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Factors influencing radon concentration during energy retrofitting in domestic buildings: A computational evaluation

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ABSTRACT

The findings of recent research signalled increased radon levels following energy retrofitting of dwellings but to date, there have been limited quantitative data to support this observation. A modelling framework was developed that incorporates a dynamic radon entry rate, capturing changes in pressure differentials, to investigate changes in radon concentration following different energy-efficient retrofit measures in naturally-ventilated dwellings. Simulations examined a range of input criteria: dwelling type, air permeabilities, radon flow exponents, pre and post thermal retrofit characteristics, outdoor weather locations and corresponding wind profiles, as well as different ventilation guidelines. A total of 3,780 simulations were carried out. The air permeability of the building had the greatest impact on radon concentration with increases of up to 107%. Non-linear increases were observed arising from the impacts on pressure differentials due to changes in air permeability. The application of representative weather profiles associated with different locations (e.g. coastal, inland) resulted in differences of up to 37%. To a lesser extent, increased indoor temperature due to thermally retrofitting the building fabric, without changes in air permeability, resulted in radon levels increasing by 7%. Additionally, it was shown that the radon flow exponent was not a significant influence on radon concentrations following a retrofit. The addition of ventilation measures means that it is possible to achieve increased airtightness without impacting on the radon concentration. Overall, the simulations provide quantitative information that explains increased airtightness and elevated radon levels, highlighting the potential for radon concentrations to either increase or decrease following an energy retrofit.

1. Introduction

As expressed by the 2015 Paris Agreement, the global reduction in carbon emissions remains a political priority. Ambitious energy efficiency measures will be required to ensure that Europe meets its obligations under the Paris Agreement. The revised Energy Performance of Buildings Directive (2018/844/EU) includes an energy efficiency target for the EU for 2030 of 32.5% with an upwards revision clause by 2023. The International Energy Agency (IEA) [1] identified that energy efficiency is a major energy resource, highlighting in 2010 that the “energy use avoided” by IEA member countries was larger than any other single supply-side resource. The IEA supports the principles of recognising energy efficiency as the “first fuel”. Importantly, the IEA also noted that while there is potential for significant health and well-being benefits associated with improved energy efficiency; it is also documented that if energy efficiency measures are implemented incorrectly, they can have negative impacts on Indoor Environmental Quality (IEQ) and thus on health and well-being. Retrofitting of the building fabric has been identified as one of the most cost-effective energy-efficiency improvements to achieve energy savings in the economy [2].

The residential sector has been highlighted as a key focus for achieving reduced carbon emissions while ensuring that the economy can remain environmentally sustainable. Ireland is considered to have one of the highest rates of energy consumption per dwelling in Europe [3]. In 2018, The Irish residential sector accounted for 23% of final energy use and, after transport, it is the second highest source of CO_2 emissions at 24%, followed by industry at 21% and services at 13% [4]. While reductions can be achieved by introducing revised building standards for future dwellings, this will only partially achieve the required reduction as the existing building stock will still be largely in use by 2050, and so there is a need to renovate the bulk of existing dwellings. The Irish Climate Action Plan committed to upgrading 500,

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000 homes (25% of the entire building stock) to an energy usage rate of less than 100 kWh m^{-2} yr^{-1} by 2030 [5,6]. These measures aim to improve the thermal and energy efficiency of the building envelope, specifying standards of building airtightness by reducing uncontrolled ventilation losses from the home. Ventilation is a key aspect that affects indoor air quality and thermal comfort in residential dwellings. However, while improving the thermal efficiency reduces energy consumption; indoor air quality may become compromised if adequate ventilation is not maintained [7–11].

Radon is the second-highest cause of lung cancer, after smoking, in many countries, and associated increased risk of leukaemia and multiple myelomas have also been reported [12]. There is no recognised threshold below which radon exposure presents no risk, and the majority of radon-induced lung cancers are caused by low and moderate radon concentrations rather than by high radon concentrations, because, in general, fewer people are exposed to high indoor radon concentrations [12]. As the population of developed countries spends on average 92% of their time indoors per day, with approximately 60% of their time in the residential environment [13,14], the residential environment therefore deserves particular attention. Each year in Ireland, exposure to radon is linked to approximately 300 cases of lung cancer [15]. Ireland has a national radon average of 77 Bq m^{-3} [16]; although, measurements range from 10 to 49,000 Bq m^{-3} with 8% of dwellings exceeding the reference level of 200 Bq m^{-3} [16–18].

Existing research has shown that energy retrofitting of dwellings may lead to greater airtightness and international research studies have reported that post-retrofit radon levels can increase by up to 42–340% [19–23]. Long and Smyth [24] examined radon pre and post energy retrofit in 142 Irish social homes and found that while the average pre-vs post-retrofit radon concentration was 56 Bq m^{-3} vs 50 Bq m^{-3}, the corresponding post-retrofit radon concentration increases ranged from 10% to 730%. Collignan et al. [25] collected data from 3233 houses in a radon-prone area in Brittany, France, between 2011 and 2014. In this study, a median radon concentration of 180 Bq m^{-3} was found for thermally-retrofitted homes, compared with a value of 114 Bq m^{-3} for non-retrofitted houses. The results of a multivariate linear regression model found that thermal retrofitting had a significant effect on the indoor radon concentration (21% increase on average). However, the focus of the study was on obtaining qualitative information through occupant questionnaire responses, rather than on obtaining quantitative information on airtightness or ventilation. Yang et al. [26] compared radon concentrations in 60 Swiss dwellings pre and post energy retrofit and reported an average of 20% increase in indoor radon concentration associated with thermal retrofitting.

Ringer [27] emphasised that developing an understanding of indoor radon requires a different approach, according to whether energy-efficient buildings are retrofitted or newly constructed. During a thermal retrofit, an increase in airtightness is only achieved for the above-ground component of the building shell, while no change is achieved in the foundation. An increase in airtightness of the above-ground alters the pressure differentials between the above-ground building shell and the foundation slab, and consequently the radon entry rate. Collignan et al. [28] reported dynamic radon entry rates that resulted in a high temporal variability of radon concentrations in residential buildings. This was attributed to small pressure differences between the indoor and outdoor environments, which gave rise to the convective transport of radon gas into dwellings. Collignan and Powaga [29] reported that indoor radon concentration depends on meteorological conditions, air permeability of a building, ventilation system type and the air change rate. These parameters have the potential to affect the level of depressurization indoors that determines the radon entry rate or the levels of radon dilution.

Milner et al. [30] carried out a simulation study based on the UK building stock and predicted indoor radon concentrations for the present day compared with various retrofitting strategies. The study investigated the consequences of reducing home ventilation by increasing the airtightness of the English housing stock and predicted that the average indoor radon concentration would increase from 21.2 Bq m^{-3} to 33.2 Bq m^{-3}. However, in this study, a constant radon emission rate based on ground floor area was applied, which neglects a dynamic radon entry rate and does not capture variations in meteorological conditions and implications for the entry rate due to changes in the air permeability of the building.

The above literature review spotlights many of the building-related and environmental factors that influence indoor radon level changes resulting from building retrofit, but to date, many of these factors, some of which are inter-dependent, have been investigated in isolation. A computational study presents an opportunity for a multi-factor assessment and the overall objective of this study is therefore to examine the implications for radon concentrations due to energy-efficient retrofit scenarios by incorporating dynamic radon entry rates and predicting post-retrofit radon concentrations in different building types. The study aims to quantify the percentage changes in radon contributions due to various changes in thermal conditions, air permeability of the building and different ventilation guidelines. Simulations are framed in the Irish building context, but the computational approach is globally applicable. The application of a novel modelling framework, including an explanation of the parameterisation following energy-retrofit measures, is presented in the next section.

2. Methodology

2.1. Modelling approach

A combined modelling framework was developed to examine the impacts on radon concentrations under different ventilation scenarios resulting from representative energy-efficient retrofits. As shown in Fig. 1, the overall modelling framework combined three existing models: CONTAM (CONTAM 3.3, NIST, Gaithersburg, MD, U.S.), EnergyPlus (EnergyPlus Version 9.1, Department of Energy's Building Technologies Office, U.S.) and Indoor Air Pollution Probabilistic Exposure Model (IAPPEM) [31–35]. EnergyPlus simulated the indoor temperature profiles for each zone within the dwellings based on satisfying the heating loads throughout the year; this accounted for changes in the indoor temperature profiles resulting from the retrofit measures (e.g. insulation, new windows, a new heating system, changes in the air permeability and installation of additional ventilation measures). CONTAM

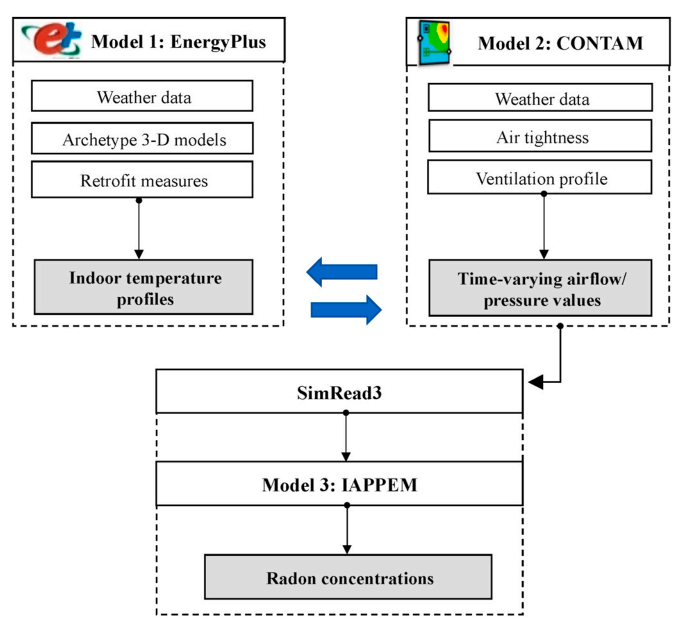

Fig. 1. Components of the modelling framework.

determined time-varying airflow and pressure values across each zone within the dwelling. CONTAM focused on incorporating the dwellings' air permeability, changes in the ventilation guidelines and the operation of intermittent extract ventilation for the wet rooms (kitchen, bathrooms, etc.) IAPPEM imported the pressure differentials to calculate a dynamic radon entry rate and time-series zonal radon concentrations; this is a necessary component as radon infiltration into a dwelling is based on pressure differentials.

Dols et al. [36] observed that both EnergyPlus and CONTAM are limited in their ability to account for thermal processes upon which building airflow may be strongly dependent, and vice versa. A quasi-dynamic coupling scheme developed by Dols, Emmerich and Polidoro [36], which allows sharing of data between independently executing simulation tools, was used. This process coupled CONTAM and EnergyPlus to capture the interdependencies between airflow and heat transfer. Pressure differentials and airflow values were exported using the SimRead3 tool (SimRead3 3.2, NIST, Gaithersburg, MD, U.S.) and then imported into the IAPPEM model which implemented pressure differentials based on the work of Collignan and Powaga [37]. Radon was assumed to infiltrate from the ground floor only (including the surface area of the walls that are in contact with the soil), based on the floor area of the room and the corresponding pressure differential. A dynamic radon entry rate was used to calculate the time-series zonal radon concentrations for ground floor rooms within the dwelling.

2.2. Parameterisation

Simulations were carried out for different combinations of input parameterisation that are representative of retrofit scenarios for Irish dwellings as summarised in NSAI [38]. This research focuses on typical Irish dwelling archetypes, however, the framework introduced is highly applicable to a range of building categories, especially because this methodology is assessed with different climate conditions and weather data files. The applicability of the proposed framework is investigated by using three archetypes with different geometrical configurations, including bungalow, semi-detached and terraced dwellings. The selected archetypes and all associated input values are based on previous studies that developed comprehensive sets of residential buildings archetypes [39,40]. The selected archetypes represent a significant proportion of the Irish dwelling stock undergoing energy-retrofit, as summarised in Table 1 and also shown in Fig. 2. There are differences between the three dwellings in terms of the number of individual rooms, the volume of each room, the presence of additional toilets or ensuite toilet/shower rooms, and single or two-storey components. The household layout and specific room dimensions are provided in the supplementary material as Figs. S1–S3 and Tables S1–S3.

The occupancy schedules and activity pattern in each model, and heating set points are assumed to be consistent in the energy analysis period. The heating systems are set to operate at 6.30–23.00 every day, in accordance with the heating setpoints. The set points, the dominant factors that control the heating system function, are set to 21 °C. The heating system operation period and set points are based on "expert interpretation" of authors from the database of the Irish Economic and Social Research Institute (ESRI)[41] for operation and occupancy pattern of the Irish residential sector".

Table 1
Summary of household characteristics for selected Irish residential archetypes.

	Bungalow	Semi-detached	Terraced
Number of floors	Single Storey	Two Storey	Two Storey
Number of Habitable rooms	5	4	3
Number of Wet rooms	2	4	3
Occupancy Level	5 people	5 people	4 people
Total Floor Area	104 m^2	85 m^2	114 m^2
Total volume	250 m^3	213 m^3	292 m^3

2.2.1. Purpose-provided ventilation retrofit cases

Fig. 3 summarises the possible ventilation scenarios pre and post energy-retrofit; which are reflective of the year in which the dwelling was built, as this is linked with the changes in the national building regulations [42], and the current guidelines for energy retrofits [38]. The simulations focus on scenarios where the air permeability levels do not reduce below 5 $m^3 h^{-1} m^{-2}$ at 50 Pa following an energy retrofit and the simulated cases included changes in the building envelope's permeability to represent pre/post energy-efficient retrofit scenarios; 5, 7, 10, 13 and 15 $m^3 h^{-1} m^{-2}$ at 50 Pa [23,43,44]. All changes in the building air permeability are assumed to only influence the external walls, windows/doors area and attic space as these spaces represent 80% of the heat loss of the dwelling and are most cost effective to retrofit [38]. An air flow coefficient of 0.66 was selected to represent the external wall air leakage.

In addition to the airflows generated by air leakage, dwellings require additional purpose provided ventilation to control the moisture content and limit harmful pollutants within dwellings. In naturally ventilated Irish dwellings, as well as other countries, this takes the form of background ventilators (BV) and Intermittent Extract Ventilation (IEV). BV are a fixed opening on an external wall or window for the purpose of ventilation within the habitable rooms (living room, bedroom, etc.) in dwellings. BV operates based on a passive approach, where the driving force is applied based on pressure differentials between inside and outdoors, as well as the wind speed and direction. IEV is a short-term increase in the ventilation for wet rooms (kitchen, bathroom/shower, etc.) generated by a mechanical fan in response to an occupant presence or a moisture-generating activity.

When applicable, all background ventilators were assumed to be at 1.75 m above the floor level. At the base of each internal door, a 10 mm gap above the floor level was provided to allow the movement of unhindered air throughout the dwelling [45]. An air flow coefficient of 0.5 was selected to represent the air flow through the background ventilators and under the doors. All internal doors remained closed during the simulations, and there were no additional changes in window or external door opening patterns. BV sizes and IEV rates are provided in Table 2. The vent sizes are listed as free areas but the equivalent area is used in the simulations in accordance with I.S. EN 13141–1: 2004. When applicable, the mechanical extract ventilation was operated based on an occupancy scenario within the dwelling as defined in Table 1. The different occupancy levels combined with the different household layouts and different type of wet rooms per dwelling resulted in different schedules for the IEV and are summarised in Tables S4–S9.

2.2.2. Energy-efficiency retrofit improvements and building materials

The retrofit modelling started with the development of three selected archetypes with an appropriate representation of geometrical features. For each archetype, two scenarios represented the pre-retrofit and post-retrofit conditions resulting in six different models. It is important to note that the geometrical layouts of the archetypes remain unaltered during the modelling process but the physical characteristics of the constructions that considerably change the indoor temperature are modified. The indoor temperature modelling is performed via EnergyPlus as a whole building energy simulation program which makes use of several inputs, for instance, physical parameters, heating systems and operation schedules [46].

In the next step, the indoor temperature as one of the outputs of the energy simulation process is calculated for each interior space. To start the energy modelling process, the pre-retrofit scenario, as the base case model, is developed for each archetype and then the suggested retrofit measures are applied to each case in order to develop the post-retrofit scenario. As a result of the energy modelling for both pre-and post-retrofit scenarios, the total site energy consumption of buildings has been significantly reduced, while, applying heat pumps as the default heating system increases the electricity consumption in those buildings. Additional information for annual energy performance of semi-

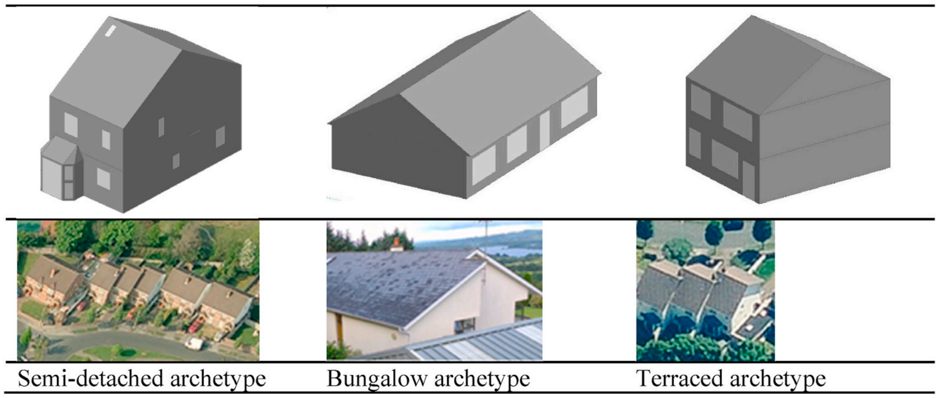

Fig. 2. The geometrical configuration of selected Irish residential archetypes.

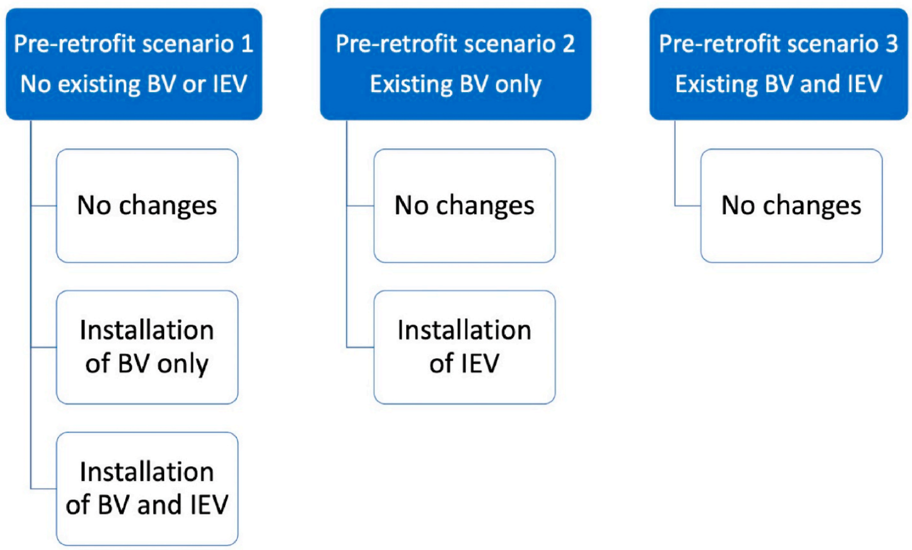

Fig. 3. Pre-retrofit ventilation scenarios (blue boxes) with the respective combination of post-retrofit for each scenario (white boxes). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Summary of background and intermittent extract ventilation rate for different rooms.

Room usage	BV vent size (mm^2)	IEV fan rating (l/s)
Habitable room	6500	Not required
Kitchen	6500	30 (suitably sited extracting cooker hood)
Bathroom/ Shower	Not required	15
WC (only)	Not required	6

detached, bungalow and terraced archetypes are included in the supplementary material as Section S1.

All the retrofit actions are based on the Irish Technical Guidance Document Part L as a reference for defining the retrofit scenario for each archetype [47] and represent standard retrofit packages as described in the 2020 Irish cost optimal report [48]. In addition to the air tightness measures listed in Section 2.2.1, each retrofit scenario aimed to improve the building energy performance by focusing on three categories of retrofit actions including thermal characteristics building elements, lighting system and the heating system. In the first category, thermal conductivity of exterior walls, roofs, exterior doors, and windows are reduced. Extra layers of insulation are included into the walls and roofs and traditional single-pane glazing systems are replaced by double-glazing systems with lower U-values in each model. In the second category, LED lighting systems are used as an optimised option for post-retrofit cases instead of low standard traditional lighting systems. The third action advances the performance of the heating system without any specific modifications to the operating schedules of these systems or the setpoints. The heating system for the pre-retrofit scenario is a common hot water radiator template, powered by a gas boiler with the overall seasonal COP/efficiency of 0.65. However, in the post-retrofit scenario, conventional low-efficiency boilers are replaced by heat pumps with COP of 2.2 as the main heating source for each building [40,47].

2.2.3. *Locations*

For each scenario and dwelling type, simulations were carried out to represent different outdoor profiles by varying the weather patterns, the terrain and wind pressure coefficients for each building [49–51]. Three locations were selected; i) a suburban environment, surrounded by obstructions equal to the height of the building – Dublin suburban (53°25′N 6°15′W), ii) a rural region with scattered windbreaks equivalent to half the height of the building – Birr (53°5′N 7°55′W), and iii) a coastal region with flat landscape with fully exposed external wall surface - Belmullet (54°13′N 10°0′W).

2.2.4. Radon flow exponent

Studies have shown that the radon entry rate into a dwelling is based on a function of the level of depressurization, which is estimated by the radon flow coefficient and exponents [28,37]. The depressurization was calculated based on the difference in pressure between the outdoors and indoors. Radon flow was assumed to only occur for depressurization. The radon flow coefficient and exponents represent the local conditions governing the flow of radon below the structure into the dwelling. Radon exponents were examined in the range of 0.6–1.2 in increments of 0.1 [28,37,52]. It was assumed that the radon flow exponents would remain unchanged during the retrofit as all retrofit measures focused on the external walls/doors/windows/attic and no retrofit measures occur to the floor.

To allow for inter-comparisons between the different input variables, in each case, the pre-retrofit baseline radon concentration scenario was set to 77 Bq m^{-3}; reflecting the current national average in Ireland [16]. A recursive algorithm determined the radon flow coefficient for each individual pre-retrofit scenario. The recursive algorithm ran each simulation to establish the desired initial concentration of 77 Bq m^{-3}. In the event that the desired initial concentration was not predicted, a step-wise adjustment was applied to the radon flow coefficient and the simulation was rerun. The approach continuously looped until the radon concentration converged on the desired initial concentration and this established the radon flow coefficient for the pre-retrofit case, which was then used for the post-retrofit scenario.

3. Results

A total of 3780 combinations were simulated, representing a combination matrix of the three different dwellings, three different outdoor locations, pre/post thermal characteristics, seven different radon flow exponents, five different air permeabilities and six different retrofit ventilation strategies.

Each simulation executed with a 5-min time resolution for a year-long profile in each room, predicting between 736 and 946 thousand radon data points per simulation, which captured the temporal and spatial variation throughout the dwelling. The data were converted into a single yearly-averaged household concentration for each simulation in accordance with the passive domestic radon measurement approach [53]. The passive radon approach uses two detectors, one placed in the main bedroom and the second is placed in the living room for a minimum period of 3 months. Seasonal correction factors are applied to determine a yearly-household concentration for each dwelling compared to the reference level. In the current simulations, the living room was on the ground floor in all three dwellings, while the bedroom was on the first floor (above ground floor) for the semi-detached and terraced scenarios (household layouts can be found in Figs. S1–S3).

Table 3 provides an example of the approach described in Section 2.2.4 and shows the lowest and highest radon flow coefficients that were determined for the pre-retrofit cases in each scenario, and for a single radon flow exponent value. In each case, the lowest coefficients corresponded to an air permeability of 5 $m^3 h^{-1} m^{-2}$ with no additional ventilation, while the highest coefficients corresponded to an air permeability of 15 $m^3 h^{-1} m^{-2}$ with BV and IEV. The higher airflow values required a higher coefficient to stabilise the baseline. Higher radon flow coefficients were needed for the two-storey dwellings compared to the single storey (bungalow) due to a reduced ground floor area-to-volume ratio. Unexpectedly, the coastal scenario had the lower radon flow coefficient despite higher air exchange rates; deeper analysis showed increased pressure differentials throughout a dwelling, resulting in the need for a lower radon flow coefficient. A comparison of the results for the suburban and coastal scenarios under the same conditions shows that the annual average pressure differentials were 1.87 Pa and 9.98 Pa respectively.

While different radon flow exponents resulted in different initial radon concentrations, once the radon flow coefficient established the same baseline concentration across the various runs, there was only a marginal difference in radon concentrations following the various retrofit scenarios. The largest difference resulted in less than 4 Bq m^{-3} difference between the highest and lowest exponent. Therefore, as the effect is marginal, the presentation of pre/post retrofit simulation results is, for clarity, confined to cases involving a single radon flow exponent of 0.8 (the halfway point).

Tables 4–6 summarise the percentage changes in annual radon concentrations for the three dwellings, in a suburban location, following an energy retrofit. The radon concentrations for all three study locations and five air permeability rural and coastal locations can be found in the supplementary material (Tables S10–S18). All the data represent the post-retrofit scenario data under a matrix combination of changes in the air permeability of the dwelling and changes in the ventilation strategy. Due to the number of combinations, Tables 4–6 only present the data for changes in air permeability in steps of 0, 5 and 10 $m^3 h^{-1} m^{-2}$. The columns represent the changes in the air permeability, where 15 → 10 $m^3 h^{-1} m^{-2}$ indicates that the initial air permeability was 15 $m^3 h^{-1} m^{-2}$

Table 4
Two-room yearly-averaged percentage radon concentration changes (post retrofit relative to pre retrofit) for the suburban bungalow, subject to different retrofit conditions (air permeability and ventilation changes). A positive percentage represents an increased radon concentration, while a negative percentage represents a reduced radon concentration following the corresponding energy retrofit.

Scenarios	% increase in radon concentration					
	15 → 15 $m^3 h^{-1} m^{-2}$	**15 → 10** $m^3 h^{-1} m^{-2}$	**15 → 5** $m^3 h^{-1} m^{-2}$	**10 → 10** $m^3 h^{-1} m^{-2}$	**10 → 5** $m^3 h^{-1} m^{-2}$	**5 → 5** $m^3 h^{-1} m^{-2}$
Pre-retrofit case 1: No existing ventilation – Advantageous infiltration only						
No changes in ventilation post-retrofit.	3%	26%	69%	3%	38%	4%
Installation of BV only.	−12%	6%	30%	−14%	6%	−20%
Installation of BV and IEV.	−23%	−10%	5%	−26%	−14%	−35%
Pre-retrofit case 2: Existing BV ventilation only						
No changes in ventilation post-retrofit.	3%	23%	51%	4%	28%	5%
Installation of IEV.	−10%	4%	22%	−12%	3%	−14%
Pre-retrofit case 3: Existing BV and IEV						
No changes in ventilation post-retrofit.	3%	20%	41%	4%	22%	6%

Table 3
The inputs used to determine the radon flow coefficients for the various combinations at a radon flow exponent of 0.8. Each parameter is multiplied by the floor area of each room to determine a radon flow coefficient per zone.

	Bungalow Low (mBq $s^{-1} m^{-2}$)	Bungalow High (mBq $s^{-1} m^{-2}$)	Semi Detached Low (mBq $s^{-1} m^{-2}$)	Semi Detached High (mBq $s^{-1} m^{-2}$)	Terraced Low (mBq $s^{-1} m^{-2}$)	Terraced High (mBq $s^{-1} m^{-2}$)
Coastal	6.591	19.078	7.832	16.733	10.178	17.185
Rural	10.035	26.446	11.787	34.969	13.625	31.208
Suburban	9.451	21.043	11.614	24.365	12.889	26.155

Table 5
Two-room yearly-averaged percentage radon concentration changes (post retrofit relative to pre retrofit) for the suburban semi-detached dwelling subject to different retrofit conditions (air permeability and ventilation changes). A positive percentage represents an increased radon concentration, while a negative percentage represents a reduced radon concentration following the corresponding energy retrofit.

Scenarios	% increase in radon concentration					
	15 → 15 $m^3 h^{-1} m^{-2}$	**15 → 10** $m^3 h^{-1} m^{-2}$	**15 → 5** $m^3 h^{-1} m^{-2}$	**10 → 10** $m^3 h^{-1} m^{-2}$	**10 → 5** $m^3 h^{-1} m^{-2}$	**5 → 5** $m^3 h^{-1} m^{-2}$
Pre-retrofit case 1: No existing ventilation – Advantageous infiltration only						
No changes in ventilation post-retrofit.	3%	24%	62%	4%	36%	6%
Installation of BV only.	−20%	−10%	4%	−24%	−12%	−31%
Installation of BV and IEV.	−24%	−15%	−3%	−29%	−18%	−36%
Pre-retrofit case 2: Existing BV ventilation only						
No changes in ventilation post-retrofit.	2%	14%	33%	3%	19%	4%
Installation of IEV.	−3%	8%	24%	−3%	12%	−3%
Pre-retrofit case 3: Existing BV and IEV						
No changes in ventilation post-retrofit.	2%	13%	31%	2%	18%	3%

Table 6
Two-room yearly-averaged percentage radon concentration changes (post retrofit relative to pre retrofit) for the suburban terraced dwelling subject to different retrofit conditions (air permeability and ventilation changes). A positive percentage represents an increased radon concentration, while a negative percentage represents a reduced radon concentration following the corresponding energy retrofit.

	% increase in radon concentration					
Scenarios	**15 → 15** $m^3 h^{-1} m^{-2}$	**15 → 10** $m^3 h^{-1} m^{-2}$	**15 → 5** $m^3 h^{-1} m^{-2}$	**10 → 10** $m^3 h^{-1} m^{-2}$	**10 → 5** $m^3 h^{-1} m^{-2}$	**5 → 5** $m^3 h^{-1} m^{-2}$
Pre-retrofit case 1: No existing ventilation – Advantageous infiltration only						
No changes in ventilation post-retrofit.	2%	24%	73%	3%	42%	3%
Installation of BV only.	−13%	−3%	13%	−20%	−6%	−32%
Installation of BV and IEV.	−15%	−5%	10%	−21%	−8%	−33%
Pre-retrofit case 2: Existing BV ventilation only						
No changes in ventilation post-retrofit.	2%	13%	32%	2%	19%	2%
Installation of IEV.	0%	11%	29%	0%	16%	0%
Pre-retrofit case 3: Existing BV and IEV						
No changes in ventilation post-retrofit.	2%	13%	32%	2%	19%	2%

and the dwelling transitioned to 10 $m^3 h^{-1} m^{-2}$ during the energy retrofit; the rows reflect changes in the ventilation strategy.

The scenarios 15 → 15, 10 → 10 and 5 → 5 $m^3 h^{-1} m^{-2}$ reflect situations where there was no change in the air permeability of the dwelling. In these cases, it can be seem from Tables 4–6 that when the dwelling underwent an energy-retrofit without any changes in air permeability or changes in ventilation strategy, the radon concentrations still increased, and this is due to temperature changes. The increase ranged from 2 to 6% across the various combinations with the higher increases linked with higher airtightness values, which are associated with reduced heat loss rates. For the suburban bungalow, in the 15 → 15 $m^3 h^{-1} m^{-2}$ case, the average yearly temperature in the living room and bedroom increased from 19.4°C to 20.8°C and 19.2°C–20.3°C respectively, although the heating set points did not change. Overall, these increases were marginal compared with changes in the air permeability.

For all scenarios, where no additional ventilation measures were introduced during the retrofit and there was a corresponding decrease in the air permeability of the building, the radon concentrations were seen to increase. The increases were largest for the scenarios without any existing BV or IEV (pre-retrofit case 1) as they corresponded to the greater percentage reduction in airflow compared with dwellings with existing BV and IEV. These changes resulted in a non-linear increase in radon concentrations; e.g. when the suburban bungalow's air permeability transitioned from 15 to 13, 10, 7 and 5 $m^3 h^{-1} m^{-2}$, there were predicted increases of 11%, 26%, 48% and 69% in radon concentrations, respectively. The starting value for the air permeability of the dwelling, as well as the degree of transition, was found to be important; when the air permeability of the suburban dwelling transitioned from 15 to 10 $m^3 h^{-1} m^{-2}$, there was a 26% predicted increase in radon concentration, but when a transition from 10 to 5 $m^3 h^{-1} m^{-2}$ occurred, the predicted increase was 38%. A transition from 15 to 5 $m^3 h^{-1} m^{-2}$ resulted in an increase of 69% in the suburban location; higher percentage increases were observed for the rural and coastal locations, where radon concentrations increased by 90% and 107% respectively. Compared with the bungalow, the semi-detached dwelling experienced increases of 62%, 101% and 91% for the suburban, rural and coastal regions respectively. Higher increases compared with the bungalow are observed for the rural region, while a reduced rate for the coastal and suburban regions. By contrast, increases of 73%, 93% and 56% for the suburban, rural and coastal regions respectively occurred in the terraced dwelling. Interestingly, while the coastal location resulted in the highest radon increase for the bungalow, it resulted in the lowest increase for the terraced dwelling.

Similar trends were observed, although to a reduced extent, if the dwelling already had BV (pre-retrofit case 2) or BV and IEV (pre-retrofit case 3) for all the bungalow scenarios, and in all three regions. For pre-retrofit case 2, following increases in airtightness when a transition from 10 to 5 $m^3 h^{-1} m^{-2}$, radon concentration increases ranged from 51 to 54%; however, by contrast, the regional factors had a larger impact on the scenarios where the dwellings already had BV and IEV (pre-retrofit case 3) with post-retrofit increases ranging from 41 to 50%. The percentage difference in radon concentration diminished between the pre-retrofit cases 2 and 3 for the coastal region (54% vs 50%) compared with the suburban location (51% vs 41%). By contrast, the largest difference between pre-retrofit case 2 and 3 for the semi-detached and terraced dwellings, following an increase in airtightness, was only 5% compared with 12% for the bungalow. In certain circumstances (semi-detached coastal region and the terraced rural and coastal region), pre-retrofit case 3 had higher percentage increases with increasing airtightness for pre-retrofit case 3 compared with pre-retrofit case 2.

The data indicate that the greatest post-retrofit reduction in radon concentration (up to 48%) occurred when there were no changes in air permeability, but both BV and IEV were installed. Furthermore, the greatest reduction in radon concentration was observed for the lowest initial air permeability value; this reflects the largest percentage increase in intrazonal airflow (air flow between the inside and outside of a building) into the dwelling. In these scenarios, where BV & IEV were installed during the retrofit, a corresponding change of less than or equal to 5 $m^3 h^{-1} m^{-2}$ in the air permeability of the building, resulted in a decrease in the radon concentration. Where a decrease in air permeability of 5 $m^3 h^{-1} m^{-2}$ occurred and provided that there was the introduction of BV, there was no notable increase in radon concentrations. The introduction of BV in the semi-detached dwelling had the greatest impact, compared with the other dwellings. However, this is due to the different volumes of the living room and bedroom in the three dwellings rather than any characteristics of the dwelling type. The vent sizes remain constant regardless of the room size, and therefore the ratio of volume to BV is different for each dwelling. The semi-detached dwelling will have a higher air change rate compared with the bungalow and terraced dwelling.

The impact of installation of IEV was more variable that the impact of BV across the different housing types, as this reflects the occupancy scenarios. The introduction of IEV resulted in up to a 29% decrease for the bungalow, while the highest reduction for the semi-detached and terraced dwellings were only 17% and 3% respectively, all for the suburban location. The terraced dwelling only had two bedrooms, resulting in a lower occupancy level, and as IEV is activated by occupants, this resulted in a lower rate of additional airflow and a lower reduction in the radon following the installation. The impact of the IEV was less obvious for the rural and coastal region scenario, where higher airflows are expected due to the increased driving forces on the BV ventilation. For the coastal semi-detached and the rural terraced dwellings, the addition of IEV in combination with BV had the effect of further decreasing the radon concentration, but only by less than 1%. In the coastal terraced scenario, radon actually increased by up to 3% with addition of IEV.

4. Discussion

This study focussed on developing a state-of-the-art computational framework that utilises a dynamic radon entry rate based on the pressure differentials within a building, with the capability of assessing changes in both temperature and air permeability. This significantly enhances the ability to assess the implication for radon concentration during an energy-retrofit compared with previous studies that either assumed a constant radon emission rate, fixed temperatures or air flows [54–57]). The issues are further complicated in naturally ventilated dwellings as the same pressure differentials drives the renewal of air throughout the dwelling [58].

Simulations carried out were representative of different pre and post energy retrofit scenarios. The results quantified the changes in indoor radon concentrations resulting from changes in the temperature profiles, varying levels of the air permeability of the building, different pre- and post-retrofit ventilation strategies, radon flow exponents and different representative regional locations. It can be noted that the interpretation of the data should be considered in the context of an indicator of relative change rather than a precise numerical calculation; in this context, it provides critical information that can enhance understanding of the relative influence of various factors during energy-efficient retrofits.

Changes in airtightness were observed to be the factor that most influenced increases in post-retrofit radon concentrations. Simulations indicate that where the initial radon concentration is above 100 Bq m^{-3}, a decrease in the air permeability of the building without the addition of any new ventilation could increase the radon concentration above 200 Bq m^{-3} post-retrofit. The results from this study are relevant to the international community as they are based upon specific guidelines for the energy-efficient retrofit of dwellings, with specific ventilation recommendations [38]. While a parameterisation that reflects the status of Irish building standards is presented here, the similarity between the Irish and UK building regulations is noted, thus demonstrating that the study has applicability that is far wider than the Irish context. The percentage increases associated with different retrofitting scenarios provide useful data for policymakers and energy retrofitting practitioners to factor into mitigation plans as a key element of any proposed retrofitting works.

The current work predicts post-retrofit versus pre-retrofit radon concentration ratios ranging from 0.51 to 2.07. This range is in agreement with Long and Smyth [24], who reported mean ratios (pre/post) per group ranging from 0.8 to 1.5. The overall decrease in the mean radon concentration reported by Long and Smyth [24] (55 Bq m^{-3} pre-retrofit, reduced post-retrofit to 50 Bq m^{-3}) is possibly attributed to the age of the dwellings, where the majority of the dwellings would have had additional ventilation installed during the retrofit. However, as these radon data were not accompanied by information on household characteristics, it is impossible to make any further comparisons. The current findings support the observations of Broderick (2017), in a study of 15 dwellings, where radon concentration was seen to increase in roughly half of the dwellings post-retrofit, and decreased in the other half. While all dwellings had increased airtightness post-retrofit, the percentage change in the airtightness was different for hollow block and cavity wall dwellings. The introduction of additional ventilation during the retrofit process explains the increases and decreases in post-retrofit concentrations. Similarly, in Switzerland, dwellings that implemented multiple thermal retrofitting strategies had 50% higher radon concentrations compared with dwellings that only implemented partial thermal retrofits [26]. Meyer [22] also reported a wider distribution of radon concentrations in energy efficiency retrofitted homes compared with non-refurbished dwellings.

In the study of 3233 French homes, Collignan [25] reported that radon concentrations were approximately 33% lower in naturally-ventilated homes compared with homes with no ventilation system. The current simulations reported similar ratios for the bungalow and semi-detached dwellings; when compared under the same airtightness, dwellings that contained BV and IEV vs those without, had decreased radon concentrations post-retrofit, ranging from 28% to 48%. Collignan and Powaga [29] also highlighted that thermal retrofitting of dwellings must include a relevant ventilation system to avoid a significant increase in the level of radon indoors; when the ventilation system fails, the indoor radon concentration will increase.

In the current work, the annual average temperatures for the living room and bedroom increased by 1.4°C and 1.1°C respectively due to a reduced heat loss rate by increased external walls and attic insulation and improved glazing systems. These changes are comparable to results reported in Irish residential dwellings that underwent energy-efficient retrofit; where the temperatures increased by 0.8°C for the living room and 1.1°C for the bedroom respectively [23]. Similarly, Hong, et al. [59] reported that averaged indoor temperatures increased by 1.9 °C in UK homes following the upgrade of insulation and central heating measures. The increased temperature resulted in overall greater temperature differences between inside and outside when the heating was not in operation. The predicted increase in radon concentrations due to higher indoor temperatures is in agreement with Keskikuru et al. [60], who reported that, in naturally-ventilated dwellings, the differences between indoor and outdoor temperatures caused additional pressure differential fluctuations.

The observed increases in radon concentrations for the terraced house scenarios, and similarly with the semi-detached house, with the addition of extract ventilation, is consistent with previous observations. Keskikuru, Kokotti, Lammi and Kalliokoski [60] reported that mechanical exhaust ventilation in an airtight house could increase the negative pressure differentials, which would increase the radon entry rate into the dwelling. Arvela et al. [61] indicated that in airtight houses with mechanical extract ventilation, pressure differentials can range from 1 to 10 Pa, while in naturally ventilated homes the differentials are typically 1–3 Pa. The additional pressure differences created by the ventilation system and airtightness increases the radon flux into the dwelling. One possible explanation as to why the effect was not observed in the bungalow scenarios in the current work is that all rooms were located on the ground floor. The extract ventilation in the upstairs bathrooms may have created an additional driving force in the semi-detached and terraced dwellings, drawing more radon upstairs. The extent of this decrease/increases on radon concentrations are dependent on the number of occupants and the occupants' behaviour. Additionally, the greater impact of the coastal weather conditions on the post retrofit radon concentrations in the bungalow scenario may in part be explained by the increased wind speeds at these locations. The bungalow experiences lower stack pressures than the other house types because it only has a single storey and so has a lower height. The two-storey buildings can have higher stack pressures that require higher wind pressures to overcome. Therefore, the wind pressure are likely to dominate the infiltration rate in the bungalow. This may explain why this effect is not as evident in the other locations. In addition, the introduction of additional background ventilation is based on a fixed vent size, regardless of the room's volume, during the retrofit. The bungalow bedroom had a larger volume compared with the bedroom in the semi-detached and terraced dwellings. These differences result in a larger airflow to volume ratio for the semi-detached and terraced dwellings than the bungalow. This point is reinforced by the fact that the semi-detached dwelling had a higher negative percentage (a greater reduction) in radon concentration than the terraced dwelling.

As previously stated, radon flow coefficients were selected to predict a pre-retrofit concentration of 77 Bq m^{-3}, determined through the recursive algorithm. When these were adjusted to P_{r4} values (a radon entry rate at a pressure differential of 4 Pa) to allow comparison with previously measured values, the values ranged from 0.026 to 0.156 Bq s^{-1} m^{-2}. These values are comparable with the range of 0.016–0.124 Bq s^{-1} $m^{-2,}$ generated for Irish dwellings in a different study with radon concentrations ranging from 63 to 84 Bq m^{-3} [52]. Similarly, Collignan (2014) reported a radon flow coefficient of 0.07 Bq s^{-1} m^{-2} for a French dwelling with a radon concentration of 55 Bq m^{-3}; all other dwellings in that study had concentrations above 300 Bq m^{-3}.

There are a number of limitations associated with this study. The sole radon entry route is assumed to be that of convective radon transport of soil-gas into the building and this is assumed to be homogeneous and does not change during the retrofit. The air permeability values of the building are uniformly distributed across the entire external wall surface of the building envelope and do not take account of any variations in specific zones post-retrofit. While the modelling framework is capable of simulating these variations per zone, there is a lack of parameterisation data available. However, the effect of any localised variations is assumed to be reduced by the year-long simulation approach. In addition, it should be emphasised that as the current simulations focus on scenarios that maintained a post-retrofit air permeability greater than 5 m^3 h^{-1} m^{-2} the current results should not be extrapolated below 5 m^3 h^{-1} m^{-2} as the impacts of further air permeability decreases on the radon entry rates are unknown.

5. Conclusions

This study presents findings that demonstrate the implications for radon concentrations of various energy-efficient retrofit scenarios in naturally-ventilated dwellings. A computational framework was developed that focussed on examining pre/post retrofit radon concentration changes in different residential building types, and considered air permeability of a building, radon flow exponents, meteorological conditions and wind profiles. This represents a simulation study that examines the impact of energy-efficiency retrofit scenarios using a dynamic radon entry rate that incorporates the impacts of both temperature and pressure differentials on pre and post retrofit radon concentrations. The current study builds upon previous simulation work that only assumed a constant radon entry rate or did not have a representative household layout (only single zone); neither of these previous approaches accurately capture changes in air permeability or ventilation during a retrofit.

For all the simulated energy-retrofit scenarios, when the air permeability of the building decreased and no additional ventilation measures were installed, there was a corresponding increase in the radon concentration. The most substantial increases in radon concentrations were associated with dwellings that increased their airtightness and had no pre-existing BV; predicted radon concentrations in these dwellings increased by up to 107%. Regardless of the geogenic radon potential, the influence of the location (coastal, suburban, rural) resulted in predicted radon concentrations that differed by up to 37% when all other parameters remained constant. To a lesser extent, even increased temperature profiles due to energy-retrofitting measures, without any corresponding changes in air permeability, resulted in increased radon concentration.

The results of this study can be used to better understand the radon concentrations in pre and post energy-efficient retrofitted dwellings and aid in improving guidance on energy renovation strategies. The results highlight that radon concentrations could potentially increase or decrease in dwellings depending on the ventilation strategies that are adopted during the retrofit. The potential for increases/decreases highlight the complexity surrounding energy-efficient retrofits and that a "one fit for all" approach will not work. Therefore, energy-retrofit policy recommendations need careful consideration to ensure that the potential benefits, including those to health, are not compromised by changes in the air permeability of a building.

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Declaration of competing interest

The authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

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References

[1] IEA, Capturing the multiple benefits of energy efficiency, in: I.E. AGENCY (Ed.), 2014. https://webstore.iea.org/capturing-the-multiple-benefits-of-energy-efficiency.
[2] D. Johnston, R. Lowe, M. Bell, An exploration of the technical feasibility of achieving CO2 emission reductions in excess of 60% within the UK housing stock by the year 2050, Energy Pol. 33 (13) (2005) 1643–1659.
[3] DCENR, Better Buildings, A national renovation strategy for Ireland, in: The Department of Communications Energy and Natural Resources, 2014. Dublin.
[4] SEAI, in: S.E.A.o. Ireland (Ed.), Energy in Ireland - Report, 2019, 2019, https://www.seai.ie/publications/Energy-in-Ireland-2019-.pdf.
[5] DCCAE, Climate Action Plan 2019 to Tackle Climate Breakdown, Department of Communications, Climate Action and Environment Dublin, 2019.
[6] Cso, Housing Stock - CSO - Central Statistics Office, Accessed 31th of, https://www.cso.ie/en/releasesandpublications/ep/p-cp1hii/cp1hii/hs/, 2019. (Accessed July 2020).
[7] S. Vardoulakis, C. Dimitroulopoulou, J. Thornes, K.-M. Lai, J. Taylor, I. Myers, C. Heaviside, A. Mavrogianni, C. Shrubsole, Z. Chalabi, M. Davies, P. Wilkinson, Impact of climate change on the domestic indoor environment and associated health risks in the UK, Environ. Int. 85 (2015) 299–313.
[8] C. Shrubsole, I. Ridley, P. Biddulph, J. Milner, S. Vardoulakis, M. Ucci, P. Wilkinson, Z. Chalabi, M. Davies, Indoor PM2. 5 exposure in London's domestic stock: modeling current and future exposures following energy efficient refurbishment, Atmos. Environ. 62 (2012) 336–343.
[9] D. Crump, A. Dengel, M. Swainson, Indoor Air Quality in Highly Energy Efficient Homes–A Review, NHBC Foundation Report NF18, National House Building Council, Milton Keynes, 2009.
[10] A. Bone, V. Murray, I. Myers, A. Dengel, D. Crump, Will drivers for home energy efficiency harm occupant health? Perspect. Public. Heal. 130 (5) (2010) 233–238.
[11] G. McGill, L.O. Oyedele, K. McAllister, M. Qin, Effective indoor air quality for energy-efficient homes: a comparison of UK rating systems, Architect. Sci. Rev. 59 (2) (2016) 159–173.

[12] WHO, WHO Handbook on Indoor Radon: a Public Health Perspective, World Health Organization2009.
[13] B. Broderick, M. Byrne, A. McNabola, L. Gill, F. Pilla, J. McGrath, A. McCreddin, PALM: A Personal Activity-Location Model of Exposure to Air Pollution, Environmental Protection Agency, Wexford, Ireland., 2015.
[14] N.E. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J. V. Behar, S.C. Hern, W.H. Engelmann, The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, J. Expo. Anal. Environ. Epidemiol. 11 (3) (2001) 231–252.
[15] DCCAE, Setting the Scene, the Fifteenth National Radon Forum 2019, Department of Communications, Climate Action & Environment (DCCAE), The Gresham Hotel, Dublin, 2019.
[16] A. Dowdall, P. Murphy, D. Pollard, D. Fenton, Update of Ireland's national average indoor radon concentration – application of a new survey protocol, J. Environ. Radioact. 169 (2017) 1–8.
[17] S.G. Fennell, G. Mackin, J. Madden, A. McGarry, J. Duffy, M. O'colmain, P. Colgan, D. Pollard, Radon in Dwellings: the Irish National Radon Survey, Radiological Protection Institute of Ireland2002.
[18] EPA, Radon Results by County, 2019. Accessed 28th of, http://www.epa.ie/radiation/radon/awareness/results/. (Accessed August 2019).
[19] A. Vasilyev, I. Yarmoshenko, Effect of energy-efficient measures in building construction on indoor radon in Russia, Radiat. Protect. Dosim. 174 (3) (2016) 419–422.
[20] I. Fojtikova, K.N. Rovenska, Influence of energy-saving measures on the radon concentration in some kindergartens in the Czech Republic, Radiat. Protect. Dosim. 160 (1–3) (2014) 149–153.
[21] D. Pressyanov, D. Dimitrov, I. Dimitrova, Energy-efficient reconstructions and indoor radon: the impact assessed by CDs/DVDs, J. Environ. Radioact. 143 (2015) 76–79.
[22] W. Meyer, Impact of constructional energy-saving measures on radon levels indoors, Indoor Air 29 (4) (2019) 680–685.
[23] Á. Broderick, M. Byrne, S. Armstrong, J. Sheahan, A.M. Coggins, A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative social housing, Build. Environ. 122 (2017) 126–133.
[24] S. Long, E. Smyth, Pilot Study on the Impact of Energy Retrofitting on Radon Levels in Local Authority Homes, National Radon Forum EPA Headquarters, Johnstown Castle Wexford., 2015.
[25] B. Collignan, E. Le Ponner, C. Mandin, Relationships between indoor radon concentrations, thermal retrofit and dwelling characteristics, J. Environ. Radioact. 165 (2016) 124–130.
[26] S. Yang, J. Goyette Pernot, C. Hager Jörin, H. Niculita-Hirzel, V. Perret, D. Licina, Radon investigation in 650 energy efficient dwellings in western Switzerland: impact of energy renovation and building characteristics, Atmosphere 10 (12) (2019) 777.
[27] W. Ringer, Monitoring trends in civil engineering and their effect on indoor radon, Radiat. Protect. Dosim. 160 (1–3) (2014) 38–42.
[28] B. Collignan, C. Lorkowski, R. Améon, Development of a methodology to characterize radon entry in dwellings, Build. Environ. 57 (2012) 176–183.
[29] B. Collignan, E. Powaga, Impact of ventilation systems and energy savings in a building on the mechanisms governing the indoor radon activity concentration, J. Environ. Radioact. 196 (2017) 268–273.
[30] J. Milner, C. Shrubsole, P. Das, B. Jones, I. Ridley, Z. Chalabi, I. Hamilton, B. Armstrong, M. Davies, P. Wilkinson, Home energy efficiency and radon related risk of lung cancer: modelling study, BMJ 348 (2014) f7493.
[31] J. McGrath, M. Byrne, M. Ashmore, A. Terry, C. Dimitroulopoulou, Development of a probabilistic multi-zone multi-source computational model and demonstration of its applications in predicting PM concentrations indoors, Sci. Total Environ. 490 (2014) 798–806.
[32] J.A. McGrath, M.A. Byrne, M.R. Ashmore, A.C. Terry, C. Dimitroulopoulou, A simulation study of the changes in PM2.5 concentrations due to interzonal airflow variations caused by internal door opening patterns, Atmos. Environ. 87 (2014) 183–188.
[33] J.A. McGrath, J.N. Sheahan, C. Dimitroulopoulou, M.R. Ashmore, A.C. Terry, M. A. Byrne, PM exposure variations due to different time activity profile simulations within a single dwelling, Build. Environ. 116 (2017) 55–63.
[34] J.A. McGrath, M.A. Byrne, M.R. Ashmore, A.C. Terry, S. Dimitroulopoulou, Simulating the effect of variations in emission source start times on indoor PM concentrations, in: Indoor Air 2014 - 13th International Conference on Indoor Air Quality and Climate, International Society of Indoor Air Quality and Climate, 2014, pp. 304–306.
[35] J. McGrath, M. Byrne, M. Ashmore, A. Terry, S. Dimitroulopoulou, Simulation of solid fuel burning events in Irish fireplaces under varying air exchange rates, 12th International Conference on Indoor Air Quality and Climate, International Society on Indoor Air Quality and Climate, 2011, pp. 2065–2066.
[36] W.S. Dols, S.J. Emmerich, B.J. Polidoro, Coupling the Multizone Airflow and Contaminant Transport Software CONTAM with EnergyPlus Using Co-simulation, Building Simulation, Springer, 2016, pp. 469–479.
[37] B. Collignan, E. Powaga, Procedure for the characterization of radon potential in existing dwellings and to assess the annual average indoor radon concentration, J. Environ. Radioact. 137 (2014) 64–70.
[38] S.R. Nsai, Code of Practice for the energy efficient retrofit of dwellings. National Standards Authority of Ireland, 2014. http://www.ili.co.uk/en/S.R.54-2014.pdf.
[39] O. Neu, S. Oxizidis, D. Flynn, D. Finn, Utilising time of use surveys to predict domestic hot water consumption and heat demand profiles of residential building stocks, Br. J. Environ. Clim. Change 6 (2) (2016) 77–89.
[40] J. Egan, D. Finn, P.H.D. Soares, V.A.R. Baumann, R. Aghamolaei, P. Beagon, O. Neu, F. Pallonetto, J. O'Donnell, Definition of a useful minimal-set of accurately-specified input data for Building Energy Performance Simulation, Energy Build. 165 (2018) 172–183.
[41] ERSI, The Economic and Social Research Institute - Informed Policy for a Better Ireland 2020. https://www.esri.ie/.
[42] DHLGH, Technical Guidance Document F - Ventilation, 2020. https://www.gov.ie/en/publication/62f06-technical-guidance-document-f-ventilation/.
[43] D. Sinnott, M. Dyer, Air-tightness field data for dwellings in Ireland, Build. Environ. 51 (2012) 269–275.
[44] D. Sinnott, Dwelling airtightness: a socio-technical evaluation in an Irish context, Build. Environ. 95 (2016) 264–271.
[45] DHLGH, Buildings Regulations 2009 - Technical Guidance Document F - Ventilation, Department of Housing, Planning and Local Government, 2009.
[46] U.S. Department of Energy's (DOE), Building Technologies Office (BTO), Energyplus, 2019, Version 9.1. https://energyplus.net/.
[47] DHPLG, Buildings Regulations 2019 - Technical Guidance Document L-Conservation of Fuel and Energy – Dwellings, 2019. https://www.gov.ie/en/publication/d82ea-technical-guidance-document-l-conservation-of-fuel-and-energy-dwellings/.
[48] DHPLG, Report on the Development of Cost Optimal Calculations and Gap Analysis for Buildings in Ireland under Directive 2010/31/EU on the Energy Performance of Buildings (RECAST), Technical Report April 2020., 2020 https://www.gov.ie/en/publication/8b915-cost-optimal-residential-report-ireland-2018/. Accessed 28th of January. 2021)
[49] M. Liddament, GU03: a Guide to Energy Efficient Ventilatiocn, Air Infiltration and, Brussels, Belgium, 1996.
[50] W.S. Dols, B.J. Polidoro, CONTAM User Guide and Program Documentation, 2015, version 3.2.
[51] EnergyPlus, Weather data by region. https://energyplus.net/weather-region/europe_wmo_region_6/IRL%20%20, 2020. (Accessed August 2020).
[52] J.A. McGrath, M.A. Byrne, An approach to predicting indoor radon concentration based on depressurisation measurements, Indoor Built Environ. (2020), https://doi.org/10.1177/1420326x20924747.
[53] ISO, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 4: Integrated Measurement Method for Determining Average Activity Concentration Using Passive Sampling and Delayed Analysis, International Organization for Standardization, Geneva, 2020.
[54] J. Milner, C. Shrubsole, P. Das, B. Jones, I. Ridley, Z. Chalabi, I. Hamilton, B. Armstrong, M. Davies, P. Wilkinson, Home Energy Efficiency and Radon Related Risk of Lung Cancer: Modelling Study, 2014.
[55] C. Shrubsole, P. Das, J. Milner, I. Hamilton, J. Spadaro, E. Oikonomou, M. Davies, P. Wilkinson, A tale of two cities: comparison of impacts on CO 2 emissions, the indoor environment and health of home energy efficiency strategies in London and Milton Keynes, Atmos, Environ. Times 120 (2015) 100–108.
[56] M. Sherman, Simplified modeling for infiltration and radon entry. Proceedings, Thermal Performance of the Exterior Envelopes of Buildings Conference V, 1992.
[57] K.L. Revzan, W.J. Fisk, Modeling radon entry into houses with basements: the influence of structural factors, Indoor Air 2 (1) (1992) 40–48.
[58] S. Wang, Y. Zhang, M. Waring, L.J. Lo, Statistical analysis of wind data using Weibull distribution for natural ventilation estimation, Science and Technology for the Built Environment 24 (9) (2018) 922–932.
[59] S.H. Hong, J. Gilbertson, T. Oreszczyn, G. Green, I. Ridley, W.F.S. Group, A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment, Build. Environ. 44 (6) (2009) 1228–1236.
[60] T. Keskikuru, H. Kokotti, S. Lammi, P. Kalliokoski, Effect of various factors on the rate of radon entry into two different types of houses, Build. Environ. 36 (10) (2001) 1091–1098.
[61] H. Arvela, O. Holmgren, H. Reisbacka, J. Vinha, Review of low-energy construction, air tightness, ventilation strategies and indoor radon: results from Finnish houses and apartments, Radiat. Protect. Dosim. 162 (3) (2014) 351–363.