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Exploring assumptions for air infiltration rate estimates using indoor radon in UK homes

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Exploring assumptions for air infiltration rate estimates using indoor radon in UK homes

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Abstract. Radon, a known carcinogen, is one of the most commonly monitored indoor contaminants. This paper utilises findings from a previous study on indoor radon measurements in United Kingdom (UK) homes to explore the UK Government's Standard Assessment Procedure (SAP) assumptions for air infiltration rates. These assumptions are important as they are used to assess the energy performance of dwellings and compliance with building regulations. Indoor radon data is aggregated by 16 combinations of home energy efficiency measures (loft and wall insulation, glazing upgrades and draught proofing) and fitted using a simple analytic radon model. We find indoor radon to be inversely proportional to air change rate and proportional to a fit coefficient, k, of 42.2 ± 3.1 (95% Confidence Interval (CI)). We also show that the assumptions within SAP used to estimate home infiltration rates can be modified to include the impact of home energy efficiency which improves the fit (R^2 from 0.38 to 0.51) to the radon data. This work provides evidence to help improve assumptions regarding the effects of home energy efficiency on infiltration rates.

1. Introduction

Countries around the world need to rapidly reduce their greenhouse gas emissions to meet net-zero targets. To achieve this, housing needs to become more energy efficient and run on renewable energy [1]. If implemented correctly, significant health benefits can also be achieved through improvements to thermal conditions [2]. Home energy efficiency (HEE) improvements to the building envelope include adding insulation to walls, loft and floors, glazing upgrades and draught proofing. These upgrades can lead to reduced air infiltration rates[1] [3]. Without provision of compensatory ventilation, this can result in increased exposures to radon and other indoor sourced pollutants leading to negative health implications [4, 5, 6].

There remains uncertainties regarding the impact of HEE measures on air infiltration rates. The UK Government's Standard Assessment Procedure (SAP) prescribes a set of assumptions used to estimate the energy consumption of homes [7]. It is used to generate Energy Performance Certificates and to ensure compliance with UK building regulations. This includes assumptions used to calculate air infiltration rates, however, the impact of some HEE interventions on infiltration rates are not included. Hong et al. (2004) is the only study to our knowledge

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[1] Infiltration refers to unintended air leakage from homes. Ventilation refers to intended air exchange with outdoors (e.g. through window opening/mechanical ventilation).

where changes in infiltration rate have been linked to HEE measures based on fan-pressurisation tests [8].

In this paper, the main aim was to explore the assumptions for air infiltration rate within SAP [7] and Hong et al. (2004) [8] using indoor radon measurements from UK homes. Improved assumptions for the impact of HEE measures on air infiltration rates can be used to make improved predictions of both current and future exposures to indoor and outdoor generated air pollution. This will help guide policy makers and practitioners to ensure future HEE programs are able to enhance population health.

2. Methodology

This work combines several data and modelling methods to achieve the aim set out in Section 1. Figure 1 provides a workflow summarising the various data and model components. The three main analysis steps were to:

(i) Estimate infiltration rates for groups of dwellings by HEE characteristics using SAP version 10.2 and evidence from air-pressurisation tests from Hong et al. (2004) [8];

(ii) Derive a simple mathematical model for the relationship between infiltration rate and indoor radon based on Jelle et al. (2012) [9];

(iii) Fit and evaluate the model using previously published indoor radon measurements grouped by HEE characteristics [4].

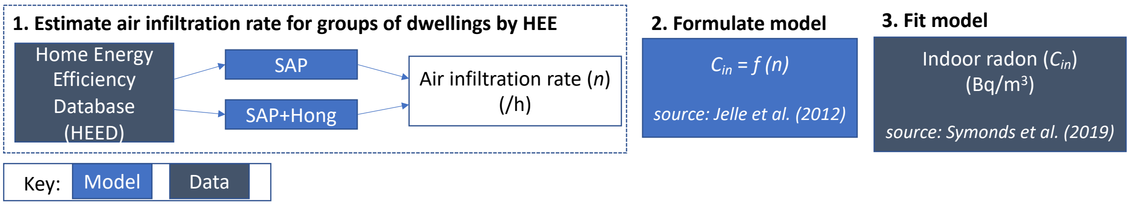


Figure 1: Overview of methodology.

2.1. Data sources and assumptions

This work leverages data within the Home Energy Efficiency Database (HEED) [10] and aggregate geometric mean radon measurements for UK dwellings grouped by HEE provided in Symonds et al. (2019) [4]. Symonds et al. (2019) used a large (N∼470,000) indoor radon dataset held by the UK Health Security Agency (UKHSA) linked to HEED at dwelling level to investigate the association between HEE measures and indoor radon. The UKHSA radon data was not used in this paper, as it is no longer accessible to the authors. All available combinations (N=16) of HEE measures are considered where measures include wall insulation (WI), loft insulation (LI), glazing upgrades (Glz) and draught stripping (DS). The no retrofit case (None) was also included.

To estimate infiltration rates for homes grouped by HEE, we first use data from HEED to estimate the group's average infiltration rate based on SAP [7]. In addition to the assumptions for the various fabric elements provided in Table 1, a factor of 0.1 multiplied by the number of stories less one is applied [7]. A shelter factor (to account for reduced wind driven infiltration) of 0.925 and 0.85 is also applied for dwellings exposed on three and two sides, respectively as per SAP [7]. Due to having limited data within HEED on the infiltration characteristics of homes (e.g. no information about floor type), we also assume an additional infiltration contribution in older homes (pre-1930s=0.8/h and 1930-1950=0.5/h) to account for infiltration from suspended timber floors, chimneys, vents and open flues [7]. We then tested two sets of assumptions for the impact of HEE on air infiltration rate based on i) SAP, and ii) SAP+Hong [8]. These assumptions are provided in Table 1 with SAP giving absolute contributions to air infiltration (air changes per hour (/h)) and Hong et al. (2004) percentage reductions in infiltration per HEE measure. Note, SAP assumes no change in infiltration for solid wall insulation.

Table 1: Assumptions for the impacts of HEE measures on air infiltration rate.

Building component	Fabric element	SAP v10.2 [7] Infiltration contribution (/h)	Hong et al. (2004) [8] (% reduction in infiltration due to HEE)
Walls	Solid	0.30	7% - SWI
	Unfilled cavity	0.35	11% - CWI
	Filled cavity	0.30	
Loft	Unsealed loft hatch	0.025	14% - LI
Glazing	Loose fitting	0.25	16% - Glz
	Well fitted, not draught sealed	0.15	
	Well fitted, draught sealed	0.05	
Draught proofing	Unsealed suspended timber floor	0.2	5% - DS
	Sealed suspended timber floor	0.1	

Abbreviations: SWI - Solid Wall Insulation, CWI - Cavity Wall Insulation, LI - Loft Insulation, DS - Draught Stripping

2.2. Formulation of a simple indoor radon model

The relationship between air infiltration (n) and indoor radon (C_{in}) is derived using the analytic model proposed by Jelle et al. (2012) [9]. Jelle's model can be simplified to include only the three dominant physical processes: i) air exchange with outdoors due to infiltration, n; ii) air leakage of radon from the ground; and iii) diffusion of radon from the ground. This yields Equation 1:

$$C_{in} = \frac{1}{n}\frac{A}{V}C_g(P + q(\theta_a - \theta_e)0.05H) \tag{1}$$

where A is the ground floor area and V is the volume of the home. C_g is the ground radon concentration, P is the diffusion coefficient of the ground floor (=1/Resistance), q is the air permeance of ground, θ_a and θ_e are indoor and outdoor temperatures, respectively, and H is the indoor/outdoor air pressure equilibrium height.

This work only includes the infiltration contribution to air exchange due to the lack of data on the ventilation component. Equation 1 indicates that C_{in} is inversely proportional to n and directly proportional to several other physical parameters, whose stock level values can be estimated with varying degrees of uncertainty. Some parameters (e.g. θ_a) are likely to be influenced by HEE, however, for the purpose of this work we treat them as having negligible impact on C_{in} compared to air infiltration, n. These parameters can be grouped together into a single value, k, such that the equation is analogous to a simple tracer gas equation:

$$C_{in} = \frac{k}{n} \tag{2}$$

The final step of the analysis is to fit Equation 2 using empirical data for C_{in} and the air infiltration estimates for various combinations of HEE measures (wall and loft insulation, glazing and draught proofing) using i) SAP, and ii) SAP+Hong. The coefficient of determination (R^2) and the Root Mean Square Error (RMSE) are used to determine the goodness of these fits to the radon data. We also compare unknown parameters within Equation 1 with the fitted coefficient, k. The values assumed by Jelle et al. (2012) are provided in Table 2.

Table 2: Default values for constants provided in Jelle et al. (2012) [9]

Constant	Value
A/V	$1/2.4 = 0.42$/m
C_g	50,000 Bq/m^3
$\theta_a - \theta_e$	20-5 = 15 ^oC
H	2.7m
q	10x10^{-4} m^3/(m^{2}hPa)
P	$1/R = 1/2.6$x10^8 = 3.8x10^{-9} m/s

3. Results

Fitting Equation 2 to the radon data grouped by HEE yields values for fit parameter, k, of 43.0 and 42.2 using the SAP and SAP+Hong estimates for infiltration rate, respectively. R^2 and RMSE values for these fits are provided in Table 3. The relationships between measured geometric means for the grouped indoor radon data and infiltration rates, n, under both assumptions are shown in Figure 2.

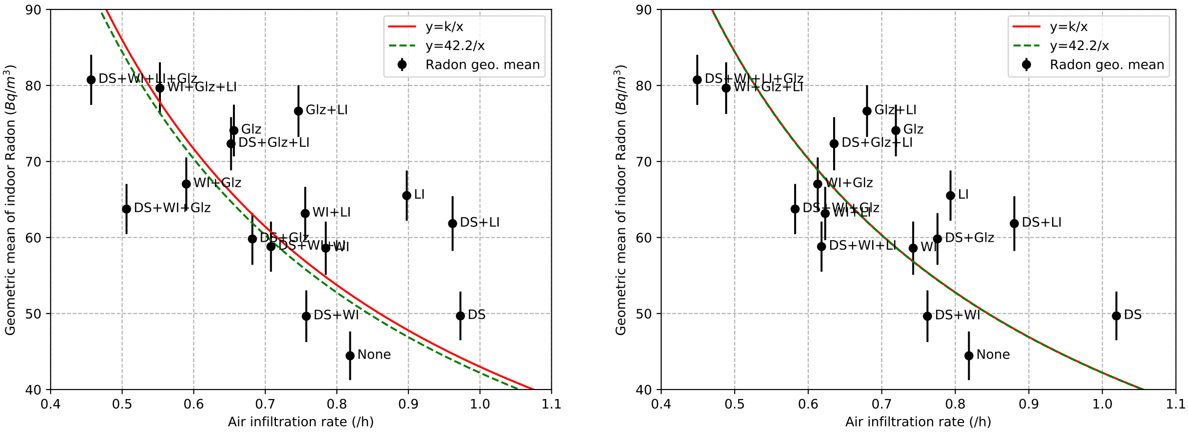
The model fits to the data yielded relatively low R^2 and high RMSE under both sets of assumptions for infiltration rate. The two fitted values for k are within 95% CIs of one another. The SAP+Hong fit performs slightly better with an R^2 of 0.51 and an RMSE of 9.4 Bq/m^3. The fitted values of k are consistent with the default parameters for constants within Equation 1 provided in Jelle et al. (2012) [9] (see Table 2) of 42.2 Bqh/m^3.

Table 3: Goodness-of-fit for Equation 2 to radon data.

Infiltration rate assumptions	Fitted k (Bqh/m^3) (±95% CI)	R^2	RMSE (Bq/m^3)
SAP	43.0 ± 3.8	0.38	11.1
SAP+Hong	42.2 ± 3.1	0.51	9.4

4. Discussion

The findings from this paper highlight the need to better understand the impact that HEE measures have on air exchange rates in naturally ventilated dwellings. Petrou et al. (2022) [11] argue for a large scale monitoring campaign of indoor air to investigate the impact of HEE on indoor air pollution. In the absence of large scale monitoring data, radon measurements can be used as a tracer to better understand how HEE impacts on air exchange rates. Fitting Equation



(a) SAP assumptions (b) SAP+Hong assumptions

Figure 2: Geometric mean of indoor radon vs air infiltration based on: a) SAP and b) SAP+Hong assumptions for dwellings grouped by HEE. Error bars show geometric standard deviations of the radon data.

2 to the radon data grouped by HEE yielded a value for k of 42.2. This gives a very similar value to plugging the default constants provided by Jelle et al. (2012) [9] (Table 2) into Equation 1. Furthermore, Equations 1 and 2 can be used to show that a reduction in infiltration rate from 0.9 /h to 0.5 /h would result in geometric mean radon levels increasing from ∼47 Bq/m^3 to ∼84 Bq/m^3 - an increase of almost a factor of two. This increase in exposure to indoor radon has potential health implications and could result in an increased risk of lung cancer [12]. There will likely also be implications for other pollutants of indoor origin and compensatory ventilation (e.g. trickle vents and extract fans) is necessary to reduce indoor exposures [5].

This study also has implications for air infiltration assumptions within SAP [7], which is currently undergoing revision to version 11. Our findings show a better agreement with the radon data when the SAP estimates for air infiltration are supplemented with assumptions from Hong et al. (2004) [8], with the R^2 increasing from 0.38 to 0.51. The RMSE also decreases from 11.1 Bq/m^3 to 9.4 Bq/m^3. The Hong et al. (2004) assumptions (see Table 1) provide percentage reductions in air infiltration as opposed to the absolute changes in SAP v10. SAP v10 also does not provide details on the impacts of solid wall and loft insulation on air infiltration, which should be updated in SAP version 11.

4.1. Limitations & Future work

The findings presented in this paper have three main limitations related to the data and assumptions used:

- Radon data: We only had access to aggregate data grouped by HEE measures in Symonds et al. (2019) [4]. This data had not been corrected for region or dwelling age or type, which are significant determinants of indoor radon.
- HEED data: HEED has significant amounts of missing data. It also lacks some key building information. For example, there is no information about floor type or ventilative properties (e.g. presence of trickle vents or extract fans).
- Air infiltration rate estimates: As mentioned, there are some ambiguities within SAP v10 on how air infiltration rates are estimated. We didn't have all the necessary contextual information (e.g. floor type, presence of chimneys, flues, fans, etc...) to input into SAP.

Consequently, we had to make some assumptions based on dwelling age. A ventilation component could also be included in future work.

Future work may seek to further investigate the model structure and assumptions using Bayesian calibration. This technique may provide improved model predictions and allows prior knowledge and uncertainties to be incorporated. We also hope to use individual dwelling level data in future analysis which would require renewed access to the radon data, potentially linked to the National Energy Efficiency Data-Framework (NEED) or Energy Performance Certificates (EPCs).

5. Conclusions

This paper makes use of a study on indoor radon measurements in UK dwellings aggregated by 16 combinations of HEE measures. The aim was to better understanding the relationship between HEE, radon and infiltration rate estimates. By fitting a simple mathematical model to the radon data, we find radon to be inversely proportional to air infiltration rate with a fitted coefficient of 42.2 ± 3.1 (95% CI). This is consistent with existing models in the literature. We also show that the fit to the radon data can be improved (R^2 from 0.38 to 0.51) by modifying the infiltration rate assumptions within SAP v10 to include assumptions on the impacts of HEE measures (wall and loft insulation, glazing upgrades and draught proofing).

Findings from this study imply that HEE may lead to decreases in air infiltration, which in turn can result in increased indoor radon concentrations (and potentially other indoor sourced pollutants). Practitioners must ensure that homes are adequately ventilated. Trickle vents and extract fans can help offset increased air tightness due to HEE installations. Policymakers may benefit from further verification and testing of the assumptions for air infiltration estimates within SAP.

Acknowledgments

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