should affect non-EWM mortality. Under the assumption that the non-heating channel has similar effects on EWM and non-EWM mortality, the lack of an effect of heating prices on non-EWM mortality indicates the importance of the heating channel—changes in heating use seem to drive the effect of heating prices on mortality.

Columns (4) to (7) disaggregate the effects by broad EWM category: the overall effect on EWM mortality is mainly driven by circulatory and respiratory causes. Online Appendix Table A11 reports results separately for each of the 14 EWM causes. The largest effect sizes are for emphysema, other chronic lower respiratory diseases, acute myocardial infarction and pneumonia. Interestingly, the price of heating does not exacerbate influenza mortality.

The effects we estimate are not due to deaths being moved earlier by just a short duration, or ‘harvesting’. Online Appendix Table A12 shows that the cumulative mortality effect is stable in magnitude when we incorporate effects in subsequent months. (For simplicity, the table reports reduced-form estimates.) The cumulative effect is statistically significant at at least the 5% level when we add up to three subsequent months and marginally significant up to six months. There is not enough statistical power to determine at what point the cumulative effect becomes essentially zero. (Note that the coefficient for any specific lag is difficult to interpret because RelPrice is serially correlated and we have a finite number of months in the sample.)

[10] We also investigated the impact of heating prices on households’ other non-energy expenditure patterns using the Consumer Expenditure Survey (CEX) data (Online Appendix Table A6). We find statistically insignificant effects, with large confidence intervals, for all broad categories of expenditure, including food and alcoholic beverages, non-durable goods and all non-energy expenditures. The effect on health expenditures is significant at the 10% level.

[11] Online Appendix Table A7 shows the first stage of the instrumental variables regression. Online Appendix Tables A8, A9 and A10 show robustness to using the age-adjusted mortality rate in levels, weighting regressions by the population in 2000, and using only natural gas variation for identification.

[12] We also investigated the effect on morbidity using the Heath and Retirement Study and on hospitalisations using the National Inpatient Sample, but due to the smaller sample sizes, we were underpowered to detect even elasticities much larger than our estimated elasticity for mortality.

[13] Online Appendix Figure A3 shows a binned scatterplot of the relationship between EWM mortality and the instrument.

Table 2. *Effect of Heating Price on Mortality from All Causes and EWM Causes of Death.*

	Dependent variable: log of mortality rate								
	All causes (1)	All EWM causes (2)	Non-EWM causes (3)	Group A EWM: non-viral, non-respiratory infections (4)	Group G EWM: neurological diseases (5)	Group I EWM: circulatory system diseases (6)	Group J EWM: respiratory system diseases (7)	All EWM causes (8)	All EWM causes (9)
Heating price proxy	0.032**	0.059***	0.0033	0.021	0.021	0.054**	0.099***	−0.015	0.090**
	[0.014]	[0.017]	[0.021]	[0.025]	[0.029]	[0.020]	[0.020]	[0.015]	[0.037]
Heating price proxy × Winter								0.073***	
								[0.019]	
Heating price proxy × HDD									0.090***
									[0.032]
Observations	153,296	152,927	151,113	108,659	110,742	151,589	148,583	366,668	366,668
Mean mortality rate	929.5	577.6	358.4	74.16	74.01	371.8	259.8	527.8	527.8
Months used	Winter	Winter	Winter	Winter	Winter	Winter	Winter	All	All

Notes: SEs clustered by state in brackets. Asterisks denote significance: ** $p < 0.05$, *** $p < 0.01$. The sample comprises county-year-month observations in the contiguous United States between 2000 and 2010. In columns (1) to (7), the sample is restricted to winter months (November–March). Mortality rates are age-adjusted mortality rates expressed as annual deaths per hundred thousand population; see Online Appendix B for further details. *Heating price proxy* is $\text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt})$, where ShareGas_{jt} is the county-year proportion of occupied housing units with natural gas as their main heating source, and RelPrice_{jt} is the ratio of the state-month citygate price of natural gas, averaged over the three- and four-month lag, to the corresponding residential price of electricity. *Winter* is a binary variable that equals one in winter months (November to March). *HDD* is the number of heating degree days in the county for the month, based on thresholds of 65 °F, in units of °F days divided by 1000, and scaled to a 30-day month. *Heating price proxy* and its interaction with *Winter*/*HDD* are instrumented using $\text{ShareGas}_{j,2000} \times \log(\text{RelPrice}_{\text{US},t})$ and its interaction with *Winter*/*HDD*. Columns (1) to (7): all columns control for county and year-month fixed effects, the interactions of $\log(\text{RelPrice}_{\text{US},t})$ with the log county household income in 1999 (25th, 50th and 75th percentiles) and the share of people aged 70 and above in 2000, the state housing price index, the unemployment rate, the state's manufacturing sector share of total employee compensation, HDDs, a quadratic in absolute humidity, the AQIs for $PM_{2.5}$, PM_{10} and No_2, and the AQI for No_2 squared. Columns (8) and (9): all columns control for the above set plus the following: all possible two-way interactions between $\text{ShareGas}_{j,2000}$, $\log(\text{RelPrice}_{\text{US},t})$ and *Winter*/*HDD*; and the two- and three-way interactions among $\log(\text{RelPrice}_{\text{US},t})$, *Winter*/*HDD* and each of the log county household income in 1999 (25th, 50th and 75th percentiles) and the share of people aged 70 and above in 2000. Column (9) also includes the interaction of the average county HDDs in winter months with $\log(\text{RelPrice}_{\text{US},t})$; and the three-way interactions of the average county HDDs in winter months, $\log(\text{RelPrice}_{\text{US},t})$ and each of $\text{ShareGas}_{j,2000}$, the log county household income in 1999 and the share of people aged 70 and above in 2000.

We next bring in data for non-winter months to estimate the winter/non-winter specification. We use either Winter (Table 2, column 8) or HDD (column (9)) to construct the additional comparison. Column (8) shows that the effect of heating prices on mortality is stronger in winter than the rest of the year. Reassuringly, the coefficient on the non-interacted heating price proxy is close to zero: the price of heating having no effect on mortality in non-winter months can be thought of as a placebo test.

Using HDD, we find that the price of heating increases mortality more in colder months. HDD is normalised so that a unit change is the difference between every day in the month being 65 °F or above and being 32 °F . As reported in column (9), a one-unit increase in HDD_{jt}, relative to the county's average winter HDD, leads to a 0.090 higher elasticity of EWM mortality with respect to the heating price.[14]

The results are similar, but somewhat weaker, when we do not control for average HDD and thus use average differences across places in the severity of their winters as additional identifying variation (see Online Appendix Table A13). This is consistent with previous findings that, due to adaptation (e.g., better insulated homes in colder places), atypical cold for an area is what especially affects mortality (Eurowinter Group, 1997).

Online Appendix Tables A14 and A15 show robustness of our results to varying the definitions of winter, RelPrice, or ShareGas; excluding states with high shares of other heating fuel sources; excluding shale-gas-producing states; dropping the Great Recession period; controlling for LIHEAP, additional air pollutants or a richer set of controls using a double-selection post-LASSO method; estimating the effects at the state level or using only within-census division variation for identification and varying the main set of control variables. Online Appendix C.2 discusses these robustness checks.

3.3. *Heterogeneous Effects on Mortality*

Table 3 augments the baseline specification to examine heterogeneous effects by poverty. Heating bills comprise a larger share of expenditures for the poor. For this reason, as well as the poor having lower baseline health and less access to health care, we expect heating prices to have larger effects on mortality among the poor. Columns (1) to (4) each use a different poverty proxy. In column (1), the proxy is whether the county's median income is in the bottom half of the distribution across counties. Columns (2) and (3) use the county's share of households below 150% of the federal poverty line, as either a continuous variable or an indicator for being below the sample median. Column (4) uses the decedent's education level, specifically an indicator for no high school degree. Across the board, the point estimates suggest larger effects among the poor, but the finding is only statistically significant in columns (2) and (3), which use the share of households below 150% of the poverty line.

Finally, Table 3, columns (5) and (6), show that the mortality effects do not significantly differ by sex or race. In Online Appendix C.3, we discuss heterogeneity by age groups.

4. Conclusion

This paper finds that lower heating prices reduce winter mortality. To put the estimated elasticity of all-cause mortality with respect to the price of heating of 0.032 in context, the price of natural

[14] The coefficient on the heating price proxy is not interpretable because we control for the county's average winter HDD in parallel to HDD_{jt} (see Online Appendix C.1).

Table 3. *Heterogeneous Effects on Mortality.*

	Dependent variable: log of all-EWM-cause mortality rate. Trait is:					
	Below-median county income (1)	Proportion below 150% of poverty line (2)	Above-median proportion below 150% of poverty line (3)	No high school degree (4)	Male (5)	Black (6)
Heating price proxy × Trait	0.021	0.36**	0.057**	0.033	0.013	0.013
	[0.032]	[0.17]	[0.026]	[0.039]	[0.026]	[0.044]
Heating price proxy	0.049***	−0.025	0.038**	0.027	0.058***	0.053***
	[0.016]	[0.037]	[0.016]	[0.045]	[0.017]	[0.017]
Observations	152,927	152,927	152,927	284,700	300,311	218,275
Mean mortality rate	577.6	577.6	577.6	999.4	605.3	739.4
Implied effect for Trait = 1	0.07**	0.33**	0.10***	0.06	0.07***	0.07
	[0.03]	[0.14]	[0.03]	[0.05]	[0.02]	[0.04]

Notes: SEs clustered by state in brackets. Asterisks denote significance: ** $p < 0.05$, *** $p < 0.01$. For columns (1) to (3), the sample comprises county-year-month observations in the contiguous United States for winter months (November–March) between 2000 and 2010. For columns (4), (5) and (6), the sample comprises county-year-month-education, county-year-month-sex and county-year-month-race groups, respectively, for winter months. Mortality rates are age-adjusted mortality rates expressed as annual deaths per hundred thousand population; see Online Appendix B for further details. *Heating price proxy* is $\text{ShareGas}_{jt} \times \log(\text{RelPrice}_{jt})$, where ShareGas_{jt} is the county-year proportion of occupied housing units with natural gas as their main heating source, and RelPrice_{jt} is the log of the ratio of the state-month citygate price of natural gas, averaged over the three- and four-month lag, to the corresponding residential price of electricity. Column (1): *Trait* is an indicator variable that equals one if the county's median household income is below the median of all counties in the sample in 1999. Column (2): *Trait* is the proportion of households in the county with income in 1999 below 150% of the poverty threshold. Column (3): *Trait* is an indicator variable that equals one if the proportion from column (2) is above the median of all counties in the sample. Column (4): *Trait* is an indicator variable that equals one for the subgroup that did not complete high school. Column (5): *Trait* is an indicator variable that equals one for the male population. Column (6): *Trait* is an indicator variable that equals one for the Black population; non-Black and non-White populations are excluded from the sample. *Heating price proxy* and its interaction with *Trait* are instrumented using $\text{ShareGas}_{j,2000} \times \log(\text{RelPrice}_{\text{US},t})$ and its interaction with *Trait*. All columns include all fixed effects and control variables from column (2) of Table 2, the main effect for *Trait* and the interaction of each fixed effect or control variable with *Trait*.

gas relative to electricity fell by 42% between 2005 to 2010. Our findings imply that this price decline caused a 1.7% decrease in the winter mortality rate for households using natural gas for heating. Given that 58% of American households use natural gas for heating, the drop in natural gas prices reduced the US winter mortality rate by 1.0%, or, equivalently, the annual mortality rate by 0.4%. This represents 12,500 deaths per year. In terms of welfare, our results map to approximately $103 billion using a value of statistical life year of $369,000 in 2016 dollars (Kniesner and Viscusi, 2019). This national-level benefit from averted deaths is twice as large as the local economic gains from fracking and should not be ignored when evaluating the effects of shale gas production (see Online Appendix C.4 for details). This estimate includes only relatively immediate effects, and the total benefit could be larger if there are also morbidity effects that affect mortality further out than six months. Our results suggest that reduced heating use (as opposed to other spending cutbacks households make when they face high heating bills) is the key channel through which expensive heating increases mortality.

Soaring energy prices in Europe caused by Russia's 2022 invasion of Ukraine have brought renewed attention to policies that can reduce home energy costs. Our findings highlight the health benefits of such policies. While price interventions can distort allocative efficiency, our estimates suggest that the health gains from these policies can be large, particularly for low-income households.

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Additional Supporting Information may be found in the online version of this article:

Online Appendix
Replication Package

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