I Z A Institute of Labor Economics
Initiated by Deutsche Post Foundation

DISCUSSION PAPER SERIES

IZA DP No. 13655

The Price of Indoor Air Pollution: Evidence from Radon Maps and the Housing Market

Edward W. Pinchbeck
Sefi Roth
Nikodem Szumilo
Enrico Vanino

SEPTEMBER 2020

I Z A Institute of Labor Economics

Initiated by Deutsche Post Foundation

DISCUSSION PAPER SERIES

IZA DP No. 13655

The Price of Indoor Air Pollution: Evidence from Radon Maps and the Housing Market

Edward W. Pinchbeck
University of Birmingham

Sefi Roth
London School of Economics and IZA

Nikodem Szumilo
University College London

Enrico Vanino
University of Sheffield

SEPTEMBER 2020

ISSN: 2365-9793

IZA – Institute of Labor Economics

Schaumburg-Lippe-Straße 5–9
53113 Bonn, Germany

Phone: +49-228-3894-0
Email: publications@iza.org

www.iza.org

ABSTRACT

The Price of Indoor Air Pollution: Evidence from Radon Maps and the Housing Market*

This paper uses the housing market to examine the costs of indoor air pollution. We focus on radon, an indoor air pollutant which is the largest source of exposure to natural ionising radiation and the leading cause of lung cancer after smoking. To overcome potential confounders, we exploit a natural experiment whereby a risk map update in England induces exogenous variation in published radon risk levels. Using a repeat-sales approach, we find a significant negative relationship between changes in published radon risk levels and residential property prices of affected properties. Interestingly, we do not find that the effect of increasing or decreasing radon risk is symmetric. We also show that the update of the risk map led higher socio-economic groups (SEGs) to move away from radon affected areas, attracting lower SEG residents via lower prices. Finally, we propose and utilise a new theoretical framework to account for preference based sorting which allows us to calculate that the average willingness to pay to avoid radon risk is $3,360.

JEL Classification: R21, R28, Q53, H23

Keywords: indoor air pollution, risk information, house prices, radon, neighbourhood sorting

Corresponding author:
Sefi Roth
The London School of Economics and Political Science
Houghton Street
London WC2A 2AE
United Kingdom
E-mail: s.j.roth@lse.ac.uk

* We would like to thank David Rees and Marie Horton from Public Health England and Monika Szumilo from Imperial College London for their kind support with this project. We also thank Gabriel Ahlfeldt, Felipe Carozzi and Christian Hilber, as well as seminar participants at the Center for Economic Performance (LSE), at the Sheeld Economics Seminars Series, the 2020 AERE Summer Conference and the 35th annual Congress of the European Economic Association for helpful comments and suggestions. This project uses Ordnance Survey AddressBase data which is Crown Copyright and is also based upon data provided by the British Geological Survey UKRI. All rights reserved. It also uses Data supplied from Public Health England under the Open Government License.

1 Introduction

The adverse impacts of ambient pollution and its associated costs have received substantial public policy attention in the last few decades. Nevertheless, the health and economic consequences of indoor pollution are often overlooked. This is surprising given that the population in developed countries spends approximately 90% of their time indoors (Klepeis et al., 2001), and the documented substantial health implications from exposure to indoor pollution. More specifically, the World Health Organisation (WHO) estimates that indoor pollution is responsible for 2.7% of the global burden of disease and 3.8 million deaths every year. Importantly, indoor pollution is not simply a by-product of ambient pollution as there are numerous indoor sources of pollution including cooking, smoking and substances of natural origin such as radon. In fact, indoor levels of pollution are in many cases higher than those outdoors. As such, focusing on reducing ambient pollution concentrations without addressing indoor sources would fail to provide adequate protection to the public against overall pollution exposure.

Assessing the economic effects of indoor pollution is challenging even compared to other non-market goods for several reasons. First, large data samples on indoor air pollution are rarely available. Second, exposure to indoor pollution may be associated with unobserved factors that are also correlated with human health and well-being (e.g. income, diet and smoking). Finally, monetizing the total cost of exposure to indoor pollution is remarkably difficult, as exposure can lead to a wide range of observed or unobserved health and wellbeing costs.[1] This paper exploits a unique opportunity to overcome these challenges to examine the costs of indoor air pollution. We accomplish this by looking at how exogenous variation in the level of indoor pollution risk, reported by governmental sources, is linked with variation in residential property prices in England.

We focus on radon, an odourless, colourless and tasteless indoor air pollutant which is formed by the natural decay of uranium from rocks and soil. Radon is considered to be the largest source of exposure to natural ionising radiation which damages human lungs and can even lead to lung cancer if inhaled and absorbed by nearby tissues. Globally, exposure to radon at homes and workplaces is estimated to cause tens of thousands of deaths each year, making it the most important cause of lung cancer after smoking (WHO, 2009; US-EPA, 2013). The main risk factors for getting lung cancer from radon depends on the level and duration of exposure and whether the individual is a smoker or has smoked in the past. However, it is important to note that while smoking is an important risk factor, exposure to radon is also the number one cause of lung cancer among non-smokers. Due to these deleterious effects on health, radon exposure is an increasingly important environmental concern for

[1] Indoor pollution can affect a wide range of outcomes including mortality, morbidity, cognitive performance and educational outcomes (Duflo et al., 2008; Künn et al., 2019; Stafford, 2015; Gilraine, 2019; Roth, 2019).

policymakers. Consequently, the US, EU and China have developed new radon policies for buildings and residents, and in many cases have commissioned radon maps of increasing accuracy and spatial granularity to increase awareness about this issue (Gruber et al., 2013; US-EPA, 2013; Zielinski et al., 2006). Nonetheless, there is very limited evidence on how effective those policies are in informing market participants about radon risk and more generally about the economic cost of radon.

We conduct our analysis using a unique data set that combines information on the universe of residential property transactions in England with detailed maps of radon risk provided by Public Health England that classifies radon risk into six categories of increasing risk, of which all but the first are classified as "radon affected areas".[2] To overcome endogeneity concerns, we exploit quasi-experimental radon risk variation resulting from the publication of an updated radon risk map in England in 2007, which did not incorporate changes in actual levels of radon, but simply new developments in risk modelling techniques. Our setting is also advantageous because since 2002 the UK standard conveyancing searches undertaken on behalf of house buyers must include information about radon risk based on the latest map.[3] The combination of arguably exogenous variation and information disclosure to home buyers provides us with a unique opportunity to estimate the effects of radon risk information in housing markets.

Our baseline specifications examine the effect of radon risk category changes on home prices using a repeat-sales approach. The principal measure of radon we use is the reclassification to and from the first category, i.e. reclassification into and out of a "radon affected area". We find a highly significant negative relationship between changes in radon risk and changes in residential property prices. The results suggest that an upward reclassification of a property (from being in a radon risk-free category to being in a radon affected category) reduces property prices by between 1.3 and 1.6 %, depending on the granularity of the spatial fixed-effects we adopt. These results are economically significant and are similar to the estimated effects found in studies that measure the impact of energy efficiency ratings, flooding risk or earthquake risk on property prices (Fuerst et al., 2015; Bosker et al., 2018; Naoi et al., 2009). In contrast, we find no evidence that downwards reclassifications of radon risk (i.e. lower radon risk) affect house prices. We posit that this asymmetry is driven by the fact that the

[2] The six categories of risk are based on the estimated percentage of houses in the grid square above the action level of 200 becquerels per cubic meter (Bq m3): 0-1% (risk free area), 1-3%, 3-5%, 5-10%, 10-30% and >30%.

[3] These conveyancing searches include enquiries that are sent to Local Authorities, which are the main units of local government in the UK. The searches are required to obtain a mortgage. They are not required for cash buyers but will usually be undertaken. As a robustness test, we confirm that our main analysis yields similar results when using a subsample of properties with only mortgage buyers. One part of the searches is the CON29 form: a standard set of questions set by the government, the Law Society and the Local Government Association. CON29 contains required and optional questions. Radon gas is on the required part, whereas flooding is on the optional part. The radon question asks if the property is in a "radon affected area", which is defined as any risk category higher than category one. There is no explicit requirement to report the specific category in which the property is although the solicitor can find this out from other sources.

buyers are responsible for conducting the conveyancing search (which includes information about the current radon risk level) and that sellers might not be fully aware of the latest radon risk classification in their area.

We next show that an increase in the radon risk level increases the number of transactions and test whether radon risk changes induce sorting. We find that it does, and more specifically we show that the share of higher educated, higher income and higher social status residents decreases in response to upward radon risk reclassification. Once again, we find no effect of downward reclassification. These findings have two important implications. First, they suggests that radon risk disproportionately affects lower socio-economic groups in our society, creating a source of environmental injustice. Second, it means that our previous estimates are "local", in the sense that they reveal the Willingness To Pay (WTP) of the specific buyers who are purchasing houses affected by radon and not the average buyer (see Greenstone (2017) for more details). Therefore, we propose and apply a new theoretical framework that uses transaction probabilities to account for sorting in order to calculate the average WTP. We also present several robustness tests and placebo exercises to provide further support to our empirical analysis and to validate our estimates.

The hedonic price method has been widely used for valuing environmental amenities, including the welfare impacts of cleanups of hazardous waste (Greenstone and Gallagher, 2008), and the capitalization of ambient air pollution (Chay and Greenstone, 2005; Currie et al., 2015). However, to the best of our knowledge, ours is the first paper to estimate the economic impact of indoor air pollution. Surprisingly, even though radon is linked with significant health risks by the epidemiological literature, it has not yet received much attention in economics and our paper addresses this gap.[4]

We believe that our study contributes to the existing hedonic literature on air pollution in two additional ways. First, the institutional set up we study determines that information on property-level radon risk is made available to buyers through standard conveyancing searches. This addresses an important concern regarding prior research studying the impact of air pollution on property prices which are less certain whether market participants are aware of pollution levels. Recent evidence on the effects of environmental information disclosure on house prices and other outcomes suggests this is a non-negligible concern (e.g Pope, 2008; Moulton et al., 2018). Second, we propose and utilise a new theoretical framework to estimate the average willingness to pay in the presence of sorting.

[4]The only exception is a paper by Smith and Johnson (1988) which studied how households form risk perceptions using a survey of households' responses to information about risks associated with radon in Maine (US).

Importantly, our paper serves to demonstrate that the stakes are high for policymakers working on indoor air pollution. Due to its geology, the UK has relatively low levels of radon when compared to those found in other countries, notably US and China. Despite this, our estimates imply that if unmitigated by remedial measures the presence of radon in our setting would reduce the total market value of residential properties in England and Wales by as much as £23 billion.[5] Consistent with approaches in other countries and other domestic policies (e.g. on energy efficiency - Fuerst et al. (2015)), the UK government radon policy centres on increasing information availability to allow markets to price environmental risks. As such, our paper provides critical insights into how the market responds to this information, complementing a growing literature on the effects of access to pollution information (Cutter and Neidell, 2009; Zivin and Neidell, 2009; Barwick et al., 2019) that has so far solely focused on ambient pollution, and to the empirical literature on the role of information in consumer choices more broadly (Hastings and Weinstein, 2008; Jessoe and Rapson, 2014; Wichman, 2017). Finally, our work also speaks to the literature on environmental justice, which denotes various channels through which environmental costs and poverty or race may be correlated, including household sorting (or "coming to the noise") and selective siting of polluting facilities (Banzhaf et al., 2019; Hausman and Stolper, 2020). The evidence on the extent to which sorting drive the observed correlations in this literature are mixed, in part reflecting considerable empirical challenges (Banzhaf et al., 2019). We contribute to this literature by showing that different socio-economic groups sort in response to radon risk change.

The rest of the paper is structured as follows: the next section provides background information about radon risk and risk information policy in the UK; section 3 presents the data and our study design; section 4 discusses the empirical strategy; section 5 presents the main results of our analysis; section 6 proposes and utilises a new theoretical framework to account for sorting and estimate the average WTP, while section 7 concludes.

2 Background on radon and the UK

2.1 Background on radon

Radon is a colourless, odourless and tasteless gas which is formed by the natural decay of uranium that occurs in all rocks and soil. Once escaped from the ground into the air, it decays and produces radioactive particles which tend to concentrate in enclosed spaces. The amount of radon in homes, schools and workplaces depends on a variety of factors including the amount of uranium in the un-

[5]This range is obtained by multiplying the average impact of being reclassified to a radon affected area (1.33%) by the number and value of all affected houses in the housing stock.

derlying rocks and soil, the available routes for radon to enter the building, and the rate of exchange between indoor and outdoor air (WHO, 2009). Radon is usually measured in becquerels per cubic meter (Bq m3) or in picocuries per liter (pCi/L). In the UK and in many other countries, a radon level of 200 (Bq m3) or above is classified as "Action Level", which means that householders are advised to take actions to reduce radon through remediation works (e.g. by installing a radon sump). The average radon level in UK homes is 20 (Bq m3), but there is significant variation across geographical areas and some dwellings have yielded readings of more than ten thousand Bq m3 (PHE, 2018).

According to the medical literature, radon can affect the human body as radioactive elements are inhaled and enter the lungs where they emit radiation. This radiation (mainly alpha particles) is absorbed by nearby tissues which can lead to lung cancer. Early epidemiological studies evaluated this link empirically among miners, and established that exposure to high levels of radon is associated with an increased risk of lung cancer (Radford and Renard, 1984; Howe et al., 1986; Tirmarche et al., 1993). Later studies have examined the relationship between residential exposure to radon and lung cancer in the general population. This strand of the literature, which relies on pooled large scale epidemiological studies, provides robust evidence that residential exposure to radon is linked with a significant number of lung cancers in China, North America and Europe (Lubin et al., 2004; Krewski et al., 2005; Darby et al., 2006). While there is a small theoretical risk that radon exposure can also cause cancer to other organs, there is currently no strong empirical evidence to support this hypothesis (AGIR, 2009).

Approximately 1,100 lung cancer deaths a year in the UK and 21,000 in the US are attributed to exposure to elevated levels of radon, making it the most important cause of lung cancer after smoking (US-EPA, 2013; Gray et al., 2009). The main risk factors for getting lung cancer from radon depends on the levels of radon exposure and whether the individual is a smoker or has smoked in the past. For example, if 1,000 people who smoke were exposed to radon level of 10 (pCi/L) over a life time, about 150 of them could get cancer compared to 36 people among a group of 1,000 people who have never smoked and were exposed to the same level of radon. Nevertheless, it is important to clarify that non-smokers are still at significant risk from radon exposure and according to the US Environmental Protection Agency (EPA), radon is the number one cause of lung cancer among non-smokers as well. There are several methods for radon prevention and mitigation at dwellings, such as increasing under-floor ventilation, installing radon sump systems, and sealing floors and walls. The appropriate remedial strategy depends on several factors including radon levels, sources and the type of floor. Importantly, none of the techniques can guarantee complete eradication of radon and sometimes a combination of strategies is required to reduce the risk. This is important given the fact that measuring radon concentration is a complex process as readings can vary between rooms, over times of day, months of the year or even with phases of the moon. Costs of these remedial techniques vary significantly, but as a rough guideline, approximate costs range between £200 and £2000 according to Public Health England.

2.2 History of radon information and policy in the UK

Developments in understanding the health risks of ionizing radiation after the Second World War led to investigations of radon levels in UK homes in the 1970s and 1980s. These initial local measurement schemes developed into a systematic measurement programme which tried to identify areas and houses exposed to the risk. The concept of "radon affected areas" was introduced in 1990s and defined as areas where 1% of houses were above a pre-specified action level. In 1993 several parts of the UK were designated as affected areas and in 1996 the first complete nation-wide map of radon was published. The map was based on over 250,000 measurements and denoted radon risk in 5km grid squares using five categories of risk based on the percentage of houses in the grid above the action level: 0-1% (risk free area), 1-3%, 3-10%,10-30% and >30%. The measurements in each dwelling were made with two detectors over a period of three months and were calculated using temperature corrections to enable to produce accurate annual estimates.[6]

A second radon map was issued in November 2002 and was in use from 2003. This map (the "2003 map") updated the 1996 map based on additional measurements (over 400,000) in the affected regions and updated probability models. It also included an additional risk category, as the 3-10% category was split into 3-5% and 5-10%. Additional measurements allowed mapping the affected areas of the South West of England in a 1km grid. A third iteration of the radon map was then released in late 2007 (the "2007 map"). This updated map incorporated further improvements to probability models, which now included not only measurements but also geological information as input variables. Importantly, two versions of this 2007 map were created from the same underlying data. The first (the "50m 2007 map") was a map using a 50m grid for the whole of England and Wales. Unlike the earlier maps, this version was not available to the public or to local government organisations free of charge, but required a fee to be accessed (a paid subscription for institutions including government organisations). However, a second publicly available version of the 2007 update was released which indicated radon risk in 1km grid squares (the "1km 2007 map"). This 1km map was created by taking the maximum category of radon risk in all the 50m squares within each 1km square.

Radon information can be obtained by individuals in two main ways. First, the maps are available

[6]Houses included in the measurement program were selected based on progressive measurements of areas where initial reading were high and geological data.

online for download, so potential buyers could in theory find this information themselves. However, since it is unlikely that the average buyer would actively search for such information online, we believe (and later document) that the main source of radon information that buyers received is the set of questions submitted to Local Authorities (LAs) by solicitors and licensed conveyancers on behalf of their clients when a property is traded or a development application is made.[7] These are know as Local Authority searches and the specific form used to make enquiries is known as CON29. CON29 contains a standard set of questions which are jointly agreed by the government and the Law Society. Part of the form indicates required questions (CON29r) and another part contains optional questions (CON29o). Information about radon has been a part of this process since 1994 and it was made compulsory in July 2002 (it was previously optional). Obtaining a CON29 is a standard part of the transaction process and a formal requirement when making a mortgage application. The information about radon is based on risk categories, but the CON29 is only strictly required to state if a property is in a radon affected area (any category other than category 1) and not its actual risk category.

The transmission of information contained in the radon maps to home buyers is an important consideration in our empirical work. In late 2002 copies of the 2003 map were provided to all Local Authorities (LAs) in the country, and contemporaneous guidance issued by the National Radon Protection Board (NRPB) indicated that the map should be used by LAs to answer enquiries by conveyancers about whether homes were in radon affected areas. For the 2007 map update, things are more complicated as Local Authorities had a choice about which map to use. Around half of the Local Authorities in the country have elected to licence the more spatially detailed 50m version of the map for some or all the period since it was released, while the other half have elected to use the freely available 1km version of the 2007 map. In our later empirical work we will define home level radon information based on the version of the 2007 map the associated LA had at the time of the home sale, and further exploit the two map versions for robustness checks.[8]

[7]Local Authorities are the main unit of local government in the UK.

[8]Besides the radon maps and the CON29 form, there are two further institutional details which are somewhat related. First, newly built houses are subject to radon policies. The general policy since 1990 has been that houses with radon levels above 200 Bq m-3 are advised to apply preventive measures and all new buildings in affected areas have to apply these measures (National Radiological Protection Board, NRPB (1996)). Second, a Home Information Packs (HIP) policy, in place from late 2007 to May 2010, required home sellers or their representatives to disclose a number of documents and pieces of information to buyers about the home before a sale: an Energy Performance Certificate, local authority searches, title documents, guarantees, etc, as well as to state if the home is in a "Radon Affected Area" as identified by the Health Protection Agency".While the HIP policy could signal a mechanism for sellers to learn of radon risk changes to their home, in practice this assumption could be tenuous as it would require that (a) the HIP contains accurate and up to date radon information from a new LA radon search, and (b) the seller carefully checking the HIP radon question. The first condition is undermined because the regulations do not specify which map should be used, and by evidence from a local survey that found five out of six HIPs contained “inaccurate, incomplete or missing information” ("Home Information Packs: a short history", House of Commons Research Paper 10/69). The second also seems improbable given that the vast majority of sellers would be unaware of the 2007 radon map update (or even that radon maps are periodically updated), and hence unlikely to carefully check through a 100 page document for this information.

3 Data and Study Design

Our final dataset combines information on house sales, radon risk and various socioeconomic characteristics from several administrative sources. Data on house sales come from the Land Registry, which contains all housing transactions in England between the years 1995-2018. From this source, we take over 2.4 million transactions that took place during our 2003-2011 study period. This is the population of all repeated transactions of the same property which is a sub-sample of the population of all 6.48 million transactions in England in this period. Our data on radon risk comes from radon maps provided by Public Health England (PHE) which are the publicly available maps and the 50m map provided by the British Geological Survey. The public maps are presented in Figure 1. Notably, the three maps include revisions of the radon level in numerous locations with the vast majority of revisions increasing the level of radon risk (see Table 1).

In order to focus our study on areas where we can be certain that buyers received information about radon and what map was used to provide it, we only consider transactions in which the first sale occurred between 2003-2007 and the second sale between 2008-2011.[9] The full database consists of 1.4m pairs of transactions, as shown in Table 1.

There are 6 radon categories in each map and home level changes can theoretically be in any of the 36 possible combinations. However, as shown in Table 1, in practice more than 91% of homes in our sample stay in the same category. Of those that do move categories, more than 7% start in category 1 and move up. Less than 1.5% start in a category higher than 1 and move down one or several categories. Moreover, some combinations of starting and ending category are very thin, especially when we condition on area fixed effects. We therefore collapse the dimensionality of this problem by either (a) focusing on particular start/end category combinations that are well-populated, (b) reclassifying moves into upwards, downwards, or stays the same, or (c) treating the change in categories as a continuous variable. Each has drawbacks, but in general in our analysis we prefer (a) and (b) to (c).

To create our final dataset, we first geocode each property in our house prices data using the AddressBase database from the Ordnance Survey. This gives us the exact location of each house, which enables us to assign a radon risk category to each transaction from the radon risk maps. We use data on periods where Local Authorities had a subscription to the 50m grid version of the 2007 radon map to ensure the radon risk in our data matches the radon information buyers receive from

[9]Starting our sample period in 2003 ensures this because this is when radon questions became compulsory in CON29. We choose to end the sample period in 2011 as this is the last year for which we have rich demographic information (from the Census).

CON29. Finally, we merge our geo-referenced data with neighbourhood-level information on socioeconomic characteristics such as education, age and ethnicity from the 2001 and 2011 Census to test for potential sorting.The spatial units we use are Output Area (OA): the smallest census geography in the UK with an average of around 100 residents. Following the public health department's method of aggregation, we measure the OA radon level as the maximum radon risk for any house in the same OA.

Table 2 presents summary statistics for all transactions in our dataset. The first two columns show that cross-sectionally, transaction prices in radon affected areas do not appear to be statistically different in the full sample, although the mean house price is slightly lower for transactions in categories higher than one. The next three columns suggest that in the repeated sale sample prices of properties where radon did not change grew faster than in places where radon risk changed (upwards or downwards) although the differences are not statistically significant. Naturally, these comparisons are very general as they do not account for confounding factors. In the next section we provide detailed explanation of possible confounders and how our empirical strategy overcomes them.

4 Empirical Strategy

Following the standard hedonic approach to modelling house prices, we begin with the following simple equation:

$$ln(P_{it}) = \beta R_{it} + \rho X_{ik} + \epsilon_{it} \tag{1}$$

Where P_{it} denotes the transaction price of property i in period (year) t, R_{it} is the level of radon for the transacted property given by the grid used by the Local Authority at the time of the transaction, X_{ik} is a vector of time invariant property characteristics, and ϵ is an idiosyncratic error term.

The usual identification problem is that radon levels can be correlated with both the features of the house and with property price. For example, geological conditions could affect the level of radon but also the amenity value of the location or construction materials used to build houses. As such, estimating equation 1 would yield a biased estimate in the presence of unobserved correlated factors. To overcome this problem we take advantage of the popular approach in the real estate literature and adopt a repeat-sales approach (Cannaday et al., 2005). More specifically, if the same property is transacted also at time τ (where $\tau > t$), we can write a first-difference model of the following form:

$$ln\left(\frac{P_{i\tau}}{P_{it}}\right) = ln(P_{i\tau}) - ln(P_{it}) = \beta \Delta R_{i\tau t} + \epsilon_{i\tau t} \tag{2}$$

The repeated sale approach removes all time-invariant characteristics and focuses our identification on changes in radon risk levels within the same property over time. The approach is particularly compelling in our context because geological conditions and actual radon levels do not change over time, yet the estimates of the radon risk do due to map updates. As radon only affects humans through the impact on their health β captures the impact of the health risk associated with radon on prices. Since time varying unobserved correlated variables remain a potential threat for causal identification, we allow for house prices to change over time by including a fixed effect θ for each pair of periods τ and t in our data:

$$ln\left(\frac{P_{i\tau}}{P_{it}}\right) = ln(P_{i\tau}) - ln(P_{it}) = \beta\Delta R_{i\tau t} + \theta_{\tau t} + \epsilon_{i\tau t} \tag{3}$$

Furthermore, we also adjust for local housing cycles by allowing each area to have its own trend in prices. We use two definitions of a local area, one broad and one tight. For the broader units we use labour market areas, know in the UK as Travel to Work Areas (TTWA), and for the tighter units we again use micro-neighbourhoods as defined by Census Output Areas (OA).[10] Specifically, our main specification takes the following form:

$$ln\left(\frac{P_{i\tau}}{P_{it}}\right) = ln(P_{i\tau}) - ln(P_{it}) = \beta\Delta R_{i\tau t} + \theta_{r\tau t} + \epsilon_{i\tau t} \tag{4}$$

Where $\theta_{r\tau t}$ is an interaction term of the area r fixed effect (TTWA or OA) with the time fixed effect $\theta_{\tau t}$, introduced in equation 3. Therefore, our identification is based on changes in radon risk levels within the same property over time, accounting for all time varying correlated factors within areas. Finally, standard errors are cluster-robust in two dimensions, over 1km grid squares and time periods.

Importantly, for equation 4 to reveal a causal estimate, several identifying assumptions should be made. First, housing market participants (buyers and sellers) must be aware of the radon risk and take it into account when making buying and selling decisions. For example, if buyers are unaware of higher radon risk in a property, they will not ask for a discount and our estimates should be zero. While this fundamental identification assumption is being made implicitly in all papers that rely on the hedonic technique, it is not frequently discussed or addressed explicitly.[11] We believe that our unique context enables us to ease concerns regarding a violation of this crucial assumption as buyers receive information about radon risk levels when buying properties. More specifically, buyers receive information

[10]Travel to Work Areas (TTWAs) are geographies used by the UK government to approximate self-contained areas in which most people live and work. There are 228 TTWAs in the UK according the 2011 Census data).

[11]There are several exceptions to this, including early work by Kask and Maani (1992). See Pope (2008) for a recent example of an environmental application that examines the effect of information disclosure.

on radon risk levels as it is included in the conveyancing process through the local authority search (CON29), which is based on the same radon risk data that we use in our study. Interestingly, while the owner will know what the radon risk was at the time of the first transaction, they will not necessarily be aware of updates to radon risk in their area. Therefore, if new data reveal that the radon risk in an area is reduced, a rational buyer might not pass this information to the seller and we are not expecting to see an effect on property prices. In our empirical section we test this prospect empirically.

Second, updates in the maps have to be exogenous to other determinants of house prices. To validate this assumption we start by demonstrating that the main treatment in our analysis (radon level going from "risk free" to "radon affected") is uncorrelated to observable variables in balancing tests in Table 3. Specifically, we show that assignment of the treatment was not related to characteristics of local populations. Regressing shares of the local population with different characteristics (taken from the 2001 Census) on an indicator for radon level going from "risk free" to "radon affected" shows that the treatment did not occur in locations that are different in terms of residents' characteristics from the rest of the sample.[12] Furthermore, we test whether radon risk is correlated with ambient air pollution which has been shown to affect house prices in numerous studies (e.g. Chay and Greenstone (2005)) and can therefore pose a risk for causal interpretation. More specifically, we examine the correlation of OA level ambient air pollution measured by PM10 and OA level radon risk.[13] In Table A1 columns (1) and (2) we regress levels of the PM10 index on levels of radon risk in 2003 and 2008 with MSOA fixed effects. Column (3) repeats this for changes in both measures of air pollution at OA level. All results indicate that ambient air pollution is not correlated with either levels or changes in radon risk. Importantly, note that since we use a first difference approach, our estimates would only be biased if the treatment was correlated to changes in other determinants of house prices. Later in the paper we test for the presence of such bias with placebo tests using periods in which there were no changes in radon maps and find no evidence of trends correlated to our treatment.

Third, in order to claim that the estimated effect is the price households attach to air pollution risk, we have to measure changes in air pollution risk observed by households. One possible concern is that radon remedial measures may introduce an misalignment between the level of risk observed in our data and by buyers, since we cannot observe if properties have remedial measures in place. For

[12] The only exception is education, as the treated areas are likely to have fewer university graduates than non-treated locations. Since the coefficient is small and it is the only variable in a group of 22 that is statistically significant, there is little evidence that the treatment is correlated to observed determinants of house prices which suggests no correlation with unobserved determinants.

[13] The information on ambient air pollution (PM10) comes from the Department for Environment Food and Rural Affairs (DEFRA). To generate PM10 measures we keep stations that have less than 10% missing values for these years and we assign pollution level to OA by linking it with the three closest monitoring stations to each OA centroid. We then use the mean value of those three measurements weighted by the inverse squared distance between the monitoring station and the OA centroid.

example, a change in the level of risk which in our data is between categories 2 and 6 could be less consequential for the buyer if the house is equipped with radon mitigation devices. Mindful of this issue, in our main results we focus on properties for which the first transaction occurred when the contemporary map indicated no risk of radon. These houses had no, or at least very low-powered, incentives to install radon mitigation devices before the update of the map. Another possible source of measurement error is that owners can measure the actual level of radon in their houses and may thus have different information than reflected on the map. For example, if the seller tests the house that has been reclassified into a high risk area and the test shows no pollution, our measure of risk would be biased. We will address this concern in Section 5.3.

Finally, it is important to note that a hedonic model only reveals the marginal willingness to pay (WTP) of the marginal buyer. This means that in order to interpret our "direct" hedonic estimates as the average WTP of the population we would have to make a number of assumptions, including that there is no sorting based on radon (Greenstone, 2017; Ekeland et al., 2002). In the next sections we will test this assumption directly and in Section 6 we will propose and apply a new theoretical framework to estimate this policy relevant parameter in a context with sorting.

5 Results

5.1 Main Results

We begin our empirical investigation by examining whether upwards and downwards movements in home level radon risk categories affect property prices.[14] Recall that radon category 1 is denoted as a "radon risk free area" in the local authority search (CON29), whereas all other categories are denoted as being in "an area that is affected by radon". Commensurate with the institutional set up, we first examine in Table 4 whether moving to and from category 1 affects house prices. In this table we partial out broad labour market-wide trends in prices by interacting sales years with labour-market area (TTWA) dummies.

In panel A, we test for upwards risk moves, using samples composed of sales that stay in category 1 (the baseline category), and homes that move from category 1 to other, by definition higher, categories. In column 1, we examine moves from category 1 (risk free) to the lowest category classified as affected by radon (category 2). Despite the relatively small increase in radon risk between categories

[14] For clarity of exposition we present upwards and downwards changes in separate regressions but collapsing them into a single regression yields almost identical results.

1 and 2, this upward risk classification decreases house prices by some 1.64%. In columns (2)-(5) we progressively expand the sample to include homes that start in category 1 but move to higher risk categories. In all cases the parameter estimates are slightly smaller in magnitude but statistically indistinguishable from our estimate in column 1.[15] Nonetheless, our best estimate of the total average impact of radon on prices of affected houses is the 1.33% discount from column (5).

Given that the updating of the maps led to reclassifications of properties downwards as well as upwards, we test downwards moves in panel B of Table 4. Our identification of the downwards moves is based on a sample of homes that stay in a given category or in category 1 (our baseline category), and homes that move from the given category to category 1. We obtain small negative coefficients that are not significantly different from zero throughout. These results suggest that conditional on labour market trends in prices, a home reclassified from a radon affected area to not being in a radon affected area does not command a statistically significant price premium.

This suggests an asymmetry in price responses to radon risk which is consistent with buyers and sellers acting on information about higher radon risk but not acting on information about lower radon risk. One possible explanation for this is the asymmetry in radon information between buyers and sellers. As mentioned above, buyers receive radon risk information from conveyancing searches, but sellers will not necessarily be fully aware of the latest radon risk classification in their area. Hence, with information mostly coming from the buyer-side, only upwards movements in radon risk classification get priced in.

In table 5, we attempt to exclude as many confounders as possible by using the tighter geographical fixed-effects available in the data (Output Area), which means that identification is based on comparing homes in the same micro locations. More specifically, we interact Output Area indicators with years of sale to focus on houses selling in the same pair of years and the same area. These specifications control for changes in local amenities such as school quality, public transport or ambient air pollution but also for changes in the composition of the neighbourhood (i.e. sorting), which helps identify the direct impact of map changes on the affected houses (Ekeland et al., 2002). Reassuringly, the estimated coefficients remain highly significant and similar to the findings in Table 4. Again, we find that upward changes in risk significantly affect house prices, but downward changes do not. However, the effect of upwards risk reclassification are slightly higher than those estimated conditional on labour-market trends, but they are also less precisely estimated given the natural reduction in the sample size when

[15] As we discuss further below, it may be that the smaller magnitude of the coefficients when we add higher risk categories follows from unobserved radon remedial works in higher risk category homes. In many later regressions we will focus solely on homes that move from category 1 to category 2 for this reason.

using such restrictive fixed-effects.

Using the results discussed above and the cumulative risks of lung cancer at different radon concentrations (category levels) by smoking status,[16] we can test whether house price responses to radon risk information updates are consistent with monetised changes in lung cancer risk. We first calculate the implied monetary values of lung cancer risk in each risk category using a value of a statistical life of £5 million,[17] and official estimates of smoking prevalence by the UK Office of National Statistics (ONS).[18] Based on the above, and by assuming an average household size of 2.3, we estimate that moving from category 1 to category 2 should yield an increase in risk with a present value of between £800 and £1,400 per household on average. While this is by necessity assumption heavy, our estimated coefficient for moving up from category 1 to category 2 in column 3 panel A of Table 5 implies a change in house prices of roughly £4,300, which is larger than the implied value of risk. This back of the envelope calculation suggests that market participants are overreacting to the risk, which would be consistent with findings in the literature (Sunstein and Zeckhauser, 2011; Dessaint and Matray, 2017). Having said that, there is considerable uncertainty about the appropriate VSL here, and in any case we cannot rule out a rational valuation of risk since the 95% confidence interval for our central estimate puts the change in house prices in the range £1,212 to £7,479.

Results so far have been based on movements from and to category 1 radon risk. In Table 6 we examine the effect of upwards and downwards movements in house level radon risk more generally. In column (1)-(3) we estimate the effect of moving up and down 1 or more categories from different starting categories conditional on labour-market price trends. In column (1) we retain houses that start in category 1, in column (2) we examine the average effect of going up or down one or more categories from categories 2 and 3, and in column (3) for houses that start initially in categories 4,5 and 6. We find that going up and down risk categories from categories 2 and 3 both yield price reductions, but the coefficients are smaller than in column (1) and not significant at any conventional level. In column (3) we find that the same result for going up and down categories when a house starts in categories 4,5 and 6. In columns (4)-(6) we repeat the analysis, but using only houses where risk categories stay the same or go up or down by 1 category (i.e. we drop houses that move more than one category). This yields similar coefficients to those obtained in columns (1) and (3), but the discount attracted

[16] The source for this is Table 4.3 of the Health Protection Agency report "Radon and Public Health: Report of the independent Advisory Group on Ionising Radiation" https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/335102/RCE-11_for_website.pdf.

[17] The choice of this VSL is of course arbitrary but this value is within the typical range used in the US.

[18] According to the UK Office of National Statistics, 14.7% of people aged 18 years and above are smokers. For more details see the following: https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/healthandlifeexpectancies/bulletins/adultsmokinghabitsingreatbritain/2018. On the basis that adults represent 70% of the population, we assume that approximately 10% of the population smoke.

by going down risk category from categories 2 and 3 is now statistically significant and comparable to our estimate in column (2).

In Table 7 we use a balanced panel of Output Areas with two periods (we collapsed years between 2003 and 2011 into periods before and after the 2007 map is issued) to test whether an increase in radon risk affects the number of housing transactions. In column (1) we show a positive correlation between the number of transactions and changes in radon. In columns (2)-(4) we estimate the effect of changes in radon risk corresponding to our earlier specifications. Similar to our house price analysis, we find that the effect is not symmetric, an increase in the radon risk level at the OA level increases the number of transactions in that area, but a reduction in the risk does not significantly affect the number of transactions. In column (5) we test the impact of changes in radon levels on the average transaction price in the OA, using all rather than just repeated sale transactions. Reassuringly, the results are consistent with our earlier estimates.

To summarise, in this section we find compelling evidence that market participants do react to house level radon risk information, but that the nature of this reaction is not straightforward. Specifically, we find large effects on house prices when a house moves from a "radon free" classification to "a radon affected area" classification, but little evidence that movements between other risk categories affect prices.[19] Finally, we find no evidence that going down categories increases prices, which might be due to sellers being unaware of changes to radon risk categories.

5.2 Sorting

In this section we investigate the possibility that changes in radon risk information may lead to taste-based sorting of residents across properties and neighbourhood for two main reasons. First, it may explain all or some of the price changes that we observed above. For example, if an upward change in radon risk level attracts less wealthy individuals, we might expect to see a drop in property prices in response to this compositional change to the extent in which living near wealthy individuals is more attractive (Ioannides and Zabel, 2003; Topa and Zenou, 2015; Kling et al., 2007). Although, our reduced from results adjust for neighbourhood composition using OA trends, it is unclear whether these estimates can be classified as the average willingness to pay to avoid radon of the average buyer, since

[19] One possible explanation for the lack of evidence for high risk categories could be that houses in these higher risk categories have undertaken radon remedial works, such as installing a radon sump, so that actual radon risk is lower than what we observe in our data. Although we lack data on house level remedial measures, Public Health England releases information on the number of house radon tests conducted in each postcode sector, which should be a good predictor of remedial measures. In table 9 we exclude postcode areas where PHE reports that the number of house radon tests is greater than 1% of the number of address points. Reassuringly, coefficients are similar to, and statistically indistinguishable from our main results.

it requires the strict assumption that buyers do not sort based on radon (Greenstone, 2017). Second, testing for sorting might also help us to shed light on issues of environmental justice (e.g. Banzhaf et al., 2019; Hausman and Stolper, 2020).

In Table 8 we test whether residents sort in response to changes in radon risk using census data by regressing changes in Output Area characteristics between the 2001 and 2011 Census on our main radon treatment variable (collapsed to the Output Area level), conditional on labour-market (TTWA) fixed effects. The table shows that the share of people with characteristics normally correlated with higher house prices, such as being educated, having higher income and social status (Ioannides and Zabel, 2003; van Ham and Manley, 2009), decreases in response to upward radon risk reclassification. Interestingly, the share of owner occupiers falls, which is expected as renters may not receive information about radon or may be more likely to accept temporary exposure related to short term tenancy. At the same time, we find that the same Census variables are not statistically correlated with reclassification downwards to a risk free area at the conventional levels. Overall these findings lead us to two important conclusions. First, radon risk falls disproportionately on lower socio-economic groups, as they move into affected areas in search for a price discount: an example of environmental injustice that results from sorting. Second, we are unable to support the assumption of no sorting as a consequence of the reclassification, and we therefore interpret our previous estimates as "local" in the sense that they reveal the WTP of the specific buyers who are purchasing houses affected by radon. In other words, it is the market price of indoor air pollution risk in the housing market, under supply determined by the pre-determined housing stock and the natural experiment, while demand is determined by preferences of the population. However, since we are also interested in the average willingness to pay for avoiding radon, in Section 6 we propose and utilise a new theoretical framework to estimate this policy relevant parameter.

5.3 Robustness and placebo tests

In this section we provide a set of placebo and robustness tests to support the soundness of our empirical analysis. We begin by conducting a placebo test in which we examine the impact of the change in radon maps introduced in 2007 on transaction pairs in which both first and second sales happen after 2010. In other words, we apply the change between the 2003 and 2007 radon maps to properties for which both transactions occurred after 2011. This approach checks for local trends correlated to changes in radon (including long-term trends induced by sorting). The first four columns in Tables 9 use the placebo treatment and find no effect, demonstrating that our treatment effect cannot be attributed to a long-term trend that is correlated to changes in radon. This also suggests that the sorting effects occur relatively quickly after the maps change.

In the last two columns of Table 9, we assess if our estimates are affected by measurement error, as previously discussed in Section 4. To address this issue, we take advantage of the fact that the majority of home radon measurements in the UK are recorded by PHE (the government agency which subsidises radon measurements). Our strategy is to replicate our results but restricting attention only to areas where fewer than 1% of houses have had measurements taken by PHE. Findings in column (5) control for labour-market trends and in column (6) adopt the more granular OA fixed effects. In both cases estimates are similar to our baseline results, demonstrating that home radon measurement are unlikely to be a major source of bias in our estimates. These findings thus provide further reassurance that our main results are robust to mis-measurement that may arise as a consequence of a dwelling having an evaluation of radon risk independent of the publicly-available radon maps.

A related problem could arise if a house is purchased with cash rather than a mortgage. Since cash buyers are not formally required to request an environmental search for their house (CON29), they may not have information on radon. In this case, it is possible that the buyer would not receive information about radon risk. To test if this is affecting our results, we use a sub sample of transactions financed by the mortgage provider Nationwide Building Society.[20] To check if transactions with mortgages are different from the rest of the sample, we add a dummy variable denoting having a mortgage from Nationwide and interact it with the treatment variable. The results presented in Table A3 in the appendix demonstrate that the sample of houses that have certainly been bought with a mortgage receives the same treatment effect as the rest of our sample. This shows that our results are unlikely to be biased by mis-measuring the information that cash buyers receive.

In our final test of robustness we explore the assumption that prices react to radon information given to buyers by Local Authorities through form CON29. More specifically we leverage that we know which version of the 2007 radon map - the 50m grid or the 1km grid - is being used by an LA to provide radon risk information at the time of the second sale, and we run tests to check that is this information which is indeed driving house price changes. In column 1 of in Table A2, we first separate out the treatment variable for the two different versions of the map and estimate the effect for each group. Reassuringly we find that the impact of radon reclassification to 'radon affected' is the same regardless of which version of the map is being used to provide this information. In column 2 we restrict attention to sales where CON29 is based on the 50m grid map and test if a radon treatment defined using the 1km grid information affects prices. Perhaps surprisingly, it does not. However,

[20] Data for transactions financed by Nationwide come directly from the lender.

more reassuringly, when information on radon changes from both 1km and 50m grids is included in this same regression in column 3, only the latter matters for transactions that have access to it. This provides further convincing evidence that the effects we estimate stem from information transmitted in the CON29 form.

6 Theoretical and empirical framework to identify WTP

Given the difficulties in estimating WTP in the presence of sorting, in this section we outline some well-known challenges in identifying WTP only from changes in market prices, and we propose a new framework, which uses transaction probabilities, to mitigate these challenges.

6.1 The household

We begin by specifying the household problem using a standard model of housing choice with heterogeneous houses and preferences suggested by Bayer et al. (2007). Here, households (q) maximise their indirect utility (V) by choosing to live in a house (i) with some characteristics (h), a level of radon risk (r) which is purchased at a certain price (p). Formally, the household maximisation problem can be written as follow:

$$maxV_i^q(h_i, r_i, p_i) = \alpha_h^q h_i + \alpha_r^q r_i - \alpha_p^q p_i \tag{5}$$

where $\alpha_{h,r,p}$ are household-specific parameters which reflect different household preferences and budgets that vary with characteristics of households (defined as z^q) such as income, race, employment status, aversion to lung cancer and smoking habits. We express the relationship between the household-specific parameter of each characteristic of a house or the area denoted by j (where, $j \in \{h, r, p\}$) as:

$$\alpha_j^q = \alpha_{0j} + \sum_{k=1}^{k} \alpha_{kj} z_k^q \tag{6}$$

This expression shows the preference of household q for characteristic j, which also applies to the preference for radon risk. The first term of the above equation gives the mean parameter across the population while the second is the idiosyncratic preference term. Naturally, the empirical challenge is to estimate α_{0r}, which is the average WTP in the population and therefore the policy relevant parameter. Note that estimating WTP only from the impact of radon on the market price requires an assumption that $\sum_{k=1}^{k} \alpha_{kj} z_k^q = 0$ which is unlikely to hold in many settings (see Kuminoff and Pope (2014) for more detail).

6.2 The housing market

The above household problem can be used to characterize housing demand. The probability that household q decides to live in house i is a function of characteristics of the household and the house (including its price and radon risk) and can be written as follow:

$$P_i^q = f_i\left(z^q, p_i, h_i, r_i\right) \tag{7}$$

The aggregate demand for house i can therefore be given by:

$$D_i = \sum_q P_i^q \tag{8}$$

The market clearing condition is that $\sum_q P_i^q = S_i$ and price p_i is the market clearing price which depends on the total amount of houses of type i and the demand for these houses.[21] Bayer et al. (2004) provide a solution to this model showing that this price increases when demand for houses of this type exceeds supply and decreases in the opposite case.

The corollary of the above is that the effect of radon on the market clearing price is not necessarily the same as the average WTP. The supply of any one type of houses is fixed so the price of an affected house is determined by matching demand for those houses to the supply. However, the average household living in a radon affected house can have a different preference for radon than an average household. If the supply of radon affected houses is high compared to demand, the price discount will be more than the WTP to avoid radon risk as even households that are more averse to radon than the average will move into an affected house when the price of that house is low enough. If the supply of radon affected houses is low compared to demand, the price discount will be less than the WTP. In this case only those who have the highest WTP for a radon affected house will purchase them. This process is usually referred to as sorting, a mechanism where households locate in places where their preference-adjusted utility is maximized (Bayer et al., 2007). Since in our model marginal utility is zero for all households, sorting is reflected in the idiosyncratic preference for characteristics of a house, and every house is inhabited by the household with the highest preference for its characteristics. To illustrate the impact of sorting on the market-clearing price, consider a simple case where characteristics of potential buyers are endogenous to prices and characteristics of the houses in the housing stock. When prices decrease, more potential buyers with a preference for low prices enter the market. When houses are treated with higher radon risk, more buyers with a preference for higher radon risk houses enter the market. These buyers will end up purchasing the affected dwellings and the observed

[21] Note that each housing type has its own equilibrium price. For simplicity we focus on modelling the price of a single type of a house (affected by radon) and ignore the general equilibrium effect on other house types.

transaction price will be higher than it would be without sorting.

6.3 Identifying WTP

As different households have different preferences, WTP is not observed directly in the data. However, we develop a strategy that allows us to estimate WTP from the impact of radon on transaction prices and the number of transactions that occur at those prices. The idea here is that if the transaction price is the market-clearing price, the probability of a transaction at that price can help us to reveal the WTP of an average treated owner. The following section explains this empirical strategy in detail.

At the very basic level, a house is sold if the value it delivers to the owner is lower than the value it delivers to the highest bidder. Both of these values are determined by the same household problem (outlined above), and the results differ due to different budgets and preferences. Based on the fact that our treatment is orthogonal to household characteristics of owners, we can assume that the distribution of preferences of the treated owners is random (reflecting different characteristics of households). At the same time, the sorting mechanism that we explained above shows that the composition of preferences of the highest bidders is likely to be endogenous to prices and the corresponding characteristics of properties in the housing stock. For example, properties affected by radon risk attract buyers with different characteristics than properties without radon risk. Furthermore, these buyers will face a different supply and demand conditions than buyers of an unaffected house.

To present a more general analysis we suppress subscripts denoting households and house types and describe a matching process of an owner and a buyer for a house of a specific type. We denote the valuation of the owner W^O and the valuation of the buyer with the highest willingness to pay for it (the maximum bidder) W^B. We assume that both valuations are random to allow for preferences. Since the treatment is assigned randomly to the owners, the preference-based idiosyncratic component of their valuation is expected to be zero on average so that the mean change in the valuation of the house on the owner side when the house is affected by radon (denoted by R) is simply the WTP denoted as ϕ and we can therefore write it as follow:[22]

$$W_R^O = W^O - \phi \tag{9}$$

On the buyer side, the situation is more complicated due to the sorting process and the potential mismatch of supply and demand for houses of a particular type. We specify this by allowing the buyer's

[22]Note that when radon is a binary variable, ϕ equals α_{0r} from the household problem above.

valuation to change by an additional factor φ, which accounts for this sorting and the mismatch between supply and demand for affected houses:

$$W_R^B = W^B - \phi + \varphi \tag{10}$$

At this point we are agnostic about the sign of φ as the above analysis shows that it could be positive, negative or zero. It simply allows buyers to be affected in different ways than owners and its value is an empirical question, which is not the focus of this paper. Importantly, φ gives the difference to the impact of radon on the average owner (not the average seller) which will allows us to identify the impact of radon on the valuation to the average owner.

The next step is to match owners of the affected houses with the highest bidders for their house. We assume that the (market clearing) transaction price is generated by a Nash bargaining solution where $0 < \alpha < 1$ gives the fraction of the surplus attributable to the buyer. For transactions that occur the bargain struck for a house without radon will pick price p that maximizes:

$$Q(p) = \left(W^B - p\right)^{\alpha} \left(p - W^O\right)^{(1-\alpha)} \tag{11}$$

For the radon affected case:

$$Q(p_R) = \left(W^B - \phi - \varphi - p_R\right)^{\alpha} \left(p_R - W^O - \phi\right)^{(1-\alpha)} \tag{12}$$

Maximizing with respect to price yields:

$$p_R = (1-\alpha)\left(W^B - \phi - \varphi\right) + \alpha\left(W^O - \phi\right) \tag{13}$$

Which gives the observed transaction prices of houses affected by radon. In this equation, buyers are allowed to sort based on their preferences and supply/demand conditions (i.e. they have a different willingness to pay than the population average of ϕ). The difference between the owner's valuation and the buyer's valuation is defined as a random variable $\lambda = W^B - W^O$. The difference between the seller and buyer valuations for a radon affected house is:

$$\lambda_R = \left(W^B - \phi - \varphi\right) - \left(W^O - \phi\right) = W^B - W^O - \varphi \tag{14}$$

This clearly shows that λ only changes due to φ. Combining the last two equations gives, for an affected and unaffected house respectively:

$$p_R = (1-\alpha)\lambda_R + W^O - \phi \tag{15}$$

$$p = (1-\alpha)\lambda + W^O \tag{16}$$

To estimate ϕ we can write first differences describing the change in the price of a house when it is re-classified from radon-free to radon-affected house:

$$p_R - p = \Delta p = (1-\alpha)(\lambda_R - \lambda) + W^O - W^O - \phi = (1-\alpha)(\lambda_R - \lambda) - \phi \tag{17}$$

Between the two cases, W^O does not change, there is no ϕ in the case of the unaffected house and $\lambda_R - \lambda = \varphi$ so the equation simplifies to:

$$\Delta p = (1-\alpha)\varphi - \phi \tag{18}$$

Which gives a very intuitive result that the change in price is the WTP plus the impact of sorting and supply/demand mismatch multiplied by the market power parameter. Furthermore, when sellers are price takers and $\alpha = 1$, this is similar to hedonic models and WTP can be calculated from changes in market prices.

Note that Δp is already estimated to be - £3,375 (from column (5) table 5) so ϕ can be calculated if φ and α are known. First, we set α to be 59.3% based on Besley et al. (2014), who estimated this parameter using the same data. Second, we note that φ can be calculated from probabilities of transactions with an identifying assumption that λ and λ_R have the same distribution denoted by $G(.)$. For simplicity (and following Besley et al. (2014)), we assume that $G(.)$ is a normal distribution. A transaction occurs only when the buyer's valuation exceeds the owner's valuation and the likelihood of this happening for a property is denoted by T and given by $P(\lambda > 0)$:

$$T = \int_0^\infty G(\lambda)d\lambda \tag{19}$$

If both valuations are affected by radon in the same way, this probability does not change (λ does not change so T remains unchanged). However, if radon affects valuations of owners and buyers differently, the probability of a transaction can change. Therefore, the probability of a transaction of a house affected by radon is T_R:

$$T_R = \int_0^\infty G(\lambda)d\lambda + \int_0^\varphi G(\lambda_R)d\lambda_R \tag{20}$$

Where the second term gives the change in the probability due to being affected by sorting on preferences for radon, as shown in Figure 2.

From this we know $T = 2.48\%$[23] and $T_R - T = 0.03\%$[24]. To solve for φ we follow Besley et al. (2014) and assume that $G(.)$ is normal with $\sigma = 7082$. This allows us to calculate $E(\lambda)$ for unaffected properties at -£13,904, $\varphi =$£36 and $\phi =$£3,360. Converting ϕ into a percentage value of the price of an unaffected property gives 1.66% which is our estimate of the average WTP. From this we conclude that the impact of sorting is very small and the hedonic estimate is very close to the average WTP.

7 Conclusion

We provide the first empirical evidence on the economic effects of indoor air pollution. By focusing on radon and the housing market, we are able to address many of the key challenges in the existing air pollution literature and provide compelling evidence that market participants react to information about indoor air pollution related to radon. Our results show that prices of houses affected by exogenous increases in radon risk decrease significantly. Our preferred specifications place the magnitude of the estimate in the range of 1.3% to 1.7%. This is larger but broadly in line with the effect which would be expected from a rational response to the health risk posed by radon (based on the value of a statistical life). We also find that changes in radon risk cause sorting and corresponding changes in characteristics of residents of the affected areas. Specifically, we show that residents from higher SEGs move out of places that are newly affected by radon, and that people from lower SEGs move in. These results thus highlight how sorting leads to the disproportionate exposure of lower SEGs to indoor air pollution. Although beyond the scope of our paper, we note that this environmental injustice may be exacerbated if individuals in these SEGs are less able to adopt radon remedial measures, for example because of credit or informational constraints.[25]

Our results prove to be robust to multiple tests, but they are still limited by the institutional setting and data availability. Most notably, while we find no evidence that reclassifying a house from a radon affected to a radon free category increases prices, we are unable to conclusively determine whether this is due to sellers being unaware of changes to radon levels (unlike the buyers), or due to small sample

[23] Estimated as the number of transactions per quarter: 3.094548 over the population of houses in the OA in 2011: 125.

[24] Estimated as $T_p = 2.48\%$ multiplied by one plus the change in transaction numbers reported in Table 7 of 1.14% giving $T_{pr} = 2.51\%$.

[25] This seems plausible because surveys suggest the main reason for households not remediating radon is cost. See Appendix D of the report of the Independent Advisory Group on Ionising Radiation https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/335102/RCE-11_for_website.pdf

size. For similar reason, we are unable to exploit changes in the magnitude of radon risk in affected houses to understand how households react to changes in risk more generally.

We also provide new evidence on how the housing market reacts to information about environmental risks. We show that mandatory information provision has a strong effect on household choices and that, at least in the case of radon, prices react to the information about the risk even when the actual level of risk is the same.

Overall, our analysis highlights the importance of considering the extent and distribution of indoor air pollution costs alongside those of ambient air pollutants. Given the significant amount of time that we spend indoors, and the relatively little policy and research attention to this subject, we argue that much more focus should be directed towards this issue in future work.

References

AGIR (2009). Radon and Public Health. Report of the independent Advisory Group on Ionising Radiation. Documents of the Health Protection Agency. Radiation, Chemical and Environmental Hazards RCE-11, Health Protection Agency.

Banzhaf, S., Ma, L., and Timmins, C. (2019). Environmental justice: The economics of race, place, and pollution. *Journal of Economic Perspectives*, 33(1):185–208.

Barwick, P. J., Li, S., Lin, L., and Zou, E. (2019). From fog to smog: The value of pollution information. Technical report, National Bureau of Economic Research.

Bayer, P., Ferreira, F., and McMillan, R. (2007). A Unified Framework for Measuring Preferences for Schools and Neighborhoods. *Journal of Political Economy*, 115(4):588–638.

Bayer, P., McMillan, R., and Rueben, K. (2004). An Equilibrium Model of Sorting in an Urban Housing Market. Technical report.

Besley, T., Meads, N., and Surico, P. (2014). The incidence of transaction taxes: Evidence from a stamp duty holiday. *Journal of Public Economics*, 119(C):61–70.

Bosker, M., Garretsen, H., Marlet, G., and van Woerkens, C. (2018). Nether Lands: Evidence on the Price and Perception of Rare Natural Disasters. *Journal of the European Economic Association*, 17(2):413–453.

Cannaday, R. E., Munneke, H. J., and Yang, T. T. (2005). A multivariate repeat-sales model for estimating house price indices. *Journal of Urban Economics*, 57(2):320–342.

Chay, K. Y. and Greenstone, M. (2005). Does Air Quality Matter? Evidence from the Housing Market. *Journal of Political Economy*, 113(2):376–424.

Currie, J., Davis, L., Greenstone, M., and Walker, R. (2015). Environmental Health Risks and Housing Values: Evidence from 1,600 Toxic Plant Openings and Closings. *American Economic Review*, 105(2):678–709.

Cutter, W. B. and Neidell, M. (2009). Voluntary information programs and environmental regulation: Evidence from 'spare the air'. *Journal of Environmental Economics and management*, 58(3):253–265.

Darby, S., Hill, D., Deo, H., Auvinen, A., Barros-Dios, J. M., Baysson, H., Bochicchio, F., Falk, R., Farchi, S., Figueiras, A., Hakama, M., Heid, I., Hunter, N., Kreienbrock, L., Kreuzer, M., Lagarde, F., Mäkeläinen, I., Muirhead, C., Oberaigner, W., Pershagen, G., Ruosteenoja, E., Rosario, A. S., Tirmarche, M., Tomášek, L., Whitley, E., Wichmann, H.-E., and Doll, R. (2006). Residential radon and lung cancer—detailed results of a collaborative analysis of individual data on 7148 persons with lung cancer and 14 208 persons without lung cancer from 13 epidemiologic studies in europe. *Scandinavian Journal of Work, Environment & Health*, 32:1–84.

Dessaint, O. and Matray, A. (2017). Do managers overreact to salient risks? Evidence from hurricane strikes. *Journal of Financial Economics*, 126(1):97–121.

Duflo, E., Greenstone, M., and Hanna, R. (2008). Indoor air pollution, health and economic well-being. *S.A.P.I.EN.S. - Surveys and Perspectives Integrating Environment and Society*.

Ekeland, I., Heckman, J. J., and Nesheim, L. (2002). Identifying hedonic models. *American Economic Review*, 92(2):304–309.

Fuerst, F., McAllister, P., Nanda, A., and Wyatt, P. (2015). Does energy efficiency matter to home-buyers? An investigation of EPC ratings and transaction prices in England. *Energy Economics*, 48:145–156.

Gilraine, M. (2019). Air Filters, Pollution and Student Achievement. Technical Report 188, Annenberg Institute at Brown University.

Gray, A., Read, S., McGale, P., and Darby, S. (2009). Lung cancer deaths from indoor radon and the cost effectiveness and potential of policies to reduce them. *BMJ*, 338.

Greenstone, M. (2017). The Continuing Impact of Sherwin Rosen's "Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition". *Journal of Political Economy*, 125(6):1891–1902.

Greenstone, M. and Gallagher, J. (2008). Does Hazardous Waste Matter? Evidence from the Housing Market and the Superfund Program. *The Quarterly Journal of Economics*, 123(3):951–1003.

Gruber, V., Bossew, P., Cort, M. D., and Tollefsen, T. (2013). The European map of the geogenic radon potential. *Journal of Radiological Protection*, 33(1):51–60.

Hastings, J. S. and Weinstein, J. M. (2008). Information, school choice, and academic achievement: Evidence from two experiments. *The Quarterly journal of economics*, 123(4):1373–1414.

Hausman, C. and Stolper, S. (2020). Inequality, information failures, and air pollution. Technical report, National Bureau of Economic Research.

Howe, G. R., Nair, R. C., Newcombe, H. B., Miller, A. B., and Abbatt, J. D. (1986). Lung Cancer Mortality (1950–80) in Relation to Radon Daughter Exposure in a Cohort of Workers at the Eldorado Beaverlodge Uranium Mine. *JNCI: Journal of the National Cancer Institute*, 77(2):357–362.

Ioannides, Y. M. and Zabel, J. E. (2003). Neighbourhood effects and housing demand. *Journal of Applied Econometrics*, 18(5):563–584.

Jessoe, K. and Rapson, D. (2014). Knowledge is (less) power: Experimental evidence from residential energy use. *American Economic Review*, 104(4):1417–38.

Kask, S. B. and Maani, S. A. (1992). Uncertainty, information, and hedonic pricing. *Land Economics*, 68(2):170–184.

Klepeis, N., Nelson, W., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. V., Hern, S. C., and Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Science and Environmental Epidemiology*, 11:231–252.

Kling, J. R., Liebman, J. B., and Katz, L. F. (2007). Experimental analysis of neighborhood effects. *Econometrica*, 75(1):83–119.

Krewski, D., Lubin, J. H., Zielinski, J. M., Alavanja, M., Catalan, V. S., Field, R. W., Klotz, J. B., Létourneau, E. G., Lynch, C. F., Lyon, J. I., Sandler, D. P., Schoenberg, J. B., Steck, D. J., Stolwijk, J. A., Weinberg, C., and Wilcox, H. B. (2005). Residential Radon and Risk of Lung Cancer: A Combined Analysis of 7 North American Case-Control Studies. *Epidemiology*, 16(2):137–145.

Kuminoff, N. V. and Pope, J. C. (2014). Do "capitalization effects" for public goods reveal the public's willingness to pay? *International Economic Review*, 55(4):1227–1250.

Künn, S., Palacios, J., and Pestel, N. (2019). Indoor air quality and cognitive performance.

Lubin, J. H., Wang, Z. Y., Boice Jr, J. D., Xu, Z. Y., Blot, W. J., De Wang, L., and Kleinerman, R. A. (2004). Risk of lung cancer and residential radon in China: Pooled results of two studies. *International Journal of Cancer*, 109(1):132–137.

Moulton, J. G., Sanders, N. J., and Wentland, S. A. (2018). Toxic assets: How the housing market responds to environmental information shocks. Technical report.

Naoi, M., Seko, M., and Sumita, K. (2009). Earthquake risk and housing prices in Japan: Evidence before and after massive earthquakes. *Regional Science and Urban Economics*, 39(6):658–669.

NRPB (1996). Radon Affected Areas: England. Doc NRPB 7(2): 1-9, NRPB.

PHE (2018). UK National Radon Action Plan. Public Health England.

Pope, J. C. (2008). Buyer information and the hedonic: the impact of a seller disclosure on the implicit price for airport noise. *Journal of Urban Economics*, 63(2):498–516.

Radford, E. P. and Renard, K. G. S. C. (1984). Lung Cancer in Swedish Iron Miners Exposed to Low Doses of Radon Daughters. *New England Journal of Medicine*, 310(23):1485–1494.

Roth, S. (2019). The contemporaneous effect of indoor air pollution on cognitive performance: Evidence from the UK. In *mimeo*.

Smith, V. K. and Johnson, F. R. (1988). How do Risk Perceptions Respond to Information? The Case of Radon. *The Review of Economics and Statistics*, 70(1):1–8.

Stafford, T. M. (2015). Indoor air quality and academic performance. *Journal of Environmental Economics and Management*, 70:34–50.

Sunstein, C. R. and Zeckhauser, R. (2011). Overreaction to Fearsome Risks. *Environmental and Resource Economics*, 48:435–449.

Tirmarche, M., Raphalen, A., Allin, F., Chameaud, J., and Bredon, P. (1993). Mortality of a cohort of French uranium miners exposed to relatively low radon concentrations. *British Journal of Cancer*, 67:1090–1097.

Topa, G. and Zenou, Y. (2015). Neighborhood and network effects. In *Handbook of regional and urban economics*, volume 5, pages 561–624. Elsevier.

US-EPA (2013). EPA map of radon zones.

van Ham, M. and Manley, D. (2009). The effect of neighbourhood housing tenure mix on labour market outcomes: A longitudinal investigation of neighbourhood effects. *Journal of Economic Geography*, 10(2):257–282.

WHO (2009). WHO handbook on indoor radon: A public health perspective. Technical report, World Health Organization.

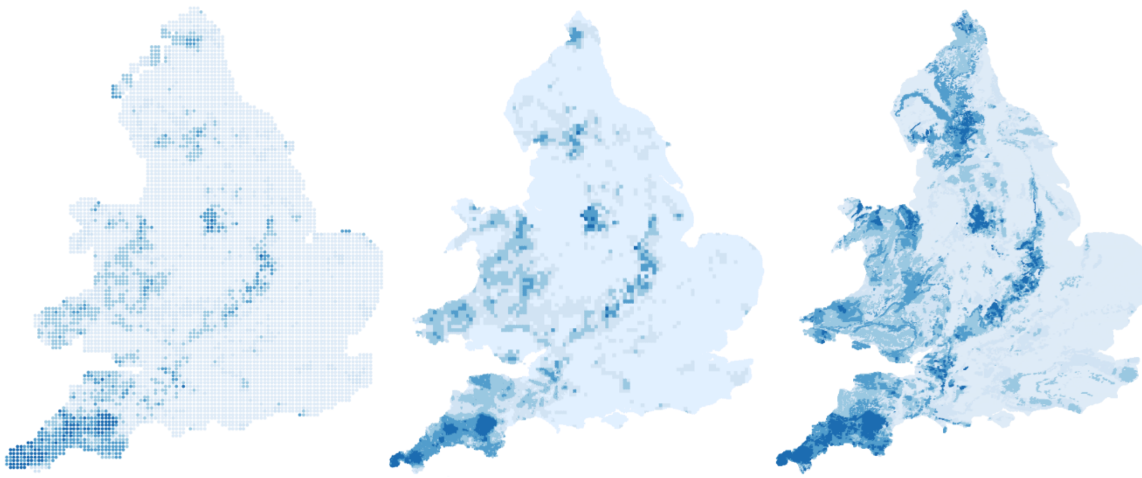
Wichman, C. J. (2017). Information provision and consumer behavior: A natural experiment in billing frequency. *Journal of Public Economics*, 152:13–33.

Zielinski, J. M., Carr, Z., Krewski, D., and Repacholi, M. (2006). World Health Organization's International Radon Project. *Journal of Toxicology and Environmental Health, Part A*, 69(7-8):759–769. PMID: 16608837.

Zivin, J. G. and Neidell, M. (2009). Days of haze: Environmental information disclosure and intertemporal avoidance behavior. *Journal of Environmental Economics and Management*, 58(2):119–128.

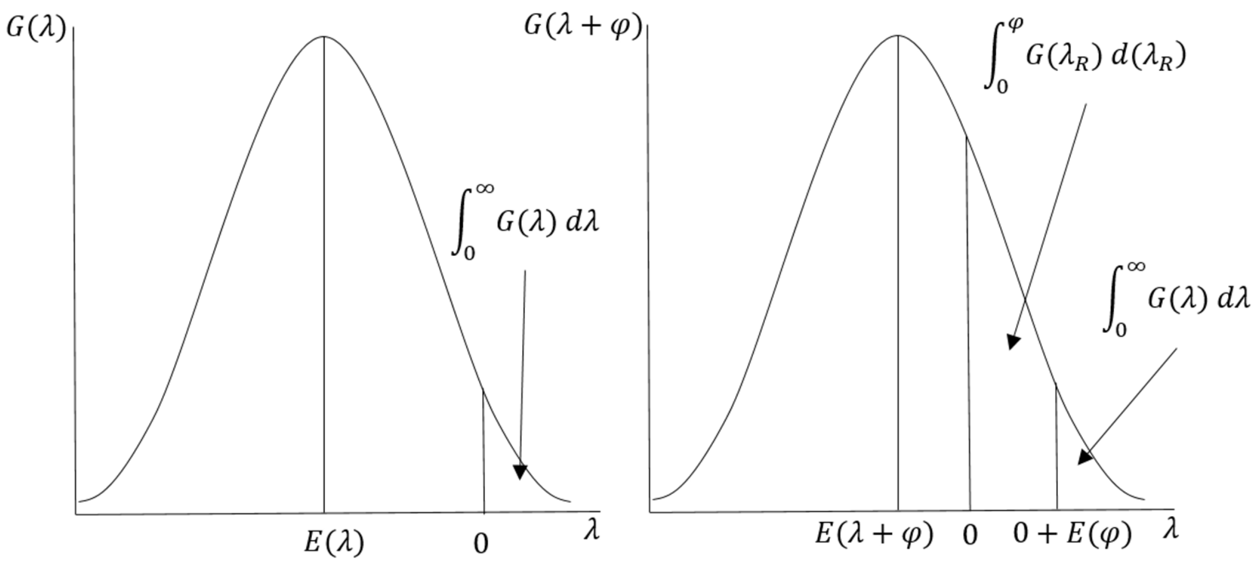
8 Tables and Figures

Figure 1: Radon Maps



Notes: The maps give the level of radon risk from 1 to 5 in the first map and from 1 to 6 in the other two with darker blue corresponding to higher levels of radon.

Figure 2: The graphical representation of the probability of transacting a house with (right) and without (left) radon.



Notes: λ: difference between the seller and buyer valuation. $G(.)$: distribution of λ. φ difference between the valuation of the highest-bidding buyer and the average buyer for a radon-affected house, $\lambda_r = \lambda + \varphi$. Probability to the right of zero gives the probability of a transaction. We are agnostic about what is the value of $E(\lambda)$ is, but based on our later results we present a case where $E(\lambda) < 0$, $E(\lambda + \varphi) < 0$, and $E(\varphi) > 0$.

Table 1: Summary statistics: Repeated transactions with changing radon levels.

	Radon 2nd sale						
Radon 1st sale	1(Radon-Free)	2	3	4	5	6	Total
1(Radon-Free)	1,099,211	81,876	12,770	8,913	3,772	440	1,206,982
2	19,855	88,180	5,912	5,909	4,287	451	124,594
3	1,823	2,142	17,794	2,457	2,702	611	27,529
4	602	401	401	11,582	3,415	1,054	17,455
5	140	184	128	664	14,145	3,566	18,827
6	0	1	0	2	149	3,391	3,543
Total	1,121,631	172,784	37,005	29,527	28,470	9,513	1,398,930

Notes: the table gives the number of repeated transactions for the estimation period which means that only first transactions after 2002 and second transactions before 2012 are included. The total number of transactions is around 2.8m. Data on transactions comes from Land Registry and on radon levels from PHE.

Table 2: Summary statistics: Average prices of house prices and changes in radon.

		(1)	(2)	(3)	(4)	(5)
		Radon=1	Radon>1	Δradon=0	Δradon>0	Δradon<0
Price	Mean	202,132	194,895			
	St. Dev.	197,498	166,836			
Change in price	Mean			34,788	28,731	21,692
	St. Dev.			92,006	71,656	65,990
N		6,482,879	2,208,866	1,234,303	254,016	26,492

Notes: the table gives the number of individual transactions in columns 1-2 and repeated transactions in columns 3-5. The data is the estimation period which means that only first transactions after 2002 and second transactions before 2012 are included. Data on transactions comes from Land Registry and on radon levels from PHE.

Table 3: Balancing tests: Output Area characteristics and changes in radon (from 1 to any other category).

Outcome variable (share of):	(1) Coefficient	(2) S.E.	(3) R^2
Students	0.000	0.0002	0.058
People in employment	0.000	0.0027	0.128
Higher social status	-0.007	0.0049	0.22
People with university degrees	-0.0109***	0.0035	0.263
People living alone	0.001	0.0006	0.064
Owner occupiers (outright or mortgage)	0.0023	0.0078	0.099
People living in social housing	0.0109	0.0075	0.076
House outright owners	-0.0001	0.0043	0.108
Households with children	0.0018	0.0016	0.034
People in their 30's	-0.0018	0.0012	0.135
Mid-aged people	0.0021	0.0013	0.094
People in their 60's	0.0033	0.0022	0.107
Households who moved into the area from far	-0.2651	0.1774	0.044
Households who moved within the area	0.0029	0.01	0.026
Houses with the lowest floor - basement	-0.0956	0.1943	0.153
Houses with the lowest floor - ground	0.8442	0.6005	0.291
Houses with the lowest floor - first	-0.7026	0.4387	0.281
People working in health services	0.1362	0.0981	0.156
People reported not to be in good health	-0.0015	0.0013	0.157
People who work from home	-0.0002	0.0009	0.093
People who work within 2km of the house	0.0018	0.0034	0.161
Houses with 4 or more rooms	0.0007	0.0031	0.072

Notes: Each row gives the results of a pairwise regression with the area characteristic as the LHS variable and change in radon at OA level on the RHS. Regressions include TTWA fixed effects. The sample size is 85515 for all regressions and the data is based on Output Areas from the 2001 census. All variables are shares. The independent variable is a dummy that equals one if the maximum level of radon changed from 1 to any other category. Only places with the 1km grid are included. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 4: The Effect of Radon Risk on House Prices with TTWA trends.

	(1) X={2}	(2) X={2,3}	(3) X={2,3,4}	(4) X={2,3,4,5}	(5) X={2,3,4,5,6}
Panel A: $1 \rightarrow X$	-0.0164+	-0.0140+	-0.0137+	-0.0133+	-0.0133+
	(0.00291)	(0.00281)	(0.00261)	(0.00258)	(0.00257)
N	496115	508891	517820	521586	522026
R^2	0.235	0.236	0.236	0.237	0.237
Panel B: X $\rightarrow$ 1	-0.00442	-0.00407	-0.00363	-0.00365	-0.00365
	(0.00377)	(0.00331)	(0.00326)	(0.00326)	(0.00326)
N	35789	39036	40325	43373	44374
R^2	0.291	0.302	0.305	0.306	0.307

Notes: Standard errors in parentheses, cluster on 1km grid and year * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$. All regressions include interactions of time controls with TTWA controls. Panel A tests for upwards risk moves, using samples composed of sales that stay in category 1 and homes that move from category 1 to other categories. In column 1, we examine moves from category 1 to the lowest category classified as affected by radon (category 2). Columns (2)-(5) progressively expand the sample to include homes that start in category 1 but move to higher risk categories. Panel B repeats the same process for downwards risk moves.

Table 5: The Effect of Radon Risk on House Prices with local area (OA) trends.

	(1)	(2)	(3)	(4)	(5)
	X={2}	X={2,3}	X={2,3,4}	X={2,3,4,5}	X={2,3,4,5,6}
Panel A: 1 $\rightarrow X$	-0.0216***	-0.0198***	-0.0167**	-0.0170**	-0.0167**
	(0.00744)	(0.00661)	(0.00680)	(0.00686)	(0.00691)
N	129397	132654	134881	135909	136040
R^2	0.704	0.703	0.704	0.704	0.704
Panel B: X $\rightarrow$ 1	-0.0138	-0.0113	-0.0113	-0.0106	-0.00365
	(0.0138)	(0.0139)	(0.0132)	(0.0133)	(0.00326)
N	9228	10037	10268	10950	44374
R^2	0.669	0.673	0.671	0.669	0.307

Notes: Standard errors in parentheses, cluster on 1km grid and year * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$. Panel A tests for upwards risk moves, using samples composed of sales that stay in category 1 and homes that move from category 1 to other categories. In column 1, we examine moves from category 1 to the lowest category classified as affected by radon (category 2). Columns (2)-(5) progressively expand the sample to include homes that start in category 1 but move to higher risk categories. Panel B repeats the same process for downwards risk moves. All regressions include OA fixed effects interacted with time trends.

Table 6: The Asymmetric Effect of Radon Risk on House Prices.

	(1)	(2)	(3)	(4)	(5)	(6)
Starting Cat:	Cat 1	Cat 2,3	Cat 4,5,6	Cat 1	Cat 2,3	Cat 4,5,6
Up	-0.0133+	-0.00398	-0.00675	-0.0164+	-0.0103**	-0.00601
	(0.00257)	(0.00355)	(0.00586)	(0.00291)	(0.00393)	(0.00655)
Down	0	-0.00572	-0.00341	0	-0.00441	-0.00289
	(.)	(0.00333)	(0.00806)	(.)	(0.00365)	(0.0120)
N	522026	63571	14143	496115	47776	11637
R^2	0.237	0.289	0.295	0.235	0.298	0.304

Notes: Standard errors in parentheses, cluster on MSOA and year * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$. All regressions include years of sale dummies (years) interacted with TTWA effects. Columns 1-3 include regressions where the move can be by any number of categories. Columns 4-6 give results only for moves by one category.

Table 7: The Effect of OA Radon Risk Level on the Number of Transactions (panel of OA averages).

	(1)	(2)	(3)	(4)	(5)
	ln(trans)	ln(trans)	ln(trans)	ln(trans)	ln(price)
$\Delta Radon_{rt}$	0.0100+				
	(0.00291)				
$1 \rightarrow Any$		0.0114***		0.0116***	-0.0121+
		(0.00436)		(0.00437)	(0.00255)
$Any \rightarrow 1$			0.00364	0.00624	-0.00235
			(0.0104)	(0.0105)	(0.00446)
N	335826	335826	335826	335826	335826
R^2	0.733	0.733	0.733	0.733	0.954

Notes: Standard errors clustered at the OA level included in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$. $\Delta Radon_{rt}$ gives changes in a categorical variable which takes values from 1 to 6. $1 \rightarrow Any$ denotes a dummy for all properties/areas that start in category one but finish in any other category. $Any \rightarrow 1$ denotes the reverse. All regressions include an OA fixed effect and a TTWA fixed effect interacted with the time trend.

Table 8: The Effect of OA Radon Risk Level on Sorting: changes in OA population shares and changes in radon from 1 to any other category.

	(1) Degree	(2) Social Status	(3) Outright	(4) Owner Occupier	(5) Income
$1 \rightarrow Any$	-0.0330+	-0.0301+	-0.00432***	-0.0208***	-0.00373+
	(0.00508)	(0.00594)	(0.00140)	(0.00664)	(0.000762)
$Any \rightarrow 1$	-0.0166	-0.0213	-0.00586	-0.0302	-0.00198
	(0.0144)	(0.0169)	(0.00398)	(0.0189)	(0.00217)
N	40836	40836	40836	40836	40877
R^2	0.016	0.019	0.040	0.026	0.302

Notes: Standard errors clustered at the MSOA level included in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$. The results are based on a cross sectional regression of changes in OA radon from one to any other category with the baseline staying in category 1 using the 2007 map change. The dependent variable is the change in the share of the OA between 2001 and 2011 Censuses. All regressions include a TTWA FE.

Table 9: Robustness of the Effect of Radon Risk on House Prices - placebo and areas with no tests.

	(1) $\Delta ln(price)$	(2) $\Delta ln(price)$	(3) $\Delta ln(price)$	(4) $\Delta ln(price)$	(5) $\Delta ln(price)$	(6) $\Delta ln(price)$
$1 \rightarrow Any$	0.000599		0.00303			
(placebo)	(0.00135)		(0.00669)			
$Any \rightarrow 1$		-0.00352		-0.00114		
(placebo)		(0.00211)		(0.0120)		
$1 \rightarrow Any$					-0.0185**	-0.0184+
(non tested)					(0.00746)	(0.00302)
Area Trend	TTWA	TTWA	OA	OA	OA	TTWA
N	1445262	1445262	342311	342311	124138	474679
R^2	0.283	0.283	0.707	0.707	0.706	0.236

Notes: Standard errors clustered at the 1km gird and year included in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$. The results in columns 1-4 are based on pairs of transactions that occurred after 2010 (using the same map). The placebo change in radon applied to those pairs is based on the change the house experienced when maps changed between 2003 and 2007. It is a falsification test. The dependent variable is price so that the results are equivalent to tables 4 and 5. $1 \rightarrow Any$ denotes a dummy for all properties/areas that start in category one but finish in any other category. $Any \rightarrow 1$ denotes the reverse. Columns 5 and 6 give results of a reclassification from no radon to any other category (again equivalent to tables 4 and 5) in areas where no more than 1% of houses have been tested for radon risk by PHE.

A Appendix

Table A1: Correlation between ambient air pollution (PM10) and radon risk.

	(1) PM10 2003	(2) PM10 2008	(3) Change in PM10
OA radon 2003	0.00233		
	(0.00563)		
OA radon 2008		0.00284	
		(0.00286)	
Change in OA radon			0.00502
			(0.00543)
N	153640	153578	153578
R^2	0.992	0.993	0.991

Notes: Standard errors in parentheses, cluster on MSOA and year * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$. All regressions inlcude an MSOA fixed effect. OA radon measures are maximum values in the area. PM10 concentration is based on air pollution readings from the three closest DEFRA monitoring stations (weighted by inverse squared distance). Change in PM10 refers to the change in levels between 2008 and 2003.

Table A2: Estimation differences using the 50m or the 1km grid radon maps.

	(1) $\Delta ln(price)$	(2) $\Delta ln(price)$	(3) $\Delta ln(price)$
$1 \rightarrow Any$ 50m grid	-0.0224*		-0.0214**
	(0.0126)		(0.00974)
$1 \rightarrow Any$ 1km grid	-0.0214**	-0.00272	-0.00221
	(0.00977)	(0.0149)	(0.0148)
Sample	FULL	50m grid only	50m grid only
Observations	129176	28345	28345
R^2	0.704	0.692	0.692

Notes: Standard errors in parentheses, cluster on grid squares * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$. All regressions include an OA fixed effects interacted with time trends. Column 1 compares the impact of radon depending on whether the best available information comes from the 50m grid or the 1km grid. Column 2 shows the impact of the 1km grid information in a sample where 50m grid data is available. Column 3 shows the impact of 50m grid information and 1km grid information in locations where 50m grid information is available.

Table A3: The impact of radon on house prices – transactions with mortgages.

	(1)	(2)
	$\Delta ln(price)$	$\Delta ln(price)$
$1 \rightarrow Any$	-0.0217***	-0.0164+
	(0.00744)	(0.00293)
Mortgage	-0.00321	-0.00606
	(0.00839)	(0.00439)
$1 \rightarrow Any$ with Mortgage	0.0280	0.00337
	(0.0220)	(0.0101)
N	129397	496115
R^2	0.704	0.235

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, + $p < 0.001$

Notes: Standard errors in parentheses, cluster on 1km grid and year * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$. Column 1 includes OA fixed effects interacted with time trends while column 2 is based on TTWA fixed effects. $Mortgage$ denotes a dummy variable that equals one if the transaction is funded by a mortgage from Nationwide. $1 \rightarrow Any$ with Mortgage is a dummy variable that equals one if the transaction is funded by a Nationwide mortgage and receives the treatment.