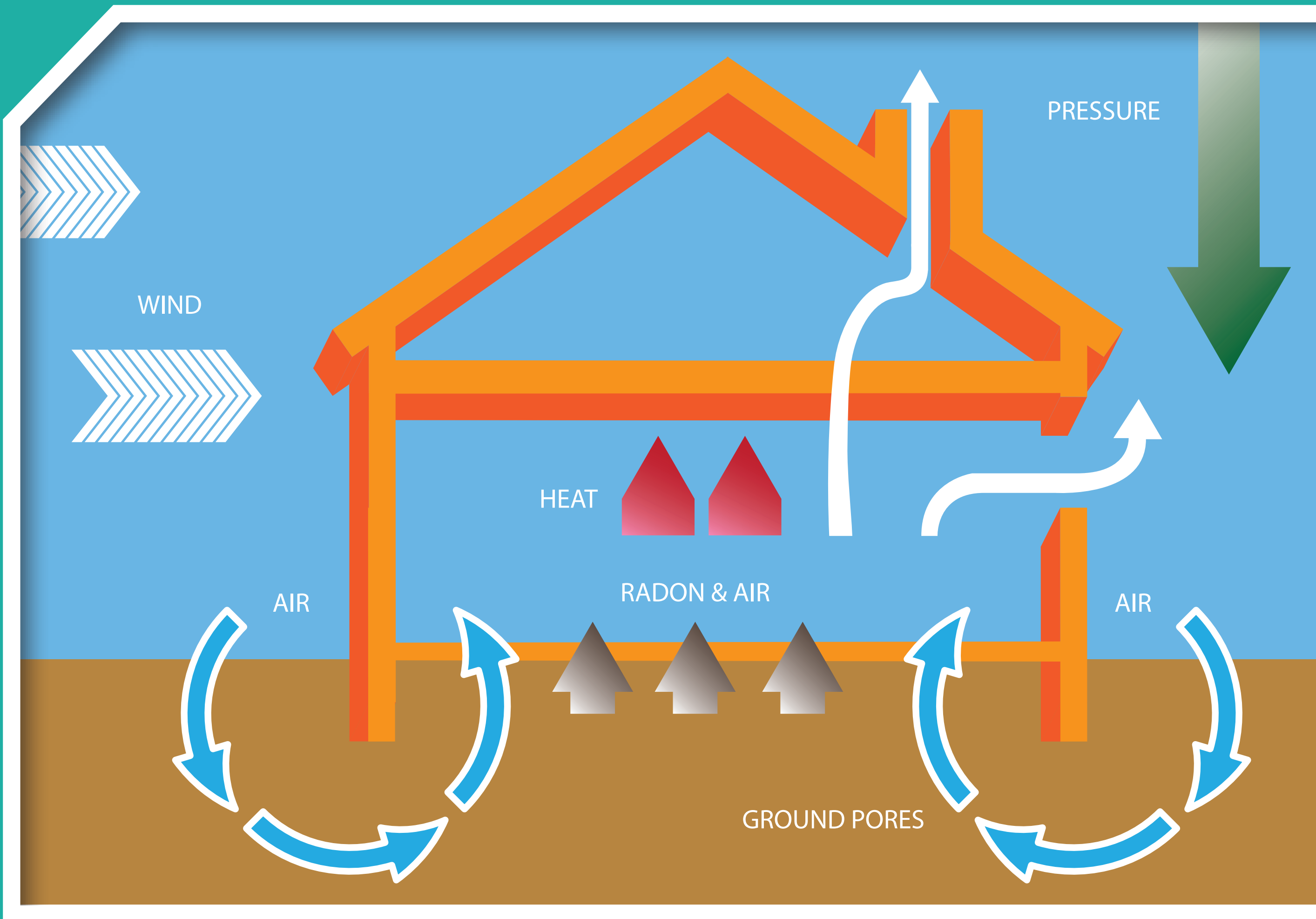
Report No. **273**

epa Research
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

UNVEIL: UNderstanding VEntilation and radon in energy-efficient buildings in IreLand

Authors: James A. McGrath and Miriam A. Byrne



www.epa.ie

Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY
The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *We provide high quality, targeted and timely environmental data, information and assessment to inform decision making at all levels.*

Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

Our Responsibilities

Licensing
We regulate the following activities so that they do not endanger human health or harm the environment:
- waste facilities *(e.g. landfills, incinerators, waste transfer stations)*;
- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
- large petrol storage facilities;
- waste water discharges;
- dumping at sea activities.

National Environmental Enforcement
- Conducting an annual programme of audits and inspections of EPA licensed facilities.
- Overseeing local authorities' environmental protection responsibilities.
- Supervising the supply of drinking water by public water suppliers.
- Working with local authorities and other agencies to tackle environmental crime by co-ordinating a national enforcement network, targeting offenders and overseeing remediation.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Prosecuting those who flout environmental law and damage the environment.

Water Management
- Monitoring and reporting on the quality of rivers, lakes, transitional and coastal waters of Ireland and groundwaters; measuring water levels and river flows.
- National coordination and oversight of the Water Framework Directive.
- Monitoring and reporting on Bathing Water Quality.

Monitoring, Analysing and Reporting on the Environment
- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
- Independent reporting to inform decision making by national and local government *(e.g. periodic reporting on the State of Ireland's Environment and Indicator Reports)*.

Regulating Ireland's Greenhouse Gas Emissions
- Preparing Ireland's greenhouse gas inventories and projections.
- Implementing the Emissions Trading Directive, for over 100 of the largest producers of carbon dioxide in Ireland.

Environmental Research and Development
- Funding environmental research to identify pressures, inform policy and provide solutions in the areas of climate, water and sustainability.

Strategic Environmental Assessment
- Assessing the impact of proposed plans and programmes on the Irish environment *(e.g. major development plans)*.

Radiological Protection
- Monitoring radiation levels, assessing exposure of people in Ireland to ionising radiation.
- Assisting in developing national plans for emergencies arising from nuclear accidents.
- Monitoring developments abroad relating to nuclear installations and radiological safety.
- Providing, or overseeing the provision of, specialist radiation protection services.

Guidance, Accessible Information and Education
- Providing advice and guidance to industry and the public on environmental and radiological protection topics.
- Providing timely and easily accessible environmental information to encourage public participation in environmental decision-making *(e.g. My Local Environment, Radon Maps)*.
- Advising Government on matters relating to radiological safety and emergency response.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

Awareness Raising and Behavioural Change
- Generating greater environmental awareness and influencing positive behavioural change by supporting businesses, communities and householders to become more resource efficient.
- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

Management and structure of the EPA
The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:
- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

UNVEIL: UNderstanding VEntilation and radon in energy-efficient buildings in IreLand

(2015-HW-DS-4)

EPA Research Report

Prepared for the Environmental Protection Agency

by

National University of Ireland Galway

Authors:

James A. McGrath and Miriam A. Byrne

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2014–2020. The EPA Research Programme is a Government of Ireland initiative funded by the Department of Communications, Climate Action and Environment. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

The authors would like to acknowledge the members of the project steering committee, namely David Fenton, EPA; Eamonn Smyth, Department of Housing, Planning and Local Government; and Paul Martin, Sustainable Energy Authority of Ireland (SEAI). The authors would also like to acknowledge the important contributions made to the project by Reihaneh Aghamolaei, Energy Institute, University College Dublin; Sean Armstrong, Department of Housing, Planning and Local Government; Bernard Collignan, Centre Scientifique et Technique du Bâtiment (CSTB); Jose Luis Guitierrez Villanueva, Grupo Radon, University of Cantabria; James O'Connell, Energy Institute, University College Dublin; Emile Powaga, CSTB; Barbara Rafferty, EPA; Chris Scivyer, Building Research Establishment (BRE); Henrik Knudsen, Aalborg University; Will Turner, Energy Institute, University College Dublin; Stuart Upton, BRE; and Simon Parker, Defence Science and Technology Laboratory.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2014–2020

Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-823-2 April 2019

Price: Free Online version

Project Partners

James A. McGrath
Centre for Climate and Air Pollution Studies
School of Physics
National University of Ireland Galway
Galway
Ireland
Tel.: +353 91 493437
Email: james.a.mcgrath@nuigalway.ie

Miriam A. Byrne
Centre for Climate and Air Pollution Studies
School of Physics
National University of Ireland Galway
Galway
Ireland
Tel.: +353 91 493394
Email: miriam.byrne@nuigalway.ie

Contents

List of Figures

List of Tables

Executive Summary

In Ireland, radon gas is considered the greatest source of radiation exposure to the general population, accounting for just over 55% of the average radiation dose, and is recognised as the second leading cause of lung cancer after tobacco smoke. Each year in Ireland, exposure to radon is linked to approximately 250 cases of lung cancer. The Irish National Energy Retrofit Programme aims to upgrade 1.2 million residential, public and commercial buildings by 2020. A review of international research shows that energy retrofitting of dwellings leads to greater airtightness and there is a possibility that radon concentrations may accordingly increase.

The National Radon Control Strategy identified a key knowledge gap: that “the relationship, if any, between increased air tightness and elevated radon levels is unknown.” The Understanding VEntilation and radon in energy-efficient buildings in IreLand (UNVEIL) project aimed to provide evidence to help understand this knowledge gap in an Irish context. The modelling framework developed solves pressure differential equations to calculate intrazonal and interzonal airflows, simulating dynamic radon entry rates, within a building influenced by meteorological conditions. This approach also examines the impact that changes in a building’s air permeability have on the zonal pressures and consequently the radon entry rate. The framework incorporates buildings’ air permeability and purpose-provided ventilation scenarios to examine the implications for radon concentrations in a number of energy-efficient retrofit scenarios that are relevant to the Irish building stock. Simulations have been carried out that examine different combinations of input parameterisation that are representative of retrofit scenarios for Irish dwellings. Three different dwellings were selected for the simulations: a bungalow, a semi-detached house and a terraced house. Simulations focused on a number of input parameters: air permeability, radon entry rates, airflow characteristics, building regulations and outdoor locations. The installation criteria for purpose-provided background ventilation following a retrofit focused on scenarios in which the post-retrofit air permeability was greater than $5\,m^3\,hr^{-1}\,m^{-2}$. A total of 960 scenarios were simulated.

This framework captures the temporal and spatial variations in radon concentrations throughout a dwelling. The framework has the capability to capture details of hourly, monthly and yearly radon concentrations. This provides an opportunity to assess the impact of changes in a building’s air permeability and changes in retrofit ventilation guidelines on indoor radon concentrations. The pre/post scenarios were analysed in terms of yearly household average concentrations in the categories of air permeability and energy retrofit guidelines.

The main conclusions were that there is the potential for radon concentrations to either increase or decrease following an energy retrofit. Any reduction in a dwelling’s air permeability without compensating with additional purpose-provided ventilation results in increases in the radon concentration. This is most evident in dwellings that already contain purpose-provided ventilation before an energy retrofit. Dwellings in which the purpose-provided ventilation was based on local by-laws, prior to the introduction of the first national building regulations, experienced the largest percentage increase in radon concentration. For dwellings without existing purpose-provided ventilation before an energy retrofit and in which purpose-provided ventilation is installed post retrofit, simulations predict that a $5\,m^3\,hr^{-1}\,m^{-2}$ reduction in a building’s air permeability can be achieved without a major change in the indoor radon concentration. The requirement for the installation of additional purpose-provided ventilation is heavily dependent on the year of construction and location of a dwelling, as this relates to the introduction of the national building standards in 1992 and local by-laws prior to an energy retrofit. The model predicts that changes in air permeability have a greater effect as air permeability tends towards $5\,m^3\,hr^{-1}\,m^{-2}$, impacting on the zonal pressure differentials and consequently on the radon entry rate into the dwelling.

1 Introduction

1.1 Overview

The Energy Efficiency Directive (EU, 2012) sets out the European policy roadmap for the period until 2020. Each Member State is required to reduce its energy consumption by 20% to meet the European Union's (EU) greenhouse gas emission reduction commitments. To achieve this objective, the Irish Government published the National Energy Efficiency Action Plan 2014 (DCENR, 2014a) to reduce energy consumption and associated emissions. Space and water heating energy consumption is estimated to account for up to 60% of the total energy consumption in Irish residential dwellings and the services sector (SEAI, 2015). The Irish National Energy Retrofit Programme aims to upgrade 1.2 million residential, public and commercial buildings by 2020 (DCENR, 2011a, 2014b).

Although lower building air exchange rates are unquestionably more energy efficient, there is currently limited understanding of the effect of reduced air infiltration on indoor air quality. Adequate ventilation is necessary to maintain thermal comfort and remove indoor air pollutant concentrations. Radon is the second-highest leading cause of lung cancer after smoking in many countries and results in over 56% of the Irish population's radiation exposure, accounting for up to 250 cases of lung cancer each year (Colgan *et al.*, 2008). There is no recognised threshold below which radon exposure presents no risk.

Recent research has shown that energy retrofitting of dwellings may lead to greater airtightness and increased indoor air pollutant concentrations, and there is a possibility that radon concentrations may increase accordingly (Long and Smyth, 2015; Collignan *et al.*, 2016; Vasilyev and Yarmoshenko, 2016). The National Radon Control Strategy (NRCS) sets out a broad range of measures to reduce radon exposure in people living in Ireland (NRCS, 2014). The strategy highlights that the economic analysis demonstrates, in general, that the proposed radon intervention measures are cost-effective. The NRCS takes into consideration the need to address radon exposure in the existing 1.6 million residential dwellings. The strategy has identified that the relationship, if any, between improved energy efficiency in buildings and indoor radon concentrations is not well understood.

1.2 Objectives

The objectives of this study are to:

1. Collect and review the current international state of knowledge concerning radon concentrations in buildings pre- and post-energy-efficient retrofit scenarios and analyse the national ventilation guidelines for the provision of ventilation following retrofit.
2. Develop a computational framework that incorporates buildings' air permeability and purpose-provided ventilation (PPV) scenarios. The model implements pressure differential equations, simulating a dynamic radon entry rate, which captures the temporal and spatial variations in radon concentrations.
3. Examine the implications for radon concentrations in different energy-efficient retrofit scenarios that are relevant to the Irish building stock. Simulate a range of initial radon concentrations and retrofit scenarios to predict post-retrofit radon concentrations in different building types.

2 Literature Review

2.1 Overview

The Irish National Energy Retrofit Programme aims to upgrade 1.2 million residential, public and commercial buildings by 2020. International research has shown that energy retrofitting of dwellings can lead to greater airtightness, reduced ventilation and increased indoor air pollutant concentrations. However, the evidence underpinning the relationship between indoor radon concentrations and energy retrofits is complex and comprises multi- and interdisciplinary research.

2.2 Objectives

The objective was to provide a detailed review of the international literature that examines any potential changes in indoor radon concentrations following an energy retrofit.

2.3 Methods

Simultaneous computerised searches of online databases were undertaken to identify key publications. Databases included Scopus (Elsevier), ScienceDirect V.4, Web of Science (Thomson Reuters), JSTOR, Academic Search Premier, Academic Search Complete, Wiley Interscience Journals, Wiley Online Library, BioMed Central (Springer), PubMed, The Cochrane Library and Geobase (Online Computer Library Center). Searches were also undertaken using Scirus and Google Scholar. Each hit or website returned was checked for relevant literature. The 2012 EU-funded project Radon Prevention and Remediation (RADPAR) was also considered, as well as the *WHO Handbook on Indoor Radon: A Public Health Perspective* (WHO, 2009).

Online searches used relevant terms associated with elements of energy retrofit and radon, combined with combinations of the following terms: “thermal”, “retrofit”, “computer modelling”, “simulations”, “ventilation”, “energy efficiency”, “indoor air quality”, “renovation”, “health impacts”, “CO_2 reduction”, “built environment”, “residential”, “measurements”, “building characterisation”.

Citations in relevant publications were checked (backward citation searches) and papers citing relevant publications were studied (forward citation searches). In addition, a systematic review of recent conference proceedings from the International Society of Indoor Air and Climate (ISAIQ) and Air Infiltration and Ventilation Centre (AIVC) (Indoor Air 2014, Healthy Buildings Europe 2015, Indoor Air 2016, ASHRAE/AIVC 2016, Healthy Buildings Europe 2017) was carried out, which kept the project team up to date with the latest developments in this field on an international scale.

2.4 Review of the Literature

2.4.1 The origins of radon

The negative impacts on human health due to exposure to ionising radiation are well documented (WHO, 2009). For the general population in Ireland, radon gas is the main source of radiation exposure, accounting for just over 55% of the average radiation dose (O’Connor *et al*., 2014). Radon gas (^{222}Rn) is a naturally occurring odourless, colourless and tasteless gas; it arises as a product of the uranium (^{238}U) decay chain. Uranium is a radioactive material found in varying quantities in soil and rocks. Radon gas has a half-life of 3.82 days, which is sufficient for it to escape from the soil and accumulate within enclosed spaces. Even though two other radon isotopes exist, ^{220}Rn and ^{219}Rn, their half-lives are only 55.6 seconds and 4.0 seconds, respectively (Lugg and Probert, 1997); therefore, they are unlikely to escape from the soil before undergoing further radioactive decay (McColl *et al*., 2010). The focus of this report is ^{222}Rn, which will simply be referred to as radon throughout this report.

Radon decays by emitting an alpha particle into a series of short-lived radioactive progeny, two of which are polonium (^{218}Po and ^{214}Po). If inhaled, the vast majority of radon gas is exhaled almost immediately. However, the short-lived radon decay products can deposit on the bronchial epithelium, exposing it to alpha radiation (IARC, 2001). The short half-lives associated with ^{218}Po and ^{214}Po, 3.1 minutes and 26.8 minutes, respectively (Lugg and Probert, 1997), often make them difficult to detect.

2.4.2 Health effects

The International Agency for Research on Cancer (IARC) reviewed radon exposure and found that there was sufficient evidence for classification of the "carcinogenicity of radon" and its decay products in humans (IARC, 1988). Overall, it concluded that radon was "carcinogenic to humans". Internationally, radon is recognised as the second-leading cause of lung cancer, after tobacco smoke. Each year in Ireland, exposure to radon is linked to approximately 250 cases of lung cancer.

In 2009, the World Health Organization (WHO) reported a relationship between radon exposure and lung cancer, indicating that the risk of lung cancer increases proportionally with increased radon exposure; there is no recognised threshold below which radon exposure presents no risk (WHO, 2009). The majority of people are exposed to concentrations ranging from low to moderate rather than high; therefore, the majority of lung cancers are related to low rather than high radon exposure.

The national action/threshold level represents the maximum accepted radon concentration in a residential dwelling before remedial action should be recommended or required. Action levels vary internationally and are summarised in Table 2.1. Reference levels should not be considered fixed values representing "safe" or "dangerous" levels, but instead are designed as a guideline for when remedial action should be considered (HSE and RPII, 2010).

In Ireland, the Radiological Protection Act, 1991 (Ionising Radiation) Order 2000 [Statutory Instrument (S.I.) No. 125/2000 (Government of Ireland, 1991)] implements the Euratom Basic Safety Standards Directive (EU, 1996). The Irish national reference level for long-term radon exposure in residential dwellings is 200 becquerels per cubic metre, or 200 $Bq\,m^{-3}$. Above this concentration, remedial work to reduce radon levels should be considered.

Darby *et al*. (2005) examined radon levels from 13 European case–control studies and the associated risk of lung cancer. The study concluded that, for every 100 $Bq\,m^{-3}$ increase in measured radon, there was an 8.4% [95% confidence interval (CI) 3.0–15.8%] increase in the risk of lung cancer.

Field and Withers (2012) reviewed the results from 22 major case–control residential radon studies and found that, in 19 studies, increased risk estimates were reported for radon levels of 100 $Bq\,m^{-3}$ (which is below the action level). In addition, the study pooled the raw data from European studies and found that for every 100 $Bq\,m^{-3}$ increase the odds ratio increased by 1.16 (95% CI 1.05–1.31).

2.4.3 Radon in the built environment

Although radon concentrations typically remain low in the outdoor environment, it accumulates and reaches higher concentrations in enclosed spaces, such as dwellings (Nero and Nazaroff, 1984; Malanca *et al*., 1992). In addition, a negative pressure differential across the substructure of the dwelling can increase the convective flow of radon into the dwelling (Keskikuru *et al*., 2001) (Figure 2.1).

Table 2.1. A summary of international reference levels

Country or organisation	Reference level ($Bq\,m^{-3}$)
Canada	200
Germany	100
Ireland	200
UK	200
USA	150
WHO	100–300

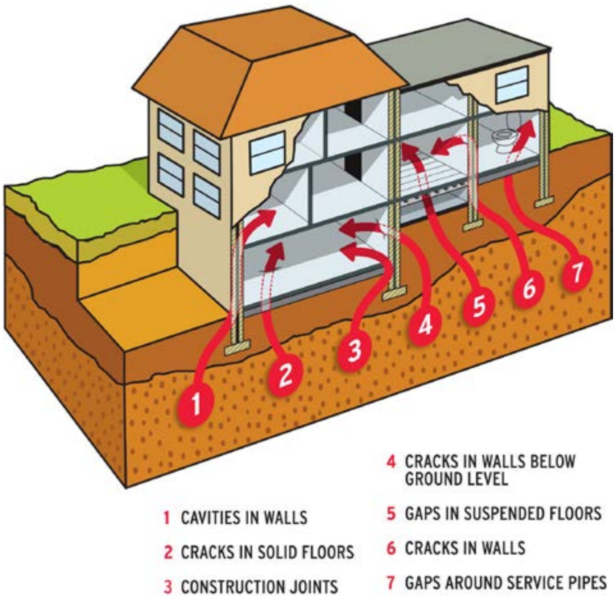


Figure 2.1. Radon entry mechanism in buildings. Source: image provided by the EPA .

Fennell *et al*. (2002) estimated a mean outdoor radon concentration of 6 Bq m^{-3} in Ireland, which was consistent with measurements conducted in other European countries. This was later confirmed by Gunning *et al*. (2014), who reported ambient radon concentrations of 5.6 ± 0.7 Bq m^{-3} after carrying out direct measurements.

The former Radiological Protection Institute of Ireland (RPII) [since merged with the Environmental Protection Agency (EPA) in August 2014] carried out a national radon survey between 1992 and 1999 using passive alpha track detectors (Fennell *et al*., 2002). The results from 11,319 houses highlighted that indoor radon concentrations ranged from 10 to 1924 Bq m^{-3}, with an average indoor radon concentration of 89 Bq m^{-3}. Based on these data, it was estimated that 91,019 houses (7%) throughout the country had a radon concentration that exceeded 200 Bq m^{-3}. Colgan *et al*. (2008) reported a concentration as high as 49,000 Bq m^{-3} in Ireland. Dowdall *et al*. (2017) estimated that, based on a newly designed survey protocol, a revised national average indoor radon concentration for Irish homes was 77 Bq m^{-3}.

In an Organisation for Economic Co-operation and Development (OECD) survey of 29 countries, Ireland was found to have the eighth-highest average indoor radon concentration (WHO, 2009). Because the populations of Western countries spend, on average, 92% of their time indoors per day, with approximately 60% of their time spent in the residential environment (Klepeis *et al*., 2001; Broderick *et al*., 2015), the residential environment deserves particular attention.

Building materials and water extracted from wells can potentially contribute to radon indoors. In most circumstances, this is marginal compared with the convective radon transport from soil–gas into the building, which is recognised as the most significant source of indoor radon (WHO, 2009; O’Connor *et al*., 2014).

Ireland has a temperate climate with summers that are typically warm and winters that are relatively mild. There is little climate variation across the country and the majority of the country falls into “Hardiness Zone 9” (DCENR, 2011a). This means that heating is needed in the winter months, but dwellings do not require air-conditioning in the summer months. The typical heating season in Ireland is considered to be from October to May, and Sinnott (2016) commented that this temperate oceanic climate means that residential dwellings are predominately naturally ventilated. Natural ventilation causes fluctuating airflows and pressure differentials that cause temporal fluctuations in radon concentrations, with levels often significantly exceeding the annual average.

Year-to-year radon fluctuations have been reported to range from 3% to 110% of the 10-year average at individual sites (Zhang *et al*., 2007; Steck, 2009). Figure 2.2 shows hourly measurements of indoor radon concentrations over 27 days, highlighting its time-varying nature (McGrath and Byrne, 2017).

Miles *et al*. (2012) measured seasonal variation patterns in radon concentrations in 91 homes in the UK over 2 years. The study reported that the average radon concentration was 137 (min. 18, max. 698) Bq m^{-3} in the winter compared with 88 (min. 17, max. 403) Bq m^{-3} in the summer.

It is possible to successfully reduce radon levels in the built environment, and remediation programmes have been justified in terms of costs and benefits (Lin *et al*., 1999; Scivyer, 2001; Boardman and Glass, 2015).

In 2009, WHO reported that indoor radon concentrations should be addressed during the construction of new dwellings (prevention) as well as reduced in existing dwellings (mitigation or remediation) (WHO, 2009). Radon prevention focuses on sealing up entry routes into dwellings, whereas

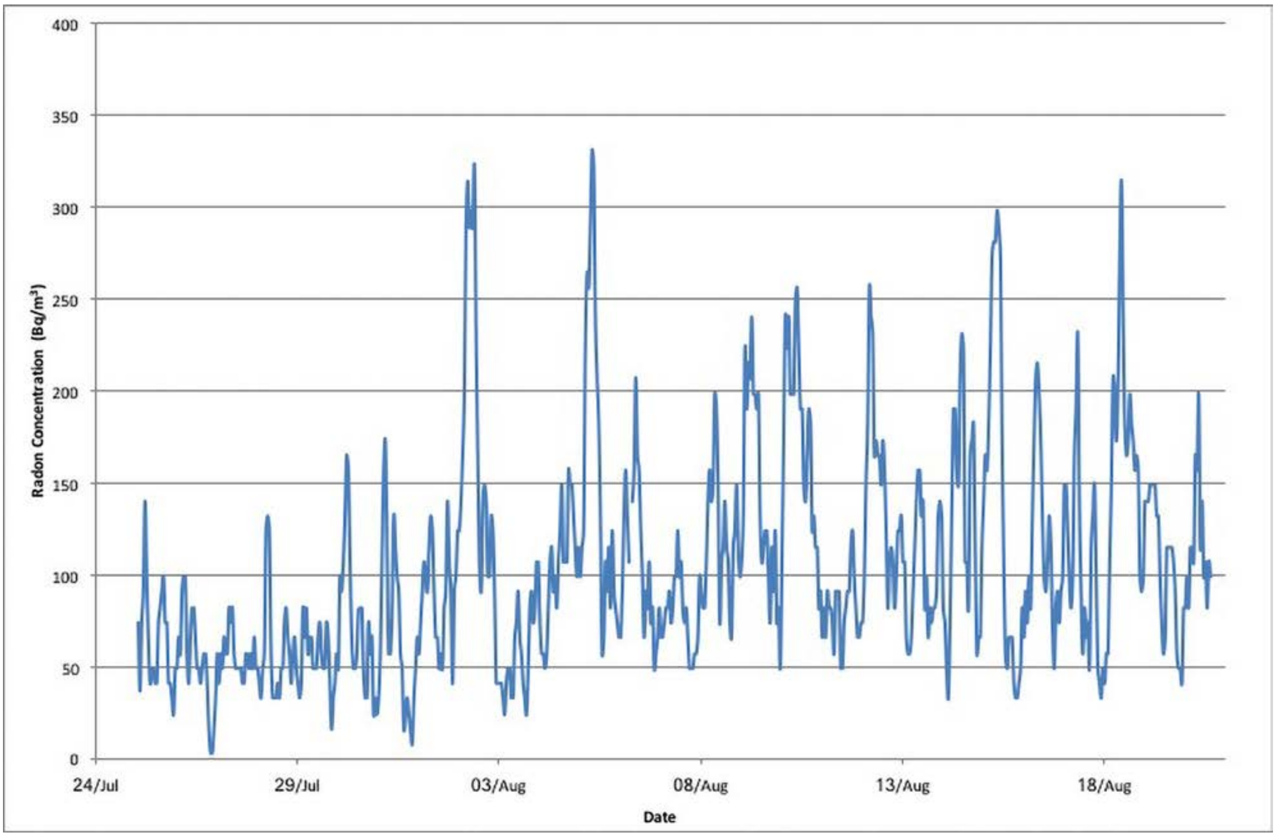


Figure 2.2. Time-varying fluctuations in indoor radon concentrations.

mitigation strategies can involve reversing the air pressure differentials between the indoors and the outdoor soil through soil depressurisation measures.

In Ireland, the most commonly used methods of radon remediation are improvement of indoor ventilation and fan-assisted sumps (Dowdall, 2015). The 1997 revision of Technical Guidance Document C introduced the requirement for a fully sealed membrane (radon barrier) in dwellings in high radon areas[1] built on or after 1 July 1998 (DEHLG, 1997a).

Rahman and Tracy (2009) reviewed radon mitigation strategies that have been employed in different countries. The choice of an optimal mitigation strategy is dependent on building type, soil and climate conditions. Radon remediation methods have been reported to successfully reduce radon concentrations by up to 90%.

Arvela *et al*. (2012) surveyed 1500 new low-rise residential houses in Finland following the revision of the building code for radon prevention in 2003–2004. The average radon concentration of all houses completed between 2006 and 2008 was 95 Bq m^{-3}, which was 33% lower than in houses completed between 2000 and 2005. This study found that the average radon concentration was reduced by 57% in houses that had taken preventative measures.

Radon concentrations may reduce as a result of the deliberate building interventions described above but may also vary as an unintended consequence of energy retrofitting strategies applied to buildings. The current state of knowledge regarding this aspect is reviewed in the next section.

2.4.4 *Energy reduction strategies*

The Energy Efficiency Directive (EU, 2012) establishes the European policy to meet the EU's greenhouse gas emission reduction commitments, a roadmap for the period from 2012 to 2020, and individual EU countries have set their own national energy efficiency targets. In 2013, Ireland's primary energy consumption was 13.9 million tonnes of oil equivalent (Mtoe); however, by 2020 Ireland is set to achieve a final energy

1 A high radon area is any area where it is predicted that 10% or more of homes will exceed the reference level of 200 Bq m^{-3}.

consumption of 11.7 Mtoe. The Irish Government has published the National Energy Efficiency Action Plan 2014 (DCENR, 2014a), highlighting its commitment to achieving a 20% energy saving and a 33% reduction in public sector energy consumption.

Ireland is considered to have one of the highest rates of energy consumption per dwelling in Europe. This is, in part, related to its smaller gas network compared with those in mainland Europe; however, it is also assumed that the Irish building stock is less energy efficient than is typical in Europe (DCENR, 2014b).

In 2014, Irish buildings accounted for 35% of the total national energy consumption and approximately 59% of electricity consumption (SEAI, 2016a). Furthermore, buildings have been consistently identified as a major potential source of cost-effective energy-efficiency improvements. 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 (Johnston *et al*., 2005). In an Irish context, the scope for economical energy-efficiency gains to be made through retrofitting of the existing building stock has been continuously identified within the National Energy Efficiency Action Plans (DCENR, 2009, 2011b, 2014a). To this end, the Irish National Energy Retrofit Programme aims to upgrade 1.2 million residential, public and commercial buildings by 2020 (DCENR, 2011a, 2014b).

The residential sector has been highlighted as a key focus for achieving reduced carbon emissions while ensuring that the economy can remain environmentally sustainable. The residential sector currently accounts for 27% of all energy usage and, after transport, it is the second-highest source of emissions in the economy (DCENR, 2014b). Even though reductions can be achieved by introducing revised building standards for future dwellings, this will only partly achieve the required reduction. Because the existing building stock will still be largely in use by 2050, there is a need to renovate the bulk of existing dwellings.

2.4.5 Irish building stock/house types

Figure 2.3 was compiled to illustrate the distribution of the housing stock based on energy rating. These data are based on information from the Central Statistics Office (CSO, 2016), representing a total of 702,489 audits conducted since January 2009. These data

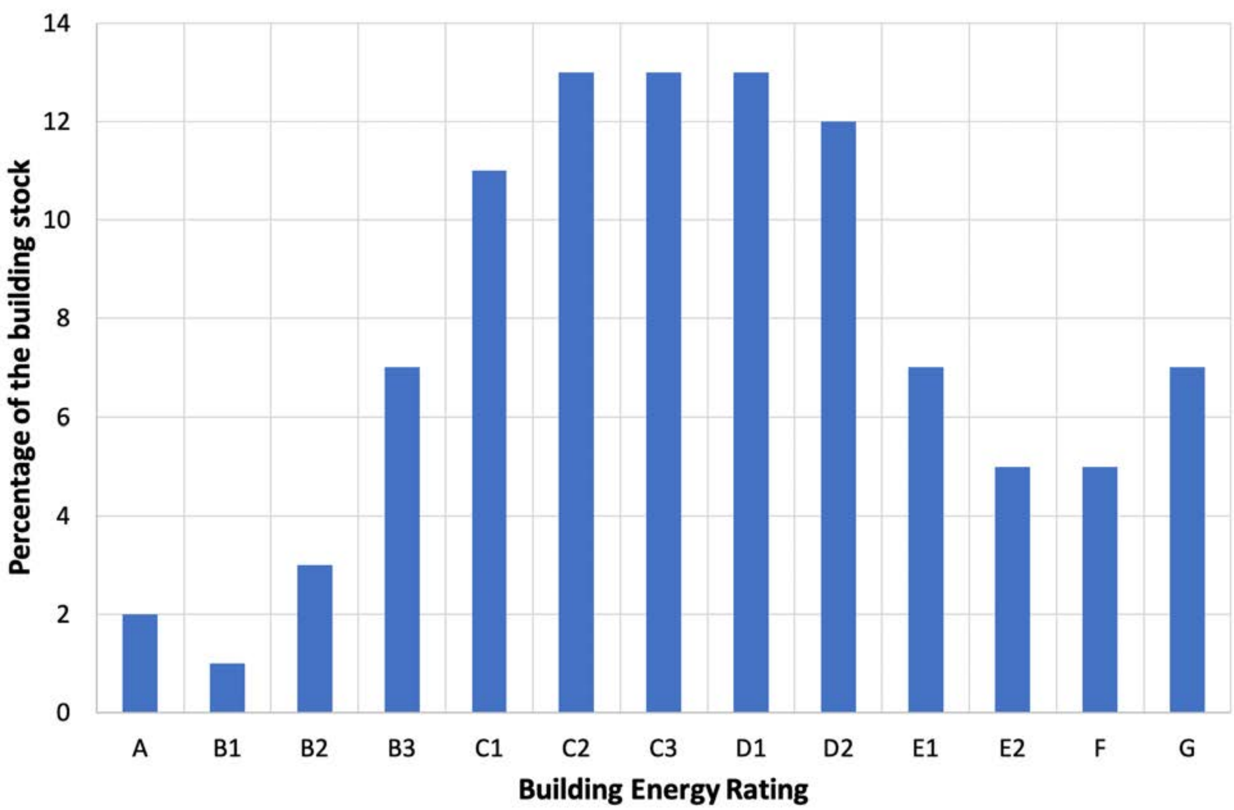


Figure 2.3. Distribution of Building Energy Rating certificates for Irish domestic dwellings.

illustrate that only 2% of all dwellings assessed were given an "A" rating (over half were built after 2010), and approximately 50% of dwellings were rated either D or greater, with A1 being the most energy-efficient rating. The poor energy performance is partly because nearly half of the current building stock was built prior to the introduction of the first national building standards. In addition, Irish houses are typically larger than European houses, with a greater number of average rooms per person.

2.4.6 Grants

In order to address the poor thermal efficiency of Irish dwellings, the Sustainable Energy Authority of Ireland (SEAI) currently offers two grant schemes to homeowners, aimed at increasing the energy efficiency of the Irish household dwellings stock: (1) the Warmer Homes Scheme (WHS) and (2) Better Energy Homes (SEAI, 2016b). The Better Energy Homes scheme provides grants for energy-efficiency improvements in the following areas: solar panels, roof or wall insulation, heating control upgrades or installation of an efficient (> 90%) gas/oil boiler. The WHS focuses on improving energy efficiency and occupants' comfort conditions in vulnerable households through the installation of draught proofing, attic insulation, lagging jackets, low-energy light bulbs and cavity wall insulation.

2.4.7 Changes in ventilation guidelines

The Building Control Act (Government of Ireland, 1990) introduced the first set of building regulations, which came into being on 1 July 1992. Prior to 1992 there were no national building standards in place throughout Ireland, although in certain parts of the country local authorities had individual by-laws. By comparison, the UK introduced the first mandatory building regulations in 1966, with revisions introduced in 1972, 1976 and 1985 (Killip, 2005).

Thirteen Technical Guidance Documents were published to accompany the building regulations, indicating how the requirements of each part were to be achieved. Three documents influence indoor air quality: (1) Technical Guidance Document F – Ventilation, (2) Technical Guidance Document C – Site Preparation and Resistance to Moisture and (3) Technical Guidance Document L – Conservation of Fuel and Energy – Dwellings (Department of the Environment, 1991a,b,c).

Each Technical Guidance Document has been revised a number of times; the current edition of Technical Guidance Document F was published in 2009, with previous editions published in 2002, 1997 and 1991. Similarly, the current edition of Technical Guidance Document L was published in 2011, with previous editions published in 2007, 2002, 1997 and 1991. The current edition of Technical Guidance Document C was introduced in 1997, with the previous edition published in 1991 (Department of the Environment, 1991a,b,c; DEHLG, 1997a,b,c, 2002a,b, 2007, 2009; DECLG, 2011).

The current version of Technical Guidance Document L of the building regulations (S.I. No. 259/2011) refers to (1) the conservation of fuel and energy, setting out minimum requirements for energy-efficiency standards, (2) the introduction of the Building Energy Rating (BER) grades for new buildings and existing buildings and (3) performance levels for air permeability of $7\,m^3\,hr^{-1}\,m^{-2}$ at 50 Pa (pascal). However, the current version of Technical Guidance Document F (S.I. No. 556/2009) requires that "Adequate means of ventilation shall be provided for people in buildings. This shall be achieved by a) limiting the moisture content of the air within the building so that it does not contribute to condensation and mould growth, and b) limiting the concentration of harmful pollutants in the air within the building." Policymakers need to ensure that energy is saved, while not undermining health. Ventilation is a key aspect that affects indoor air quality and thermal comfort in residential dwellings. Although improved thermal efficiency aims to save energy consumption, this may compromise indoor air quality if adequate ventilation is not maintained (Crump *et al*., 2009; Bone *et al*., 2010; Shrubsole *et al*., 2012; Vardoulakis *et al*., 2015; McGill *et al*., 2016).

2.4.8 The National Radon Control Strategy

In 2010, the Health Service Executive (HSE) and the former RPII published a joint statement on radon, calling for a coordinated national response on radon (HSE and RPII, 2010). In September 2011, an interagency group was established to develop a NRCS for Ireland, in line with the *WHO Handbook on Indoor Radon* (WHO, 2009) and the Euratom Basic Safety Standards Directive (EU, 1996).

The NRCS (NRCS, 2014) aims to reduce the individual and population risk for people living with high radon concentrations; however, knowledge gaps exist, which inhibit the effective delivery of the strategy. The research working subgroup of the interagency group identified knowledge gaps where further targeted research could support and improve the effectiveness of the NRCS. One key knowledge gap is that "the relationship, if any, between increased air tightness and elevated radon levels is unknown".

2.4.9 Studies of the effect of energy retrofit on radon concentration

Collignan *et al*. (2016) collected data from 3233 houses in a radon-prone area in Brittany, France, between 2011 and 2014. They found that thermally retrofitted homes have a median radon concentration of 180 Bq m^{-3} compared with 114 Bq m^{-3} in non-retrofitted houses. The study highlighted the challenges faced when determining a relationship between radon levels and period of construction because of the strong interrelationships with the type of foundation, main construction materials and thermal retrofit. The results of a multivariate linear regression model showed that thermal retrofitting had a significant effect on indoor radon concentrations (a 21% increase).

Pressyanov *et al*. (2015) studied 20 rooms in 16 different dwellings in Bulgaria. All rooms had a minimum degree of reconstruction installing new energy-efficient windows. The study found that, in 7 out of 20 rooms, radon concentrations increased significantly, whereas in the remaining rooms no significant change was observed.

Jiránek and Kačmaříková (2014) examined radon concentrations in four habitable rooms in a single dwelling for 1 year, before and after implementation of energy-saving measures. The average concentration before retrofit was 337 Bq m^{-3}, rising to 1117 Bq m^{-3} after retrofit, an increase by a factor of 3.4; however, the radon concentration in the main bedroom was found to increase by a factor of 4.9.

In 1990 in the Czech Republic, 264 reconstructed buildings were examined and a mean indoor radon concentration of 125 Bq m^{-3} was reported; this compared with 204 Bq m^{-3} in 2011 (Fojtikova and Navrátilová Rovenska, 2014). In a separate study, radon levels were measured in over 1500 schools and preschool facilities in the Czech Republic, revealing that long-term average radon concentrations increased in schools that had undergone thermal retrofit (Fojtíková and Navrátilová Rovenská, 2015).

A study of residential dwellings in the city of Ekaterinburg, Russia, built before and after the introduction of energy-efficiency requirements, reported that indoor radon concentrations in modern buildings were double those of older dwellings (Vasilyev *et al*., 2015). In a further study, Vasilyev and Yarmoshenko (2016) examined the implementation of energy-efficient measures based on measurements in 83 regions of Russia. Taking the city of Ekaterinburg as a representative case, the authors forecast the distribution of radon concentrations for 2030. The study compared measurements for 2000 with predictions for 2030 and concluded that the average radon concentration would increase by a factor of 1.42; the percentage of dwellings that would have values exceeding the reference level (300 Bq m^{-3}) would increase by a factor of 4.

Milner *et al*. (2014) carried out a simulation study based on the English building stock and predicted how indoor radon concentrations might change with various retrofitting strategies that were designed to achieve carbon dioxide reduction targets. 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}.

A pilot study carried out by the EPA (Long and Smyth, 2015) assessed the impact of energy retrofitting on radon concentrations in 142 social homes. The average pre-retrofit radon concentration was 56 Bq m^{-3}, whereas the average post-retrofit radon concentration was 50 Bq m^{-3}. However, the individual ratios for radon concentrations post retrofit versus pre retrofit ranged from 0.1 to 7.3. Retrofit measures such as attic and cavity wall insulation and draught-proofing were found to contribute to the highest average post-/pre-retrofit ratio of 1.5.

Doll *et al*. (2016) collected measurements from 69 pre- and post-weatherisation homes in North Carolina, USA. The results indicated that there was a statistically significant lower post-retrofit radon concentration. However, the authors noted that both pre- and post-retrofit average concentrations were less than 1 pCi l^{-1} (picocuries per litre of air) (37 Bq m^{-3}).

Ringer (2014) reported radon concentrations in 37 low-energy and passive homes in Austria. The study found that, in newly constructed dwellings, radon concentrations were approximately one-third lower in energy-efficient dwellings than in conventional dwellings. This was based on ensuring a highly airtight building envelope and foundation with a controlled mechanical ventilation system. The study highlighted that developing an understanding of indoor radon requires different approaches depending on whether retrofitted buildings or newly constructed energy-efficient buildings are considered. During thermal retrofit, an increase in airtightness is achieved for only the above-ground component of the building shell, with no change achieved in the foundation. However, an increase in airtightness of the above-ground component of the building alters the pressure differentials between the above-ground building shell and the foundation slab and consequently the radon entry rate.

In Germany, Guhr and Leißring (2005) carried out a survey of reconstructed buildings, where the aim was to achieve energy savings, and reported a two- to eight-fold increase in radon concentrations post reconstruction in approximately 50% of the buildings. In certain cases, 10- and 12-fold increases in radon concentrations were reported.

In a Swiss study, measurements were taken in 163 dwellings before and after thermal retrofit. On average, it was found that radon concentrations increased by 26% post retrofit (G. Roserens, Swiss Federal Office of Public Health, 2010, personal communication; cited in Ringer, 2014). The study reported that the replacement of windows was the retrofit measure that had the greatest effect on indoor radon concentrations.

Broderick *et al.* (2017) reviewed indoor air quality in 15 semi-detached residential dwellings located 12 km outside Dublin. The average radon concentration pre retrofit was 56.42 Bq m^{-3} compared with 42.07 Bq m^{-3} post retrofit. However, when the dwellings were examined individually, radon concentrations were seen to increase by up to 41% in eight of the dwellings and decrease by up to 50% in the remaining seven dwellings.

3 Methodology

3.1 Overview

The NRCS identified that the relationship, if any, between improved energy efficiency in buildings and indoor radon concentrations is not well understood. This is partly because radon cannot be detected without specialised equipment and short-term radon concentrations are known to fluctuate considerably, thus measurements provide only a crude estimation of the long-term average radon concentration. Owing to the complexities of occupant behaviour, the number of building parameters that influence radon concentrations and the time-consuming nature of pre- and post-retrofit measurements, this report uses modelling approaches to enhance understanding of the effect that energy-efficient retrofit strategies have on indoor radon concentrations.

The overall objective of this desk study is to fill this knowledge gap by collecting and analysing existing literature-based data, using these data as the basis to complement a computational study of the implications for ventilation and radon concentrations of a number of energy-efficient retrofit scenarios relevant to the Irish building stock.

In order to generate these data, a modelling framework was developed that focuses on simulating radon concentrations based on building dimensions and ventilation characteristics that are representative of the Irish dwelling stock. Simulations focus on predicting indoor radon concentrations following retrofit for a series of representative retrofit scenarios and ventilation conditions.

3.2 Modelling Approaches

As described in the previous sections, radon concentrations are subject to a range of factors, requiring indoor deposition and radioactivity decay, as well as descriptions of the behaviour of individuals that cause alterations in ventilation patterns, to be included in a model of dynamic processes of radon entry. Modelling approaches allow the effective analysis of different ventilation strategies (Dimitroulopoulou *et al*., 2000; Emmerich, 2001).

Single-zone modelling approaches are regarded as too simplistic to capture the complexity of the residential environment and fail to capture zonal (room-to-room) variations, especially regarding the inclusion of PPV (i.e. vents) following energy retrofits. On the other hand, sub-zonal (sub-zones in each room) or computational fluid dynamics (CFD) models require extensive parameterisation and computational run-time (i.e. hours or even days). Multi-zone models, at present, balance the requirements for accuracy versus computational resources and excessive parameterisation. Multi-zone models can accurately simulate indoor air pollutant concentrations for realistic homes with computational run-times requiring minutes and without the need for extensive parameterisation.

3.2.1 Previous modelling approaches

Sherman (1992) developed a simplified modelling approach for estimating the ventilation rate and radon entry rate based on the airtightness of the envelope and the driving forces. The simplified approach treated the building as a single well-mixed zone, which assumed that the interior structure had a single pressure and radon concentration. However, this assumption neglected the influence that internal partitions (internal walls and doors) have on localised pressurisation and air flows (Modera *et al*., 1991; Ferro *et al*., 2009; Du *et al*., 2012; McGrath *et al*., 2014a).

Fang and Persily (1995) examined a 12-storey multi-family residential building, two multi-storey office buildings with mechanical ventilation and a single-storey mechanically ventilated school. This model calculated the radon entry rate based on a pressure differential between the basement floor and the outdoors. The study examined the effects on airflow rates and dispersal of radon concentrations of various parameters: building ventilation systems, wind speed and direction, and indoor–outdoor temperature differences.

Man and Yeung (1999) modelled indoor radon concentrations in a newly constructed uninhabited high-rise building in Hong Kong and examined indoor and outdoor radon concentrations over 18 storeys.

Based on measured data, the study predicted indoor radon concentrations using exhalation rates of concrete, outdoor radon concentrations and air exchange rates. The study was conducted over a period of only 4 days, to minimise variations in temperature, pressure and humidity.

Milner *et al*. (2014) investigated the impacts on radon-related lung cancer deaths of reductions in home ventilation as part of the implications of energy-efficiency measures. The study simulated 10 housing archetypes under a range of ventilation strategies. The study accounted for geographical variations in radon levels by simulating low, medium and high radon concentrations. The study focused on the impacts of changes in air permeability of dwellings without compensating with additional PPV. The study applied a constant radon emission rate based on the proportional area in the ground floor rooms. However, by neglecting a dynamic radon entry rate, the study failed to capture variations caused by meteorological conditions and the implications for the entry rate due to changes in the air permeability of buildings. In a follow-on paper, Shrubsole *et al*. (2015) modelled the 2010 building stock and assessed the health impacts of three future housing decarbonisation scenarios that would be applied to the housing stock in London and Milton Keynes. In this study, the authors examined the impacts of the inclusion and exclusion of PPV, but chose to maintain the same constant radon emission rate approach as in the previous study.

3.3 Modelling Framework

The overall modelling framework couples two existing models: CONTAM and the indoor air pollution probabilistic exposure model (IAPPEM) (McGrath *et al*., 2014b). The CONTAM model focuses on determining time-varying airflow and pressure values across each zone within the dwelling. The IAPPEM model implements pressure differential and mass balance equations to calculate a dynamic radon entry rate and time-series zonal radon concentrations.

This modelling framework examines any potential impact that changes in a building's air permeability have on the pressure differentials and consequently the radon entry rate. This allows the opportunity to assess the impact that changes in air permeability and retrofit ventilation guidelines for a building have on indoor radon concentrations. This expands on the assumptions of previous simulation studies (Shrubsole *et al*., 2012, 2015; Milner *et al*., 2014), aimed at investigating the effect of reducing home ventilation as part of household energy-efficiency measures, which assumed a constant radon entry rate.

3.3.1 CONTAM

CONTAM is a multi-zone airflow model, developed by the US National Institute of Standards and Technology. CONTAM determines both external and interzonal airflows within a building based on wind speeds, outdoor pressure, internal pressures differentials and buoyancy effects, which are influenced by indoor and outdoor air temperature differences.

CONTAM has been used for a variety of applications. CONTAM calculates the time-vary airflow rates and pressure values for each zone of the building by incorporating the distribution of airflow within a building, the impacts of air tightening on infiltration rates of the building, PPV and ventilation mechanical extract.

The software is capable of providing summary and detailed reports, as well as customisable reports that can include values ranging from sub-hourly to annual. The output values can be reported in ASCII (American Standard Code for Information Interchange) text, which allows values to be easily imported into external programmes.

3.3.2 Indoor air pollution probabilistic exposure model

The IAPPEM is a state-of-the-art probabilistic exposure model, designed to fully assess the distribution of indoor air pollutants in dwellings. IAPPEM has a 1-minute time resolution, can simultaneously include up to 12 indoor emission sources and variable intrazonal and interzonal airflow rates and can include up to 15 interconnecting rooms. IAPPEM has already been used to provide a detailed analysis of the overall particulate matter (PM) contribution from multiple different emission sources, in a variety of different internal rooms within a single dwelling, and the effect that both emission source location and internal household configuration have on PM transfer throughout a dwelling has been quantified (McGrath *et al*., 2011, 2014a,b,c, 2017).

The IAPPEM has been modified to import zonal pressure values, as well as intrazonal and interzonal airflow values, as inputs into the model. Based on these values, IAPPEM calculates dynamic radon entry rates for each zone using Equation 3.1, which has been adapted from Collignan and Powaga (2014):

$$Q_k = R\left(\Delta P_k\right)^n \tag{3.1}$$

The IAPPEM calculates the change in indoor radon concentrations by solving the mass balance differential equation (Equation 3.2), which is solved at each time-step and considers the infiltration of outdoor radon, the infiltration of radon from soil into the dwelling, air transport between rooms, indoor deposition and radioactive decay. For example, the solution for room 1 at time 11:00 becomes the initial concentration for room 1 at 11:01, and so on. When simulations include multiple rooms, the solution is used in the calculation for different rooms.

The model has also been converted to run for year-long:

$$\frac{dC_k}{dt} = \frac{\left(\lambda_{0k}\right)}{V_k}\left(f_k{*}C_0 - C_k\right) - v_g\left(\frac{A_k}{V_k}\right)C_k + \left(\frac{Q_k * A_k}{V_k}\right) - \left(C_k - C_k e^{-\frac{t}{\tau}}\right) + \sum_{i=1}^{n}\frac{\left(\lambda_{ik}\right)}{V_k}\left(C_i - C_k\right) \tag{3.2}$$

Equations 3.1 and 3.2 are solved for each k, where k represents each individual room. Subscripts of 0, 1 and 2 are used to represent outside, room 1 and room 2, respectively, for different parameters. C_k represents the radon concentrations in room k (Bq m^{-3}) and C_0 represents the outdoor radon concentration (Bq m^{-3}); f_k represents the building filtration factors between the outdoors and room k; v_g is the radon deposition velocity (m hr^{-1}); λ_{ik} is the interzonal airflow between internal rooms, e.g. λ_{12} represents the airflow of pollutants from room 1 into room 2, λ_{0k}, and the intrazonal airflow, the airflow from outside into room k (m^3 hr^{-1}); A_k is the surface area of room k (m^2); V_k is the volume of room k (m^3); Q_k is the indoor radon emission rate of the pollutant in room k (Bq hr^{-1} m^{-2}), which was generated using Equation 3.1; τ is the average half-life (hr^{-1}) for radioactive decay; and R is the radon flow coefficient (Bq Pa^{-1} m^{-2} hr^{-1}) and n is the radon flow exponent.

3.4 Parameterisation

3.4.1 Household type

Three different dwellings were selected for the simulations: a bungalow, a semi-detached house and a terraced house (Figure 3.1). The dwellings are listed as case studies in the National Standards Authority of Ireland's (NSAI) *Code of Practice for the Energy Efficient Retrofit of Dwellings, Standard Recommendation S.R. 54:2014* (NSAI, 2014). The dwelling layouts are shown in Figures 3.2–3.4.

3.4.2 Building dimensions

The room dimensions of the three dwellings are shown in Tables 3.1–3.3.

3.4.3 Purpose-provided ventilation

There is a need to consider PPV following energy retrofit. There are three possible scenarios that can exist before an energy retrofit, which depend on building age:

1. no existing background ventilation in some or all habitable rooms and no extract ventilation in wet rooms;
2. existing purpose-provided background ventilation in each habitable room and no extract ventilation provided in wet rooms;
3. existing purpose-provided background ventilation in each habitable room and extract ventilation provided in wet rooms.

In each case, the pre-retrofit status of the dwelling determines if there is a requirement to install purpose-provided background ventilation following retrofit. This is based on the guidance for the provision of ventilation for retrofit works with air permeability levels > 5 m^2 at 50 Pa (NSAI, 2014), as shown in Table 3.4.

Prior to the introduction of the first Technical Guidance Document F – Ventilation (1991) (Department of the Environment, 1991a), the construction of dwellings was subject only to local by-laws and purpose-provided background ventilation was not required. Dwellings typically had a higher "air leakage", which provided air exchange through unintentional infiltration.

Figure 3.1. Three dwellings selected to represent different household types: (a) a semi-detached house, (b) a bungalow and (c) a terraced house. Images were derived from the TABULA/EPISCOPE database and are presented in NSAI's S.R. 54 document. Reproduced from NSAI (2014) with permission from the publisher.

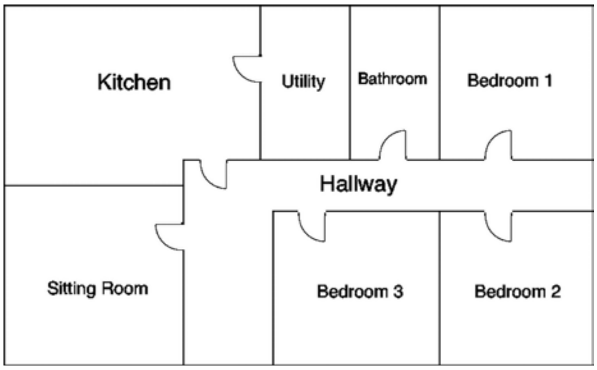


Figure 3.2. Room layout for the bungalow.

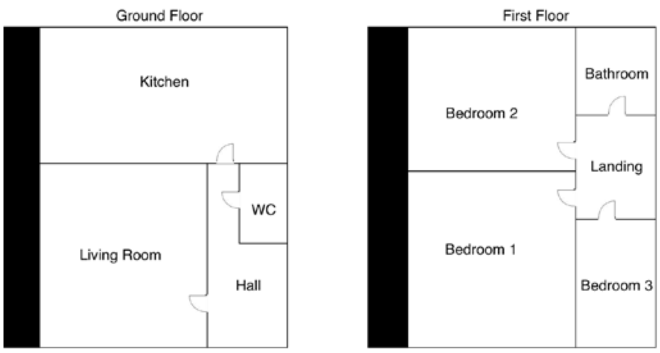


Figure 3.3. Room layout for the two-storey semi-detached dwelling. The black strip represents the adjoining dwelling.

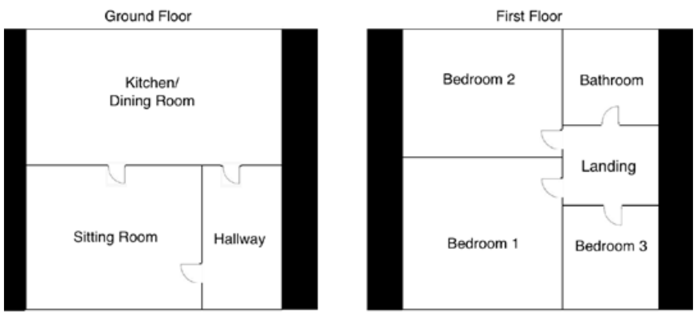


Figure 3.4. Room layout for the terraced dwelling. The black strips represent the adjoining dwellings.

Table 3.1. Summary of the room dimensions of the bungalow

Room	Floor area (m²)	Total external wall surface (m²)	Volume (m³)
Kitchen	24.91	30.98	63.27
Utility	7.81	5.42	19.83
Hall	19.71	8.52	50.05
Living room	18.22	21.68	46.27
Bedroom 1	13.38	18.59	34.00
Bedroom 2	13.38	18.59	34.00
Bedroom 3	14.50	10.07	36.83
Bathroom	7.81	5.42	19.83
Total	119.72	119.26	304.09

Table 3.2. Summary of the room dimensions of the terraced dwelling

Room	Floor area (m²)	Total external wall surface (m²)	Volume (m³)
Ground floor			
Kitchen	21.08	15.75	53.54
Hall	7.20	5.08	18.29
Living room	15.12	10.67	38.40
First floor			
Landing	4.60	0.00	11.68
Bedroom 1	14.82	9.91	37.64
Bedroom 2	12.48	9.91	31.70
Bedroom 3	5.98	5.84	15.19
Bathroom	5.52	5.84	14.02
Total	86.80	62.99	220.47

Table 3.3. Summary of the room dimensions of the two-storey semi-detached dwelling

Room	Floor area (m²)	Total external wall surface (m²)	Volume (m³)
Ground floor			
Kitchen	21.70	24.64	55.12
Toilet	2.20	5.08	5.59
Hallway	7.46	11.94	18.95
Living room	18.86	10.41	47.90
First floor			
Landing	5.46	6.60	13.87
Bedroom 1	18.45	10.41	46.86
Bedroom 2	14.76	10.41	37.49
Bedroom 3	6.93	13.72	17.60
Bathroom	4.62	10.92	11.73
Total	100.44	104.14	255.12

Table 3.4. Guidance for the provision of ventilation for retrofit works

Retrofit works		Existing dwelling condition		
		A. No existing background ventilation in some or all habitable rooms and no extract ventilation in wet rooms	B. Existing purpose - provided background ventilation in each habitable room. No extract ventilation provided in wet rooms	C. Existing purpose - provided background ventilation in each habitable room. Extract ventilation provided in wet rooms
1	Internal/external/ cavity insulation for walls	• Background ventilation should be provided to rooms without background ventilation in accordance with Column 2, Table 31 • It is advised to provide extract ventilation in wet rooms in accordance with Column 3, Table 31 • Where evidence of inadequate ventilation exists (e.g. mould, condensation), extract ventilation should be provided to all wet rooms in accordance with Column 3, Table 31	• No requirement to upgrade background ventilation • It is advised to provide extract ventilation in wet rooms in accordance with Column 3, Table 31 • Where evidence of inadequate ventilation exists (e.g. mould, condensation), extract ventilation should be provided to all wet rooms in accordance with Column 3, Table 31	• No requirement to provide further ventilation
2	Replacement of windows			
3	Sealing/insulating of timber - suspended floors			
4	Two or more of the above measures done in combination or seperately	• Background and extract ventilation should be provided to all wet rooms in accordance with Table 31	• No requirement to upgrade background ventilation • Extract ventilation should be provided to all wet rooms in accordance with Table 31	• No requirement to provide further ventilation

Note: Table 31 referred to in the table is from NSAI (2014).
Source: NSAI (2014).

For this reason, three different combinations of pre-retrofit scenarios were selected for simulation: (1) no existing PPV, (2) PPV in place with vent sizes of 4600 mm^2 per habitable room (this represents a 3.5" pipe) and (3) PPV in place with vent sizes of 6500 mm^2 per habitable room (as specified in Technical Guidance Document F, 1991) (Department of the Environment, 1991a.) The vent sizes are listed as free area, but the equivalent area is used in the simulation in accordance with I.S. EN 13141-1: 2004 (NSAI, 2004). Two post-retrofit scenarios were selected: (1) each dwelling had purpose-provided background ventilation without extract ventilation and (2) each dwelling had purpose-provided background ventilation and extract ventilation.

3.4.4 Air permeability measurements: Ireland

Sinnott and Dyer (2012) surveyed the air permeability of 28 Irish houses built in three different periods: 1941–1974, 1980–1986 and more recently in 2008. The study reported that the mean air permeability at 50 Pa was 9.1 $m^3 hr^{-1} m^{-2}$, with a minimum of 5.12 $m^3 hr^{-1} m^{-2}$ and a maximum of 14.42 $m^3 hr^{-1} m^{-2}$; 50% of the dwellings were found to have air permeability values exceeding 10 $m^3 hr^{-1} m^{-2}$, which was defined as the "reasonable upper limit" in the 2007 Technical Guidance Document L – Conservation of Fuel and Energy (DEHLG, 2007).

Gillott *et al*. (2016) demonstrated that, using conventional draught-proofing measures, it was possible to improve the air permeability of dwellings from 15.57 to 4.74 $m^3 hr^{-1} m^{-2}$ at 50 Pa in a retrofit context. However, the authors acknowledged that this was achievable only by ensuring that installation instructions were strictly followed. In a study of 15 semi-detached dwellings built in the 1990s, Broderick *et al*. (2017) reported that the building air permeability at 50 Pa decreased from pre-retrofit values ranging from 9.26 to 10.00 $m^3 hr^{-1} m^{-2}$ to average post-retrofit values of 5.53 $m^3 hr^{-1} m^{-2}$ for cavity wall dwellings and 8.61 $m^3 hr^{-1} m^{-2}$ for hollow block dwellings.

Based on the measured values cited above, the simulated cases in this study were designed to include different combinations of the building envelope's permeability, representing pre- and post-energy-efficient retrofit scenarios of 5, 7, 10, 13 and 15 $m^3 hr^{-1} m^{-2}$ at 50 Pa.

3.4.5 Weather patterns

In the simulations, two different outdoor locations were selected to highlight variation due to meteorological conditions: Belmullet (54°13´N 10°0´W) and Dublin (53°25´N 6°15´W). Weather files were input into CONTAM and provided year-long data at hourly intervals for temperature, relative humidity, wind speed and direction; all of these factors influence zonal pressures and airflow values.

It is important to note that these locations reflect only different meteorological conditions at these two locations and are not linked to the predicted radon entry rates into dwellings in Dublin and Belmullet, as reflected in the EPA radon map (EPA, 2017).

Radon flow coefficients

There are three different cases of geogenic radon potential: low (< 100 $Bq\,m^{-3}$), medium (> 100 $Bq\,m^{-3}$ and < 200 $Bq\,m^{-3}$) and high (> 200 $Bq\,m^{-3}$), which are representative of dwellings situated in different geographical locations throughout the country.

Flow coefficients of 0.02, 0.04, 0.06, 0.08, 0.10, 0.12, 0.15 and 0.20 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$ were selected to represent these different geogenic radon potentials. Based on the work of Collignan and Powaga (2014), a value of 0.66 was selected for the radon flow exponent as a representative case.

3.5 Simulations

Simulations that examined different combinations of input parameterisation, representative of Irish dwelling retrofit scenarios, were carried out. All internal doors were assumed to remain closed during the simulations. A total of 960 scenarios were simulated. Each simulation was run with a 5-minute time resolution. Once fully developed, it took the model approximately 4 minutes to run each simulation and a total of 50 Gb of data were generated.

3.5.1 Assumptions

Soil properties are assumed to be homogeneous. Although the modelling framework has the potential to predict inhomogeneity in the soil, there is insufficient information available for a detailed parameterisation. Therefore, a single radon flow coefficient was used across the entire ground floor of a dwelling, although dynamic radon entry rates are still calculated for each zone based on their pressure values.

The model assumes uniform distribution and instantaneous mixing throughout each zone within the dwelling and that the radon gas does not react with other substances or is not removed by processes other than ventilation, deposition and natural radioactive decay. In addition, the model assumes that the sole radon entry route is from convective radon transport of soil–gas into the building.

Air permeability values of buildings are calculated across the entire external wall surface of the building envelope. The values are uniformly distributed across each zone and do not account for any variations in specific zones in the post-retrofit scenario. This is because of the lack of availability of parameterisation data for any specific retrofit cases on a room-by-room basis. The NSAI Certification I.S. EN ISO 9972:2015 – Thermal Performance of Buildings – Determination of Air Permeability of Domestic Buildings – Fan Pressurisation Method is the standard guideline for measuring the air permeability of a dwelling and focuses only on obtaining a whole dwelling measurement (NSAI, 2015).

Vent sizes were selected based on the information available (NSAI, 2014). The model calculates the airflow values based on the equivalent area of the vent size and meteorological conditions. However, owing to a range of localised conditions, these values might not always be achieved.

4 Results

The results chapter is divided into two main sections. The first section (section 4.1) highlights variations in radon concentrations and the impact that individual factors have on radon concentrations, as well as demonstrating the capabilities of the model. Hourly, monthly and yearly radon concentrations are presented and room-to-room variations, variations as a result of location (where different weather patterns prevail) and variations as a result of dwelling type are also shown. These data provide the context for pre- and post-retrofit radon concentration estimates, which are presented in the second section. All simulations in the first section refer to an air permeability of 13 $m^3 hr^{-1} m^{-2}$ without PPV and a single radon flow coefficient is used to allow for comparison between the results.

The second section (section 4.2) focuses on examining the impacts of energy retrofit on radon concentrations by comparing pre- and post-energy-efficient retrofit scenarios that are representative of the Irish building stock. Owing to the large number of permutations for the input parameterisation and the quantity of time-varying radon concentration values per room, before and after scenarios were analysed in terms of yearly household averages under the categories of air permeability and the different requirements of pre- and post-energy-efficient retrofit guidelines. This also allows alignment with the results from the 3-month passive radon measurements, which were adjusted to correspond to a household yearly profile.

4.1 Predicted Room-specific Indoor Radon Concentrations

Figure 4.1 illustrates the high temporal variability of the simulated indoor radon concentrations over a month-long period in the living room of the bungalow, which is assumed to be unoccupied. Although the month-long average radon concentration was 90 $Bq\,m^{-3}$, radon concentrations fluctuate above and below this value; this is partly because they are strongly influenced by meteorological conditions, both in terms of the pressure differential for radon entry rate but also in terms of the intrazonal airflow.

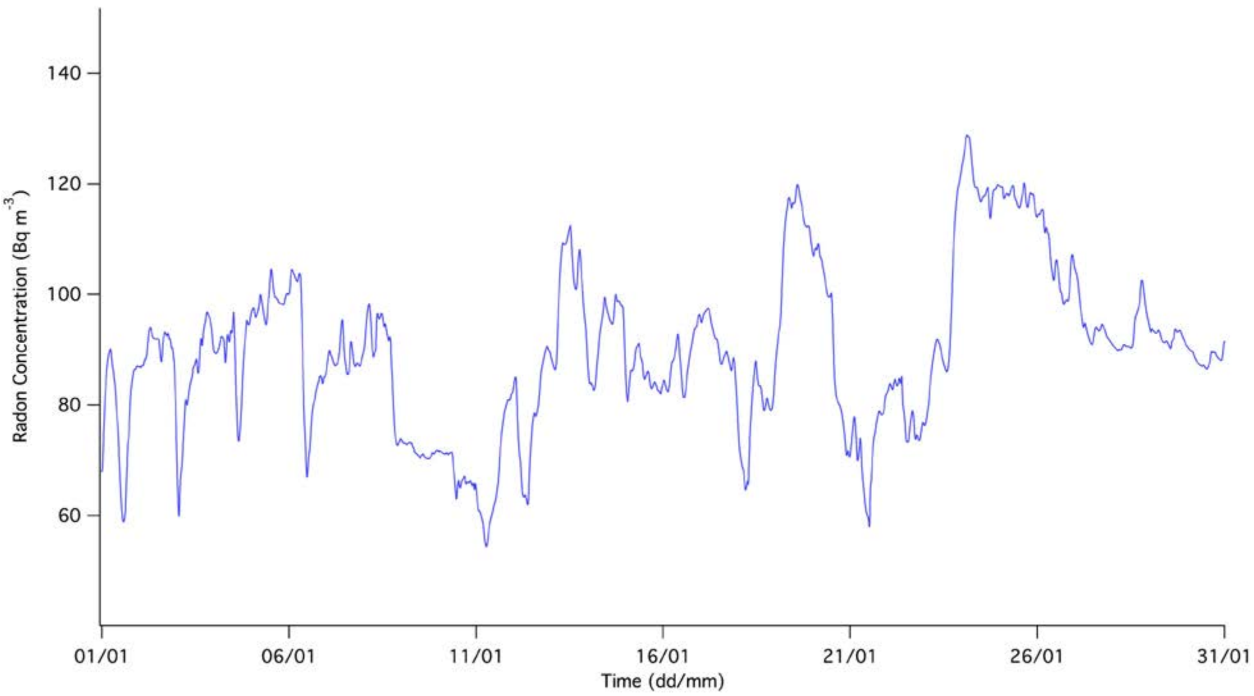


Figure 4.1. A monthly profile that highlights time-varying indoor radon concentrations in the bungalow.

Similar effects are observed in Figure 4.2, which illustrates year-long data for the same room. Simulated monthly average values are summarised in Table 4.1, which demonstrate that the model is successfully predicting the seasonal variability of radon concentrations while also capturing room-to-room variations within the same dwelling.

From Table 4.1, the hallway had the highest radon concentration in the bungalow, as it has the highest ratio of floor area to external wall surface, meaning that there is greater potential for radon entry, combined with lower airflow because of a smaller external wall surface. A similar effect is noticed when comparing bedroom 2 and bedroom 3. Although the floor areas are comparable, bedroom 3 has only one external

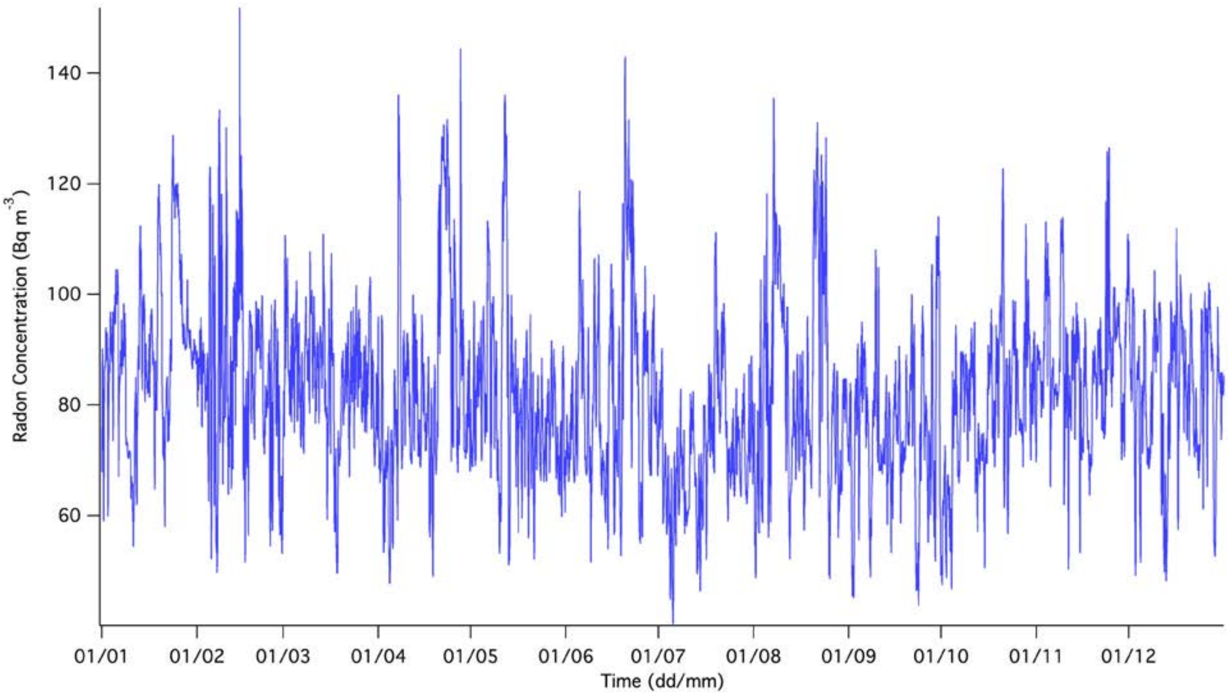


Figure 4.2. Yearly profile highlighting the time-varying indoor radon concentrations in the bungalow.

Table 4.1. Average monthly radon concentrations for each room within the bungalow

Month	Kitchen ($Bq\,m^{-3}$)	Utility ($Bq\,m^{-3}$)	Bathroom ($Bq\,m^{-3}$)	Hallway ($Bq\,m^{-3}$)	Bedroom 1 ($Bq\,m^{-3}$)	Bedroom 2 ($Bq\,m^{-3}$)	Bedroom 3 ($Bq\,m^{-3}$)	Living room ($Bq\,m^{-3}$)
1	95	101	103	113	92	82	115	90
2	123	154	109	120	77	85	132	85
3	87	105	122	119	101	98	145	85
4	88	108	112	113	88	90	130	85
5	92	105	101	106	82	80	115	81
6	84	92	94	99	76	76	110	83
7	75	83	93	96	77	82	111	71
8	93	110	100	103	74	76	120	84
9	86	102	102	104	83	80	117	75
10	80	99	109	108	99	77	121	79
11	88	97	108	114	93	88	129	87
12	91	108	109	114	97	85	122	82
Yearly average	90	105	105	109	86	83	122	82

wall compared with bedroom 2, so there is a higher airflow into bedroom 2, thereby reducing the radon concentration.

Comparison of radon concentrations in bedroom 1 and bedroom 2 highlights an interesting scenario: both rooms have the same floor area and external wall surface area, but there is no month-to-month consistency with regard to which room has the higher radon concentration. Meteorological conditions, primarily wind speed and direction, are causing these fluctuations and the effect of these factors can be seen in Figure 4.3, which compares the time-varying fluctuations in the two rooms.

4.2 Pre- and Post-retrofit Comparison (Whole Dwelling, Yearly Averages)

Tables 4.2–4.4 summarise the average yearly household radon concentrations for the three dwellings. For ease of readability, the results presented in the tables summarise the data for air permeability values of 5, 10 and 15 $m^3 hr^{-1} m^{-2}$ for weather conditions appropriate to Dublin only. Appendices 1 and 2 provide the full dataset for air permeability values of 5, 7, 10, 13 and 15 $m^3 hr^{-1} m^{-2}$ and for weather conditions appropriate to both Dublin and Belmullet.

In Tables 4.2–4.4, the shaded values denote the three initial cases (low, medium and high radon concentrations) in which a 15 $m^3 hr^{-1} m^{-2}$ air permeability is assumed; the effect of any intervention in terms of air permeability and/or ventilation can then be determined by selecting the relevant row and column in the table.

Data shown in Table 4.2 indicate that, for any decrease in the bungalow's air permeability levels, without any additional changes in the PPV, the result is an increase in the yearly averaged household radon concentration. In the scenarios where air permeability changes from (1) 15 $m^3 hr^{-1} m^{-2}$ to 10 $m^3 hr^{-1} m^{-2}$ and (2) from 10 $m^3 hr^{-1} m^{-2}$ to 5 $m^3 hr^{-1} m^{-2}$, when there is no existing PPV in the bungalow the largest percentage increases in radon concentrations are experienced: 24% and 41%, respectively. When comparing the same scenarios, but when there is existing PPV, changes in building air permeability have a reduced effect on the radon concentrations. Bungalows containing PPV with extract ventilation experience a 17% and 22% increase in radon concentrations for scenarios (1) and (2), respectively; this is in part because of the overall higher airflow that is maintained through PPV. This highlights that changes in air permeability have a

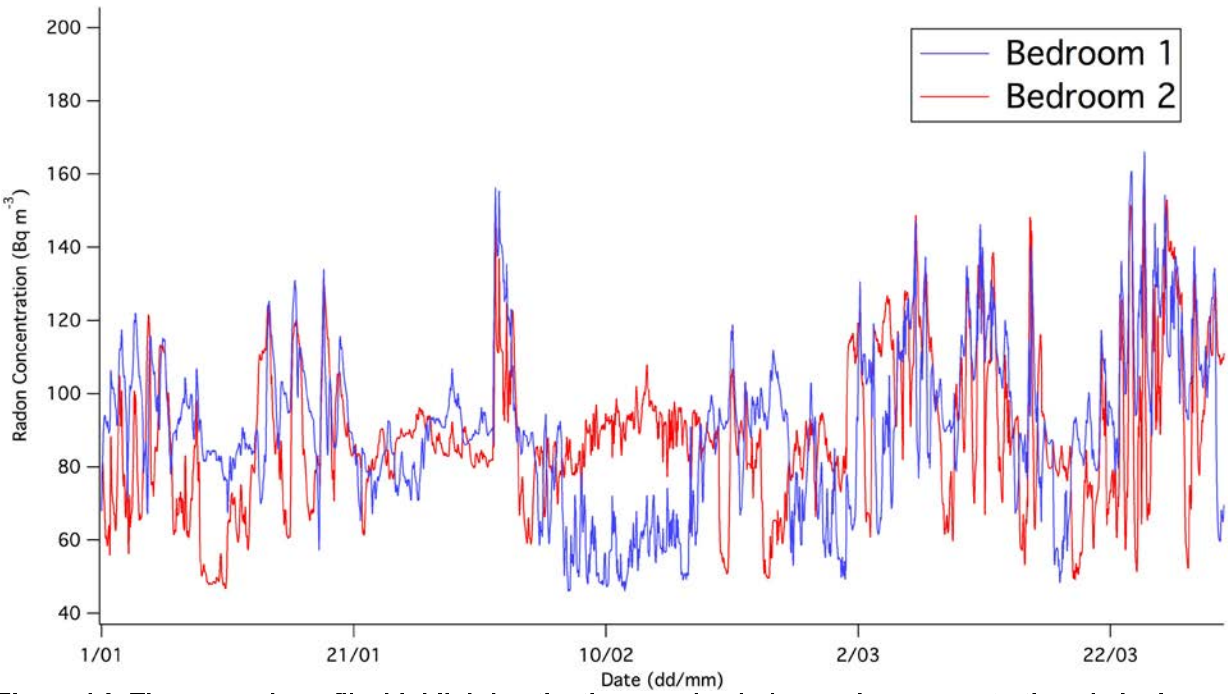


Figure 4.3. Three-month profile, highlighting the time-varying indoor radon concentrations in bedroom 1 and bedroom 2 in the bungalow.

Table 4.2. Household average yearly radon concentrations (Bq m⁻³) for the bungalow under different air permeability levels and ventilation scenarios

Air permeability ($m^3 hr^{-1} m^{-2}$)	Ventilation scenario			
	No PPV ($0 mm^2$)	Local by-laws ($4200 mm^2$)	PPV ($6500 mm^2$)	PPV with extract ($6500 mm^2$)
Initial radon concentration < 100 Bq m^{-3}				
5	158	123	115	100
10	112	95	91	82
15	91	80	77	70
Initial radon concentration 100–200 Bq m^{-3}				
5	315	243	228	198
10	222	188	179	160
15	178	156	150	137
Initial radon concentration > 200 Bq m^{-3}				
5	471	362	341	295
10	332	280	267	239
15	266	233	224	204

The shaded cells indicate low, medium and high radon concentrations when an air permeability of 15 $m^3 hr^{-1} m^{-2}$ is assumed.

Table 4.3. Household average yearly radon concentrations (Bq m^{-3}) for the semi-detached dwelling under different air permeability levels and ventilation scenarios

Air permeability ($m^3 hr^{-1} m^{-2}$)	Ventilation scenario			
	No PPV ($0 mm^2$)	Local by-laws ($4200 mm^2$)	PPV ($6500 mm^2$)	PPV with extract ($6500 mm^2$)
Initial radon concentration < 100 Bq m^{-3}				
5	147	110	102	79
10	102	84	80	65
15	80	69	67	56
Initial radon concentration 100–200 Bq m^{-3}				
5	292	218	202	154
10	201	165	156	127
15	156	135	130	109
Initial radon concentration > 200 Bq m^{-3}				
5	437	325	301	229
10	299	245	232	189
15	233	201	193	162

The shaded cells indicate low, medium and high radon concentrations when an air permeability of 15 $m^3 hr^{-1} m^{-2}$ is assumed.

Table 4.4. Household average yearly radon concentrations (Bq m^{-3}) for the terraced dwelling under different air permeability levels and ventilation scenarios

Air permeability (m^3 hr^{-1} m^{-2})	Ventilation scenario			
	No PPV (0 mm^2)	Local by-laws (4200 mm^2)	PPV (6500 mm^2)	PPV with extract (6500 mm^2)
Initial radon concentration < 100 Bq m^{-3}				
5	128	91	82	82
10	89	72	68	68
15	71	61	58	58
Initial radon concentration 100–200 Bq m^{-3}				
5	254	179	162	162
10	175	141	132	132
15	138	119	114	114
Initial radon concentration > 200 Bq m^{-3}				
5	379	267	241	241
10	261	210	197	197
15	206	178	169	169

The shaded cells indicate low, medium and high radon concentrations when an air permeability of 15 m^3 hr^{-1} m^{-2} is assumed.

greater effect as the values tend towards 5 m^3 hr^{-1} m^{-2}, impacting on the pressure difference and consequently on the radon entry rate into the dwelling.

Based on the guidance provided in the S.R.54 (NSAI, 2014), bungalows that have no existing PPV before an energy retrofit are required to install PPV in all habitable rooms following the retrofit. When the bungalow's air permeability changes from 15 m^3 hr^{-1} m^{-2} to 10 m^3 hr^{-1} m^{-2} and the required PPV is installed, there is no predicted change in radon concentration, i.e. it remains at 91 Bq m^{-3}. If the bungalow's air permeability changes from 10 m^3 hr^{-1} m^{-2} to 5 m^3 hr^{-1} m^{-2} and the required PPV is installed, there is only a marginal increase in radon concentration, from 112 to 115 Bq m^{-3}. In both cases, if additional extraction ventilation is installed in the dwelling (which is required if two or more retrofitted measures were carried out), it is observed that radon concentrations decrease below their initial values. However, the extent of this decrease would vary largely depending on the number of occupants and their individual behaviour, as there is a large degree of variability surrounding the operation of extract ventilation.

Where the bungalow already has existing PPV, there is no requirement under S.R. 54:2014 guidance (NSAI, 2014) to install additional PPV, and in these cases the predicted radon concentration in the bungalow is seen to increase. This presents an interesting scenario in dwellings built prior to 1992 as, because of the ventilation requirements under some local by-laws, the pattern of radon concentration change post retrofit can be quite different. Assuming the same radon flow coefficient in locations where the local by-laws had no requirement for PPV, these dwellings would have had higher radon concentrations initially than those where a PPV of 4200 mm^2 was required, e.g. 91 Bq m^{-3} compared with 80 Bq m^{-3}. However, following an energy retrofit and a consequent change in the buildings air permeability to 10 m^3 hr^{-1} m^{-2}, the dwelling that initially had no PPV is required to install it with vent sizes of 6500 mm^2. Consequently, the dwelling that had the initially higher radon concentration remains unchanged at 91 Bq m^{-3}, but the dwelling that initially had a PPV of 4200 mm^2 is not required to increase the vent sizes to 6500 mm^2 and the radon concentration increases in this dwelling from 80 to 95 Bq m^{-3}. The effect is even more evident when air permeability decreases to 5 m^3 hr^{-1} m^{-2}.

In summary, the simulations for which data are shown in Table 4.2 indicate that, when the initial radon concentration is below 100 Bq m^{-3}, even though concentrations can increase across the different air permeability change/ventilation installation scenarios, in no case does the post-retrofit concentration exceed the reference level of 200 Bq m^{-3}. However, when the initial radon concentration is above 150 Bq m^{-3}, there is evidence to suggest that this could exceed 200 Bq m^{-3} following a 5 $m^3 hr^{-1} m^{-2}$ change in a building's air permeability.

Tables 4.3 and 4.4 show radon concentrations in a semi-detached house and terraced house, respectively, for dwellings undergoing an air permeability reduction and/or ventilation installation following a retrofit. Although there are some minor variations in the percentage increases in radon concentrations for the semi-detached and terraced dwellings, overall the same trends are observed as for the bungalow (see Table 4.2).

The only significant differences between the semi-detached and the terraced dwelling concentration estimates are when local by-laws are implemented or PPV is installed. Figure 3.3 shows the location of the downstairs toilet in the semi-detached dwelling; this is classified as a wet room and the only requirement is to install extract ventilation. In cases of local by-laws or PPV, there is no ventilation in this room, thus reductions in air permeability increase radon concentrations. This represents a larger percentage of the overall ground floor area of the dwelling compared with the bungalow and as a result the effects are more evident.

5 Discussion

This research focused on using a state-of-the-art computational tool that incorporates changes in a building's air permeability, installation of PPV and a dynamic radon entry rate to examine the implications of energy retrofit for indoor radon concentrations in the domestic Irish building stock. It is important to highlight that any modelling approaches rely on numerous assumptions and that the interpretation of the results should be in the context of an indicator of relative change rather than a precise numerical calculation. The results provide information on the relative radon concentration changes as a means of examining the impact of ventilation-altering actors, such as weather conditions, building air permeability, the installation of PPV and the operation of extract ventilation following energy retrofit. The findings from this project provide evidence to explain some of the impacts that can be expected; however, it must be emphasised that, because of unpredictable local factors, re-testing of indoor radon levels following an energy retrofit is always recommended.

- The results of this study are broadly in agreement with the field study of pre-/post-retrofit radon concentration ratios in 143 houses reported by Long and Smyth (2015). Based solely on changes in a building's air permeability and without the inclusion of occupant behaviour, the current work predicts post-retrofit versus pre-retrofit ratios ranging from 0.61 to 1.78. Even though this range is narrower than that reported by Long and Smyth (2015), where the individual values ranged from 0.1 to 7.3, the mean ratio (pre-/post-retrofit concentration) per group ranged from 0.8 to 1.5, indicating some outliers. Without detailed housing characteristics, which were not available, it is impossible to make any further comparisons. The overall decrease in the mean radon concentration reported by Long and Smyth (2015) is possibly in part due to the weighting of the age of the dwellings (the majority of the dwellings were built pre 1992).
- The first set of Irish building regulations only came into force on 1 July 1992. Prior to this date, each local authority was responsible for the building guidelines in its jurisdiction. This means that, prior to 1992, some dwellings in some locations required PPV and others did not. The location of a dwelling therefore influences the ventilation requirements post retrofit, which, as seen from data generated in the current work, has considerable implications for radon concentrations, without even considering the additional impacts of localised geogenic radon potential.
- The results of the current work should be interpreted only as an indication based solely on guidelines for retrofit, as they do not consider the impacts of occupant activities. The installation of PPV can result in additional changes in the indoor built environment (e.g. noise, localised draughts, reduced room temperature), which may influence occupant behaviour. For example, Sinnott (2016) reported that, in some post-retrofitted Irish homes, occupants expressed dissatisfaction with the newly installed passive wall vents and, as a result, decided to cover the vents with tape. This current study assumes that all PPV is implemented and operates according to design specifications and did not consider that the efficiency of extract ventilation may decrease over time if not properly maintained.
- The current simulations focus only on retrofitted dwellings achieving an air permeability of $5\,m^3\,hr^{-1}\,m^{-2}$ or greater. This minimum value was based on what was considered representative of the majority of dwellings described in the literature and the envisaged air permeability considered achievable in the current framework of SEAI grant schemes. The current results cannot be extrapolated to scenarios in which air permeability is below $5\,m^3\,hr^{-1}\,m^{-2}$, which is outside the range considered. It is likely that there is a substantial difference in the ventilation requirements post retrofit; furthermore, the impact of decreased air permeability on the radon entry rates are unknown.

- In a UK-based study, Shrubsole *et al*. (2015) reported similar findings to those in the current study, whereby, with the inclusion of additional PPV, radon concentrations decreased marginally; however, without additional PPV there is was a significant increase in radon concentrations. The study also reported that, even though the UK building regulations state that air quality should be made no worse following retrofitting, there is no specific guidance regarding the ventilation requirements for energy efficiency retrofits. By comparison, the current work was able to base the ventilation requirement on Standard Recommendation S.R. 54:2014 (NSAI, 2014) and examined the specific guidance regarding ventilation for energy efficiency retrofits.

6 Conclusions

6.1 Summary of Research

The UNVEIL project investigated the knowledge gap that was identified in the NRCS, which stated that “the relationship, if any, between improved energy efficiency in buildings and indoor radon concentrations is not well understood” (NRCS, 2014, p. 4).

The three primary objectives of the project were realised, specifically:

1. The current state of international knowledge concerning radon concentrations in buildings pre- and post-energy-efficient retrofit scenarios was reviewed and an analysis was carried out regarding the national ventilation guidelines for the provision of ventilation following retrofit.
2. A computational framework was developed that incorporated buildings’ air permeability and PPV scenarios. The model implemented pressure differential equations, simulating a dynamic radon entry rate, which captured the temporal and spatial variations in radon concentrations.
3. The implications for radon concentrations using energy-efficient retrofit scenarios relevant to the Irish building stock were examined. A range of initial radon concentrations and retrofit scenarios was simulated to predict post-retrofit radon concentrations in different building types.

6.2 Main Findings

The main findings of this study, based on the results from the computer simulations, are as follows:

- The model’s predictions highlight that the year of construction and location of a dwelling have an impact on the indoor radon concentrations before and after energy retrofit. This links to the introduction of the national building standards in 1992 and the local by-laws prior to an energy retrofit.
- A building’s air permeability is a key factor in influencing indoor radon concentrations. The model predicts that reducing a building’s air permeability from $10\,m^3\,hr^{-1}\,m^{-2}$ to $5\,m^3\,hr^{-1}\,m^{-2}$ has a larger impact than a reduction from $15\,m^3\,hr^{-1}\,m^{-2}$ to $10\,m^3\,hr^{-1}\,m^{-2}$. This is because of the combination of reduced airflow entering the dwelling and changes in the pressure differentials and consequently the radon entry rate.
- The results of this study provide some evidence to help explain the previously observed increases and decreases in pre-/post-retrofit ratios that were observed by Long and Smyth (2015). As discussed above, the requirement to install PPV in dwellings built prior to 1992 helps provide some explanation for decreasing radon concentrations.
- For dwellings without existing PPV before an energy retrofit and where PPV is installed post retrofit in accordance with S.R. 54:2014 guidance (NSAI, 2014), simulations predict that a $5\,m^3\,hr^{-1}\,m^{-2}$ reduction in building air permeability can be achieved without major changes in indoor radon concentrations.
- For dwellings that contain PPV before an energy retrofit, as there is no requirement to change PPV after an energy retrofit, regardless of initial vent sizes, any decreases in a dwelling’s air permeability results in increases in radon concentrations. The largest impact is seen in dwellings where PPV was based on local by-laws, as these vent sizes were typically smaller than those specified in the first Technical Guidance Document F – Ventilation (Department of the Environment, 1991a).
- In all of the scenarios simulated, when dwellings had an initial radon concentration at the current national average level of $77\,Bq\,m^{-3}$, the predicted radon concentration did not exceed the action level of $200\,Bq\,m^{-3}$ following changes in a building’s air permeability.

6.3 Recommendations for Further Research

- The UNVEIL project focused on examining changes in building air permeability to a value as low as $5\,m^3\,hr^{-1}\,m^{-2}$. In June 2016, SEAI hosted the National Deep Retrofit Conference and announced a Deep Retrofit Pilot Programme. A deep retrofit results in air permeability below 5 $m^3 hr^{-1} m^{-2}$. It is unclear how the additional reduction in a building's air permeability and changes in ventilation strategies will affect indoor radon concentrations in post-retrofit scenarios, and this presents an important question for future research.

- Additional data are required on the impact of changes in building air permeability as a consequence of different retrofit scenarios. Data relating to specific retrofit measures with corresponding changes in building air permeability are lacking. These data would help homeowners understand changes in air permeability as a consequence of different retrofit measures. In addition, localised air permeability for individual rooms would provide a more in-depth analysis of localised fluctuations in indoor radon concentrations. Currently, existing data examine only the changes in the whole building envelope and neglect variations between individual rooms.
- A detailed study that combines the distribution of the entire housing stock with retrofit scenarios should be considered to better understand the consequences for the population. A combined modelling approach that incorporates the statistical distribution of both the building stock and the retrofits associated with each dwelling would estimate potential changes in the national average radon level.
- The model could be improved if representative values for the radon flow coefficient and the radon flow exponent were determined for Irish dwellings. The methodology should characterise the radon potential in existing dwellings under various pressure differentials.

References

Arvela, H., Holmgren, O. and Reisbacka, H., 2012. Radon prevention in new construction in Finland: a nationwide sample survey in 2009. *Radiation Protection Dosimetry* 148: 465–474.

Boardman, C. and Glass, S.V., 2015. Basement radon entry and stack driven moisture infiltration reduced by active soil depressurization. *Building and Environment* 85: 220–232.

Bone, A., Murray, V., Myers, I., Dengel, A. and Crump, D., 2010. Will drivers for home energy efficiency harm occupant health? *Perspectives in Public Health* 130: 233–238.

Broderick, B., Byrne, M., McNabola, A., Gill, L., Pilla, F., McGrath, J. and McCreddin, A., 2015. *PALM: A Personal Activity–Location Model of Exposure to Air Pollution*. Environmental Protection Agency, Johnstown Castle, Ireland.

Broderick, Á., Byrne, M., Armstrong, S., Sheahan, J. and Coggins, A.M., 2017. A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative social housing. *Building and Environment* 122: 126–133.

Colgan, P., Organo, C., Hone, C. and Fenton, D., 2008. *Radiation Doses Received by the Irish Population*. Radiological Protection Institute of Ireland, Dublin.

Collignan, B. and Powaga, E., 2014. Procedure for the characterization of radon potential in existing dwellings and to assess the annual average indoor radon concentration. *Journal of Environmental Radioactivity* 137: 64–70.

Collignan, B., Le Ponner, E. and Mandin, C., 2016. Relationships between indoor radon concentrations, thermal retrofit and dwelling characteristics. *Journal of Environmental Radioactivity* 165: 124–130.

Crump, D., Dengel, A. and Swainson, M., 2009. *Indoor Air Quality in Highly Energy Efficient Homes – A Review*. NHBC Foundation Report NF18. National House Building Council, Milton Keynes.

CSO (Central Statistics Office), 2016. *Domestic Buildings Energy Ratings Quarter 3 2016*. CSO, Cork. Available online: http://www.cso.ie/en/releasesandpublications/er/dber/domesticbuildingenergyratingsquarter32016/ (accessed 20 October 2016).

Darby, S., Hill, D., Auvinen, A., Barros-Dios, J., Baysson, H., Bochicchio, F., Deo, H., Falk, R., Forastiere, F. and Hakama, M., 2005. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case–control studies. *BMJ* 330: 223.

DCENR (Department of Communications, Energy and Natural Resources), 2009. *Maximising Ireland's Energy Efficiency. The National Energy Efficiency Action Plan 2009–2020*. DCENR, Dublin.

DCENR (Department of Communications, Energy and Natural Resources), 2011a. *National Energy Retrofit Programme*. DCENR, Dublin.

DCENR (Department of Communications, Energy and Natural Resources), 2011b. *Ireland's Second National Energy Efficiency Action Plan to 2020*. DCENR, Dublin.

DCENR (Department of Communications, Energy and Natural Resources), 2014a. *National Energy Efficiency Action Plan 2014*. DCENR, Dublin.

DCENR (Department of Communications, Energy and Natural Resources), 2014b. *Better Buildings. A National Renovation Strategy for Ireland.* DCENR, Dublin

DECLG (Department of the Environment, Community and Local Government), 2011. *Building Regulations 2011 – Technical Guidance Document L – Conservation of Fuel and Energy – Dwellings*. DECLG, Dublin.

DEHLG (Department of the Environment, Heritage and Local Government), 1997a. *Building Regulations 1997 – Technical Guidance Document C – Site Preparation and Resistance to Moisture.* DEHLG, Dublin.

DEHLG (Department of the Environment, Heritage and Local Government), 1997b. *Building Regulations 1997 – Technical Guidance Document F – Conservation of Fuel and Energy.* DEHLG, Dublin.

DEHLG (Department of the Environment, Heritage and Local Government), 1997c. *Building Regulations 1997 – Technical Guidance Document L – Ventilation.* DEHLG, Dublin.

DEHLG (Department of the Environment, Heritage and Local Government), 2002a. *Building Regulations 2002 –Technical Guidance Document F – Ventilation.* DEHLG, Dublin.

DEHLG (Department of the Environment, Heritage and Local Government), 2002b. *Building Regulations 2002 – Technical Guidance Document L – Conservation of Fuel and Energy.* DEHLG, Dublin.

DEHLG (Department of the Environment, Heritage and Local Government), 2007. *Building Regulations 2007 – Technical Guidance Document L – Conservation of Fuel and Energy.* DEHLG, Dublin.

DEHLG (Department of the Environment, Heritage and Local Government), 2009. *Building Regulations 2009 – Technical Guidance Document F – Ventilation.* DEHLG, Dublin.

Department of the Environment, 1991a. *Building Regulations, 1991 – Technical Guidance Document F – Ventilation.* Department of the Environment, Dublin.

Department of the Environment, 1991b. *Building Regulations, 1991 – Technical Guidance Document C – Site Preparation and Resistance to Moisture.* Department of the Environment, Dublin.

Department of the Environment, 1991c. *Building Regulations, 1991 – Technical Guidance Document L – Conservation of Fuel and Energy 1991.* Department of the Environment, Dublin

Dimitroulopoulou, C., Ashmore, M.R., Byrne, M.A., Hill, M.T.R., Kinnersley, R.P., Mark, D. and Ni Riain, C., 2000. Modelling of indoor aerosol concentrations in UK buildings. *Journal of Aerosol Science* 31: 564–565.

Doll, S.C., Davison, E.L. and Painting, B.R., 2016. Weatherization impacts and baseline indoor environmental quality in low income single-family homes. *Building and Environment* 107: 181–190.

Dowdall, A., 2015. *Current Remediation Methods and Costs in Ireland*. The National Radon Forum, Environmental Protection Agency, Johnstown Castle, Ireland. Available online: http://www.epa.ie/pubs/conferencesandevents/nrf/nrftwelfth/Forum2015_AD.pdf (accessed January 2017).

Dowdall, A., Murphy, P., Pollard, D. and Fenton, D., 2017. Update of Ireland's national average indoor radon concentration – application of a new survey protocol. *Journal of Environmental Radioactivity* 169: 1–8.

Du, L., Batterman, S., Godwin, C., Chin, J.Y., Parker, E., Breen, M., Brakefield, W., Robins, T. and Lewis, T., 2012. Air change rates and interzonal flows in residences, and the need for multi-zone models for exposure and health analyses. *International Journal of Environmental Research and Public Health* 9: 4639–4661.

Emmerich, S.J., 2001. Validation of multizone IAQ modeling of residential-scale buildings: a review. *American Society of Heating, Refrigerating and Air Conditioning Engineers Transactions* 107: 619.

EPA (Environmental Protection Agency), 2017. *Radon Map*. Available online: http://www.epa.ie/radiation/radonmap/ (accessed 15 March 2017).

EU (European Union), 1990. Council Directive 90/641/Euratom of 4 December 1990 on the operational protection of outside workers exposed to the risk of ionizing radiation during their activities in controlled areas. OJ L 349, 13.12.1990, p. 21–25. Available online: http://data.europa.eu/eli/dir/1990/641/oj (accessed 18 July 2016).

EU (European Union), 1996. Council Directive 1996/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. OJ L 159, 29.6.1996, p. 1–114. Available online: http://data.europa.eu/eli/dir/1996/29/oj (accessed 26 May 2016).

EU (European Union), 2012. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32. OJ L 315, 14.11.2012, p. 1–56.

Fang, J.B. and Persily, A.K., 1995. Airflow and radon transport modeling in four large buildings. *American Society of Heating, Refrigerating and Air Conditioning Engineers Transactions* 101: 1100–1100.

Fennell, S.G., Mackin, G., Madden, J., McGarry, J., Duffy, J., O'Colmain, M., Colgan, P. and Pollard, T., 2002. *Radon in Dwellings: The Irish National Radon Survey*. Radiological Protection Institute of Ireland, Dublin.

Ferro, A.R., Klepeis, N.E., Ott, W.R., Nazaroff, W.W., Hildemann, L.M. and Switzer, P., 2009. Effect of interior door position on room-to-room differences in residential pollutant concentrations after short-term releases. *Atmospheric Environment* 43: 706–714.

Field, R.W. and Withers, B.L., 2012. Occupational and environmental causes of lung cancer. *Clinics in Chest Medicine* 33: 681–703.

Fojtíková, I. and Navrátilová Rovenská, K., 2014. Influence of energy-saving measures on the radon concentration in some kindergartens in the Czech Republic. *Radiation Protection Dosimetry* 160: 149–153.

Fojtíková, I. and Navrátilová Rovenská, K., 2015. Methodology for measurement in schools and kindergartens: experiences. *Radiation Protection Dosimetry* 164: 612–617.

Gillott, M.C., Loveday, D.L., White, J., Wood, C.J., Chmutina, K. and Vadodaria, K., 2016. Improving the airtightness in an existing UK dwelling: the challenges, the measures and their effectiveness. *Building and Environment* 95: 227–239.

Government of Ireland, 1990. Building Control Act. Office of Public Works, Trim, Ireland.

Government of Ireland, 1991. Radiological Protection Act, 1991 (Ionising Radiation) Order 2000 (S.I. No. 125/2000). Available online: http://www.irishstatutebook.ie/eli/2000/si/125/made/en/print (accessed 11 April 2016).

Guhr, A. and Leißring, B., 2005. Gesundheitsrisiko infolge natürlicher Radioaktivität in Wohn- und Aufenthaltsräumen. *Umwelt-Medizin-Gesellschaft* 18: 126–129.

Gunning, G., Pollard, D. and Finch, E., 2014. An outdoor radon survey and minimizing the uncertainties in low level measurements using CR-39 detectors. *Journal of Radiological Protection* 34: 457–467.

HSE (Health Service Executive) and RPII (Radiological Protection Institute of Ireland), 2010. *Radon Gas in Ireland – Joint Position Statement by the Radiological Protection Institute of Ireland and the Health Service Executive*. Health Service Executive and Radiological Protection Institute of Ireland, Dublin. Available online: https://www.hse.ie/eng/services/Publications/Environmentalhealth/Radon%20Gas%20in%20Ireland.pdf (accessed November 2016).

IARC (International Agency for Research on Cancer), 1988. Man-made mineral fibres and radon. *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans* 43: 1–300.

IARC (International Agency for Research on Cancer), 2001. Some internally deposited radionuclides. *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans* 78: 1–600

Jiránek, M. and Kačmaříková, V., 2014. Dealing with the increased radon concentration in thermally retrofitted buildings. *Radiation Protection Dosimetry* 160: 43–47.

Johnston, D., Lowe, R. and Bell, M., 2005. An exploration of the technical feasibility of achieving CO_2 emission reductions in excess of 60% within the UK housing stock by the year 2050. *Energy Policy* 33: 1643–1659.

Keskikuru, T., Kokotti, H., Lammi, S. and Kalliokoski, P., 2001. Effect of various factors on the rate of radon entry into two different types of houses. *Building and Environment* 36: 1091–1098.

Killip, G., 2005. *Built Fabric and Building Regulations.* Environmental Change Institute, University of Oxford, Oxford. Available online: http://www.eci.ox.ac.uk/research/energy/downloads/40house/background_doc_f.pdf (accessed November 2016).

Klepeis, N.E., Nelson, W.C., 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 Analysis and Environmental Epidemiology* 11: 231–252.

Lin, C., Gelman, A., Price, P. and Krantz, D., 1999. Analysis of local decisions using hierarchical modeling, applied to home radon measurement and remediation. *Statistical Science* 14: 305–337.

Long, S. and Smyth, E., 2015. *Pilot Study on the Impact of Energy Retrofitting on Radon Levels in Local Authority Homes*. National Radon Forum, 3 June 2015. Environmental Protection Agency, Johnstown Castle, Ireland.

Lugg, A. and Probert, D., 1997. Indoor radon gas: a potential health hazard resulting from implementing energy-efficiency measures. *Applied Energy* 56: 93–196.

McColl, N.P., Miles, J.C.H., Green, B.M.R., Dixon, D.W., Fey, R., Meara, J.R., Harrison, J.D. and Cooper, J.R., 2010. *Limitation of Human Exposure to Radon: Advice from the Health Protection Agency.* Health Protection Agency, London.

McGill, G., Oyedele, L.O., McAllister, K. and Qin, M., 2016. Effective indoor air quality for energy-efficient homes: a comparison of UK rating systems. *Architectural Science Review* 59: 159–173.

McGrath, J. and Byrne, M., 2017 An experimental validation of an indoor radon model that examines energy retrofit buildings. 38th AIVC Conference, 6th TightVent Conference and 4th Venticool Conference, Nottingham, 13–14 September.

McGrath, J., Byrne, M., Ashmore, M., Terry, A., and Dimitroulopoulou, S., 2011. Simulation of solid fuel burning events in Irish fireplaces under varying air exchange rates. 12th International Conference on Indoor Air Quality and Climate, Austin, Texas, 5–10 June, pp. 2065–2066.

McGrath, J.A., Byrne, M.A., Ashmore, M.R., Terry, A.C. and Dimitroulopoulou, C., 2014a. A simulation study of the changes in PM2.5 concentrations due to interzonal airflow variations caused by internal door opening patterns. *Atmospheric Environment* 87: 183–188.

McGrath, J., Byrne, M., Ashmore, M., Terry, A. and Dimitroulopoulou, C., 2014b. Development of a probabilistic multi-zone multi-source computational model and demonstration of its applications in predicting PM concentrations indoors. *Science of the Total Environment* 490: 798–806.

McGrath, J.A., Byrne, M.A., Ashmore, M.R., Terry, A.C. and Dimitroulopoulou, S., 2014c. Simulating the effect of variations in emission source start times on indoor PM concentrations. Indoor Air 2014 – 13th International Conference on Indoor Air Quality and Climate, Hong Kong, 7–12 July, pp. 304–306.

McGrath, J.A., Sheahan, J.N., Dimitroulopoulou, C., Ashmore, M.R., Terry, A.C. and Byrne, M.A., 2017. PM exposure variations due to different time activity profile simulations within a single dwelling. *Building and Environment* 116: 55–63.

Malanca, A., Cassoni, F., Dallara, G. and Pessina, V., 1992. Radon in dwellings: the importance of ventilation. *Aerobiologia* 8: 57–61.

Man, C.K. and Yeung, H.S., 1999. Modeling and measuring the indoor radon concentrations in high-rise buildings in Hong Kong. *Applied Radiation and Isotopes* 50: 1131–1135.

Miles, J., Howarth, C. and Hunter, N., 2012. Seasonal variation of radon concentrations in UK homes. *Journal of Radiological Protection* 32: 275–287.

Milner, J., Shrubsole, C., Das, P., Jones, B., Ridley, I., Chalabi, Z., Hamilton, I., Armstrong, B., Davies, M. and Wilkinson, P., 2014. Home energy efficiency and radon related risk of lung cancer: modelling study. *BMJ* 348: f7493.

Modera, M., Dickerhoff, D., Jansky, R. and Smith, B., 1991. *Improving the Energy Efficiency of Residential Air Distribution Systems in California – Final Report: Phase I*. Lawrence Berkeley National Laboratory Report, LBL-30886. Lawrence Berkeley National Laboratory, San Francisco, CA.

Nero, A.V. and Nazaroff, W.W., 1984. Characterising the source of radon indoors. *Radiation Protection Dosimetry* 7: 23–39.

NRCS (National Radon Control Strategy), 2014. *The National Radon Control Strategy*. Available online: https://www.dccae.gov.ie/en-ie/environment/publications/Documents/4/National%20Radon%20Control%20Strategy.pdf (accessed March 2016).

NSAI (National Standards Authority of Ireland), 2004 . *I.S. EN 13141-1: 2004 Ventilation for Buildings – Performance Testing of Components/Products for Residential Ventilation. Externally and Internally Mounted Air Transfer Devices*. Available online: https://infostore.saiglobal.com/en-gb/Standards/I-S-EN-13141-1-2004-871717_SAIG_NSAI_NSAI_2072720/ (accessed January 2017).

NSAI (National Standards Authority of Ireland), 2014. *Code of Practice for the Energy Efficient Retrofit of Dwellings. Standard Recommendation S.R. 54:2014*. NSAI, Dublin. Available online: http://www.ili.co.uk/en/S.R.54-2014.pdf (accessed March 2016).

NSAI (National Standards Authority of Ireland), 2015. *Thermal Performance of Buildings – Determination of Air Permeability of Buildings – Fan Pressurization Method (ISO 9972:2015).* NSAI, Dublin. Available online: https://infostore.saiglobal.com/preview/98706588708.pdf?sku=879191_SAIG_NSAI_NSAI_2089125 (accessed 8 November 2016).

O'Connor, C., Currivan, L., Cunningham, N., Kelleher, K., Lewis, M., Long, S., McGinnity, P., Smith, V. and McMahon, C., 2014. *Radiation Doses Received by the Irish Population 2014*. Radiological Protection Institute of Ireland, Dublin.

Pressyanov, D., Dimitrov, D. and Dimitrova, I., 2015. Energy-efficient reconstructions and indoor radon: the impact assessed by CDs/DVDs. *Journal of Environmental Radioactivity* 143: 76–79.

Rahman, N.M. and Tracy, B.L., 2009. Radon control systems in existing and new construction: a review. *Radiation Protection Dosimetry* 135: 243–255.

Ringer, W., 2014 . Monitoring trends in civil engineering and their effect on indoor radon. *Radiation Protection Dosimetry* 160: 38–42.

Scivyer, C., 2001. Radon protection for new buildings: a practical solution from the UK. *Science of the Total Environment* 272: 91–96.

SEAI (Sustainable Energy Authority of Ireland), 2015. *Renewable Heat in Ireland to 2020. Achieving Ireland's 2020 Renewable Heat Target: Analysis of Policy Options*. SEAI, Dublin.

SEAI (Sustainable Energy Authority of Ireland), 2016a. *Energy Efficiency in Ireland*. SEAI, Dublin.

SEAI (Sustainable Energy Authority of Ireland), 2016b. *SEAI Grants Available*. SEAI, Dublin. Available online: http://www.seai.ie/Power_of_One/Grants_Available/ (accessed 7 September 2018).

Sherman, M.H., 1992. Superposition in infiltration modeling. *Indoor Air* 2: 101–114.

Shrubsole, C., Ridley, I., Biddulph, P., Milner, J., Vardoulakis, S., Ucci, M., Wilkinson, P., Chalabi, Z. and Davies, M., 2012. Indoor $PM_{2.5}$ exposure in London's domestic stock: modeling current and future exposures following energy efficient refurbishment. *Atmospheric Environment* 62: 336–343.

Shrubsole, C., Das, P., Milner, J., Hamilton, I., Spadaro, J., Oikonomou, E., Davies, M. and Wilkinson, P., 2015. 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. *Atmospheric Environment* 120: 100–108.

Sinnott, D., 2016. Dwelling airtightness: a socio-technical evaluation in an Irish context. *Building and Environment* 95: 264–271.

Sinnott, D. and Dyer, M., 2012. Air-tightness field data for dwellings in Ireland. *Building and Environment* 51: 269–275.

Steck, D.J., 2009. Annual average indoor radon variations over two decades. *Health Physics* 96: 37–47.

Vardoulakis, S., Dimitroulopoulou, C., Thornes, J., Lai, K.-M., Taylor, J., Myers, I., Heaviside, C., Mavrogianni, A., Shrubsole, C., Chalabi, Z., Davies, M. and Wilkinson, P., 2015. Impact of climate change on the domestic indoor environment and associated health risks in the UK. *Environment International* 85: 299–313.

Vasilyev, A. and Yarmoshenko, I., 2016. Effect of energy-efficient measures in building construction on indoor radon in Russia. *Radiation Protection Dosimetry* 174: 419–422.

Vasilyev, A., Yarmoshenko, I. and Zhukovsky, M., 2015. Low air exchange rate causes high indoor radon concentration in energy-efficient buildings. *Radiation Protection Dosimetry* 164: 601–605.

WHO (World Health Organization), 2009. *WHO Handbook on Indoor Radon: A Public Health Perspective*. WHO, Geneva.

Zhang, Z., Smith, B., Steck, D.J., Guo, Q. and Field, R.W., 2007. Variation in yearly residential radon concentrations in the Upper Midwest. *Health Physics* 93: 288–297.

Abbreviations

AIVC	Air Infiltration and Ventilation Centre
Bq	Becquerel
CI	Confidence interval
EPA	Environmental Protection Agency
EU	European Union
IAPPEM	Indoor air pollution probabilistic exposure model
Mtoe	Million tonnes of oil equivalent
NRCS	National Radon Control Strategy
NSAI	National Standards Authority of Ireland
Pa	Pascal
PM	Particulate matter
Po	Polonium
PPV	Purpose-provided ventilation
Rn	Radon
RPII	Radiological Protection Institute of Ireland
SEAI	Sustainable Energy Authority of Ireland
S.I.	Statutory Instrument
WHO	World Health Organization
WHS	Warmer Homes Scheme

Appendix 1 Expanded Dataset: Dublin

Table A1.1. Summary of the time-weighted average yearly household radon concentration (Bq m^{-3}) for the bungalow using Dublin weather patterns under various radon flow coefficients

Air permeability (m^3 hr^{-1} m^{-2})	Ventilation scenario			
	No PPV (0 mm^2)	Local by-laws (4200 mm^2)	PPV (6500 mm^2)	PPV with extract (6500 mm^2)
Radon flow coefficient of 0.02 Bq m^{-2} Pa^{-1} s^{-1}				
5	158	123	115	100
7	137	110	104	92
10	112	95	91	82
13	98	85	82	74
15	91	80	77	70
Radon flow coefficient of 0.04 Bq m^{-2} Pa^{-1} s^{-1}				
5	315	243	228	198
7	272	216	205	180
10	222	188	179	160
13	193	167	161	145
15	178	156	150	137
Radon flow coefficient of 0.06 Bq m^{-2} Pa^{-1} s^{-1}				
5	471	362	341	295
7	407	323	306	269
10	332	280	267	239
13	288	249	239	216
15	266	233	224	204
Radon flow coefficient of 0.08 Bq m^{-2} Pa^{-1} s^{-1}				
5	627	482	453	393
7	542	430	407	358
10	442	372	356	318
13	383	331	318	287
15	354	309	298	271
Radon flow coefficient of 0.10 Bq m^{-2} Pa^{-1} s^{-1}				
5	784	602	566	490
7	677	536	508	446
10	552	465	444	396
13	478	413	397	358
15	441	386	371	338
Radon flow coefficient of 0.12 Bq m^{-2} Pa^{-1} s^{-1}				
5	1061	824	775	679
7	812	643	608	535
10	661	557	532	475
13	573	495	475	429
15	529	462	445	405

Table A1.1. Continued

Air permeability ($m^3 hr^{-1} m^{-2}$)	Ventilation scenario			
	No PPV (0 mm^2)	Local by-laws (4200 mm^2)	PPV (6500 mm^2)	PPV with extract (6500 mm^2)
Radon flow coefficient of 0.15 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	1174	902	847	733
7	1014	803	760	668
10	826	695	664	593
13	716	618	593	536
15	660	577	555	505
Radon flow coefficient of 0.20 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	1565	1202	1129	977
7	1351	1070	1012	889
10	1100	926	884	789
13	953	823	790	713
15	880	768	739	672

Table A1.2. Summary of the time-weighted average yearly household radon concentration ($Bq\,m^{-3}$) for the semi-detached dwelling using Dublin weather patterns under various radon flow coefficients

Air permeability ($m^3 hr^{-1} m^{-2}$)	Ventilation scenario			
	No PPV (0 mm^2)	Local by-laws (4200 mm^2)	PPV (6500 mm^2)	PPV with extract (6500 mm^2)
Radon flow coefficient of 0.02 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	75	57	53	41
7	63	50	47	38
10	52	44	41	34
13	45	39	37	31
15	41	36	35	30
Radon flow coefficient of 0.04 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	147	110	102	79
7	124	97	91	72
10	102	84	80	65
13	87	74	71	60
15	80	69	67	56
Radon flow coefficient of 0.06 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	220	164	152	116
7	185	145	135	107
10	151	124	118	96
13	129	110	105	88
15	118	102	98	83

Table A1.2. Continued

Air permeability ($m^3 hr^{-1} m^{-2}$)	Ventilation scenario			
	No PPV (0 mm^2)	Local by-laws (4200 mm^2)	PPV (6500 mm^2)	PPV with extract (6500 mm^2)
Radon flow coefficient of 0.08 Bq m^{-2} Pa^{-1} s^{-1}				
5	292	218	202	154
7	246	192	180	141
10	201	165	156	127
13	171	145	139	116
15	156	135	130	109
Radon flow coefficient of 0.10 Bq m^{-2} Pa^{-1} s^{-1}				
5	365	272	251	192
7	307	239	224	176
10	250	205	194	158
13	213	181	173	144
15	195	168	161	136
Radon flow coefficient of 0.12 Bq m^{-2} Pa^{-1} s^{-1}				
5	437	325	301	229
7	367	286	268	210
10	299	245	232	189
13	255	216	207	172
15	233	201	193	162
Radon flow coefficient of 0.15 Bq m^{-2} Pa^{-1} s^{-1}				
5	546	406	375	286
7	458	357	334	262
10	374	306	290	235
13	318	270	257	214
15	291	251	240	202
Radon flow coefficient of 0.20 Bq m^{-2} Pa^{-1} s^{-1}				
5	727	540	499	380
7	610	475	444	349
10	497	407	385	312
13	423	359	342	284
15	386	333	319	269

Table A1.3. Summary of the time-weighted average yearly household radon concentration (Bq m^{-3}) for the terraced dwelling using Dublin weather patterns under various radon flow coefficients

Air permeability (m^3 hr^{-1} m^{-2})	Ventilation scenario			
	No PPV (0 mm^2)	Local by-laws (4200 mm^2)	PPV (6500 mm^2)	PPV with extract (6500 mm^2)
Radon flow coefficient of 0.02 Bq m^{-2} Pa^{-1} s^{-1}				
5	65	47	43	43
7	55	42	39	39
10	46	38	35	35
13	40	34	32	32
15	37	32	31	31
Radon flow coefficient of 0.04 Bq m^{-2} Pa^{-1} s^{-1}				
5	128	91	82	82
7	108	82	76	76
10	89	72	68	68
13	77	65	62	62
15	71	61	58	58
Radon flow coefficient of 0.06 Bq m^{-2} Pa^{-1} s^{-1}				
5	191	135	122	122
7	160	121	112	112
10	132	107	100	100
13	113	96	91	91
15	105	90	86	86
Radon flow coefficient of 0.08 Bq m^{-2} Pa^{-1} s^{-1}				
5	254	179	162	162
7	213	161	148	148
10	175	141	132	132
13	150	127	120	120
15	138	119	114	114
Radon flow coefficient of 0.10 Bq m^{-2} Pa^{-1} s^{-1}				
5	317	223	202	202
7	266	200	184	184
10	218	176	164	164
13	187	158	149	149
15	172	149	141	141
Radon flow coefficient of 0.12 Bq m^{-2} Pa^{-1} s^{-1}				
5	379	304	267	241
7	318	267	240	220
10	261	228	210	197
13	224	202	189	179
15	206	188	178	169

Appendix 2 Expanded Dataset: Belmullet

Table A2.1. Summary of the time-weighted average yearly household radon concentration (Bq m^{-3}) for the bungalow using Belmullet weather patterns under various radon flow coefficients

Air permeability (m^3 hr^{-1} m^{-2})	Ventilation scenario			
	No PPV (0 mm^2)	Local by-laws (4200 mm^2)	PPV (6500 mm^2)	PPV with extract (6500 mm^2)
Radon flow coefficient of 0.02 Bq m^{-2} Pa^{-1} s^{-1}				
5	166	118	109	99
7	141	104	98	90
10	112	90	86	82
13	96	81	77	72
15	88	75	72	68
Radon flow coefficient of 0.04 Bq m^{-2} Pa^{-1} s^{-1}				
5	330	232	214	194
7	279	206	192	176
10	221	178	168	160
13	189	158	150	141
15	173	147	141	133
Radon flow coefficient of 0.06 Bq m^{-2} Pa^{-1} s^{-1}				
5	494	347	320	289
7	417	307	286	262
10	331	265	250	239
13	282	235	224	210
15	258	219	210	198
Radon flow coefficient of 0.08 Bq m^{-2} Pa^{-1} s^{-1}				
5	658	461	426	385
7	555	408	381	349
10	440	352	332	318
13	375	312	297	278
15	343	291	278	262
Radon flow coefficient of 0.10 Bq m^{-2} Pa^{-1} s^{-1}				
5	821	576	531	480
7	693	510	475	435
10	549	439	414	396
13	468	389	370	347
15	428	363	347	327
Radon flow coefficient of 0.12 Bq m^{-2} Pa^{-1} s^{-1}				
5	985	691	637	576
7	831	611	569	521
10	658	526	497	475
13	561	466	444	416
15	513	435	416	392

Table A2.1. Continued

Air permeability ($m^3 hr^{-1} m^{-2}$)	Ventilation scenario			
	No PPV (0 mm²)	Local by-laws (4200 mm²)	PPV (6500 mm²)	PPV with extract (6500 mm²)
Radon flow coefficient of 0.15 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	1231	862	795	719
7	1038	763	711	651
10	822	657	620	593
13	700	582	554	519
15	641	543	519	489
Radon flow coefficient of 0.20 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	1640	1149	1059	957
7	1383	1016	947	867
10	1095	875	826	790
13	932	775	737	691
15	853	723	690	650

Table A2.2. A summary of the time-weighted average yearly household radon concentration ($Bq\,m^{-3}$) for the semi-detached dwelling using Belmullet patterns conditions under various radon flow coefficients

Air permeability ($m^3 hr^{-1} m^{-2}$)	Ventilation scenario			
	No PPV (0 mm²)	Local by-laws (4200 mm²)	PPV (6500 mm²)	PPV with extract (6500 mm²)
Radon flow coefficient of 0.02 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	78	56	52	31
7	66	50	47	38
10	54	44	42	35
13	46	39	38	32
15	42	37	35	31
Radon flow coefficient of 0.04 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	154	110	101	58
7	128	97	91	73
10	104	84	80	66
13	89	75	72	61
15	81	70	67	58
Radon flow coefficient of 0.06 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	230	163	150	85
7	191	144	134	107
10	155	125	118	97
13	132	111	106	89
15	121	104	99	85

Table A2.2. Continued

Air permeability ($m^3\,hr^{-1}\,m^{-2}$)	Ventilation scenario			
	No PPV (0 mm^2)	Local by-laws (4200 mm^2)	PPV (6500 mm^2)	PPV with extract (6500 mm^2)
Radon flow coefficient of 0.08 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	306	216	199	112
7	254	191	178	142
10	205	165	156	128
13	175	147	140	118
15	160	137	131	112
Radon flow coefficient of 0.10 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	382	270	248	139
7	317	238	222	176
10	256	206	194	159
13	218	182	174	146
15	199	170	163	139
Radon flow coefficient of 0.12 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	458	323	297	166
7	380	285	266	211
10	307	246	232	190
13	260	218	208	175
15	238	204	195	166
Radon flow coefficient of 0.15 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	572	403	370	207
7	474	356	331	263
10	383	307	290	237
13	325	272	259	217
15	297	254	243	207
Radon flow coefficient of 0.20 $Bq\,m^{-2}\,Pa^{-1}\,s^{-1}$				
5	761	537	493	274
7	631	474	441	349
10	509	408	385	315
13	432	362	345	289
15	394	338	323	274

Table A2.3. A summary of the time-weighted average yearly household radon concentration (Bq m^{-3}) for the terraced dwellings using Belmullet weather patterns under various radon flow coefficients

Air permeability (m^3 hr^{-1} m^{-2})	Ventilation scenario			
	No PPV (0 mm^2)	Local by-laws (4200 mm^2)	PPV (6500 mm^2)	PPV with extract (6500 mm^2)
Radon flow coefficient of 0.02 Bq m^{-2} Pa^{-1} s^{-1}				
5	55	39	36	36
7	46	36	33	33
10	38	32	30	30
13	33	32	28	28
15	31	27	26	26
Radon flow coefficient of 0.04 Bq m^{-2} Pa^{-1} s^{-1}				
5	107	76	68	68
7	89	68	63	63
10	73	60	56	56
13	63	60	52	52
15	58	51	49	49
Radon flow coefficient of 0.06 Bq m^{-2} Pa^{-1} s^{-1}				
5	159	112	101	101
7	132	100	92	92
10	108	88	83	83
13	93	88	76	76
15	86	75	72	72
Radon flow coefficient of 0.08 Bq m^{-2} Pa^{-1} s^{-1}				
5	211	148	134	134
7	175	132	122	122
10	143	116	109	109
13	123	116	100	100
15	113	99	95	95
Radon flow coefficient of 0.10 Bq m^{-2} Pa^{-1} s^{-1}				
5	263	184	166	166
7	218	165	152	152
10	178	145	136	136
13	153	145	124	124
15	141	123	118	118
Radon flow coefficient of 0.12 Bq m^{-2} Pa^{-1} s^{-1}				
5	315	220	199	199
7	261	197	181	181
10	213	173	162	162
13	183	173	148	148
15	168	147	140	140

Table A2.3. Continued

Air permeability ($m^3 hr^{-1} m^{-2}$)	Ventilation scenario			
	No PPV (0 mm^2)	Local by-laws (4200 mm^2)	PPV (6500 mm^2)	PPV with extract (6500 mm^2)
Radon flow coefficient of 0.15 Bq m^{-2} Pa^{-1} s^{-1}				
5	393	275	248	248
7	326	246	226	226
10	265	215	202	202
13	228	215	184	184
15	210	183	175	175
Radon flow coefficient of 0.20 Bq m^{-2} Pa^{-1} s^{-1}				
5	523	365	329	329
7	434	326	300	300
10	352	286	268	268
13	302	286	244	244
15	279	243	232	232

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d’earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d’Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 273

UNVEIL: UNderstanding VEntilation and radon in energy-efficient buildings in IreLand

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Authors: James A. McGrath and Miriam A. Byrne

Identifying Pressures

The EU Energy Performance of Buildings Directive (2010/31/EU) contains a range of provisions to improve the energy performance of new and existing buildings. In Ireland, regulations transposing this Directive (S.I. 243 of 2012) are aimed at improving the thermal and energy efficiency of the building envelope, window upgrades and specifying standards of building airtightness. Limited studies have examined radon concentrations in low-energy-efficient homes and fewer still have examined radon concentrations in pre/post retrofits. Ireland has some of the highest indoor radon concentrations in the world and, consequently, there is concern surrounding further increases in concentrations as a result of increased building airtightness. A survey of 142 Irish social homes showed radon concentration ratios for pre versus post retrofit ranging from 0.1 to 7.3, illustrating the need to fully understand the impact of retrofitting on indoor radon concentrations. This knowledge gap is emphasised in the National Radon Control Strategy (NRCS).

Informing Policy

Since 1997, Technical Guidance Document C (Site Preparation and Resistance to Moisture) has stated that all new dwellings must incorporate radon protection measures in high radon areas. Research has shown the positive benefit of this legislation change; The Environmental Protection Agency report that the average indoor radon concentration was 86 Bq m^{-3} in dwellings built before 1998 and 64 Bq m^{-3} in dwellings built after 1998. Building Regulations 2011 (S.I. No. 259 of 2011), Technical Guidance Document L on Conservation of Fuel and Energy – Dwellings, specifies standards of building airtightness by reducing uncontrolled ventilation losses from the home. S.R. 54 of 2014, published by the National Standards Authority of Ireland, gives guidance on the provision of ventilation with retrofit works, with an air permeability of > 5 m^{-3} hr^{-1} m^{-2}. The National Radon Control Strategy (NRCS) was developed to address the long-term radon exposure risk and highlights the need to strengthen technical guidance and legalisation to protect against and prevent radon exposure in buildings (Actions 4, 5, 20, 24 and 27 of the NRCS).

Developing Solutions

The European 7th Environment Action Programme (1386/2013/EU) aims to ensure a “healthy environment for healthy people”. To meet the above challenges, pressures and policies, Ireland needs to take account of the environmental health implications of developing building regulations that lean towards reducing ventilation rates. In the absence of a full-scale study of indoor radon concentrations in energy-efficient buildings, the current project has examined international research on radon concentrations in retrofitted houses and provides simulation data on the ventilation status of the national building stock and the implications of pre/post retrofits for indoor radon concentrations. This meets a strategic knowledge gap identified by the NRCS, under Action 9 (develop recommendations regarding future funding of research priorities). In addition, the project helps inform the development of further research needs under phase 2 of the NRCS, expected to be implemented from 2019.

EPA Research: McCumiskey House, Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie

EPA Research Webpages
www.epa.ie/researchandeducation/research/