The Heath Implications of Unconventional Natural Gas Development in Pennsylvania

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Abstract

We investigate the health impacts of unconventional natural gas development of Marcellus shale in Pennsylvania between 2001 and 2013 by merging well permit data from Pennsylvania Department of Environmental Protection with a database of all inpatient hospital admissions. Through a difference-in-differences regression analysis that compares changes in hospitalization rates over time for air pollution-sensitive disease in counties with unconventional gas wells to changes in hospitalization rates in non-well counties, we find significant associations between shale gas development and hospitalizations for acute myocardial infarction (AMI), pneumonia, and upper respiratory infections (URI). In particular, we find that county-level hospitalization rates for AMI among young adults (aged 20-44) increased by 24 percent due to shale gas development. Hospitalizations for pneumonia and URI also increased by 8.5 percent and 17 percent, respectively, among the elderly. These adverse effects on health are consistent with higher levels of air pollution resulting from unconventional natural gas development.

Keywords: shale gas development, air pollution, pneumonia, asthma

1. Introduction

Natural gas has become a key source of energy in the United States. Over the past decades, technological advancements in horizontal drilling and hydraulic fracturing (often referred to as "fracking") have made natural gas trapped beneath various shale formations more economically accessible. The contribution of shale gas to total U.S. natural gas production increased drastically from less than 2 percent in 2000 to over 20 percent in 2010; it is also projected that 46 percent of the natural gas supply will come from shale gas by 2035 (EIA, 2013). With this rapid expansion of shale gas development, the potential health risks have drawn attention from the public and regulators at various levels.

Typically, the process to develop shale gas wells involves well pad preparation and construction, drilling and well construction, hydraulic fracturing, flaring of excess natural gas, and gas extraction and compression. Air pollution can occur during each stage of the process, while water contamination mostly occurs during wellbore drilling and hydraulic fracturing (see Appendix A1 for a more detailed description of the stages of shale gas development). Numerous studies have documented that emissions of greenhouse gases (predominantly water vapor, carbon dioxide, methane, and ozone), volatile organic compounds (VOCs), other air pollutants, and hazardous chemicals increase as a result of unconventional natural gas development (GAO, 2012; NRDC, 2014). Based on data from a natural gas emissions inventory recently created by the Pennsylvania Department of Environmental Protection (PADEP), levels of air pollutant emissions (CO, NO_X, $PM_{2.5}$, PM_{10}, etc.) attributable to unconventional natural gas drilling mostly increased between 2011 and 2012 as the number of gas wells in the state rose by nearly 30% (see Table 1).[1]

[1] Pennsylvania Department of Environmental Protection (PADEP). Air Emissions Data from Natural Gas Operation. Accessed on March 10, 2015 at

Despite the fact that air pollution has clear adverse health effects, there is little scientific research on the impact of shale gas development on human health (see Appendix A2 for a detailed discussion of the link between air pollution and human health). We know of only a few studies that investigate the direct impact of shale gas development on health. In particular, Hill (2012) finds a higher incidence of low birth weight among babies born to mothers living in the vicinity of shale gas wells in Pennsylvania. Casey et al (2015) investigate the associations between unconventional natural gas development and birth outcomes using a linked dataset that contains information on both mothers and neonates. They find that exposure to unconventional natural gas development activities (measured by proximity to unconventional gas wells) is associated with increased risk of preterm birth. Jemielita et al (2015) report that shale gas development between 2007 and 2011 in two counties (Bradford and Susquehanna) in Pennsylvania are significantly associated with increased hospitalization for cardiology and neurology patients. They also find suggestive evidence of increased hospitalization rates for dermatology, oncology, and urology.

In this paper, we build on Jemielita et al (2015) and examine the impact of unconventional natural gas drilling in Pennsylvania on the treatment of several air-pollution-sensitive medical conditions at Pennsylvania hospitals. The state of Pennsylvania is rich in Marcellus shale reserves[2] and has witnessed a significant expansion of unconventional natural gas development in the past decade, making it a good location to study the effects of drilling. Our paper extends the work of Jemielita et al (2015) in several important dimensions. First, we expand the scope of analysis from a few counties to the entire state of Pennsylvania in order to capture potential spill-

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http://www.portal.state.pa.us/portal/server.pt/community/emission_inventory/21810/marcellus_inventory/1829967

[2] Marcellus shale (also known as the Marcellus formation) is a geological formation found in eastern North America, spanning 6 states in the northeast U.S. It is a unit of marine sedimentary rock that contains largely untapped natural gas reserves.

over effects and increase the generalizability of our results. Second, the timeframe of our study is from 2001-2013, which encompasses the recent expansion in unconventional natural gas extraction. The longer time horizon allows us to better control for secular trends in the hospitalization rates. The number of shale gas wells increased exponentially in 2012 and 2013, and incorporating these data allows us to uncover new health effects and assess the robustness of the results reported in Jemielita et al (2015). Third, we include a rich set of county characteristics in our fixed-effects regression models. This allows us to control for both time-varying observed and time-invariant unobserved confounders. Our identification strategy exploits changes in the timing of drilling in each county. Provided the commencement of drilling was unrelated to the unobservable determinants of pollution-related disease, then our estimates can be interpreted as causal effects of unconventional natural gas development on hospitalization rates.

We focus on the effect of Marcellus well development on the county-level hospitalization rates for acute myocardial infarction (AMI), chronic obstructive pulmonary disease (COPD), asthma, pneumonia, and upper respiratory infections (URI). We find that unconventional natural gas development was associated with a significant increase in rates of URI among the elderly, and high hospitalization rates for AMI among young adults. We also find that shale gas development increased the hospitalization rate for pneumonia among the elderly. These findings are consistent with higher levels of air pollution.

2. Data

We obtained data on natural gas wells from the PADEP Oil and Gas Reports. The Spud Data Report contains information on the drilling commencement date (i.e. spud date), location, operator, and configuration of all conventional and unconventional natural gas wells drilled in

Pennsylvania between 2001 and 2013. Unfortunately, these data do not include the well completion date, which indicates when the well is ready to produce natural gas.[3] We also obtained data on total annual gas production from the PADEP statewide well production database, which contains this information for all active natural gas wells. We linked spud dates to the gas production data using a unique well permit number, allowing us to determine the annual gas production for each active well after its spud date. Table 2 contains a list of all Pennsylvania counties that had unconventional natural gas wells drilled during the timeframe of this study. Our health outcome measures are derived from the Pennsylvania Health Care Cost Containment Council's (PHC4) compilation of all inpatient hospital admission records in the state during 2001-2013. We use ICD-9-CM codes to identify the main diagnosis for each inpatient admission and then group related diagnoses into clinically meaningful categories using the Clinical Classification Software (CCS) developed by the Agency for Healthcare Research and Quality (AHRQ) (see Appendix Table A1 for how each condition is defined).[4] We focus our analysis on the following five health conditions that are sensitive to air pollution: acute myocardial infarction (AMI), chronic obstructive pulmonary disease (COPD), asthma, pneumonia, and upper respiratory infections (URI). Although many known or possible carcinogenic chemicals are used during the well development process (such as the BTEX compound), we do not consider cancer in this analysis due to the short time frame of our data.[5] Persistent correlations between the above five conditions and air pollution have been established in the epidemiological literature (for example, see Lee, Kim and Lee (2014); Garshick (2014);

[3] For wells that begin producing immediately after drilling, the spud date and completion date are the same.
[4] The CCS can be accessed at http://www.hcup-us.ahrq.gov/toolssoftware/ccs/ccs.jsp.
[5] For example, a recent study measuring the impact of diesel exhaust exposure on the incidence of lung cancer among miners used a 15-year lag between the time of exposure and diagnosis of the illness. See Attfield MD[1], Schleiff PL, Lubin JH, Blair A, Stewart PA, Vermeulen R, Coble JB, Silverman DT. The Diesel Exhaust in Miners study: a cohort mortality study with emphasis on lung cancer. J Natl Cancer Inst. 2012 Jun 6;104(11):869-83.

Neupane et al. (2010); Schwartz et al. (1993); Dockery and Pope (1994); Dominici et al. (2006); Brunekreef and Holgate (2002); Eder, Ege and von Mutius (2006)).

3. Empirical methods

We stratify the sample into four age groups: 5-19, 20-44, 45-64, and above 65 because the pollution caused by shale gas development might have a more pronounced effect on one age group than others. For example, elderly individuals with a pre-existing respiratory illness are more sensitive to air pollution, and are more likely than younger individuals to contract pneumonia. Because hospitalization rates for AMI and COPD are either very low or zero among children ages 5-19, we only estimate models for asthma, pneumonia, and URI for this age group. In each year, we construct county-level measures of the five health conditions by first aggregating the individual-level PHC4 data into county-year cells, and then normalizing the total number of inpatient admissions for each condition by the population of that county in each age group,[6] so that the measures reflect hospitalizations per one thousand people.

The average hospitalization rates for AMI, COPD, asthma, pneumonia, and URI are higher in counties containing unconventional natural gas wells than those without wells. This is likely because poverty rates are 28% higher in well counties, on average, and the fact that these counties have much higher levels of extraction of other natural resources, such as coal (see Table 3). Furthermore, the hospitalization rates for certain conditions and age groups exhibit strong secular trends over time in both well and non-well counties. In order to address both of these issues, we estimate the impact of unconventional natural gas development on county-level hospitalization rates using a difference-in-differences strategy. Specifically, we exploit the

[6] These data are obtained from the Census Bureau Population Estimates Program, which can be accessed at http://www.census.gov/popest/.

plausibly exogenous variation in the timing of drilling in each county (see Table 2). We estimate the following "staggered treatment" specification:

$$y_{ct} = X'_{ct}\,\beta + \sum_{r=0}^{s}\alpha_r W_{c,t-r} + \sum_{r=0}^{s}\theta_r L_{c,t\text{-}r} + \psi_c + \zeta_t + u_{ct}, \qquad (1)$$

where y_{ct} is the health outcome of interest in county c and year t, X_{ct} is a vector of county characteristics (more discussion below), W_{ct} is an indicator variable that equals to one if there are active unconventional wells in the county in year t,[7] L_{ct} is the log of natural gas output[8] from all active unconventional wells in the county in year t (we add 1 to the level of output in counties without wells because output is equal to 0 for them), and u_{it} is a random error term assumed to be uncorrelated with all of the regressors. The county fixed effects ψ_c and year fixed effects ζ_t control for time-invariant unobserved county-level heterogeneity and overall common shocks to the outcomes, respectively.

For our main results, we use one lag for both the binary well indicator and log of output. The main reason for choosing this specification is that air pollution may have lagged effects on health, especially for some of the chronic conditions we examine. Even for acute conditions like asthma, it is possible that an individual must be exposed to certain air pollutants for an extended period of time before experiencing symptoms. We note that air pollution may come from gas well development activities (site construction, drilling, and initial hydraulic fracturing) as well as ongoing extraction activities (gas production, compression, and fuel transportation). Therefore, the treatment dummies in (1) will capture the effects of well development activities, while the inclusion of log of output in our model will capture the intensity of ongoing extraction activities.

[7] Once an unconventional well is drilled, a county remains "treated" for the rest of the sample period.
[8] Natural gas output is measured in thousand cubic feet (MCF).

The parameters of interest, α and θ, measure the reduced-form effects of Marcellus shale gas development and production on the county-level hospitalization rate for each medical condition. Since only about half of the counties had unconventional wells drilled during our sample period, the identification of the treatment effects comes from changes in hospitalization rates over time in counties with unconventional wells relative to the change in hospitalization rates over time in counties with *no* unconventional wells. Furthermore, because drilling commences in different years in many counties, some counties with wells serve as control counties in earlier years of the data sample.

Our models also contain control variables for county-level demographic composition, economic conditions and activities, as well as measures of patient characteristics at each county's hospitals (see Table 3). Specifically, we include the county-level unemployment rate, poverty rate, the log of county population density, quartiles of county median household income, and the percentage of the county population in each five-year age category, from 0-4 to 85 and above. These measures are derived from Small Area Income and Poverty Estimates (SAIPE) and the Population Estimates Program (PEP) data made available by the U.S. Census Bureau.[9, 10]

Greater availability and lower prices of natural gas may reduce the demand for other fuels that generate pollution during their extraction and use (EPA, 1999; NRC, 2010). As unconventional natural gas extraction in Pennsylvania has increased, the extraction of coal for electricity generation has decreased. In order to capture this substitution of fuels we include in

[9] We use the annual quartiles of household income due the methodological changes in SAIPE. For the series of SAIPE state and county estimates, notable differences include the break between 2004 and 2005 due to the switch from Current Population Survey Annual Social and Economic Supplement (CPS ASEC) to American Community Survey (ACS) data in SAIPE modeling. For that reason, estimates for these particular years are directly comparable.

[10] The Intercensal Population Estimates released by the U.S. Census Bureau provide estimates of county-level population by five-year age groups. We include percentages of population in each age group for each county-year in all of our models to account for the demographic changes in the counties.

our models the log of annual county-level production of coal from surface and underground mining reported to the U.S. Energy Information Administration (EIA).

Finally, we construct county-level measures of patient characteristics from the PHC4 inpatient admission records and include these in our models. These are the county-level proportion of female patients, the proportion of patients of different racial and ethnic categories (white, black, Asian, Hispanic, and other races), the proportion of different types of admissions (elective, urgent, emergency, and other types), and the proportion of patients in mutually exclusive insurance categories (private insurance, Medicaid, Medicare, other government insurance, self-pay, and all other payers), and the county average Charlson index (Charlson, 1987).[11] In Table 3 we report descriptive statistics for all variables used in this analysis by age group. As expected, the county-level hospitalization rates for pollution-sensitive conditions, and the Charlson index increase with age.

4. Results

Overall, the estimates from our empirical models suggest that unconventional natural gas development is positively and consistently associated with significantly higher rates of hospitalization for all five pollution-sensitive conditions. There are, however, differences across the conditions in which age groups are most affected and at what point in time gas development translates into higher hospitalization rates. We summarize the results below, and report our full set of estimates in Table 4:

AMI: Unconventional well development in the previous year is associated with an increase of 0.11 hospital admissions per one thousand people aged 20-44, which is a 24 percent increase

[11] To avoid endogeneity, we only use contemporaneous secondary diagnoses when computing the Charlson index.

relative to the state average hospitalization rate for AMI for this age group. We do not find any statistically significant effects of well development activities (treatment dummies) for the other age groups. We do find that higher levels of gas output in the previous year are associated with higher rates of AMI hospitalizations among those aged 45-64 as well as those aged 65 and above.

COPD: Among individuals aged 20-44, we find that well development in the current year is associated with an increase of 0.06 admissions for COPD per one thousand people, while well development in the previous year is associated with a decrease of 0.08 admissions per one thousand people. Because these two effects offset each other, this result may reflect a temporary shift in hospitalizations one year earlier (i.e. well development accelerates COPD hospitalizations, but does not cause a higher overall hospitalization rate).

Asthma: Although we find a statistically significant association between previous year well development and higher hospitalizations for individuals aged 20-44, the sensitivity analyses we present below indicate that this result could be spurious. We do not find any consistent associations among other age groups.

Pneumonia: We find that unconventional well development in the previous year is associated with an increase of 1.5 admissions per one thousand people, or 8.5 percent relative to the state mean, among the elderly. We also find that higher levels of gas output in the previous year are associated with higher rates of pneumonia hospitalizations among those aged 20-44.

URI: We find unconventional gas well development in the previous year is associated with an increase of 0.2 admissions per one thousand people among the elderly. This is a 17 percent increase relative to the overall state mean. However, it is interesting that among the elderly natural gas output is found to have a modest negative effect. We do not find any effects in any other age groups.

Robustness and falsification tests: We conduct a series of additional checks in order assess the robustness of our results. Importantly, our estimates are reliable only if the model either captures or removes county-level factors that are correlated with both unconventional well development and hospitalization rates. We first conduct a falsification test using hospitalizations for trauma-related disorders[12] as an alternative outcome. These disorders should not be related to pollution, so finding a statistically significant impact of well development on trauma hospitalizations would indicate the presence of uncontrolled unobservable factors that are confounding the relationship between well development and the other health outcomes. In addition, hospitalizations for trauma are very common, so this falsification test has good statistical power. In support of our empirical approach, we do not find any statistically significant associations between the well development or gas output variables and the hospitalization rate for trauma-related disorders, with the only exception of the contemporaneous treatment dummy being marginally significant in age group 20-44 (see column 6 in Table 4).

Next, we subject our models to several alternative specifications. If counties that are more likely to have higher growth rate in hospitalization rates are also more likely to have unconventional wells, then our estimates will be upward biased. In order to assess whether there exist such pre-existing trends in the outcomes, we estimate a set of models with 2 leads of the treatment dummy (contemporaneous well development) and no output variables. We report the point estimates from this exercise in Table 5. Across these models, the only statistically significant coefficient estimate (at 10 percent level) is the second lead in the model of COPD among individuals aged 45-64. This is less of a concern since we do not find any effects on COPD in this age group. It is also worth noting that we do find the current year dummy to be

[12] These conditions include joint dislocations, fractures, intracranial injury, crushing injury or internal injury, open wounds, burns, and other conditions due to external cause.

statistically significant for pneumonia among the elderly. These results suggest that it is unlikely that our main findings are driven by pre-existing differential trends within counties.

To further assess the impact of pre-treatment deviation in the outcomes, we augment our baseline model with *county-specific* linear and quadratic trends. These are very demanding models where identification of the treatment effects come from the sharp deviations in the outcomes from quadratic trends in the respective counties. We present the coefficient estimates in Appendix Table A2. The coefficient estimate on the first lag of treatment dummy in the model of pneumonia among the elderly remains largely unchanged and is still statistically significant at 5 percent level. This suggests that our finding on pneumonia is robust to such extremely flexible specification. At the same time, we note that the statistical significance on the other conditions drops below the 10% level with the inclusion of county-specific trends. However, this does not necessarily mean that our findings on the other outcomes are due entirely to county-specific time-varying unobserved factors. As pointed out by Meer and West (2015), inclusion of group-specific trends will greatly attenuate the estimated treatment effect if the treatment results in a change in the growth rate instead of a discrete change in the level of the outcome. This is likely the case for at least some of the conditions we examine since it is unlikely that drilling of unconventional wells in a particular year would cause sudden increase in the *level* of the hospitalization rates. Therefore, our preferred estimates are from models without county-specific trends.

Finally, we conduct a Monte Carlo simulation designed to detect spurious correlations between the well development indicators and outcome variables. We subset the sample to 2000-2005 and randomly assign placebo treatments to counties that contained wells in the post-2005 period by drawing the year of drilling in the pre-well period from a uniform distribution. We then estimate equation (1) for each condition with current and lagged placebo treatment indicators, but without the output variables (see Appendix section A3 for a detailed description). In general, the probability of a Type I error (incorrectly rejecting the null hypothesis of no effect) is very close to the levels of significance we report (see Table 5). For example, we find that the coefficient estimate on the first lag of treatment dummy is significant at 1 percent level in our preferred specification. The simulations indicate that among 10,000 replications of a placebo treatment there are 126 times when the null hypothesis is falsely rejected, implying the probability of Type I error is 1.26 percent. This suggests that the likelihood of a false positive in our models is nearly the same as a model that conforms perfectly to the assumptions of linear regression. The only exception is the estimated effect on asthma among those aged 20-44. The simulations suggest that the probability of Type I error is around 18 percent instead of 10 percent. In this case, we caution that the estimated effect could be spurious.

5. Discussion and conclusions

We examine the causal impact of unconventional natural gas development, which is known to cause air pollution, on human health. Our results show that horizontal drilling and hydraulic fracturing into Marcellus shale in the state of Pennsylvania over the past decade is associated with significant increases in hospitalization rates for AMI (aged 20-44), pneumonia (65 and above), and URI (65 and above). Notably, we do not find any impact of gas well development on asthma, pneumonia, or URI among children aged 5-19. Because children spend more time outdoors, breath more rapidly than adults, and breath through their mouths rather than filtering air through their nose, their exposure to air pollution is typically assumed to be higher than adults (California OEHHA, 2003). It is possible that the impact of air pollution from well development has a longer term impact on children through the development of respiratory and other illnesses that we are unable to detect during the limited timeframe of our analysis. In contrast, the effects we find among adults may reflect the acute aggravation of pre-existing conditions. Nonetheless, differences in exposure within the group of adults could explain why, for example, unconventional gas well development has a statistically impact on AMI hospitalizations among young adults aged 20-44, but not older adults who spend relatively less time outdoors.

Another noteworthy finding is that most of the adverse effects we identify are likely due to well development and not natural gas extraction and compression. The only exceptions are significant associations between lagged gas output and AMI hospitalizations among 45-64 year olds, and pneumonia among those aged 20-44. A significant source of air pollution during well development is the diesel engines that power heavy equipment used to build roads, clear well sites, construct wells, drill, and inject fracking fluid into the wells. Horizontal drilling followed by hydraulic fracturing is more energy intensive than traditional vertical drilling, and the diesel engines used to pump fracking fluid commonly exceed 2000 bhp (Treida, 2010).

Our analysis does have some limitations that should be kept in mind when interpreting the results. The large-scale development of Marcellus shale has inevitably caused migration into affected communities by gas workers and other individuals seeking jobs created by greater economic activity associated with growth in the gas industry. Likewise, shale gas development has resulted in out-migration by individuals that have sold their land to gas companies, or have been displaced by rising cost of housing in well counties. We have included variables in our empirical models that capture changes in the county-level age distribution over time. Nonetheless, if the net impact of migration was to increase (decrease) the number of individuals with pollution-sensitive diseases in well counties, or decrease (increase) the number of individuals with these conditions in non-well counties, our estimates will be upwardly (downwardly) biased. Despite these limitations, our study helps establish a consistent link between unconventional natural gas extraction and higher rates of disease. Our results have important implications for public policy because they provide evidence of an adverse impact of shale gas development on health, which is currently of concern to policy makers. For example, in April 2012, the U.S. Environmental Protection Agency (EPA), Department of Energy, and Department of Interior agreed to collaborate on research in order to improve the "scientific understanding of hydraulic fracturing". In June, 2015, the EPA released the results from a national study that investigates the potential impact of hydraulic fracturing on drinking water resources. They did not find evidence that hydraulic fracturing has led to widespread, systemic impacts on drinking water resources in the United States, despite some isolated cases of contaminated drinking water wells (EPA, 2015).

In 2010 and 2011, the Pennsylvania DEP conducted three short-term studies to determine whether shale gas development affects air quality in the southwestern, northeastern, and northcentral regions of the state. In all three studies, natural gas constituents and associated compounds were detected in the air near Marcellus shale drilling operations, but the DEP concluded that none of the compounds reached a level of concentration that could cause air-related health issues (PADEP 2011a; 2011b; 2011c). However, a recent study conducted by the Southwest Pennsylvania Environmental Health Project (SWPA-EHP), a non-profit environmental health organization, found short-term high values of particulate matter in the air and concluded that current methods of collecting and analyzing air pollutants emission data are not sufficiently accurate for evaluating the health risks of unconventional natural gas development (Brown et al, 2014).

In the absence of strong scientific evidence on the relationship between shale gas development and health, states in the mid-Atlantic region have demonstrated conflicting regulatory objectives. In February 2012 the Pennsylvania General Assembly passed Act 13, which was a major overhaul of the state's oil and gas law. According to the new law, municipal governments are not allowed to impose stricter regulations on drilling activities than other industries and must allow oil and gas operations in "all zoning districts" (The General Assembly of Pennsylvania, 2011). This portion of the law resulted in disputes between local communities and state government and was subsequently ruled unconstitutional by the Pennsylvania Supreme Court (Cusick, 2013). In contrast, after conducting a 7-year study, the state of New York officially banned natural gas extraction activities that involve high-volume hydraulic fracturing on June 29, 2015 (NY DEC, 2015).

We seek to inform future regulatory policy on unconventional natural gas development by providing evidence on the link between Marcellus shale gas development and health. Because we find that unconventional natural gas well development has a stronger link to poor health than post-development gas production, there is more limited justification for natural gas extraction taxes based on pollution-related externalities than per-well fees (for example, under Pennsylvania's Act 13 of 2012, operator have to pay an annual "impact fee" on every Marcellus well they drill). However, our results demonstrate a clear need for additional studies to confirm the precise causal pathways between unconventional gas well development, elevated levels of air pollution, and adverse health effects among different age groups.

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Tables

Table 1. Statewide air emissions from unconventional natural gas development in Pennsylvania, 2011-2012

Emissions (tons)	2011	2012	Change (%)
Air pollutants			
CO	6852	7350	7.26%
NOx	16542	16361	-1.09%
PM-10	577	600	4.05%
PM-2.5	505	548	8.56%
SOx	122	101	-17.32%
VOC	2820	4024	42.69%
Benzene	20	25	26.97%
Ethyl Benzene	5	6	11.25%
Formal dehyde	251	374	48.93%
n-Hexane	51	98	92.96%
Toluene	34	33	-2.64%
Xylenes	26	34	32.30%
2,2,4-Trimethyl pentane	4	19	439.11%
Greenhouse gases			
CO_2	N/A	4291316	N/A
Methane	N/A	123884	N/A
Nitrous Oxide	N/A	209.3	N/A
Number of active unconventional wells	4052	5253	29.64%

Notes: These emission data are only for drilling and production phases, and do not include the emissions from the well pad construction phase. Emissions for CO_2, methane, and nitrous oxide are not available for 2011.

Table 2. List of counties with unconventional natural gas wells

County name	Drilling year	County name	Drilling year
Allegheny	2008	Susquehanna	2006
Armstrong	2009	Tioga	2006
Beaver	2009	Venango	2011
Bedford	2010	Warren	2007
Blair	2010	Washington	2002
Bradford	2005	Wayne	2008
Butler	2006	Westmoreland	2003
Cambria	2009	Wyoming	2009
Cameron	2008	**Non-well counties (*N*=28)**	
Centre	2007	Adams	Philadelphia
Clarion	2007	Berks	Pike
Clearfield	2007	Bucks	Schuylkill
Clinton	2008	Carbon	Snyder
Columbia	2010	Chester	Union
Crawford	2012	Cumberland	York
Elk	2005	Dauphin	
Fayette	2006	Delaware	
Forest	2009	Erie	
Greene	2006	Franklin	
Huntingdon	2010	Fulton	
Indiana	2003	Juniata	
Jefferson	2008	Lancaster	
Lackawanna	2009	Lebanon	
Lawrence	2011	Lehigh	
Luzerne	2010	Mifflin	
Lycoming	2007	Monroe	
Mckean	2006	Montgomery	
Mercer	2012	Montour	
Potter	2007	Northampton	
Somerset	2004	Northumberland	
Sullivian	2010	Perry	

Table 3. Summary statistics, county-level, 2001-2013

	Age 5-19		Age 20-44		Age 45-64		Age 65 and above	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Patient characteristics								
Age	14.424	0.430	32.011	0.616	55.179	0.402	77.982	0.705
Female	0.570	0.046	0.701	0.033	0.495	0.024	0.562	0.026
White	0.847	0.142	0.881	0.121	0.909	0.102	0.947	0.079
Black	0.071	0.098	0.053	0.081	0.045	0.080	0.022	0.053
Asian	0.004	0.005	0.005	0.007	0.002	0.003	0.001	0.002
Other race	0.078	0.076	0.061	0.063	0.043	0.050	0.030	0.053
Hispanic	0.038	0.059	0.027	0.049	0.015	0.040	0.009	0.040
Private	0.589	0.088	0.545	0.079	0.574	0.082	0.060	0.028
Medicare	0.004	0.008	0.083	0.023	0.227	0.047	0.924	0.034
Medicaid	0.364	0.090	0.308	0.065	0.153	0.046	0.004	0.005
Government insurance	0.014	0.011	0.013	0.011	0.015	0.012	0.005	0.006
Self-pay	0.021	0.016	0.045	0.020	0.025	0.014	0.002	0.010
Other insurance	0.007	0.011	0.006	0.009	0.005	0.008	0.005	0.012
Admission: emergency	0.415	0.152	0.322	0.137	0.427	0.168	0.479	0.205
Admission: urgent	0.286	0.140	0.241	0.133	0.261	0.165	0.283	0.205
Admission: elective	0.293	0.111	0.431	0.098	0.308	0.058	0.235	0.058
Admission: other type	0.000	0.002	0.000	0.001	0.000	0.001	0.000	0.001
Charlson index	0.157	0.064	0.274	0.060	1.065	0.156	1.484	0.263
County-level hospitalization rate (cases per 1000 people)								
Acute myocardial infarction (AMI)	0.002	0.011	0.447	0.243	3.577	1.090	12.080	3.720
Chronic obstructive pulmonary disease (COPD)	0.018	0.044	0.223	0.201	3.001	1.390	12.450	4.474
Asthma	0.719	0.749	0.780	0.449	1.296	0.791	2.075	1.226
Pneumonia	0.737	0.435	1.008	0.466	3.237	1.269	17.686	5.484
Upper respiratory infection (URI)	0.058	0.104	0.129	0.140	0.276	0.229	1.164	0.765

County Characteristics (across all age groups)

	Well counties		Non-well counties	
	Mean	Standard deviation	Mean	Standard deviation
Poverty rate* (percent)	13.351	2.719	10.401	3.759
Household median income* (thousand, in 2013 dollars)	44.515	4.452	56.191	11.573
Unemployment rate* (percent)	6.832	1.775	6.133	1.936
Population density* (Number of people per square mile)	4.520	1.019	5.744	1.209
Log of coal production (underground, short tons)**	1.199	5.115	0.007	0.030
Log of coal production (surface, short tons)**	0.276	0.593	0.034	0.173
Has a well in following year (0/1)***	0.568	0.496		
Has a well in current year (0/1)***	0.491	0.500		
Has a well in previous year (0/1)***	0.414	0.493		
Log of output in current year*** (million cubic feet)	5.144	6.971		
Log of output in previous year*** (million cubic feet)	4.087	6.410		

Notes: *U.S. Census Bureau, Small Area Income and Poverty Estimates (SAIPE); **U.S Energy Information Administration; ***Pennsylvania Department of Environmental Protection; Natural gas output is measured in thousand cubic feet (MCF); Household median income is unadjusted due to the methodological change of SAIPE after 2005. County level incidences are calculated by first aggregating the individual-level PHC4 data to county-year cells for each age group, and then normalizing by the population in that age group. All patient characteristics are county-level means from the PHC4 data.

Table 4. Impact of shale gas development on county-level hospitalization rates, 2001-2013

	(1)	(2)	(3)	(4)	(5)	(6)
	AMI	COPD	Asthma	Pneumonia	URI	Trauma
Panel A. Age 5-19						
Well in current year			0.000	0.061	-0.021	0.168
			(0.065)	(0.073)	(0.017)	(0.141)
Well last year			-0.048	0.071	0.019	0.111
			(0.060)	(0.077)	(0.019)	(0.131)
Log output			-0.000	-0.010	0.000	-0.018
			(0.006)	(0.008)	(0.002)	(0.016)
1st lag of log output			-0.005	0.001	-0.000	0.017
			(0.006)	(0.007)	(0.002)	(0.012)
Panel B. Age 20-44						
Well in current year	-0.058	0.055**	-0.036	0.068	0.044	-0.058
	(0.044)	(0.026)	(0.045)	(0.057)	(0.033)	(0.044)
Well last year	0.105**	-0.081*	0.089*	-0.005	-0.057	0.105**
	(0.047)	(0.041)	(0.048)	(0.072)	(0.044)	(0.047)
Log output	-0.002	0.001	-0.009	0.001	0.003	-0.002
	(0.004)	(0.003)	(0.006)	(0.007)	(0.003)	(0.004)
1st lag of log output	-0.001	-0.001	0.006	0.011*	-0.001	-0.001
	(0.004)	(0.003)	(0.005)	(0.006)	(0.003)	(0.004)
Panel C. Age 45-64						
Well in current year	-0.075	-0.005	0.004	0.149	0.030	-0.075
	(0.120)	(0.148)	(0.078)	(0.156)	(0.040)	(0.120)
Well last year	-0.012	-0.267	0.070	0.133	-0.009	-0.012
	(0.141)	(0.164)	(0.077)	(0.177)	(0.035)	(0.141)
Log output	0.001	0.019	0.005	-0.017	0.000	0.001
	(0.013)	(0.015)	(0.007)	(0.016)	(0.004)	(0.013)
1st lag of log output	0.018*	-0.007	-0.007	0.011	0.000	0.018*
	(0.010)	(0.016)	(0.005)	(0.015)	(0.004)	(0.010)
Panel D. Age 65 and above						
Well in current year	0.114	0.465	-0.009	0.790	-0.009	0.114
	(0.346)	(0.385)	(0.164)	(0.485)	(0.103)	(0.346)
Well last year	0.355	0.505	0.118	1.493***	0.198**	0.355
	(0.381)	(0.444)	(0.125)	(0.393)	(0.080)	(0.381)
Log output	-0.001	-0.044	-0.012	-0.003	-0.020*	-0.001
	(0.046)	(0.048)	(0.016)	(0.068)	(0.010)	(0.046)
1st lag of log output	0.080**	0.007	-0.004	-0.028	-0.000	0.080**

	(0.039)	(0.037)	(0.014)	(0.056)	(0.009)	(0.039)

Notes: *p<0.1, **p<0.05, ***p<0.01. Standard errors are clustered at county level. Total of number of observations is 804. All models include county and year fixed effects. Other control variables include average age, the share of different types of insurance (Medicare, Medicaid, private, self-pay, government, and other insurance), the share of female patients, the share of different race and ethnicity groups (white, black, Asian, Hispanic, and other race), the share of different types of admission (emergency, urgent, elective, and other types), average Charlson index, county-level unemployment rate, poverty rate, annual quartiles of median household income, log of population density, log of annual coal production (both surface and underground) and entire county-level age distribution.

Table 5. Coefficient estimates from pre-trend test

	(1)	(2)	(3)	(4)	(5)
	AMI	COPD	Asthma	Pneumonia	URI
Panel A. Age 5-19					
Well current			-0.026	0.006	-0.007
			(0.051)	(0.063)	(0.015)
1st lead of well current			-0.018	0.008	0.015
			(0.075)	(0.075)	(0.019)
2nd lead of well current			-0.040	0.067	-0.006
			(0.067)	(0.076)	(0.015)
Panel B. Age 20-44					
Well current	-0.000	0.037	0.022	-0.001	-0.002
	(0.047)	(0.029)	(0.053)	(0.068)	(0.028)
1st lead of well current	0.010	-0.042	0.004	0.108	0.043
	(0.052)	(0.040)	(0.064)	(0.094)	(0.034)
2nd lead of well current	-0.013	-0.005	0.025	0.004	0.016
	(0.038)	(0.036)	(0.050)	(0.082)	(0.025)
Panel C. Age 45-64					
Well current	0.017	-0.046	0.045	0.049	-0.021
	(0.140)	(0.169)	(0.090)	(0.165)	(0.040)
1st lead of well current	-0.089	-0.220	0.089	0.039	0.035
	(0.178)	(0.234)	(0.089)	(0.183)	(0.033)
2nd lead of well current	-0.025	0.376*	-0.057	0.164	0.033
	(0.160)	(0.203)	(0.071)	(0.148)	(0.044)
Panel D. Age 65 and above					
Well current	0.078	0.344	-0.024	1.339**	0.084
	(0.350)	(0.450)	(0.151)	(0.610)	(0.106)
1st lead of well current	0.330	0.235	-0.012	-0.004	-0.124
	(0.401)	(0.503)	(0.121)	(0.575)	(0.117)
2nd lead of well current	-0.218	0.443	0.057	0.302	0.060
	(0.349)	(0.504)	(0.158)	(0.559)	(0.117)

Notes: *p<0.1, **p<0.05, ***p<0.01. Standard errors are clustered at county level. Total of number of observations is 737. All models include county and year fixed effects. Other control variables include average age, the share of different types of insurance (Medicare, Medicaid, private, self-pay, government, and other insurance), the share of female patients, the share of different race and ethnicity groups (white, black, Asian, Hispanic, and other race), the share of different types of admission (emergency, urgent, elective, and other types), average Charlson index, county-level unemployment rate, poverty rate, annual quartiles of median household income, log of population density, log of annual coal production (both surface and underground) and entire county-level age distribution.

Table 5. Rejection rates for H_0 from Monte Carlo simulations of placebo treatments, 2000-2005

	Age 5-19			Age 20-44			Age 45-64			Age 65 and above		
	<0.01	**<0.05**	**<0.1**	**<0.01**	**<0.05**	**<0.1**	**<0.01**	**<0.05**	**<0.1**	**<0.01**	**<0.05**	**<0.1**
AMI												
Well current year				1.27%	6.18%	11.92%	1.54%	6.42%	12.25%	1.49%	6.02%	11.93%
Well last year				1.32%	5.81%	12.03%	1.54%	6.64%	12.51%	1.48%	6.77%	12.74%
COPD												
Well current year	1.34%	6.26%	11.71%	1.66%	7.73%	14.46%	2.14%	8.25%	14.88%	0.75%	4.51%	10.16%
Well last year	1.22%	5.99%	11.46%	1.38%	7.29%	13.80%	2.11%	7.77%	14.05%	0.87%	4.50%	9.73%
Asthma												
Well current year	1.33%	5.90%	11.70%	2.73%	10.25%	17.12%	1.34%	5.68%	10.89%	3.51%	12.20%	19.96%
Well last year	1.35%	6.08%	11.45%	3.36%	11.14%	18.46%	1.71%	6.82%	12.61%	3.68%	12.01%	19.82%
Pneumonia												
Well current year	1.47%	6.43%	12.24%	1.24%	5.57%	10.66%	0.98%	6.73%	12.95%	1.19%	5.87%	12.28%
Well last year	1.32%	6.46%	12.18%	1.34%	5.68%	10.83%	1.07%	6.28%	12.76%	1.26%	6.73%	13.61%
URI												
Well current	1.08%	5.41%	10.62%	0.78%	4.72%	9.53%	0.82%	4.24%	9.36%	1.90%	7.22%	13.66%
Well last year	1.01%	5.92%	11.65%	0.89%	4.60%	9.47%	0.55%	4.04%	9.17%	1.61%	6.82%	12.80%

Notes: Results are based on 10,000 replications. All models include county and year fixed effects. Control variables include average age, the share of different types of insurance (Medicare, Medicaid, private, self-pay, government, and other insurance), the share of female patients, the share of different race and ethnicity groups (white, black, Asian, Hispanic, and other race), the share of different types of admission (emergency, urgent, elective, and other types), average Charlson index, county-level unemployment rate, poverty rate, annual quartiles of median household income, log of population density, log of annual coal production (both surface and underground), and the entire county-level age distribution

Appendix

A1 Shale gas development process

Unlike conventional natural gas development, extracting natural gas from unconventional formations relies heavily on horizontal drilling and hydraulic fracturing. Typically, operators first construct a well pad at the location suitable for drilling, build infrastructure, and transport equipment to the drilling site. In the next stage, a hole (wellbore) is drilled into the earth through a combination of vertical and horizontal drilling. Casing[13] and cement are inserted into the wellbore in order to isolate it from the surrounding formation. Finally, hydraulic fracturing is used to stimulate the shale formation. This involves the injection of highly pressurized fracturing fluid through the holes created by a perforating tool inserted in the casing and cement. As fracturing fluid is forced into the surrounding formation, fractures or cracks are created or expanded in the target formation. The underlying gas is then released and collected. It is worth noting that throughout the production period it may be necessary to re-stimulate the wells (also known as re-fracturing or well workovers) by repeating the hydraulic fracturing process, the frequency of which depends on the characteristics of geologic formation and production phase of a particular well (DOE, 2009). When estimating annual greenhouse gas emission from natural gas production, the Environmental Protection Agency use the assumption that 10 percent of unconventional wells need re-stimulation every year (EPA, 2012).

A2 Potential public health risks

Shale gas development and production may pose a threat to public health through air pollution (NRDC, 2014). First, the construction of infrastructure at the drilling site requires

[13] Casing is a metal pipe that is inserted inside the wellbore to prevent high pressure fluids outside the formation from entering the well and to prevent drilling mud inside the well from fracturing fragile sections of the wellbore.

massive transportation of water, sand, chemicals, and heavy machinery. Air pollutants such as nitrogen oxides (NO_X) and particulate matters (PM) contained in the engine exhaust brought about by increased traffic are released into the atmosphere. In addition, the development and production process requires substantial amount of power, which is often supplied by diesel engines. The burning of diesel fuel also generates exhaust. Second, for operational reasons, flaring (burning) or venting (direct release into the atmosphere) of natural gas during the development and production process is sometimes necessary, which leads to emissions of carbon dioxide and the release of methane and volatile organic compounds (VOCs). Third, evaporation of fracturing fluid and produced water may also emit hazardous chemicals into the atmosphere. Some of the air pollutants and chemicals from the drilling and gas production activities may be harmful to human health and even carcinogenic. NO_X can form small particles through reactions with ammonia, moisture, and other compounds. These particles penetrate deeply into the sensitive part of lungs and cause or worsen respiratory diseases (EPA, 1998). In addition, when reacting with VOCs in the presence of heat and sunlight, NO_X can form ground-level Ozone (smog), which irritates the respiratory system, reduces lung function, aggravates chronic conditions such as asthma and chronic bronchitis, and potentially results in permanent lung damage (EPA, 2009).

Particulate matter (PM) is also harmful. Short-term exposure to fine particles can cause asthma attacks and acute bronchitis, and increases the risk of heart attacks and arrhythmias among people with heart disease (EPA, 2003). There are a multitude of studies that attempt to uncover the link between air pollution and adverse health outcomes. In general, researchers have found consistent evidence that air pollution is associated with respiratory problems. For example, Ko et al (2007) find that levels of major air pollutants (NO_2, O_3, PM_{10}, and $PM_{2.5}$) in Hong Kong were associated with increased hospital admissions, with O_3 being the most important contributor. Likewise, Zanobetti and Schwartz (2006) find that air pollution in the greater Boston area was associated with a higher risk of hospitalization for pneumonia among individuals aged 65 and older.

Colborn et al (2011) compile a list of 632 chemicals used during the fracturing and drilling stages of natural gas development and report that many of them could have a negative impact on human health. In particular, more than 75 percent of the chemicals could affect the respiratory system; about half could affect the immune and cardiovascular systems; and 25 percent could cause cancer. A similar analysis was conducted in a congressional report by the Committee on Energy and Commerce of the U.S. House of Representatives. The report reviews the type and volume of hydraulic fracturing products used by 14 leading oil and gas companies between 2005 and 2009 and finds that the most widely used chemical during that period was methanol, which is a hazardous air pollutant, and that more than 650 hydraulic fracturing products contain 29 chemicals that are known or possible human carcinogens (Committee on Energy and Commerce, U.S. House of Representatives, 2011). These chemicals are either regulated under the Safe Drinking Water Act for their risks to human health, and/or listed as hazardous air pollutants under the Clean Air Act. For instance, the BTEX compounds (benzene, toluene, xylene, and ethylbenzene) were found in many of the hydraulic products. Each BTEX compound is a regulated contaminant under the Safe Drinking Water Act and a hazardous air pollutant under the Clean Air Act. Benzene alone is also known to be carcinogenic.

A3 Monte Carlo simulation

Using a Monte Carlo simulation, we investigate whether our findings could result from spurious correlation between drilling activity and county-level disease trends. The simulation results indicate that the potential for unobservable county-level attributes to confound our findings in this manner is small.

In order to conduct the simulation we first subset the sample to 2000 - 2005, the period before unconventional drilling in Marcellus shale began, and then randomly assign the "treatment" of unconventional wells to counties that contained wells in the post-2005 period. These wells are assigned by drawing the year of drilling in the pre-well period from a uniform distribution. We then estimate equation (1) for each condition with current and lagged placebo treatment indicators, but without the output variables.

Provided there are no unobserved determinants of hospitalization rates in well counties, the coefficients on the placebo treatment variables should be statistically significant under a t-test at the same rate at the α level of the test (i.e. the Type 1 error rate). If, however, we find a spurious correlation between the placebo treatment and hospitalization rates at a higher rate than the α level of the test, it indicates that there are unobservable differences in factors determining hospitalization rates that are not accounted for by our models, which may lead us to incorrectly conclude that there is a statistically significant relationship between shale gas development and health. We report the 1%, 5%, and 10% rejection rates for the placebo treatments for the models corresponding to our health outcomes in Table 5.

Table A1. ICD-9-CM diagnosis codes for all five conditions

AMI

4100 41000 41001 41002 4101 41010 41011 41012 4102 41020 41021 41022 4103 41030 41031 41032 4104 41040 41041 41042 4105 41050 41051 41052 4106 41060 41061 41062 4107 41070 41071 41072 4108 41080 41081 41082 4109 41090 41091 41092

COPD

490 4910 4911 4912 49120 49121 49122 4918 4919 4920 4928 494 4940 4941 496

Asthma

49300 49301 49302 49310 49311 49312 49320 49321 49322 49381 49382 49390 49391 49392

Pneumonia

00322 0203 0204 0205 0212 0221 0310 0391 0521 0551 0730 0830 1124 1140 1144 1145 11505 11515 11595 1304 1363 4800 4801 4802 4803 4808 4809 481 4820 4821 4822 4823 48230 48231 48232 48239 4824 48240 48241 48242 48249 4828 48281 48282 48283 48284 48289 4829 483 4830 4831 4838 4841 4843 4845 4846 4847 4848 485 486 5130 5171

URI

4660 4661 46611 46619 0320 0321 0322 0323 0340 460 4610 4611 4612 4613 4618 4619 462 4640 46400 46401 46410 46411 46420 46421 46430 46431 4644 46450 46451 4650 4658 4659 4730 4731 4732 4733 4738 4739 78491

Table A2. Coefficient estimates from models with county-specific trends

	(1)	(2)	(3)	(4)	(5)
	AMI	COPD	Asthma	Pneumonia	URI
Age 5-19					
Well in current year	-0.002	0.004	0.028	0.044	-0.018
	(0.003)	(0.014)	(0.080)	(0.089)	(0.018)
Well last year	0.003	-0.025	-0.089	0.077	-0.007
	(0.003)	(0.017)	(0.076)	(0.108)	(0.016)
Log output	-0.000	0.003	0.002	-0.011	0.002
	(0.000)	(0.002)	(0.008)	(0.009)	(0.002)
1st lag of log output	-0.001	-0.001	-0.013	-0.003	-0.001
	(0.001)	(0.002)	(0.009)	(0.010)	(0.002)
Age 20-44					
Well in current year	-0.058	0.047	-0.013	-0.031	0.006
	(0.056)	(0.032)	(0.058)	(0.070)	(0.032)
Well last year	0.092	-0.065	0.156**	-0.014	-0.063
	(0.056)	(0.045)	(0.071)	(0.092)	(0.051)
Log output	-0.003	-0.001	-0.013	-0.002	0.005
	(0.005)	(0.004)	(0.008)	(0.009)	(0.004)
1st lag of log output	-0.001	-0.004	0.004	0.009	-0.004
	(0.006)	(0.003)	(0.007)	(0.007)	(0.004)
Age 45-64					
Well in current year	-0.046	-0.141	-0.024	0.153	-0.046
	(0.151)	(0.174)	(0.080)	(0.164)	(0.053)
Well last year	0.015	-0.103	-0.121	0.162	-0.048
	(0.159)	(0.181)	(0.074)	(0.250)	(0.050)
Log output	0.002	0.007	0.029***	-0.033	0.001
	(0.016)	(0.016)	(0.007)	(0.024)	(0.006)
1st lag of log output	0.002	-0.017	-0.011	0.014	-0.006
	(0.012)	(0.025)	(0.008)	(0.017)	(0.005)
Age 65 and above					
Well in current year	0.129	-0.061	-0.005	0.537	0.036
	(0.367)	(0.441)	(0.170)	(0.649)	(0.096)
Well last year	0.145	-0.257	-0.211	1.406***	0.145
	(0.470)	(0.493)	(0.131)	(0.528)	(0.102)
Log output	-0.021	0.002	0.014	-0.031	0.003
	(0.049)	(0.037)	(0.016)	(0.063)	(0.010)
1st lag of log output	0.038	-0.022	0.012	0.045	-0.001

	(0.037)	(0.057)	(0.014)	(0.061)	(0.011)

Notes: *p<0.1, **p<0.05, ***p<0.01. Standard errors are clustered at county level. Total of number of observations is 804. All models include county and year fixed effects. Other control variables include average age, the share of different types of insurance (Medicare, Medicaid, private, self-pay, government, and other insurance), the share of female patients, the share of different race and ethnicity groups (white, black, Asian, Hispanic, and other race), the share of different types of admission (emergency, urgent, elective, and other types), average Charlson index, county-level unemployment rate, poverty rate, annual quartiles of median household income, log of population density, log of annual coal production (both surface and underground) and entire county-level age distribution.