FEAR OF FRACKING: THE IMPACT OF THE SHALE GAS EXPLORATION ON HOUSE PRICES IN BRITAIN

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Abstract

Shale gas has grown to become a major new source of energy in countries around the globe. While its importance for energy supply is well recognized, there has also been public concern over potential risks – such as damage to buildings and contamination of water supplies – caused by geological disturbance from the hydraulic fracturing ('fracking') extraction process. Although commercial development has not yet taken place in the UK, licenses for drilling were issued in 2008 implying potential future development. This paper examines whether public fears about the geological impacts of fracking are evident in changes in house prices in areas that have been licensed for shale gas exploration. Our estimates suggest differentiated effects. Licensing did not affect house prices but areas where shale gas development was mentioned in the license application experienced an average house price decrease between 1 and 1.5 percent for the period 2008-2014. This was a response to geological events related to fracking. Specifically, two very minor earthquakes caused by the process in 2011 were strong drivers of this price drop. We find a 2.7-4.1 percent house price decrease in the area where the earthquakes occurred. Robustness checks confirm our findinds.

JEL Classifications: Q5, Q42, Q51
Keywords: shale gas, fracturing, property valuation, housing prices, consumer expectation, hedonic price, United Kingdom

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1 Introduction

The advent of cost-reducing technological innovations associated with hydraulic fracturing and horizontal drilling has allowed shale gas to become one of the most promising and viable new global sources of energy. With the discovery of large reserves around the world, shale gas can support global energy needs for decades. The US Energy Information Administration estimated in 2012 that United States natural gas resources will last for up to 87 years and the British Department of Energy and Climate Change suggested in 2013 that Britain has enough shale gas deposits to supply the UK for about 25 years.

In the US, a shale gas boom has boosted domestic energy supplies and the profits of producers (Feyrer et al. 2015). At the same time, shale gas development has raised concerns about externalities (i.e., environmental, disamenity, and other costs borne by nearby landowners and other stakeholders besides the drilling company). During the extraction process, large amounts of high-pressure water and additives are used to fracture the rock layer and release embedded shale gas. The water is transported by trucks, thus raising concerns about noise, road damage and accidents due to increased traffic (Gilman et al. 2013, Muehlenbachs and Krupnick 2014). Increased air pollution may result from this truck traffic and from drilling operations (Colborn et al. 2014, Caulton et al. 2014, Roy et al. 2014). Moreover, there is a risk of soil or water contamination caused by metals, radioactive and saline wastewater, or by the added chemicals used to treat the wells (Olmstead et al. 2013, Warner et al. 2013, Fontenot et al. 2013). More recently, there have also been rising concerns about seismic activity induced by gas exploration (Koster and van Ommeren 2015). In the US, these costs may be compensated to some degree, with many US households owning the rights to their underlying minerals and receiving offsetting lease payments.

This paper looks at the impact of prospective hydraulic fracturing for shale gas in the United Kingdom. The UK differs in important ways from the US in that (i) there is no royalty-based compensation for the costs of shale gas extraction as all subterranean petroleum is owned by the

Crown since the 1934 Petroleum Act,[1] and (ii) commercial shale gas extraction has not yet begun, although Petroleum Exploration and Development Licenses (PEDL) grant the right to explore for shale gas or coal bed methane. Licenses awarded under the 13th licensing round in 2008 mention shale gas exploration projects for the first time. Exploration implies drilling a test well to get accurate estimates of the recoverable shale resources. If firms want to go beyond the exploration stage and actually frack a well, this will require additional consents and planning permissions.[2] By 2016, a number of exploration wells have been drilled but only one well had been fracked. This situation allows us to take a closer look at the *expected* costs and benefits of shale gas extraction.

To assess expectations, we employ regression methods and look at whether the expectation of hydraulic fracturing happening in PED license areas was capitalized in house prices. Buying a house is a significant financial commitment and buyers will likely consider the expected costs and benefits of shale gas extraction. To estimate unbiased effects of the expectation of shale gas extraction, we exploit detailed information on every house transaction in the years before and after the 2008 round of licensing. This allows us to compare changes in house prices in the licensed area to changes in the prices of comparable houses outside that area in a difference-in-differences procedure. The approach controls flexibly for all time-invariant local attributes (observed or unobserved) that might be correlated with licensing and house prices. Moreover, it also controls for all time-varying characteristics through the use of well-chosen control locations. Our control group definitions include (i) areas bordering the newly licensed areas; (ii) areas that are further away to account for expectations of spatial spillovers, (iii) areas that were licensed before 2008; and (iv) areas where the underlying geology promises shale gas deposits. We further address the possibility that licensed areas may have experienced trends different from those in non-licensed

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[1] While individual homeowners in the UK will not receive royalty payments from shale development as they do in the US, the UK Onshore Oil and Gas Industry's *Community Engagement Charter* promises approximately 100,000 GBP as a community benefit per well site where hydraulic fracturing takes place, plus one percent of the future production revenue (UKOOG 2013). Moreover, the industry commits to make a voluntary one-off payment of £20,000 for the right to use deep-level land for each unique horizontal well that extends by more than 200 meters. These payments are voluntary but the government reserves powers to make these payments compulsory if firms fail to volunteer.

[2] Drilling requires the landowners' consents, planning permissions from the local community, permits from the environmental agencies, positive reviews form the Health and Safety Executive, and permission from the DECC (see DECC 2015a for details). Note that the 2015 Infrastructure Act provides automatic access to deep level land below 300m for the purpose to exploit petroleum or deep geothermal energy by hydraulic fracturing. As a result, operators do not need access rights from every individual landowner whose land is drilled under at a depth below 300m.

areas with a triple-difference strategy in which we compare license areas where license holders explicitly mentioned shale gas exploration to license areas where shale gas exploration was not mentioned explicitly.

Our estimates suggest differentiated effects. While licensing did not seem to affect house prices, we find a statistically significant negative effect on house prices in areas where shale gas development was mentioned in the license application. The negative house price effect ranges between 1 and 1.5 percent for the period 2008-2014. This raises the question as to what accounts for this house price drop. Our results suggest that seismic activity is a main concern for house buyers. After Cuadrilla – one of the companies involved in UK shale gas exploration – hydraulically fractured the first (and so far only) well in the UK near Blackpool, two small earthquakes of magnitude 2.3 and 1.5 on the Richter scale were detected by the British Geological Survey in February and May 2011. These are very minor earthquakes, of a magnitude which would not have caused any structural damage, although some residents reported noticeable shaking of windows and furniture.[3] Earthquakes of this magnitude are not uncommon in the U.K., but subsequent investigations and a well-publicized report, showed that these earthquakes were very probably caused by hydraulic fracturing. In a slight modification of our design, we therefore focus within the shale gas areas on those areas where hydraulic fracturing likely caused seismic disruption in 2011. Once we allow for a change in house prices after the 2011 earthquakes, we see that the licensing effect is largely driven by those events. Depending on the control group specification, we estimate negative house price effects that range between 2.7 and 4.1 percent following the incidents in 2011. Distance decay specifications show that this affects licensed areas within a radius of 30 km distance from the well where the earthquake happened. We can further show that house prices in the earthquake region are persistently decreasing after 2011, suggesting that the fear of fracking is not a temporary phenomenon.

Our findings contribute to an ongoing discussion about the expected effects of shale gas extraction. In the UK, media like the Sunday Times (Leake and Thomson, 2014) have reported house price drops in the vicinity of the exploration wells, but these articles were dismissed by the British

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[3] http://www.bbc.co.uk/news/uk-england-12930915

Department of Energy and Climate Change (DECC) for lack of evidence. DECC went on to counter these news releases, arguing that shale gas operations—like other oil and gas exploration over the past half a century—should not affect real estate values (DECC 2014a). Moreover, our results contribute to a rising literature trying to quantify the welfare effects of shale gas activity. Studies that have adopted this approach include Klaiber and Gopalakrishnan (2014), who measure the temporal impact of shale gas wells in Washington County, Pennsylvania, and Muehlenbachs et al. (2015) use data from all of Pennsylvania to conduct a triple-difference analysis of the effect of shale gas development on groundwater dependent homes, along with a double-difference analysis of the effect on all nearby homes regardless of water source. While that paper finds some evidence of small gains for houses dependent upon public water sources (likely arising from lease payments) it finds evidence of significant negative net effects on groundwater dependent houses. Other research has also recovered evidence of concerns over risks to a household's water source (Throupe, Simons and Mao 2013), or large negative effects on house values more generally (James and James 2014), although other researchers have found much smaller effects (Delgado, Guilfoos, and Boslett 2014).

More broadly, our paper connects to the literature that examines earthquakes induced by natural gas extraction (Koster and van Ommeren 2015), locally undesirable land uses (LULUs) including superfund sites (Greenberg and Hughes 1992; Kiel and Williams 2007; Greenstone and Gallagher 2008; Gamper-Rabindran and Timmins 2013), brownfield redevelopment (Haninger et al. 2012; Linn 2013), commercial hog farms (Palmquist et al. 1997), underground storage tanks (Zabel and Guignet 2012), cancer clusters (Davis 2004), electric power plants (Davis 2011), and wind farms (Gibbons 2015; Dröes and Koster, 2015).

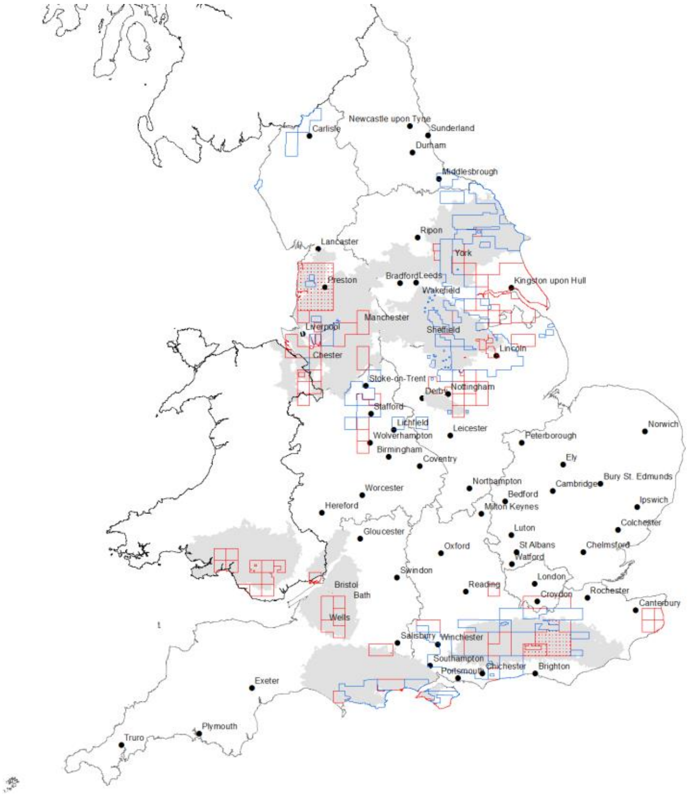
In the remainder, we discuss relevant literature in Section 2, followed by a description of the hedonic method in Section 3 and a detailed data description in Section 4. We present our results on the 13th licensing round in Section 5, discuss the house price impacts of expected seismic activity in Section 6, and draw conclusions in Section 7.

2 Shale Gas Development in the U.K.

Onshore shale gas production was first proposed in the United Kingdom in 2007. In that process, the Department of Energy and Climate Change (DECC) identified areas in the east and south of England as having potential for shale gas development. Figure 1 maps areas where Petroleum Exploration and Development licenses (PEDL) were distributed under the 13th Onshore Oil and Gas Licensing round in 2008. These licenses (red areas) and existing licenses (blue areas) allow the holder to explore for and develop unconventional gas – to "search for, bore and get hydrocarbons" subject to access rights, planning permission, environment and health & safety permits. In these licensing rounds, a tranche of 10km x 10km blocks of land are offered by the government for potential exploration and development. Exploration and production (E&P) companies can apply for a license to drill exploration wells in one or more of these blocks (with only one drill per block). Cuadrilla Resources, IGas and Third Energy are the companies who drilled Shale gas exploration wells by 2014. However, beside test wells, there has not been any commercial drilling in the UK to date.

The 14th Onshore Oil and Gas Licensing Round was launched on 28 July 2014 and closed on 28 October 2014. According to the Oil & Gas Authority (OGA), "a total of 95 applications were received from 47 companies covering 295 Ordnance Survey Blocks. Following scrutiny of each applicant's competency, financial viability, environmental awareness and geotechnical analysis, and following the decision not to award licenses in Scotland and Wales, 159 blocks were taken forward for further consideration." On 17 December 2015, the OGA announced that 159 license blocks were formally offered under the 14th round. We do not look at the house price impacts of this licensing round in our main specification since it is too recent, but we will utilize the areas offered as a control group for areas offered in the 13th licensing round in one part of our estimation strategy.

Figure 1: Licensed Blocks from 13th Onshore Licensing Round



Note: The figure shows blocks that were licensed for shale gas development in the 13th round in 2008 (red) and blocks that were licensed in previous rounds with the licenses still being valid in 2008 (blue). Dotted red areas mentioned shale gas development explicitly in their license application. Grey shaded areas indicate regions with shale gas potential according to the British Geological Survey (BGS). Note that output areas are not perfectly nested in license blocks which leads to small differences. We do not consider Scotland in the north.

Shale gas development is considered a promising energy strategy in the UK for several reasons. First, it can contribute to energy security, reducing the UK's reliance on offshore gas and imported gas. Second, it is thought to support the UK's attempted transition to a low-carbon economy as it emits less CO_2 than oil or coal. If shale gas replaced these alternative energy sources it could have a positive effect on the UK's carbon footprint. Third, developments in the U.S. show that commercial drilling can have significant economic benefits not only with respect to possible independence from fossil fuel but also for the local communities where the drilling sites are located. DECC (2013) suggests that "UK shale gas production would be a net benefit to public finances, could attract annual investment of £3.7 billion and support up to 74,000 jobs directly, indirectly and through broader economic stimulus." Additionally, the UK onshore oil and gas industry (UKOOG) agreed in their 2013 Community Engagement Charter to pay £100,000 to local communities situated near exploratory well sites regardless of whether or not recoverable deposits are found. On top of that, they promised 1 percent of production revenues to communities during the production stage, which may amount to £5-10m per well over a period of 25 years. Finally, the industry confirmed a voluntary one-off payment of £20,000 per horizontal well to local communities in return for the right to use deep-level land that extends by more than 200 meters.[4] We do not expect these schemes to be capitalized in house prices for two reasons. First, only one well has been fracked and only a few additional wells were drilled in the UK by 2015. Accordingly, not much money has been paid yet. Second, the expectation of future payments may not be capitalized in house prices because they are not formally guaranteed (though such payments could be made compulsory if companies fail to volunteer) and because they are paid to the community instead of the individual landowner. For community payments to be capitalized in house prices, house buyers would probably need more information about the exact benefits of community projects.

Cuadrilla was the first company to receive a license for shale gas exploration along the coast of Lancashire (the dotted red area in the north-west of Figure 1). In August 2010, they started hydraulically fracturing the well *Preese Hall 1*, which is located near Blackpool. This was the first time that a well had been fracking in the UK and as of 2015, it remains the only one. On 1 April 2011, the British Geological Survey (BGS) reported an earthquake of magnitude 2.3 on the Richter scale near *Preese Hall 1*. Following this event, Cuadrilla installed local seismometer stations around the exploration well that did not observe any further seismic activity. On May 26th, Cuadrilla resumed hydraulic fracturing and only 10 hours later, the BGS reported another earthquake of magnitude 1.5 on the Richter scale. Following these events, Cuadrilla announced on 31st May 2011 a halt due to unstable seismic activity (De Pater and Baisch 2011). Cuadrilla then commissioned a series of geomechanical studies to investigate the connection between the seismic events and the hydraulic fracturing operations.

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[4] In 2014, it was enacted that operators do not need access rights from every individual landowner whose land is drilled under at a depth below 300m.

The reports concluded that the observed seismic activity "was caused by direct fluid injection into an adjacent fault zone during the treatments, but that the probability of further earthquake activity is low" (Green et al. 2012). A subsequent official UK government report acknowledged that hydraulic fracturing caused the seismic activities. Despite that, the report did not recommend stopping further operations but rather called for careful monitoring of seismic activities around fracking wells. Subject to stricter rules, the Secretary of State announced on 13 December 2012 that exploratory hydraulic fracturing for shale gas could resume in the UK. However, there were no further wells being fracked by the end of 2015, partly because local communities delayed the planning permission process or refused them. As a reaction, the government announced a number of measures to speed up the permission process for shale gas development projects on 13 August 2015. The Secretary of State can now (i) take the final decision on the appeal from a refusal of local authorities; (ii) call in planning applications for his own determination before local planning authorities have come to a decision; and (iii) determine applications to local planning authorities that are underperforming, i.e. take too long to decide.

3 Estimation Strategy

Our aim is firstly to estimate if and by how much house prices are affected when the area in which a house is located is licensed for shale gas exploration and is thus exposed to potential future shale gas development. There are fundamental econometric challenges to this exercise. Places offered, chosen and licensed for shale gas exploration are selected for their potential gas productivity and may therefore differ from unlicensed areas on many dimensions. The licensing decisions may also be influenced by planning considerations and the potential impacts on local residents. Both of these considerations imply that house prices may be different in licensed and unlicensed areas, for reasons other than a causal effect of licensing on prices.

As a first step to address these problems and assess how licensing an area for shale gas development affects house prices, our baseline approach involves regression-based 'difference-in-difference' methods that compare the average change in property prices before and after the 13th licensing round to the average house price change in a comparison group. We use the comparison group to show how house prices in a treated unit would have developed in the absence of licenses being issued (the 'counterfactual'). To make this comparison group more similar to the areas licensed for gas exploration, we impose a number of sample restrictions. Firstly, we always exclude urbanized areas that are fundamentally unlike the predominantly rural and semi-rural areas where shale gas exploration is an issue. Specifically, we drop all output areas in the top quartile of the population density distribution. We then go on to consider different geographical definitions of the comparison group (based on distance buffers around the license zones) to determine control areas where the trend should closely resemble that in licensed areas.

Difference-in-Differences

We start with a diff-in-diff strategy where we use four different control group specifications. All four control groups are mapped in Figure 2, Panels A-D. Our first control group in Panel A is composed of areas that are proximate to the licensed areas but not within those areas. Specifically, we draw a 20km buffer around all licensed areas and restrict our estimations to the area that is licensed and the surrounding 20km.[5] The strategy should reduce potential effects from unobserved heterogeneity between license areas and the control group. One concern with this strategy is that areas that are licensed for shale gas development may affect bordering areas negatively—because e.g. increased truck traffic would spill over into neighboring communities—or positively if shale gas stimulates the local economy and creates new jobs (Freyer et al. 2015). To account for that, we consider a second specification where we use the area that was offered under the future 14th licensing round but we exclude all areas that overlap with the 20km buffer used in specification (1). Note that we restrict our observation period to mid-2014 when the 14th licensing round started. The corresponding area covered by this control group is mapped in Panel B.[6]

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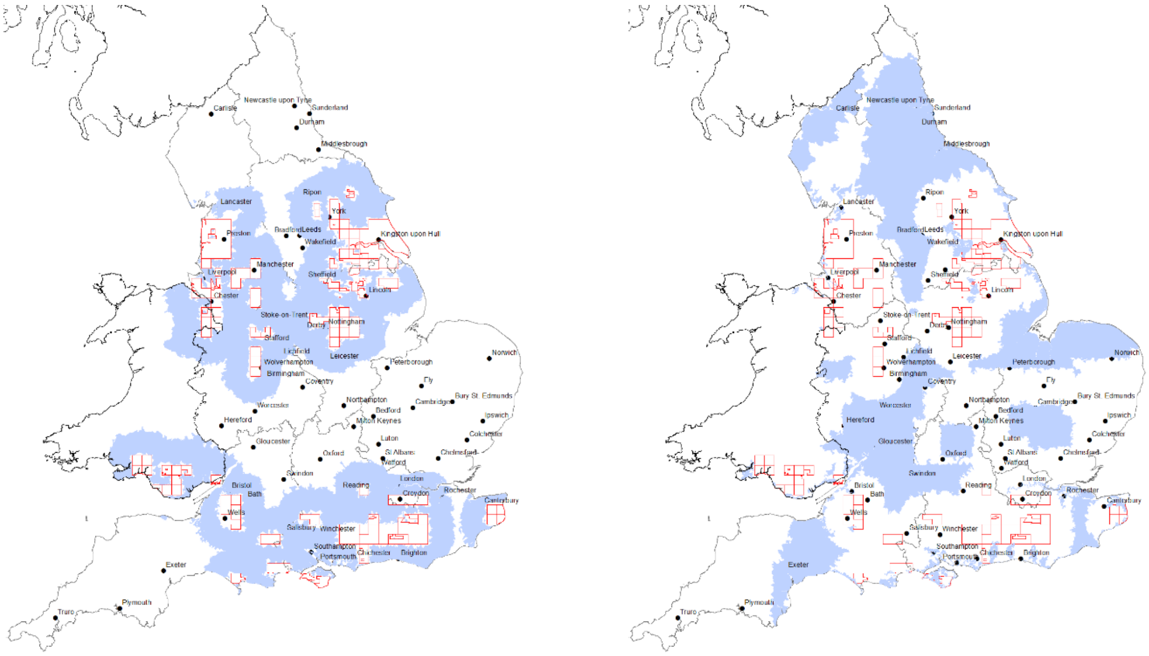
[5] Unreported specifications where we use a 10km buffer lead to very similar results.

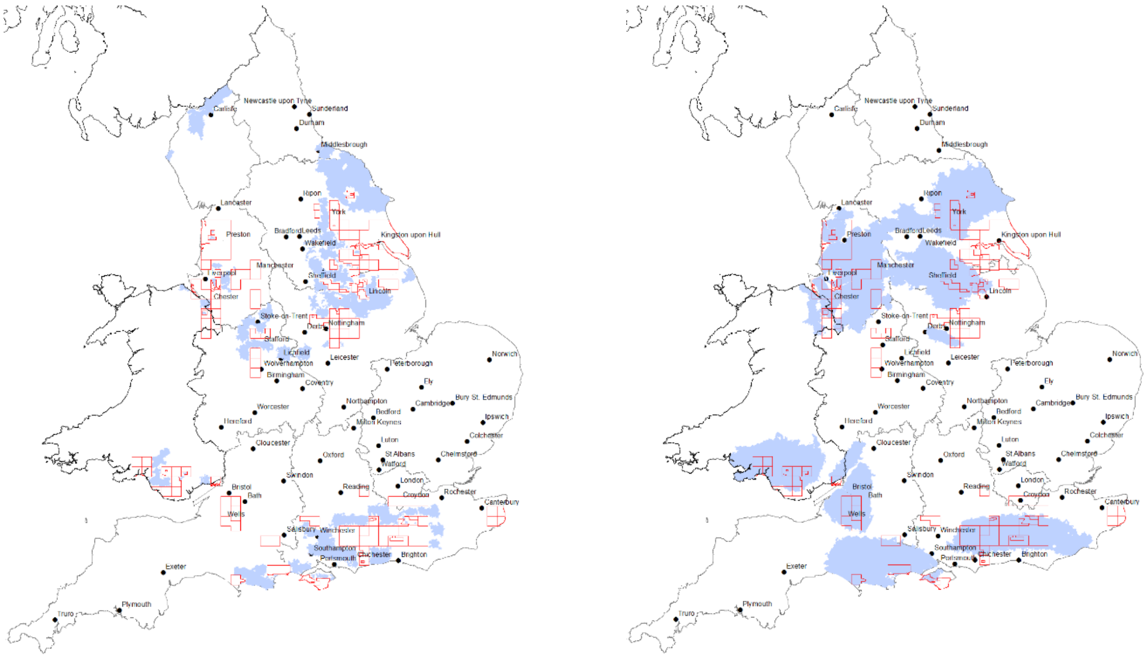
[6] In additional unreported specifications we considered smaller distance buffers. We find similar effects. The results are displayed in Appendix Table 1A.

Figure 2: Control Group Specifications

Panel A: 20km buffer *Panel B: Offered 14th Round w/o 20km Buffer*



Panel C: Pre-2008 and post-2008 licenses *Panel D: Geography*



Note: The Figure shows four different control group definitions. The red outlines indicate blocks that were licensed under the 13th round in 2008 and the blue shaded areas mark the respective output areas that comprise the control group.

Panel C presents a control group specification where we use all existing license areas. Prior to the advances in drilling technology that made hydraulic fracturing lucrative, licenses holders engaged in *conventional* oil and gas exploration. With the rise of hydraulic fracturing technologies, existing PED licenses could also be used for *unconventional* shale gas exploration. However, while a license grants exclusivity to the holder within the licensed area, it does not imply a right to drill a well. Initial seismic investigations can be undertaken but further steps towards exploration and exploitation require consent from the national authority *DECC* and an additional planning permission from the relevant *Mineral Planning Authority* (MPA). One can therefore think of the already licensed areas as regions where some consent for oil and gas development has been granted. Using them as control group therefore accounts for unobserved effects that are specific to areas that get licensed.

While PED licenses allow shale gas exploration (conditional on consent from the national and local authorities), exploration will only happen in areas with the right underlying geology. To account for that, we exploit the exogenous assignment of geology to create a fourth control group that allows us to compare licensed areas with an underlying geology that is promising for shale gas development to regions with a less promising geology (Panel D). Information on geological features that are promising for shale gas development stems from the British Geological Survey (BGS). This strategy accounts for unobserved license area effects and it also accounts for geological specificities. For instance, if the underlying shale rock implied better (or worse) natural amenities we would face a bias if these amenities were captured in house prices.

To implement our strategy, we exploit house transaction data for the period January 2005 to June 2014 and estimate the following baseline equation:

$$lnP_{it} = \alpha_i + \lambda_t + \rho License_i \times Post2008_t + X'_{it}\delta + \varepsilon_{it} \qquad (1)$$

The dependent variable is the log of the mean property transaction price observed in output area *i* in quarter *t*. Output areas are spatial units defined in the 2001 census that contain on average 10 postcodes at the 6 digit level with an average of 50 households. α_i indicates a vector of output area fixed effects. λ_t indicates a full set of $quarter \times year$ dummies that control for general time trends in house prices. In an alternative specification, we deflate house prices with an annual price index instead of using this flexible time trend. ρ is the coefficient of interest that will tell us how much the house price is affected by the licensing. The corresponding regressor is an interaction between two dummy variables. $License_i$ takes the value 1 if a house is located within an area that has been licensed for shale gas development under the 13th licensing round in 2008 and $Post2008_t$ takes the value 1 if a house was sold after the licensing round in February 2008 (i.e., after the first quarter of 2008). Consequently, the interaction is unity in the treatment locations that were licensed for shale gas development after 2008. Note that we do not include the components of the interaction term (i.e., $License_i$ and $Post2008_t$) in this flexible specification because they are already controlled for by the output area and time dummy variables. Our main coefficient of interest is therefore on the interaction term, which measures the average treatment effect on the treated (ATT) associated with shale gas licensing. X'_{it} is a matrix of covariates including sets of control variables for the proportion of sales of detached, semi-detached, and terraced houses or flat/maisonette.[7] Beyond that, we interact year with four elevation groups ($0 < e \leq 25m$; $25m < e \leq 50m$; $50m < e \leq 100m$; $e > 100m$) to capture terrain differences and interactions between year and the log of distance to the coast, distance to the next center with 1,000, 10,000, and 50,000 inhabitants. These controls along with the output area fixed effects, should capture unobserved geographic differences that simultaneously affect the (un)attractiveness of an area and the availability of shale gas. Across all specifications, standard errors are clustered on the output area level.[8]

In specification (1), ρ estimates the average treatment effect on the treated for the post-period from 2008-2014. However, as discussed in Section 2, two earthquakes occurred early in 2011which were subsequently attributed to Cuadrilla's shale gas exploration well *Preese Hall 1* near Blackpool. This seismic activity attracted substantial media attention and it took one year of investigations before the government lifted the ban from all exploration activities. This may have been bad publicity for shale gas developers and we allow this potential negative effect to be captured separately. To assess this additional event, we estimate the following extended equation:

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[7] We will present additional specifications were we use property transaction data from Nationwide which allow us to control for further house attributes.

[8] Alternative specifications where we allow for common shocks within larger spatial units do not change our results.

$$lnP_{it} = \alpha_i + \lambda_t + \sum_k \rho_k License_i \times Post_t^k + X'_{it}\delta + \varepsilon_{it} \quad (2)$$

Where k distinguishes the two events—licensing and earthquake—such that $Post_t^k$ takes the value 1 starting in the quarter after the event (i.e., from the 2nd quarter of 2008 and the 3rd quarter of 2011 on). The interaction of $Post_t^k$ with $License_i$ then gives us the event specific interaction that is unity if we observe a house transaction in a licensing area in the respective period k. The coefficient ρ_k quantifies the average house price effect after the respective event. Those coefficients should be interpreted as cumulative effects. We consider the same controls as in specification (1) and cluster our standard errors on the level of output areas. Main effects are covered by the output area fixed effects and time dummies.

One last concern is that Petroleum Exploration and Development Licenses (PEDL) are not limited to unconventional shale gas exploration. They also cover conventional exploration methods. Conventional gas exploration methods have been used for almost 50 years and are less likely to be of concern in terms of the potential for groundwater contamination, air pollution, and other local disamenities. As a result, combined estimations that consider licenses for conventional and unconventional exploration jointly may be downward biased. To account for that, we exploit additional information provided by DECC on the type of exploration project to identify a separate effect for areas which are licensed for shale gas exploration. We estimate the following triple-difference equation:

$$lnP_{it} = \alpha_i + \lambda_t + \sum_k \rho_k License_i \times Post_t^k + \sum_k \gamma_k ShaleGasLicense_i \times Post_t^k + \sum_k \theta_k License_i \times Post_t^k \times ShaleGasLicense_i + X'_{it}\delta + \varepsilon_{it}$$

(3)

Since $ShaleGasLicense \subseteq License, \gamma_k = \theta_k$ and the equation simplifies to:

$$lnP_{it} = \alpha_i + \lambda_t + \sum_k \rho_k License_i \times Post_t^k + \sum_k \gamma_k ShaleGasLicense_i \times Post_t^k + X'_{it}\delta + \varepsilon_{it}$$

(4)

Where γ_k now denotes the coefficients of interest. These coefficients measure whether areas with the higher likelihood of experiencing shale gas exploration experienced stronger house price effects than other licensing areas where conventional exploration projects took place. Note that this specification controls for differences in house price trends between areas that were licensed for exploration (either conventional or shale gas) and control areas and the non-exploration control areas. For instance, licensing areas may be environmentally less attractive and thus follow a different house price trend. Or areas that receive licenses may be economically less vibrant and seek gas exploration and development since it may create jobs or generate municipal income.

Following the same logic, we can exploit the fact that license areas where the earthquake happened are a subset of the shale gas licensed regions ($Earthquake \subseteq ShaleGasLicense$). To identify a markup in those license areas where the earthquake happened, we can simply add another interaction term $\sum_k \theta_k Earthquake_i \times Post_t^k$ to Equation 4 where θ_k now measures a potential difference in the house prices effects in those license areas that experienced the earthquake.

4 Data

Housing transaction data were taken from the “Land Registry Price Paid Data” provided by the UK government for England and Wales. The data go back to 1995, but we restricted the data to the period between the first quarter of 2004 and the second quarter of 2014 for the purpose of this research. We further drop all observations that are the top and bottom 1% of the transaction prices. The data include information on the sales price, four property types – detached, semi-detached, terraced or flat/maisonette – whether the property is new, and whether it is sold on freehold or leasehold basis. Housing transactions are mapped into 2001 census output areas and aggregated to mean output area-by-quarter cells. This leaves us with a panel of quarterly sales at the level of 175,434 output areas. The panel is unbalanced because we do not observe sales for every output area in every quarter. Table 1 provides descriptive statistics of our data separated by license area, period, and the respective control groups.

We supplement the land registry data with property sales data from the Nationwide building society, which covers about 15 percent of the transactions reported in the land registry database. These data allow us to consider additional house characteristics including floor area, the number of bathrooms and bedrooms, housing tenure and whether the house comes with a garage or not. We do not aggregate these data but use them on the individual house level to make better use of the house characteristics.

Further controls for socio-economic characteristics at the output area level are taken from the 2001 Census. Since our specifications all include output-area fixed effects, time invariant output area characteristics do not play a role. To account for potentially time varying effects, we present robustness checks where we interact additional characteristics with flexible time trends.

Information on the areas licensed under the 13th and 14th licensing round are published by the UK Oil and Gas Authority. These data include detailed information on the licensing blocks, the proposed exploration, and the companies that hold licenses. The data further include information from the British Geological Survey on areas whose geology renders them promising for shale gas development. We use these data to determine whether output areas are within the licensed area and whether the license covers shale gas development.

Lastly, we calculate a number of geographic control variables to account for the geographic location of an output area. These involve four elevation categories ($0 < e \leq 25m;\ 25m < e \leq 50m;\ 50m < e \leq 100m;\ e > 100m$) to capture terrain differences and interactions between year and the log of distance to the coast, distance to the next center with 1,000, 10,000, and 50,000 inhabitants.

5 Results

5.1. Baseline

Table 2a and 2b present our baseline specifications for the four control group definitions described above. Panel A uses as control group a 20km buffer around the area licensed under the 13th licensing round. The control group in Panel B is the area under consideration for the 14th licensing round minus of the 20km buffer in Panel B. In Panel C, we present specifications with areas that were licensed under previous rounds as control group. Finally, in Panel D, we use information on the underlying geology to distinguish between areas where shale gas development is more or less likely to happen.

We exclude in all specifications output areas in the top quartile of the population density distribution because these concentrated areas are likely inner-city areas where shale gas development is unlikely to happen at any time. All of our regressions further include a full set of quarter-by-year dummies, output area fixed effects, basic house controls (share of four property types, share of new properties and the share of properties sold as freehold) and geographic control variables interacted with year dummies to account for the geographic location of an output area (four elevation categories, log of distance to the coast, and distance to the next center with 1,000, 10,000, and 50,000 inhabitants). Our baseline specification is a simple diff-in-diff where the coefficient of interest tells us whether licensed areas experienced a house price drop in the post period from the second quarter of 2008 till the second quarter of 2015. The estimated coefficient in Columns 1 is small and ranges between a positive effect of 1.8 and a negative effect of 1.4 percent across Panels A-D.

In column 2, we add region trends calculated as interaction between indicators for ten broad regions and year dummies.[9] Doing so gives us a more uniform picture across all four panels. We find negligible house price effects between 0.1 and 0.5 percent. In column 3, we split the "after" period up and allow for a different effect in licensed areas after hydraulically fracturing the first well in the UK resulted in two earthquakes. There is no strong evidence that the licensed areas experienced a drop in house prices after 2011. The cumulative effect for the period after 2011 ranges between -0.1 and 1.2 percent. If anything, this suggests a small increase in house prices in the license areas, suggesting that licensing itself does not seem to have a direct house price effect.

In column 4, we split the licensed areas and introduce an indicator variable that takes the value 1 if shale gas development was mentioned in the 2008 license application. Once we separate the shale gas exploration effects in these DDD specifications, we observe more pronounced results. The estimates in column 4 now suggest a small and sometimes insignificant house price effect in license areas of 0.7 percent or below while shale gas areas (i.e. areas where shale gas development was mentioned in the license) face significant house price drops between -0.9 and -1.5 percent.

In column 5, we test whether the shale gas exploration effect was a reaction to the licensing or a reaction to the earthquake. For this purpose, we interact indicators for the time after the licensing

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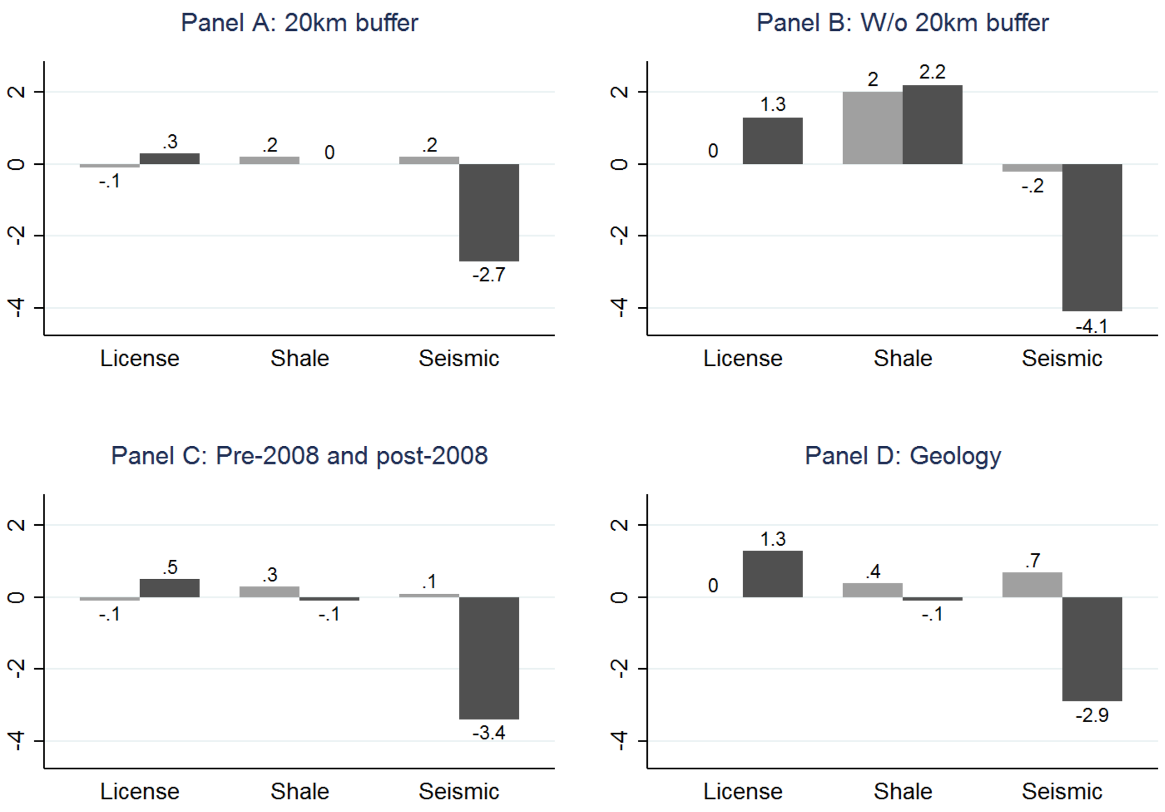
[9] The regions are North East, Yorkshire and the Humber, North West, East Midlands, West Midlands, East Anglia, South East, South West, Wales, London.

in 2008 and the time after the earthquake in 2011 with indicators for licenses where shale gas was mentioned in the application (see equation 4). Doing so shows that the effect is predominantly driven by the time after the seismic incidences in 2011 and it is restricted to those areas where shale gas development was explicitly mentioned in the license application. We find no indication of a negative effect of licensing per se in our four specifications. Negative effects seem to be driven by those areas with a license that mentioned unconventional shale gas exploration as planned development.

For a better understanding of the drivers underlying the house price effects in shale gas areas, we focus in columns 6 and 7 on those license areas where the first hydraulic fracturing attempt caused two earthquakes in 2011. For this purpose, we include an additional interaction between an indicator for license areas where the earthquake happened and a time indicator for either post-2008 or post-2011 in our estimation equations. We show results for interactions with the post-2008 dummy and interactions with both, the post-2008 (column 6) and the post-2011 dummy (column 7). The results are clear. We continue to find small and positive effects in the license areas and no effect for areas where shale gas was mentioned in the license, neither after the licenses were issued nor after the earthquakes in 2011. The results are entirely driven by a substantial negative house price effect in the earthquake region after the earthquake happened. The cumulative effect ranges between -2.7 and -4.1 percent. For the post-2008 period, we find no effect in Panels A, C and D and a negative effect of -2.4 in Panel B.

For ease of interpretation, we summarize the cumulative effects from the full specification in Column 7 for the four control group specifications and the post-2008 (light bars) and post-2011 (dark bars) period in Figure 3. The figures illustrates the pronounced earthquake effect after 2011 while there is no evidence for negative effects in licensed areas or shale areas. Unlike the other Panels, Panel B suggests a positive house price effect of about 2 percent in the shale gas areas, pointing to some difference between our control region specifications. However, this does not affect our conclusions that seismic activity was the main driver of the sharp drop in house prices after 2011.

Figure 3: Cumulative Effects



Note: The Figure shows cumulative effects for the coefficients in Table 2a/b, Column 7. Light grey bars refer to interactions with an after-2008 dummy and dark grey bars to interactions with the after-2011 dummy. The three areas are licensed areas, licensed areas where shale gas development was mentioned, and finally the one region where fracking caused two earthquakes (seismic).

Overall, these results suggest that shale gas exploration was only perceived as a disamenity as a result of the earthquake, and in the areas where the earthquake took place. Another interpretation is that the earthquake raised people's awareness of shale gas exploration and the potential risks—but only in proximity to the location where the incident happened.[10]

5.2. Robustness

We will now consider a number of additional specifications to probe the robustness of our preferred findings. The results are displayed in Table 3. In Column 1, we deflate the house prices

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[10] In Section 6, we will analyse the earthquake effect more closely when we estimate distance decay specifications.

with a price index for the ten regions used to calculate region trends with 2008 as base year. In Column 2, we include socio-demographic characteristics from the 2001 census interacted with linear time trends to allow for some time-variant differences between output areas that are not captured by the output area fixed effects, the limited number of time-variant house characteristics or the region trends. Specifically, we include controls for the proportion of individuals without basic high school qualifications, the proportion of highly qualified individuals with a university degree, the proportion of individuals born in UK, the proportion of individuals of white ethnicity, the proportion of employed individuals, and the proportion of individuals who live in social housing.

Next, we allow for a linear and a 4th-order polynomial output area trends to capture unobserved output area characteristics. The inclusion of these controls increases our estimated effects slightly. We still find small and often insignificant effects for license areas and license areas where shale gas development was mentioned while the post-earthquake effects on house prices in the earthquake region now ranges between -3 and -5.4 percent. We may thus think of our baseline effects as conservative lower bound.

Finally, we consider an alternative clustering level for our standard errors and use wards instead of output areas. Wards include on average 73 output areas. This more conservative clustering on a higher level of aggregation does not seem to affect our outcomes. In fact, this is the case for most of our robustness tests, which confirm the results described in Tables 2a and 2b.

5.3. Nationwide data

So far, our regressions have relied on data from the Land Registry database. This is the most comprehensive dataset on property transactions available but it comes with a fairly limited number of house-level control variables. To assess whether unobserved property characteristics bias our estimates, we now turn to specifications using a second dataset on property transactions from the building society Nationwide. This dataset covers about 15 percent of all transactions reported in the register data; in particular, 13.5 for specification (1) and 14.6 of specification (2). We introduce this additional dataset because it comes with more detailed house characteristics including floor space and number of bedrooms. This helps us assess whether these characteristics act as omitted variables that may bias our estimations.

The results where we use these data are displayed in Table 4. Using this dataset, we find somewhat smaller coefficients that match the pattern from Table 2 very well. We find a cumulative negative effect that ranges between -1.5 and -3.5 percent in those license areas that experienced the earthquake.

5.4. Balancing Tests

This section explores which other observable house characteristics in an output area changed around the time that our treatment areas were licensed in 2008.[11] This should give us some idea about potentially biasing effects from unobserved characteristics across output areas. Table 5, Column 5 presents the results of regressions using different house characteristics as outcomes. Note that we do not control for house characteristics in this specification. Since the land registry data come with a limited number of house characteristics, we supplement our balancing tests with Nationwide data.

Looking at the diff-in-diff and triple-difference coefficients, we see mostly insignificant and economically irrelevant effects that are zero. Our main concern would be that the observed price change is being driven by the sale of lower quality houses rather than by the expectation of shale gas development. We find no indication for such a bias. We only find some indication of a larger number of sales in the register data and for some differences in the house size in the Nationwide data.

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[11] In unreported specifications, we include post-2008 and post-2011 interactions. As in the post-2008 interactions, we cannot see any differences in the observable characteristics (apart form the number of sales), the estimated effects are all zero.

6 Extensions

6.1 Distance Decay Effects around *Preese Hall 1* Well

To understand the extent of the observed effect around the *Preese Hall 1* site where the earthquake happened, we now turn to a set of distance decay models. Figure 4 shows distance rings set to 10, 20, 30, 40, 50, 75, 100km from the well that induced the earthquake. We can see that a maximum distance of 100km includes the Bowland Basin in the north-west (grey shaded area) which, according to a 2013 study by the British Geological Survey (Andrews, 2013), holds significant shale gas resources. Their gas-in-place assessment suggests 37.6 trillion cubic meters (tcm) and potentially recoverable resources of 1,800-13,000 billion cubic meters (bcm) at a recovery factor of 8-20% which is common for the U.S. To put this into perspective: DECC suggest an annual UK gas consumption of 70 bcm for 2014 (DECC, 2015b). The importance of the Bowland Basin for UK shale gas development is further underlined by the fact that it is the only area where shale gas exploration wells have been drilled by 2015. Our distance decay estimations seek to explore the extent to which the 2011 seismic activities spread fear of fracking in this designated area.

Figure 4: Distance Rings around *Preese Hall 1*

Note: The figure shows Preese Hall well (red triangle) and 7 distance rings around it. The rings are at 10, 20, 30, 40, 50, 75, and 100km from the well. The red blocks indicate areas licensed under the 13th licensing round in 2008 and the grey areas indicate a geology that is promising for shale gas.

To estimate the distance decay effect, we modify our estimation equation slightly and estimate the change in the house price trend after the earthquake incidence in 2011. In a first specification, we estimate:

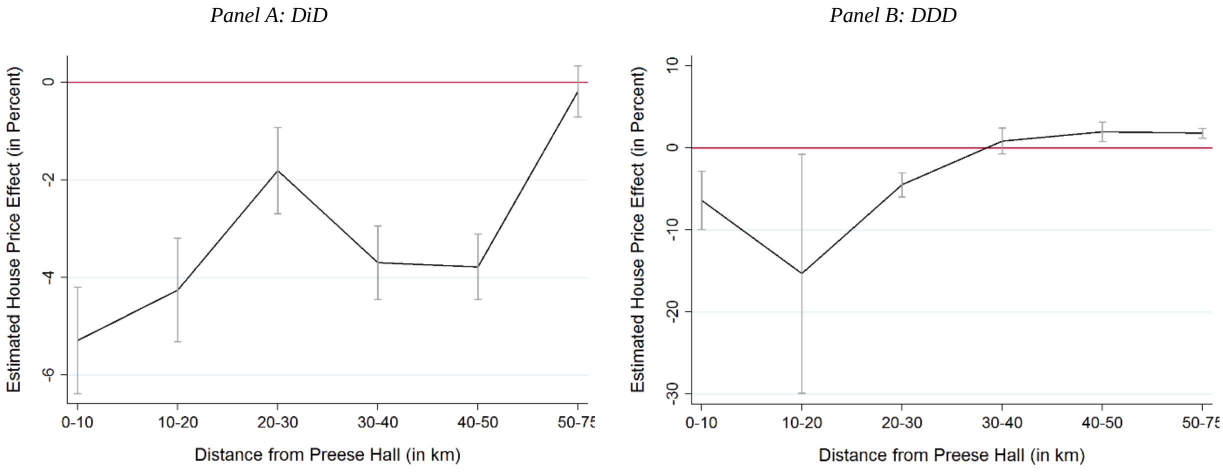
$$lnP_{it} = \alpha_i + \lambda_t + \sum\nolimits_r \delta_r Dist_i^r \times Post_{t=2011} + X'_{it}\delta + \varepsilon_{it} \qquad (5)$$

For distance rings $r \in \{[0,10), [10,20), [20,30), [30,40), [40,50), [50,75)\}$. The $[75,100)$ km ring is the reference group. In this estimation, δ_r will tell us the effect of the earthquake shock on house prices in the six different distance rings thus revealing any distance decay patterns. In a second step, we extend this estimation equation and allow within distance rings for differential effects between licensed and non-licensed areas. Specifically, we estimate:

$$\begin{aligned} lnP_{it} = \alpha_i + \lambda_t + \sum_r \delta_r Dist_i^r \times Post_{t=2011} + \\ \sum\nolimits_r \varphi_r License_i \times Dist_i^r \times Post_{t=2011} + X'_{it}\delta + \varepsilon_{it} \ (6) \end{aligned}$$

Where φ_r will now tell us whether licensed areas within a given distance ring were affected differently than non-licensed areas. We condition our regressions on the same sets of controls as before.

Figure 5: Distance Decay Estimations



Panel A: DiD

Panel B: DDD

Note: The figure shows the estimated coefficients δ_r from equation 5 (Panel A) and φ_r from equation 67 (Panel B) enclosed by 90%-confidence intervals. The omitted category is the bin (75,100].

To facilitate interpretation, we present the results of our distance decay regressions in a graph. Panel A of Figure 5 shows results for a distance decay specification where we measure changes in house price effects following the 2011 seismic incidences relative to a pre-period form 2008-2011 in the distance rings described above. All estimates are reported with 90%-confidence intervals. We see negative house price effects up to the (40,50] bin. However, it is not clear whether this effect is driven by the earthquake or a spurious trend. To identify how the earthquake spread a fear of fracking, we estimate a second specification where we control for changes within a given distance ring after the earthquake and then look for an on-top effect of licensed areas within this distance ring. Doing so shows a similar pattern but suggests effects that only reach out to the (20,30] bin. After that distance, we cannot disentangle license area specific house trends from a generally negative house price trend in these areas. Note that the large confidence interval for the (10,20] bin is likely the result of a very small number of observations which are not licensed, thus making the estimations more susceptible to outliers.

6.2 Event Study Estimation

One assumption underlying our DiD estimations is that the different control groups will describe how the treated regions would have developed in the absence of licensing. To shed more light on the price trends before and after the beginning of our treatment period, we present an event study with 2008 as base year and interactions between the different license area definitions in the pre-period (2004-2007) and the post-period (2009-2015). Note that we extend the time period to the end of 2015 in this exercise. Doing so will tell us whether house price trends were affected by the 14th licensing round that started in 2014 or by the introduction of the Community Charter that promised payments to communities that allow fracking.

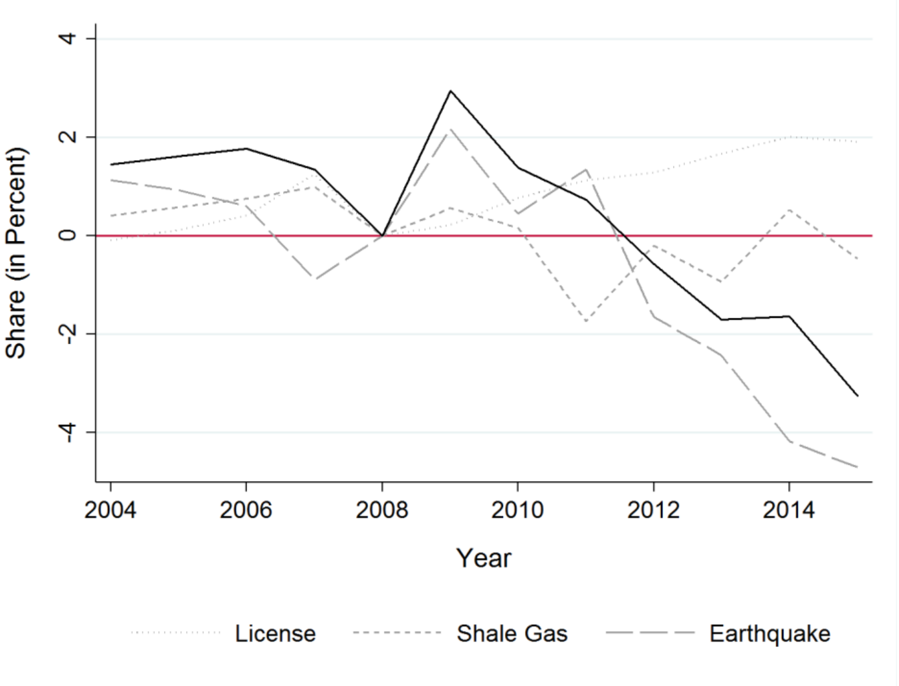
The estimation equation for these dynamic effects is a modification of equation 4. Instead of interacting the license, shale gas and earthquake dummies with post-2008 and post-2011 dummies, we now interact them with year-indicators, $D_t^y, y \in \{2004, \ldots 2015\}$, in the pre and post period:

$$lnP_{it} = \alpha_i + \lambda_t + \sum_y \rho_y License_i \times D_t^y + \sum_y \gamma_y ShaleGasLicense_i \times D_t^y +$$

$$\sum_y \vartheta_y Earthquake_i \times D_t^y + X'_{it}\delta + \varepsilon_{it} \quad (7)$$

We present the result of the event study for specification 4 where we restrict our sample to output areas on promising shale geology. Graphs for the other three sample specifications look very similar. In Figure 6, the dashed and dotted lines describe house price trends as measured by the event time indicators ρ_y, γ_y, and δ_y. Since $Earthquake \subseteq ShaleGasLicense \subseteq License$, the effects are again cumulative. To facilitate reading, the solid black line shows the cumulative effect for the earthquake regions over time.

Figure 6: Event Study



Note: The figure shows estimates of the event time indicators ρ_y, γ_y, and δ_y in grey and the cumulative effect black..

The graph holds several messages. First, we see not much happening in the license and shale gas group over time (the table with detailed coefficients and standard errors is available from the authors upon request). By contrast, the earthquake group region experienced a significant drop in house prices after the seismic activity in 2011. Importantly, this effect is persistent for the entire period between 2011 and 2015, suggesting that fear of fracking is not a temporary phenomenon.

Second, we do not see an indication that announcing the community charter changed the house price trend. One explanation why we observe no effect is that there have not been any exploration activities going on since 2013. Consequently, there were no payments to communities that could have been perceived as benefits of shale gas development. An alternative explanation is that the scheme is not publicly known, not formally guaranteed, or not generous enough. The latter case would point to the need to communicate and institutionalize the community engagement charter and it would also require a better understanding of the costs of cumulative costs of shale gas development that have to be compensated by corresponding payments to local communities. This paper's goal is to provide a first estimate of the social costs.

7 Discussion and Conclusion

We measure the consequences of the 13th round of onshore oil and gas licensing on property values across different control groups. By carefully defining control groups, our estimates account for a number of fixed and time-varying factors that could possibly confound the effect of nearby licensing. In particular, we utilize a difference-in-differences identification strategy to quantify the change in housing prices attributable to the issuance of licenses in 2008 and the subsequent earthquake in 2011. We find similar effects when we use information on the underlying geology as an instrument and when using a matching strategy to cut out the time dimension in our comparison. Our estimations suggest that on average, areas that were licensed for conventional and unconventional oil and gas exploration did not experience any house price effects. Only those areas where hydraulic fracturing caused seismic activity suffer from a house price drop of up to 4.1 percent.

A long line of theoretical literature on 'hedonic' models and empirical applications has shown that these price effects can be interpreted as home-buyers' 'marginal willingness to pay' to avoid (or marginal willingness to accept) exposure to shale gas development in the vicinity of their homes.

This interpretation requires some quite strong assumptions and approximations, but if applied in our case implies that an average household would be willing to pay between £4,866 and £7,388 per year, depending on the specification in Table 2a/b, Column 7, to avoid areas where fracking induced seismic activity.[12] If we multiply these average individual losses with the total number of transactions (22,821) in the period after the earthquake, i.e. between the third quarter of 2011 and the second quarter of 2014, we arrive at a cumulative house price loss that ranges between £111-169 million (in 2008-prices).[13] We can think of this number as a lower bound because fear of fracking does not just affect houses that are being sold. It also devalues houses that are not being sold and it may even devalue land without houses. To get an idea of the upper bound of the costs, we multiply the number of households in the earthquake area (145,018 in 2011) by the average loss in house value. This gives us a cumulative loss that ranges between £706 million and £1.1 billion. These numbers are restricted to the license blocks where the earthquake happened. Our distance decay specifications suggest that this effect likely reaches out beyond this area. Moreover, we see that the effect is not a short-term reaction. If anything, it strengthens over time. This implies that the costs may even exceed this upper bound.

These numbers are clearly substantial, even more so since the effects of actual shale gas exploration have not yet been experienced and the results were solely a reaction founded on house owners fears. The implication is that there are ‘psychic costs’ associated with fracking, which may need to be compensated even when there is no actual damage on which to base a claim. As the United Kingdom is on the verge of initiating further shale gas exploration projects, it is important to consider this evidence of impacts on homeowner valuations in the public policy debate. These estimated costs could be offset to some extent, at the community level, by payments made through the Community Engagement Charter (UKOOG, 2013), but exactly how these payments would be

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[12] Rosen (1974) provides the seminal theoretical analysis. The challenges to recovering information on underlying consumer preferences from empirical analysis are discussed in Brown and Rosen (1982), Mendelsohn (1985), Bartik (1987), Epple (1987), Ekeland et al. (2004), Bajari and Benkard (2005), Heckman et al. (2010), Bishop and Timmins (2012) and Yinger (2015). Other empirical applications include, to name just a few: valuations of air quality (Chay and Greenstone 2005; Bajari et al. 2012; Bui and Mayer 2003; Harrison Jr and Rubinfeld 1978; Ridker and Henning 1967), water quality (Walsh et al. 2011; Poor et al. 2007; Leggett and Bockstael 2000), school quality (Black 1999, Gibbons, Machin and Silva 2013), crime (Gibbons 2004, Linden and Rockoff 2008; Pope 2008b), airport noise (Andersson et al. 2010; Pope 2008a) and wind turbines (Gibbons 2015).

[13] The deflated house price (in 2008 £) in the pre-period in earthquake areas is £180,204.2 which is multiplied by the estimated coefficients (between -2.7% and -4.1%).

distributed is unknown at this time. However, our estimates suggest that the size of the appropriate compensatory payments is well in excess of the level of payments set in the existing Community Engagement Charter which offers payments of £100,000 to communities where exploration takes place and the additional (voluntary) industry commitment to pay £20,000 for every unique horizontal well.

At the moment, at the beginning of 2016, a total of 159 blocks were formally offered to successful applicants under the 14th Onshore Oil and Gas Licensing Round. Given the vibrant debate about the size of local disamenities associated with expected drilling activities, estimates like ours are important to inform the policy debate. In the light of the above findings, we conclude that the existing voluntary payments are likely too low to compensate house owners. Further, it seems more appropriate to target them to areas where wells have actually been fracked or where seismic activity has occurred instead of compensating all exploration areas. A final concern relates to the legal force of the voluntary compensation schemes paid to communities. Since these payments are not legally binding and it is not clear how benefits will be distributed, house owners may value these payments less than individual compensation payments. Formal regulation to guarantee payments to individual house owners or for specific community projects could help overcome this problem.

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Table 1: Descriptive Statistics, 2001-2015 England and Wales

	Treatment						Control							
	License 2008		Shalegas		Earthquake		Sample A		Sample B		Sample C		Sample D	
	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.
Panel A: 2005-2014														
Log price	12.07	0.56	12.07	0.53	11.91	0.46	12.10	0.55	11.99	0.52	12.06	0.57	11.93	0.56
New built	0.03	0.15	0.03	0.14	0.03	0.14	0.03	0.15	0.03	0.16	0.04	0.16	0.03	0.15
Detached house	0.28	0.41	0.29	0.41	0.25	0.39	0.27	0.40	0.29	0.40	0.32	0.42	0.27	0.40
Semi-detached house	0.12	0.30	0.12	0.29	0.10	0.27	0.13	0.31	0.09	0.25	0.10	0.27	0.08	0.24
Terraced house	0.36	0.43	0.40	0.44	0.45	0.44	0.34	0.42	0.34	0.42	0.35	0.42	0.36	0.43
Flat/Maisonette	0.24	0.38	0.19	0.35	0.20	0.36	0.26	0.39	0.28	0.40	0.23	0.37	0.29	0.41
Freehold	0.81	0.36	0.77	0.38	0.75	0.40	0.81	0.36	0.87	0.30	0.87	0.30	0.79	0.38
Number of sales	2.06	2.63	2.04	2.27	2.00	2.30	2.08	2.56	2.09	2.60	2.05	2.13	2.02	2.27
Panel B: 2005-2008														
Log price	12.05	0.54	12.06	0.51	11.92	0.45	12.07	0.53	11.97	0.51	12.04	0.56	11.91	0.54
New built	0.04	0.16	0.03	0.15	0.03	0.15	0.04	0.16	0.04	0.16	0.04	0.17	0.04	0.16
Detached house	0.27	0.39	0.28	0.39	0.24	0.38	0.25	0.38	0.27	0.39	0.31	0.41	0.26	0.39
Semi-detached house	0.12	0.29	0.12	0.28	0.10	0.27	0.13	0.30	0.09	0.25	0.10	0.26	0.08	0.23
Terraced house	0.36	0.42	0.40	0.42	0.44	0.43	0.35	0.41	0.34	0.41	0.36	0.41	0.37	0.42
Flat/Maisonette	0.25	0.38	0.21	0.35	0.21	0.36	0.27	0.38	0.29	0.39	0.24	0.37	0.30	0.40
Freehold	0.81	0.36	0.77	0.38	0.75	0.39	0.80	0.36	0.87	0.30	0.87	0.29	0.78	0.38
Number of sales	2.38	3.30	2.35	2.82	2.32	2.86	2.38	3.14	2.41	3.23	2.34	2.62	2.33	2.82
Panel C: 2008-2011														
Log price	12.08	0.56	12.07	0.53	11.91	0.46	12.11	0.56	12.00	0.53	12.08	0.58	11.95	0.56
New built	0.04	0.17	0.03	0.15	0.03	0.14	0.04	0.17	0.04	0.18	0.04	0.18	0.04	0.17
Detached house	0.29	0.42	0.29	0.42	0.26	0.40	0.28	0.41	0.30	0.42	0.33	0.43	0.28	0.41
Semi-detached house	0.12	0.30	0.12	0.30	0.10	0.29	0.13	0.31	0.09	0.26	0.10	0.27	0.08	0.25
Terraced house	0.36	0.44	0.40	0.45	0.45	0.46	0.34	0.43	0.35	0.43	0.35	0.43	0.36	0.44
Flat/Maisonette	0.23	0.39	0.18	0.35	0.18	0.36	0.25	0.40	0.27	0.40	0.22	0.38	0.28	0.41
Freehold	0.81	0.37	0.77	0.39	0.75	0.41	0.81	0.37	0.88	0.30	0.87	0.31	0.79	0.38
Number of sales	1.76	1.97	1.72	1.65	1.67	1.71	1.78	2.10	1.78	1.94	1.77	1.63	1.72	1.64
Panel D: 2011-2014														
Log price	12.10	0.59	12.07	0.55	11.88	0.46	12.13	0.58	12.01	0.54	12.09	0.60	11.95	0.58
New built	0.02	0.11	0.02	0.11	0.01	0.10	0.02	0.12	0.02	0.12	0.02	0.12	0.02	0.12
Detached house	0.30	0.42	0.30	0.42	0.27	0.41	0.28	0.41	0.30	0.42	0.34	0.43	0.29	0.41
Semi-detached house	0.12	0.30	0.12	0.29	0.10	0.28	0.13	0.31	0.09	0.25	0.10	0.27	0.08	0.24
Terraced house	0.35	0.43	0.40	0.45	0.45	0.46	0.34	0.43	0.34	0.43	0.34	0.43	0.36	0.44
Flat/Maisonette	0.23	0.39	0.18	0.35	0.18	0.36	0.25	0.40	0.28	0.41	0.22	0.38	0.28	0.41
Freehold	0.81	0.36	0.78	0.39	0.76	0.40	0.81	0.36	0.88	0.30	0.88	0.30	0.79	0.38
Number of sales	1.76	1.32	1.75	1.29	1.67	1.18	1.77	1.39	1.77	1.43	1.77	1.29	1.71	1.30

Notes: *Among the control groups, Sample (A) uses all output areas within a buffer of 20km around the licensed areas as control group; Sample (B) uses the 14th licensing round areas but exclude the 20km buffer around the licensing area; Sample (D) uses pre-2008 and post-2008 areas under a Petroleum Exploration and Development License (PEDL) as control group; Sample (C) restricts the sample to all output areas which the British Geological Survey classifies as promising for shale gas development. Output areas in the top quartile of the population density distribution are excluded from all specifications. The time horizon is 2001-2015.*

Table 2a: Baseline Estimations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: 20km Buffer							
After 2008 * License Area	-0.014***	-0.000	-0.001	0.001	-0.001	0.001	-0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
After 2011 * License Area			0.002		0.004***		0.004***
			(0.001)		(0.001)		(0.001)
After 2008 * License Area*Shale				-0.010***	0.001	-0.001	-0.001
				(0.002)	(0.003)	(0.004)	(0.005)
After 2011 * License Area*Shale					-0.022***		-0.002
					(0.003)		(0.006)
After 2008 * License Area*Earthquake						-0.012**	0.002
						(0.005)	(0.006)
After 2011 * License Area*Earthquake							-0.029***
							(0.007)
Observations	2,001,301	2,001,301	2,001,301	2,001,301	2,001,301	2,001,301	2,001,301
R-squared	0.353	0.365	0.365	0.365	0.365	0.365	0.365
Panel B: Offered 14th Licensing Round without 20km Buffer							
After 2008 * License Area	0.018***	0.005***	-0.000	0.007***	0.000	0.006***	-0.000
	(0.001)	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)	(0.002)
After 2011 * License Area			0.012***		0.014***		0.013***
			(0.002)		(0.002)		(0.002)
After 2008 * License Area*Shale				-0.022***	-0.010***	0.007	0.007
				(0.003)	(0.003)	(0.005)	(0.005)
After 2011 * License Area*Shale					-0.025***		0.002
					(0.003)		(0.006)
After 2008 * License Area*Earthquake						-0.042***	-0.024***
						(0.006)	(0.006)
After 2011 * License Area*Earthquake							-0.039***
							(0.007)
Observations	1,168,445	1,168,445	1,168,445	1,168,445	1,168,445	1,168,445	1,168,445
R-squared	0.339	0.347	0.347	0.347	0.347	0.347	0.347
Year-Quarter-FE	Y	Y	Y	Y	Y	Y	Y
House Controls	Y	Y	Y	Y	Y	Y	Y
Geo Controls	Y	Y	Y	Y	Y	Y	Y
Region Trends	N	Y	Y	Y	Y	Y	Y

*Notes: The table reports results from fixed effects regressions of log price on an interaction between an indicator for time which either indicates the post-license period (after 2008) or the post-earthquake period (after 2011) and an indicator for (i) licensed areas, (ii) areas licensed for shale gas exploration, or (iii) areas licensed for shale gas exploration where the earthquake happened. All regressions are conditional on quarter-by-year fixed effects, house controls, geo-by-year controls and, with the exception of Column 1, region-by-year controls. Panel A uses all output areas within a buffer of 20km around the licensed areas as control group. Panel B uses the 14th licensing round areas but exclude the 20km buffer around the licensing area. Output areas in the top quartile of the population density distribution are excluded from all specifications. The time horizon is 2001-2015. Standard errors are clustered on the output area level. *** p<0.01, ** p<0.05, * p<0.10*

Table 2b: Baseline Estimations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel C: Pre-2008 and Post-2008 Licensed Areas							
After 2008 * License Area	-0.004**	0.001	-0.001	0.002	-0.001	0.002	-0.001
	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
After 2011 * License Area			0.003		0.006***		0.006***
			(0.002)		(0.002)		(0.002)
After 2008 * License Area*Shale				-0.014***	-0.001	-0.005	-0.002
				(0.003)	(0.003)	(0.005)	(0.005)
After 2011 * License Area*Shale					-0.028***		-0.004
					(0.003)		(0.006)
After 2008 * License Area*Earthquake						-0.014***	0.002
						(0.005)	(0.006)
After 2011 * License Area*Earthquake							-0.035***
							(0.007)
Observations	751,001	751,001	751,001	751,001	751,001	751,001	751,001
R-squared	0.352	0.363	0.363	0.363	0.363	0.363	0.363
Panel D: Geology							
After 2008 * License Area	0.010***	0.003**	-0.001	0.006***	-0.000	0.006***	-0.000
	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
After 2011 * License Area			0.008***		0.013***		0.013***
			(0.002)		(0.002)		(0.002)
After 2008 * License Area*Shale				-0.017***	-0.003	-0.011**	-0.009
				(0.003)	(0.003)	(0.005)	(0.006)
After 2011 * License Area*Shale					-0.030***		-0.005
					(0 .004)		(0.006)
After 2008 * License Area*Earthquake						-0.009	0.008
						(0.006)	(0.006)
After 2011 * License Area*Earthquake							-0.036***
							(0.007)
Observations	838,276	838,276	838,276	838,276	838,276	838,276	838,276
R-squared	0.335	0.343	0.343	0.343	0.343	0.343	0.343
Year-Quarter-FE	Y	Y	Y	Y	Y	Y	Y
House Controls	Y	Y	Y	Y	Y	Y	Y
Geo Controls	Y	Y	Y	Y	Y	Y	Y
Region Trends	N	Y	Y	Y	Y	Y	Y

*Notes: The table reports results from fixed effects regressions of log price on an interaction between an indicator for time which either indicates the post-license period (after 2008) or the post-earthquake period (after 2011) and an indicator for (i) licensed areas, (ii) areas licensed for shale gas exploration, or (iii) areas licensed for shale gas exploration where the earthquake happened. All regressions are conditional on quarter-by-year fixed effects, house controls, geo-by-year controls and, with the exception of Column 1, region-by-year controls. Panel C uses pre-2008 and post-2008 areas under a Petroleum Exploration and Development License (PEDL) as control group. Panel D restricts the sample to all output areas which the British Geological Survey classifies as promising for shale gas development. Output areas in the top quartile of the population density distribution are excluded from all specifications. The time horizon is 2001-2015. Standard errors are clustered on the output area level. *** $p<0.01$, ** $p<0.05$, * $p<0.10$*

Table 3: Robustness Tests

	Panel A: 20km Buffer					*Panel B: 14th Licensing Round w/o 20km Buffer*				
	Deflated	Census Cont.	Linear Trend	Polyn. Trend	Cluster Ward	Deflated	Census Cont.	Linear Trend	Polyn. Trend	Cluster Ward
	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
Panel A: 20km Buffer										
After 2008 * License Area	-0.002*	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	0.001	0.001	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
After 2011 * License Area	0.005***	0.005***	0.004***	0.004***	0.004**	0.015***	0.012***	0.014***	0.014***	0.013***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
After 2008 * License Area*Shale Gas	0.003	-0.002	-0.002	-0.002	-0.001	0.010*	0.005	0.005	0.005	0.007
	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)	(0.005)	(0.005)	(0.005)	(0.005)	(0.007)
After 2011 * License Area*Shale Gas	-0.005	-0.003	-0.003	-0.003	-0.002	-0.002	0.001	0.001	0.001	0.002
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
After 2008 * License Area*Earthquake	-0.003	0.005	-0.004	-0.003	0.002	-0.029***	-0.018***	-0.028***	-0.029***	-0.024***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.007)	(0.006)	(0.006)	(0.006)	(0.006)	(0.008)
After 2011 * License Area*Earthquake	-0.022***	-0.027***	-0.033***	-0.034***	-0.029***	-0.032***	-0.035***	-0.043***	-0.041***	-0.039***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.008)
Observations	2,001,301	2,001,301	2,001,301	2,001,301	2,001,442	1,168,445	1,168,445	1,168,445	1,168,445	1,168,531
	Panel C: Pre-2008 and Post-2008 Licensed Areas					*Panel D: Geology*				
After 2008 * License Area	-0.002	-0.001	0.001	0.000	-0.001	0.000	-0.002	-0.000	-0.000	-0.000
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
After 2011 * License Area	0.007***	0.005***	0.007***	0.008***	0.006**	0.013***	0.012***	0.013***	0.013***	0.013***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
After 2008 * License Area*Shale Gas	0.001	-0.002	-0.004	-0.003	-0.002	-0.005	-0.008	-0.008	-0.008	-0.009
	(0.005)	(0.005)	(0.005)	(0.005)	(0.007)	(0.006)	(0.006)	(0.006)	(0.006)	(0.007)
After 2011 * License Area*Shale Gas	-0.008	-0.003	-0.005	-0.005	-0.004	-0.010	-0.004	-0.005	-0.005	-0.005
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
After 2008 * License Area*Earthquake	-0.004	0.006	-0.011*	-0.007	0.002	0.003	0.012*	0.004	0.005	0.008
	(0.006)	(0.006)	(0.006)	(0.006)	(0.008)	(0.006)	(0.006)	(0.007)	(0.007)	(0.008)
After 2011 * License Area*Earthquake	-0.028***	-0.032***	-0.045***	-0.052***	-0.035***	-0.029***	-0.033***	-0.039***	-0.042***	-0.036***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.008)	(0.007)	(0.007)	(0.007)	(0.007)	(0.008)
Observations	751,001	751,001	751,001	751,001	751,043	838,276	838,276	838,276	838,276	838,336
Year-Quarter-FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
House Controls	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Geo Controls	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Region Trends	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

*Notes: The table reports results from fixed effects regressions of log price on an interaction between an indicator for time which either indicates the post-license period (after 2008) or the post-earthquake period (after 2011) and an indicator for (i) licensed areas, (ii) areas licensed for shale gas exploration, or (iii) areas licensed for shale gas exploration where the earthquake happened. All regressions are conditional on quarter-by-year fixed effects, house controls, geo-by-year controls and region-by-year controls. Panel A-D use the sample restrictions from the baseline results in tables 2 and 3. Output areas in the top quartile of the population density distribution are excluded from all specifications. The time horizon is 2001-2015. Standard errors are clustered on the output area level and in column 6 on the ward level. *** p<0.01, ** p<0.05, * p<0.10*

Table 4: Nationwide Estimations

	Panel A: 20km Buffer				*Panel B: 14th Licensing Round w/o 20km*		
	(1)	(2)	(3)		(4)	(5)	(6)
Panel A: 20km Buffer							
After 2008 * License Area	0.001	0.001	0.001		0.013***	0.013***	0.013***
	(0.002)	(0.002)	(0.002)		(0.003)	(0.003)	(0.003)
After 2011 * License Area	-0.001	0.002	0.001		0.004	0.006*	0.005
	(0.002)	(0.002)	(0.002)		(0.003)	(0.003)	(0.003)
After 2008 * License Area*Shale		0.004	-0.000			0.000	0.001
		(0.006)	(0.008)			(0.006)	(0.008)
After 2011 * License Area*Shale		-0.018***	-0.007			-0.024***	-0.011
		(0.006)	(0.008)			(0.006)	(0.009)
After 2008 * License Area*Earthquake			0.007				-0.001
			(0.010)				(0.011)
After 2011 * License Area*Earthquake			-0.020*				-0.024**
			(0.011)				(0.012)
Observations	274,824	274,824	274,824		161,528	161,528	161,528
R-squared	0.719	0.719	0.719		0.719	0.719	0.719
	Panel C: Pre-2008 and Post-2008 Licenses				*Panel D: Geology*		
After 2008 * License Area	-0.004	-0.004	-0.004		0.006*	0.006*	0.006*
	(0.003)	(0.003)	(0.003)		(0.003)	(0.004)	(0.004)
After 2011 * License Area	-0.003	0.001	-0.000		-0.001	0.003	0.003
	(0.004)	(0.004)	(0.004)		(0.004)	(0.004)	(0.004)
After 2008 * License Area*Shale		0.002	-0.002			-0.000	-0.003
		(0.006)	(0.008)			(0.006)	(0.009)
After 2011 * License Area*Shale		-0.024***	-0.010			-0.023***	-0.010
		(0.006)	(0.009)			(0.007)	(0.009)
After 2008 * License Area*Earthquake			0.007				0.005
			(0.011)				(0.012)
After 2011 * License Area*Earthquake			-0.026**				-0.022*
			(0.012)				(0.012)
Observations	99,022	99,022	99,022		101,049	101,049	101,049
R-squared	0.723	0.723	0.723		0.705	0.705	0.705
Year-Quarter-FE	Y	Y	Y	Y	Y	Y	Y
House Controls	Y	Y	Y	Y	Y	Y	Y
Geo Controls	Y	Y	Y	Y	Y	Y	Y
Region Trends	N	Y	Y	Y	Y	Y	Y

*Notes: The table reports results from fixed effects regressions of log price on an interaction between an indicator for time which either indicates the post-license period (after 2008) or the post-earthquake period (after 2011) and an indicator for (i) licensed areas, (ii) areas licensed for shale gas exploration, or (iii) areas licensed for shale gas exploration where the earthquake happened. All regressions are conditional on quarter-by-year fixed effects, house controls, geo-by-year controls and, with the exception of Column 1, region-by-year controls. Panel A uses all output areas within a buffer of 20km around the licensed areas as control group. Panel B uses the 14th licensing round areas but exclude the 20km buffer around the licensing area. Panel C uses pre-2008 and post-2008 areas under a Petroleum Exploration and Development License (PEDL) as control group. Panel D restricts the sample to all output areas which the British Geological Survey classifies as promising for shale gas development. Output areas in the top quartile of the population density distribution are excluded from all specifications. The time horizon is 2001-2015. Standard errors are clustered on the output area level. *** p<0.01, ** p<0.05, * p<0.10*

Table 5: Balance Tests

	Register Data											
	Share Detached				Share Semi-Detached				Share Terraced			
	(A)	(B)	(C)	(D)	(A)	(B)	(C)	(D)	(A)	(B)	(C)	(D)
After 2008 * License Area	0.000**	-0.000**	-0.000	-0.000	-0.000	0.000	-0.000	0.000*	-0.000*	-0.000	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
After 2008 * License Area*Shale	0.000	-0.000	0.000	-0.000	-0.000	-0.000	-0.000	-0.000*	0.000	0.000	-0.000	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
After 2008 * License Area*Earthquake	0.000	0.000***	0.000	0.000	-0.000	0.000	0.000	0.000	-0.000	0.000***	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Share Flat				Share New				log number sales			
After 2008 * License Area	0.000***	-0.000	0.000	-0.000	0.000	-0.000	0.000	-0.000	0.007***	0.027***	0.001	0.004
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)	(0.003)	(0.004)	(0.003)
After 2008 * License Area*Shale	-0.000**	0.000	-0.000	-0.000	0.000**	0.000	-0.000	0.000	-0.006	0.004	-0.002	0.002
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.010)	(0.010)	(0.010)	(0.010)
After 2008 * License Area*Earthquake	0.000	-0.000	-0.000	0.000	-0.000*	0.000	-0.000**	-0.000	0.024**	-0.009	0.004	0.014
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.012)	(0.013)	(0.013)	(0.013)
	Nationwide Data											
	Tenure				Garage				Bathrooms			
	(A)	(B)	(C)	(D)	(A)	(B)	(C)	(D)	(A)	(B)	(C)	(D)
Panel C: 20km Buffer												
After 2008 * License Area	0.002	-0.001	-0.004	-0.003	0.005	0.038**	-0.005	-0.003	-0.005	0.004	-0.001	0.015
	(0.003)	(0.004)	(0.005)	(0.004)	(0.012)	(0.017)	(0.018)	(0.015)	(0.008)	(0.011)	(0.012)	(0.010)
After 2008 * License Area*Shale	-0.005	-0.008	-0.001	0.002	-0.000	-0.009	0.019	0.003	0.025	0.020	0.028	0.028
	(0.012)	(0.013)	(0.013)	(0.013)	(0.040)	(0.042)	(0.042)	(0.042)	(0.027)	(0.028)	(0.028)	(0.028)
After 2008 * License Area*Earthquake	0.005	-0.001	-0.007	-0.003	-0.061	-0.050	-0.089	-0.072	0.012	0.028	0.033	0.010
	(0.017)	(0.018)	(0.018)	(0.017)	(0.053)	(0.057)	(0.057)	(0.055)	(0.036)	(0.039)	(0.038)	(0.038)
	Bedrooms				log Size				Year Built			
After 2008 * License Area	0.002	-0.013	0.022	0.022**	0.003	-0.008	0.007	0.009*	-0.114	0.235	0.616	0.719
	(0.009)	(0.013)	(0.014)	(0.011)	(0.003)	(0.005)	(0.005)	(0.004)	(0.410)	(0.653)	(0.674)	(0.558)
After 2008 * License Area*Shale	-0.027	-0.021	-0.022	-0.024	-0.003	-0.002	-0.003	-0.004	-0.259	-0.545	-0.372	0.023
	(0.034)	(0.035)	(0.035)	(0.035)	(0.013)	(0.014)	(0.014)	(0.014)	(1.570)	(1.659)	(1.661)	(1.660)
After 2008 * License Area*Earthquake	0.078*	0.061	0.065	0.081*	0.021	0.019	0.023	0.026	1.560	1.907	1.772	1.025
	(0.042)	(0.045)	(0.044)	(0.044)	(0.016)	(0.018)	(0.018)	(0.017)	(1.983)	(2.141)	(2.118)	(2.097)

*Notes: Notes: The table reports results from fixed effects regressions of different house characteristics on an interaction between an indicator for time which either indicates the post-license period (after 2008) or the post-earthquake period (after 2011) and an indicator for (i) licensed areas, (ii) areas licensed for shale gas exploration, or (iii) areas licensed for shale gas exploration where the earthquake happened. All regressions are conditional on quarter-by-year fixed effects, house controls, geo-by-year controls and, with the exception of Column 1, region-by-year controls. Sample (A) uses all output areas within a buffer of 20km around the licensed areas as control group. Sample (B) uses the 14th licensing round areas but exclude the 20km buffer around the licensing area. Sample (C) restricts the sample to all output areas which the British Geological Survey classifies as promising for shale gas development. Sample (D) uses pre-2008 and post-2008 areas under a Petroleum Exploration and Development License (PEDL) as control group. Output areas in the top quartile of the population density distribution are excluded from all specifications. The time horizon is 2001-2015. Standard errors are clustered on the output area level.*** p<0.01, ** p<0.05, * p<0.10*