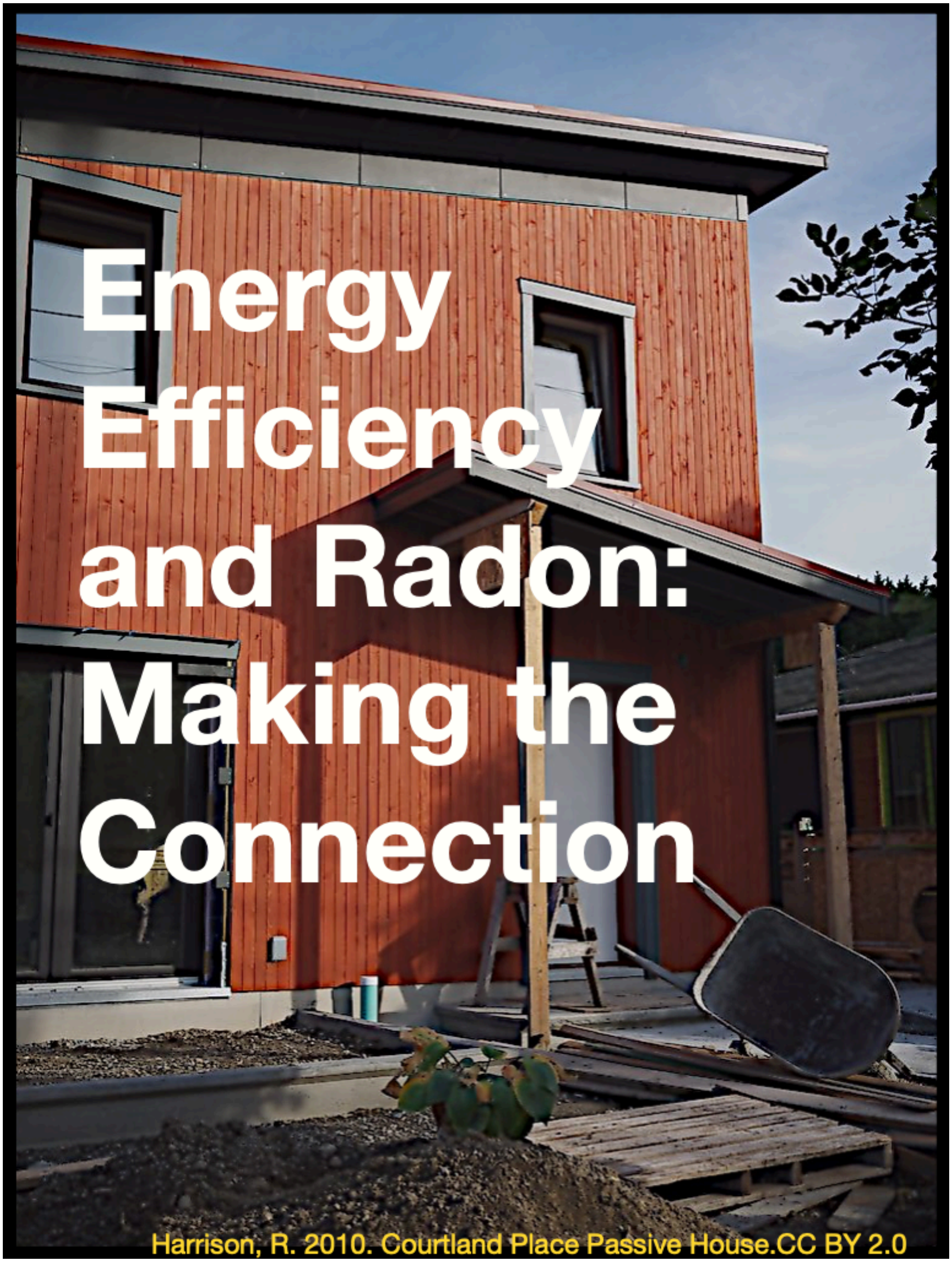
Energy Efficiency and Radon: Making the Connection



Harrison, R. 2010. Courtland Place Passive House.CC BY 2.0

BC LUNG FOUNDATION

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About our program. The BC Lung Foundation's Healthy Indoor Environments program is focused on providing education, resources, and policy options for addressing priority indoor air pollutants in British Columbia. Canadians spend 90% of their day indoors, with about 70% at home and 20% at work or school. The air we breathe indoors can contain particulates, gases, allergens and fumes that can significantly affect our health in both the short and long term. Knowing the main indoor air pollutants, their sources, and how to reduce them are key to reducing harm to our health. Radon has been identified as the leading environmental carcinogen in Canada. For more information visit our website at https://bclung.ca/programs-initiatives/healthy-indoor-environments-program

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Executive Summary

Radon is a known human lung carcinogen, indoor air quality hazard, and emergent area of public health planning, policy, and regulation. Despite revisions to building codes in Canada in the last decade, elevated radon persists in newer homes. At the same time, there is a pressing need in the climate emergency to address energy efficiency and greenhouse gas emissions in both new and older buidlings. This report concerns the links between energy efficiency measures and increase radon levels relevant to the Canadian context. Since indoor radon was discovered as a large scale public health problem in the 1980s, researchers have also recognized that the "tighter" the home, the more opportunity exists for radon levels to increase if radon is present in soils. This report reviews literature on the links between radon and energy efficiency and shows there is a strong connection.

While building codes across Canada have introduced radon resistant construction techniques in the last decades, these have limited effects unless occupants test for radon and upgrade systems—which seldom happens. Alternatively, techniques for controlling and reducing air flow –a mainstay of energy efficiency measures-- can not only decrease ventilation that might otherwise help dissipate radon, but they can also have more consistent negative pressure that sucks radon in. If radon is ignored, energy efficiency improvements can significantly increase radon levels in both new construction and through the retrofitting process.

This report describes existing research on the relationship between energy efficiency efforts and increased radon levels, dating from the 1980s to the present. Major studies in the USA, United Kingdom, Russia, and Europe confirm the correlation using both theoretical modelling and measurement studies. The report highlights work from the United States Department of Energy Weatherization Assistance Program which included detailed analysis of radon in the retrofitting process and which led to new retrofitting standards to address radon. The report considers research on how radon levels are increasing in Canada due to new construction techniques—average radon levels will increase significantly unless specific strategies are implemented to address radon. The report canvasses research on radon in high-performance homes (built to standards such as Net-Zero Ready or Passive House) and shows there is no in principle reason why energy efficiency measures need to exacerbate radon problems.

The recognition that renovations can alter indoor radon levels needs to be translated broadly to Canadian building trades and science professionals, the construction industry, government energy efficiency leaders and energy auditors. The message needs to be spread that even basic steps - replacing windows or adding weatherstripping- can reduce indoor ventilation and make indoor air quality worse. A broader awareness program —and better government policies—are needed to ensure energy efficiency and climate action does not sacrifice health.

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Introduction

Radon is a known human lung carcinogen and an indoor air quality hazard. While radon is present in soil at some level almost everywhere on earth, it quickly dissipates when it reaches the surface. However, radon can at times build up to dangerous levels indoors, depending on radon prevalence in the underlying soil and the characteristics of the building. The risks of developing lung cancer increase with radon exposure and most industrialized countries have set guidelines for allowable radon concentrations in indoor air—generally between 100 and 300 Bq/m^3. The number of homes that exceed these guidelines vary significantly by geography: A large scale Health Canada survey in 2012[1] estimated 6.9% of homes exceed Canada's Radon Guideline of 200 Bq/m^3: Research in some regions such as Canada's Praries show nearly 18% of homes are above the guideline[2], and data for specific cities such as Prince George, British Columbia show 30% of homes tested over the guideline.[3]

Radon gas is formed during the radioactive decay of uranium and is found in varying concentrations in most soils across Canada. Radon "ingress" (or entry into a building) usually occurs because the lower parts of buildings have negative air pressure relative to outside—a phenomenon known as the 'stack effect'. If the inside of a building has negative pressure, radon will be drawn in through even tiny fissures, cracks in walls and foundations or gaps around pipes. Standard radon-resistant building techniques now include ensuring an impermeable membrane sits under the building slab, in an attempt to stop gas ingress. However, the preferred method for removing radon is through 'sub-slab depressurization'—a hole is drilled into the building foundation and connected to a pipe which vents through the building walls or roof. This provides a path for radon to move from under the building to outside, but also ensures that the pressure in the lower part of the building is not significantly less than outside. Many building codes in Canada now require a radon 'rough-in'—the bare bones of a sub-slab depressurization system which are to be upgraded once occupants test and discover high radon. As well, sub-slab depressurization systems can also be retrofitted into most older homes. Unfortunately, rates of radon testing remain very low. (Statistics Canada surveys show as of 2019 that 54% of Canadian households reported that they had heard of radon and 6% of non-apartment households that had heard of radon indicated that they had tested for radon at

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[1] Health Canada. Cross Canada Survey of Radon Concentrations in Homes, Final Report. 2012 https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/radiation/cross-canada-survey-radon-concentrations-homes-final-report-health-canada-2012.html accessed September 20, 2022

[2] Stanley, F.K., Irvine, J.L., Jacques, W.R., Salgia, S.R., Innes, D.G., Winquist, B.D., Torr, D., Brenner, D.R. and Goodarzi, A.A., 2019. Radon exposure is rising steadily within the modern North American residential environment and is increasingly uniform across seasons. Scientific reports, 9(1), pp.1-17.

[3] British Columbia Centre for Disease Control, 2022. British Columbia Radon Map. https://bccdc.shinyapps.io/bcradonmap/ accessed September 20, 2022

some point in the past.[4]) As such, upgrades to rough-ins or mitigations remain far from the norm. A secondary approach is to use ventilation, which can dilute radon levels, but this is generally not as reliable at reducing very high radon levels, nor cost effective in the long term in many residential homes.[5]

It has long been understood that there is a relationship between radon levels and air flow in homes- the "tighter" the home, the more opportunity exists for radon levels to increase if radon is present in soils. Energy efficiency renovations often include strategies like sealing cracks and weatherstripping that make homes more airtight. The research summarized in this report illustrates how efficiency improvements in new homes and through renovations can result in higher radon levels in homes.

Energy Efficiency Initiatives are Becoming Standard Policy

The housing sector is a major energy consumer, and contributor to greenhouse gas emissions (GHG) both in Canada[6] and globally.[7] Transforming the building stock is now well recognized as a central component to climate action and meeting globally agreed GHG reduction targets.[8] For newer homes, this can be built in from the start, and low carbon design specifications included in building codes. However, only a small percentage of buildings are new each year: Addressing the existing building stock through energy efficiency renovations is an important step—often cheaper and easier to implement than decarbonization in other sectors.

In step with adopting significant climate action policies, governments across Canada have begun reforms to building codes (such as British Columbia's Energy Step Code) and subsidy and incentive programs for energy retrofits, such as the federal Canada Greener Homes Initiative[9] and CleanBC's Betterhomes program.[10] Homeowners and

[4] Statistics Canada, 2020. Households and the Environment: Radon awareness and testing, 2019. https://www150.statcan.gc.ca/n1/daily-quotidien/201201/dq201201d-cansim-eng.htm accessed Sept 20, 2022

[5] Health Canada. Reducing Radon Levels in Existing Homes: A Canadian Guide for Professional Contractors, 2010. https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/radiation/reducing-radon-levels-existing-homes-canadian-guide-professional-contractors-health-canada-2010.html, accessed October 3, 2022. Canadian General Standards Board and Standards Council of Canada. Radon control options for new construction in low-rise residential buildings, CAN/CGSB-149.11-2019. https://publications.gc.ca/site/eng/9.882605/publication.html accessed September 20, 2022

[6] Government of Canada. A healthy environment and an health economy Annex: Homes and Buildings available at https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/healthy-environment-healthy-economy/annex-homes-buildings.html, accessed September 23, 2022

[7] Nejat P, Jomehzadeh F, Taheri MM, Gohari M, Majid MZ. A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries). Renewable and sustainable energy reviews. 2015 Mar 1; 43:843-62.

[8] Hoicka CE, Das R. Ambitious deep energy retrofits of buildings to accelerate the 1.5 C energy transition in Canada. The Canadian Geographer/Le Géographe Canadien. 2021 Mar;65(1):116-27.

[9] Natural Resources Canada. Canada Greener Homes,. Website. Available at https://www.nrcan.gc.ca/energy-efficiency/homes/canada-greener-homes-grant/23441, accessed October 3, 2022

[10] CleanBC Better Homes, Website. https://betterhomesbc.ca, accessed October 3, 2022

others receive partial reimbursements for the cost of hiring energy auditors, and for improvements such as increased insulation, sealing cracks and gaps, upgrading windows, replacing older appliances, or switching out heating systems to heat pumps. There has been significant uptake of these programs by homeowners and by July 2022, the Canada Greener Homes program alone has given out over 38 million dollars for energy retrofitting. At the time of writing, this national program has committed 2.6 billion dollars to go towards energy retrofits for Canadian homes.[11]

Energy Efficiency Renovations Can Make Indoor Air Quality Worse

Buildings use energy primarily to 'condition' air (e.g., make warmer or colder, depending on outdoor temperature), and for lighting and appliances (such as stoves or dishwashers). Energy in air can dissipate across walls or roofs, and improving insulation is a major step in reducing how much energy is spent on conditioning air. A further prominent technique is to control and reduce air flow, and so reduce how much air needs to be conditioned. However, reducing air flow can have significant repercussions for health: If there isn't enough fresh air entering a building, indoor air quality can suffer. There are many sources of pollutants inside homes, such as carpets, gas stoves, cleaners, solvents, pets or tobacco smoke. Poor air flow trap pollutants, and allow moulds and humidity to flourish, with significant effects for allergies and lung health.

Historically, most homes were not built to be airtight, and occupants could rely on "natural ventilation" such as open windows or airflow through cracks in walls, windows and doors. By the 1970s and 80s homeowners began to address energy loss by adding weather stripping, double paned windows, and other strategies to improve thermal comfort and reduce costs. After such strategies were widely implemented, a variety of indoor air quality related health problems emerged, such as headaches, allergies, moulds and exacerbation of existing lung diseases such as asthma.[12] Sick building syndrome (SBS) or building-related illness was identified in the 1980s by the United States Environmental Protection Agency.[13] Investigations of SBS determined that poor ventilation, coupled with chemical contaminants from indoor and outdoor sources were the main culprits. Solutions lay with increasing ventilation options, adding exhaust fans, ensuring routine maintenance of ventilation systems, and removing source contaminants (such as cleaners, solvents, or tobacco smoke). While SBS was most common in office buildings,

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[11] Natural Resources Canada, Canada Greener Homes Grant Spring 2022 Update https://www.nrcan.gc.ca/energy-efficiency/homes/canada-greener-homes-grant/canada-greener-homes-grant-spring-2022-update/24060, accessed October 3, 2022

[12] Brambilla A, Sangiorgio A. Mould growth in energy efficient buildings: Causes, health implications and strategies to mitigate the risk. Renewable and Sustainable Energy Reviews. 2020 Oct 1; 132:110093.

[13] US EPA Indoor Air Facts #4 1991 Sick Building Syndrome. https://www.epa.gov/sites/default/files/2014-08/documents/sick_building_factsheet.pdf accessed October 3, 2022

the same risks from poor ventilation also affect homes.[14] Currently, we are seeing renewed interested in tightening the building envelope, but less emphasis on the need for good air flow. For instance, most energy efficiency grant programs in Canada, including the Canada Greener Homes program, do not normally cover the costs of installing new ventilation systems.[15] The health problems associated with more airtight homes has not gone away and may be exacerbated by new efforts to address the climate emergency.

Radon Has Long Been Linked to Energy Efficiency

The research linking energy efficiency efforts and poor indoor air quality are very clear around radon.[16,17] Well-functioning sub-slab depressurization systems can reduce radon to safe levels in air-tight homes. However, without a radon reduction system in place, an air-tight home can have the unintended consequence of having enough openings to let radon in, but not enough to allow ventilation to dissipate the radon. Air-tight homes can also exacerbate radon through more consistent negative pressure. For instance, in an air-tight home, a strong kitchen or bathroom fan can create significant negative pressure through the home, sucking more radon in from the underlying soil. If radon is ignored, energy efficiency improvements in new builds or retrofits can significantly increase radon levels.

There has been extensive research globally on the relationship between energy efficiency efforts and increased radon levels, dating back to the 1980s when radon was newly identified as a carcinogenic exposure in homes. The United States Department of Energy (DOE) supported much of this early work, which highlighted the increased risk posed by radon in homes with tighter envelopes and fewer air exchanges.[18] A study in 1986 projected up to a 115% increase in lung cancer deaths for homes where air exchanges were reduced because of retrofitting.[19] Into the 1990s, research on residential radon in the USA generated new knowledge about radon ingress and the distribution of the radon problem across the country. This work led to the creation of new residential mitigation technologies. Building science researchers promoted retrofitting solutions that

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[14] Saijo, Y. (2020). Sick Building/House Syndrome. In: Kishi, R., Norbäck, D., Araki, A. (eds) Indoor Environmental Quality and Health Risk toward Healthier Environment for All. Current Topics in Environmental Health and Preventive Medicine. Springer, Singapore. https://doi.org/10.1007/978-981-32-9182-9_2

[15] Quastel, N., Kassay, S. James, N., and Nonis, M.. 2022. Energy Efficiency and Radon: Gaps in the System. BC Lung Foundation.https://bclung.ca/radon-and-energy-efficiency accessed October 3, 2022

[16] Fisk, William J., Brett C. Singer, and Wanyu R. Chan. "Association of residential energy efficiency retrofits with indoor environmental quality, comfort, and health: A review of empirical data." Building and Environment 180 (2020): 107067.

[17] Yarmoshenko IV, Malinovsky GP, Onishchenko AD, Vasilyev AV. Problem of radon exposure in energy-efficient buildings: a review. Radiatsionnaya Gygiena= Radiation Hygiene. 2020 Jan 6;12(4):56-65.

[18] Rector HE, Koontz MD, Cade DR, Nagda NL. Impact of energy conservation measures on radon and radon progeny concentrations: a controlled study. ASHRAE Trans.;(United States). 1985 Jan 1;91(CONF-850606-).

[19] Brambley MR, Gorfien M. Radon, and lung cancer: Incremental risks associated with residential weatherization. Energy. 1986 Jun 1;11(6):589-605.

did not impact radon levels, such as heat exchange systems[20] but little of this work was adopted. By 1995, the United States Agency for Toxic Substances and Disease Registry (ATSDR) had issued a public warning[21] about residential radon, noting that energy efficiency efforts could increase indoor radon levels, but that soil gas was the primary driver of whether radon was a problem in a specific geographical region.

Interest in radon gas and energy efficiency also emerged in the United Kingdom (UK) and Europe as efforts towards energy conservation increased in this region. The findings from European researchers were like those from the early United States studies. UK public health researchers issued warnings about radon resulting from more airtight homes.[22] [23]

Broader concerns about global sustainability and residential energy use grew particularly in Europe during the 1990s. Radon and retrofits continued to be an area of concern although this more recent research benefitted from improvements in study design (for example, using larger sample size and comparisons with control homes) and the inclusion of more modern efficiency options and building designs. As detailed below, research continued in this area along two different trajectories: (1) Theoretical modeling studies of potential radon ingress using different building types, standards, and materials, and (2) measurement studies of homes where energy retrofits have been undertaken.

Energy Efficiency and Radon: Modeling Studies

The modeling studies results that examine radon levels and energy conservation efforts are quite clear and consistent across countries.[24] Milner[25] (UK), Collignan[26]

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[20] Renken, K. J., & Konopacki, S. J. (1993). An innovative radon mitigation-energy conservation retrofit system for residential buildings. Air & Waste, 43(3), 310-315 and Nazaroff WW, Boegel ML, Hollowell CD, Roseme GD. The use of mechanical ventilation with heat recovery for controlling radon and radon-daughter concentrations. 1980. *and* Ericson SO, Schmied H. Installation of supply/exhaust ventilation as a remedial action against radon from soil and/or building materials. Science of The Total Environment. 1985 Oct 1; 45:499-505.

[21] Upfal, Mark, Pamela S. Wigington, and Beverley Harris. "Radon toxicity." (2000). U.S. Dept. of Health and Human Services, Agency for Toxic Substances and Disease Registry, Division of Health Education and Promotion,

[22] Bone A, Murray V, Myers I, Dengel A, Crump D. Will drivers for home energy efficiency harm occupant health. Perspectives in public health. 2010 Sep;130(5):233-8.

[23] Lugg A, Probert D. Indoor radon gas: A potential health hazard resulting from implementing energy-efficiency measures. Applied Energy. 1997 Feb 1;56(2):93-196.

[24]Wilkinson, P. Health Impact Assessment of Energy Efficiency Improvements in the Built Environment in Pursuit of Climate Change Objectives. Epidemiology, 20, 6 2009 Nov p. S261

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

[26] Collignan, Bernard, and Emilie Powaga. "Impact of ventilation systems and energy savings in a building on the mechanisms governing the indoor radon activity concentration." Journal of Environmental Radioactivity 196 (2019): 268-273. *and* Collignan B, Lorkowski C, Améon R. Development of a methodology to characterize radon entry in dwellings. Building and environment. 2012 Nov 1; 57:176-83.

(France), McGrath[27] (Ireland), Arvela[28] (Finland), Vasilyev[29] (Russia), Cucos[30] (Romania) and Akbari[31] (Sweden) all determined that sealing and tightening homes would lead to higher radon levels indoors. The impacts of efficiency measures on radon levels were significant, ranging from mean increases of 56.6% (Milner) to a doubling of home radon levels (100%- Arvela, 107% McGrath). Milner et al. used these estimates to predict the burden for the UK, suggesting that energy-efficiency efforts could cause up to 278 more cancer cases annually, even with only modest average increases in radon. All authors concluded that radon levels will go up in homes where ventilation was restricted or limited. Strategies such as adding mechanical ventilation, particularly air intakes, were hypothesized to help offset radon increases, although these efforts were recognized as requiring additional energy use, a trade- off for efficiency as well as attention from homeowners if not automatic. These results echo the findings from the 1980s, but provide further consistent results, even though national building codes, energy efficiency standards, and radon policies had evolved.

Energy Efficiency and Radon: Measurement Studies

An alternative research method is to directly measure radon levels before and after energy retrofitting. This work is important to both understand the accuracy of modeling as well as observing whether unanticipated factors are at play. This empirical research has confirmed modelers' predictions: Increasing airtightness generally increases radon levels. This relationship has been consistent across countries and different types of housing.

Most measured evidence come from individual studies and projects, although Fisk et al. (2020)[32] undertook a literature review of empirical retrofit research conducted to 2019. This knowledge synthesis examined radon, other IAQ parameters, and general health symptoms before and after home energy retrofits. Studies required pre- and post-retrofit radon measurements as inclusion criteria. Ten studies which measured radon were included and compared. The authors found that elevated radon was the clearest and most consistent adverse outcome from energy retrofits, particularly where ventilation was not added a part of the renovation. Formaldehyde levels also increased post energy retrofits but not as consistently as radon across studies. Levels of other contaminants such as

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[27] McGrath JA, Byrne MA. UNVEIL: UNderstanding VEntilation and radon in energy-efficient buildings in IreLand. https://www.epa.ie/publications/research/environment--health/Research_Report_273.pdf

[28] Arvela, H., et al. "Review of low-energy construction, air tightness, ventilation strategies and indoor radon: results from Finnish houses and apartments." Radiation protect. dosimetry 162.3 (2014): 351-363.

[29] Vasilyev A, Yarmoshenko I. Effect of energy-efficient measures in building construction on indoor radon in Russia. Radiation Protection Dosimetry. 2017 Apr 28;174(3):419-22.

[30] Cucoş AL, Dicu T, Cosma C. Indoor radon exposure in energy-efficient houses from Romania. Rom. J. Phys.2015;60(9–10):1574-80.

[31] Akbari K, Mahmoudi J, Ghanbari M. Simulation of ventilation effects on indoor radon. Management of Environmental Quality: An International Journal. 2013 Apr 12.

[32] Fisk WJ, Singer BC, Chan WR. Association of residential energy efficiency retrofits with indoor environmental quality, comfort, and health: A review of empirical data. Building and Environment. 2020 Aug 1;180:107067.

nitrogen dioxide (NO) and volatile organics (VOC) showed mixed results after energy renovations.

Measurement studies in homes pre- and post- energy renovations provide interesting insights concerning which types of renovations matter. UK research by Symonds et al.[33] (of over 450,000 homes) found that homes where double-glazed windows were added had the most significant jump in radon levels. Insulating walls and roofs also lead to increases and homes which undertook all of these measures reported the highest radon levels. Similar findings were echoed by Italian researchers[34] who examined readings from 154 homes with pre- and post-renovation radon measurements. Here, the replacement of windows had the most significant effect on radon levels; homes without window replacement did not show statistically significantly elevated radon levels post retrofit. A 2016 French[35] study of 3,400 dwellings compared retrofitted homes to those without energy efficient renovations. The most common energy renovations were window replacements and added insulation. Using an explanatory model which controlled for other variables, radon levels were found to be 21% higher in renovated homes than those without renovations. These results correlate to those of modeling studies, which posited that radon levels increase because of design changes that conserve heat and energy through added insulation and reduced natural ventilation opportunities.

Multi-Unit Residential Buildings (MURBs)

Urban densification initiatives—again driven by climate emergency concerns—is driving an increase in multi-unit residential buildings (MURBs). The effects on radon levels of energy retrofits in MURBs is relatively understudied, but some work has been done in Europe. The Insulate Study[36] of MURBs in Lithuania and Finland examined radon levels pre-and post-energy retrofits. Lithuanian apartments had small but significantly higher radon levels after renovations (average 14 Bq/m^3), while Finnish apartments saw decreases in radon levels. The difference between MURBs was attributed to the presence of mechanical ventilation: None of the Lithuanian buildings had mechanical ventilation whereas all the Finnish buildings did. A Russian[37] assessment of large, multi-unit buildings of varying ages and building materials renovated for energy efficiency in four cities found higher radon levels in newer construction with lower ventilation rates. The authors also

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[33] Symonds P, Rees D, Daraktchieva Z, McColl N, Bradley J, Hamilton I, Davies M. Home energy efficiency and radon: An observational study. Indoor air. 2019 Sep;29(5):854-64.

[34] Pampuri L, Caputo P, Valsangiacomo C. Effects of buildings' refurbishment on indoor air quality. Results of a wide survey on radon concentrations before and after energy retrofit interventions. Sustainable Cities and Society. 2018 Oct 1; 42:100-6.

[35] Collignan, Bernard, Eline Le Ponner, and Corinne Mandin. "Relationships between indoor radon concentrations, thermal retrofit and dwelling characteristics." Journal of environmental radioactivity 165 (2016): 124-130.

[36] Du L, Leivo V, Prasauskas T, Täubel M, Martuzevicius D, Haverinen-Shaughnessy U. Effects of energy retrofits on Indoor Air Quality in multifamily buildings. Indoor air. 2019 Jul;29(4):686-97.

[37] Yarmoshenko IV, Onishchenko AD, Malinovsky GP, Vasilyev AV, Nazarov EI, Zhukovsky MV. Radon concentration in conventional and new energy efficient multi-storey apartment houses: Results of survey in four Russian cities. Scientific reports. 2020 Oct 22;10(1):1-4.

found that in newer energy efficient buildings, radon levels remained similar from the ground floor up to even the 25th floor. As the need for greater density grows along with concerns for energy efficiency, more research is warranted, particularly for the Canadian housing context.

Learning from US Weatherization Research

Much of the research on radon and energy efficiency has been conducted in Europe, Russia, and the UK. There are important differences in building materials, construction methods, geology, climate, and energy standards that limit generalizability outside of these regions. While little pre- and post- energy retrofit research on radon has been conducted in Canada, there is evidence from the United States useful to the Canadian context. Most of this research has been supported by the US Department of Energy (DOE) through analyses of their Weatherization Assistance Program[38] (WAP). The WAP helps lower costs and improve thermal comfort for people living in low-income housing through energy efficiency upgrades. Approximately 35,000 homes per year access this program, which has been offered since 1976. The WAP covers a range of activities including mechanical and appliance upgrades, insulation, sealing, replacing and repairing windows, and education. The DOE continues to support on-going research of this program, which then leads to program improvement, providing an interesting model of reflexive policy and program design.

DOE research has included a large scale, multi-state project conducted between 2008-2011 involving 514 homes renovated through the WAP program.[39] This found that the most common weatherization procedures done to the homes were added sealing and insulation— some homes also replaced appliances. Radon levels were tested pre- and post- retrofit and homes were found to have a small but statistically significant increase in radon levels (22% higher after retrofits). The increase in radon was correlated to tighter homes and was more pronounced in regions with lower outdoor temperatures. Homes with continuous ventilation were found to have lower radon levels, although only a very small proportion of homes had this type of ventilation in the study. The authors concluded that strategies which reduced air leakage likely increase radon levels. A small follow-up of 18 homes from this project examined the impact of exhaust-only ventilation which had been installed to be compliant with ASHRAE-62.2 (e.g. ventilation standards).[40] None of

[38] United States Office of Energy Efficiency and Renewable Energy. Weatherization Assistance Program. Available at https://www.energy.gov/eere/wap/weatherization-assistance-program, accessed Sept 21,2022

[39] Pigg S, Cautley D, Francisco P, Hawkins B, Brennan T. Weatherization and indoor air quality: Measured impacts in single-family homes under the weatherization assistance program. Oak Ridge, Tennessee, USA: Oak Ridge National Laboratory. 2014 Sep 1.https://web.archive.org/web/20161223162404id_/http://info.ornl.gov/sites/publications/files/Pub49468.pdf, accessed October 3 2022

[40] Pigg S. National Weatherization Assistance Program Impact Evaluation: Impact of Exhaust-Only Ventilation on Radon and Indoor Humidity–A Field Investigation. Available at https://weatherization.ornl.gov/wp-content/uploads/pdf/WAPRetroEvalFinalReports/ORNL_TM-2014_367.pdf accessed September 30, 2022

these follow-up homes showed increases in radon post retrofits. While this appears to vindicate mechanical ventilation as a radon fix, the authors cautioned that the relationship between mechanical ventilation and radon was complex, the sample size small, and that more work was needed to understand how ventilation influenced indoor radon levels.

Recognizing that WAP strategies may have been increasing radon levels, the DOE supported further research (the BARRIER projects).[41] This work examined additional low-cost precautionary measures added during weatherization to help offset increases in radon. These strategies included sealing sump pumps, adding one way valves in floor drains and enhanced sealing of ducts, walls and floors in basements and crawl spaces. Houses in this study were also checked to ensure that they had continuous ventilation compliant with ASHRAE 62.2 (promoted by WAP for retrofits). The precautionary measures undertaken varied by homes and most homes in the study had basements. The researchers found that radon levels on the main floor of homes did not change significantly after energy retrofits. However, basement radon levels did increase on average by 7.5%. Explanatory variable analyses found that homes with more sealing efforts and taller building heights had higher radon levels. The WAP then adopted the precautionary measures for future retrofits to prevent radon increases.

Published in 2020, the BEX report, funded by the US DOE, covers follow-up studies from the BARRIER project.[42] This work included a larger sample of homes retrofitted using the WAP-adopted precautionary measures (limited to mechanical ventilation that met ASHRAE 62.2 requirements, air sealing and insulating with airflow reduced to 50 cfm, sealed sump pumps covers and well-sealed ground covers). 276 treatment homes were examined pre and post WAP renovation across 6 states. Radon levels on the first floors of homes were not significantly different post-renovation, although there were small increases to average levels. Conversely, basement radon levels were elevated post-retrofit and this change was statistically significant (between 7-12%). The authors concluded that the additional precautionary measures were warranted during WAP but that exttra considerations were needed for basements, particularly those used for sleeping. In these cases, they felt that WAP efforts could require ventilation be added for basement with sleeping facilities or recommend similar ventilation strategies where basements were the lowest living level.

The US research is useful to help understand the relationship between radon levels and energy retrofits in Canada, given the good study design and similarities in construction

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[41] Francisco PW, Gloss S, Wilson J, Rose W, Sun Y, Dixon SL, Breysse J, Tohn E, Jacobs DE. Radon and moisture impacts from interventions integrated with housing energy retrofits. Indoor air. 2020 Jan;30(1):147-55. and Francisco PW, Jacobs DE, Targos L, Dixon SL, Breysse J, Rose W, Cali S. Ventilation, indoor air quality, and health in homes undergoing weatherization. Indoor Air. 2017 Mar;27(2):463-77.

[42] Francisco PW, Gloss S, Wilson J, Sun Y, Dixon SL, Merrin Z, Breysse J, Tohn E, Jacobs DE. Building Assessment of Radon Reduction Interventions with Energy Retrofits Expansion (The BEX Study). Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States); 2020 Sep 1.

materials, house design and geography. However, there are some caveats. The homes involved in the DOE supported research were those accessing the WAP program, which tends to focus on modest or lower income homes. Energy retrofits and radon levels may be different in homes that have larger footprints or many floors or include architectural features that can alter air flow (such as vaulted ceilings). Building codes, standard and energy requirements are also different between the US and Canada. Finally, US radon research generally uses only short term radon measurements in contrast to Canada, where 90+ days for testing is considered the norm.

The United States has moved to adopt policies and guidance on radon during retrofits. The Environmental Protection Agency's initial published *Healthy Indoor Environment Protocols for Home Energy Upgrades,* (2014) [43] and later *Energy Efficiency Plus Health: Indoor Air Quality Guidelines* (2021). [44] These provide guidance to the home energy retrofit industry and governments on how to improve indoor air quality while increasing energy efficiency. Radon is one of the priority indoor air contaminants addressed in these guidelines. The US EPA adopts the precautionary measures used by WAP but goes further, asking for post-retrofit testing and installation of radon prevention systems if retrofitting may have contributed to unacceptable radon levels.

New Construction

Most studies linking radon to energy efficiency focus on energy retrofits, the majority of which are done on older homes where upgrades can make a significant difference. This raises the issue as to whether newer housing stock offer solutions to radon. Research on this topic from Europe is mixed- in some countries such as Norway[45] new construction appears to have lower radon levels but in Russia[46] and Lithuania[47], newer homes had higher radon levels. These results likely reflect difference in building codes, practices, and construction materials. There are challenges in applying these results to Canada.

Two studies have looked at radon by year of build in Canada and these suggest that radon is not being "built out" of newer homes. In fact, newer homes may have even

[43] United States Environmental Protection Agency, Healthy Indoor Environment Protocols for Home Energy Upgrades, 2014. https://19january2017snapshot.epa.gov/indoor-air-quality-iaq/healthy-indoor-environment-protocols-home-energy-upgrades_.html accessed Oct 3, 2022

[44] United States Environmental Protection Agency, Energy Savings Plus Health: Indoor Air Quality Guidelines.2021 https://www.epa.gov/sites/default/files/2021-05/documents/epa-oria_singlefamilyprotocols_2021_final_508.pdf, Accessed Sept 8, 2022

[45]Finne IE, Kolstad T, Larsson M, Olsen B, Prendergast J, Rudjord AL. Significant reduction in indoor radon in newly built houses. Journal of Environmental Radioactivity. 2019 Jan 1;196:259-63.

[46]Zhukovsky MV, Yarmoshenko IV, Onishchenko AD, Malinovsky GP, Vasilyev AV, Nazarov EI. Assessment of radon levels in multistory buildings on example of eight Russian cities. Radiatsionnaya Gygiena= Radiation Hygiene. 2022 Apr 4;15(1):47-58.

[47] Cucoş AL, Dicu T, Cosma C. Indoor radon exposure in energy-efficient houses from Romania. Rom. J. Phys.2015;60(9–10):1574-80.

higher radon average levels than those built in the past. Stanley et al.[48] reviewed a sample of 18,000 Canadian homes and found an increasing trend of higher radon levels in more recent builds. The authors project that average radon levels will increase significantly unless strategies to address radon specifically are considered. Research on year of build and radon by Khan et al.[49] also points to troubling increases in radon levels in newer Canadian homes, with increases coinciding with standards designed to address energy loss. Increased radon was most pronounced in single family homes and occurred even though mechanical ventilation and heat recovery systems were added to home designs. There are two likely explanations here. First, Canadian building codes often call for radon rough-ins, however rates of testing and completing systems with fans remains low. Second, mechanical ventilation systems in Canada typically depend on homeowner attention (for example, they are not designed to operate autonomously), and occupants may not be ensuring proper maintenance.

Radon in High-Performance Homes

While Canadian building codes have been ramping up energy efficiency, there is an increasing focus on high-performance buildings standards such as Net-Zero Energy Ready or Passive Houses that offer much deeper efficiency gains. Unfortunately, these do not explicitly incorporate the full range of radon resistant construction techniques. They often do incorporate an under-slab membrane, but, unless the provincial building code specifies or developer/builders take exemplary action, will not normally have any sort of rough-in or ready-built passive or active sub-slab depressurization system. Occupants are also unlikely to test for radon and upgrade, given the current statistics on radon testing. Some homes built to the Passive House standard have been found to have radon problems.[50] However, Passive House and other energy efficiency standards often do include strict requirements for mechanical ventilation.

There is now some research on radon in high performance homes. German research[51] compared radon levels in energy renovated homes, and energy efficient (Passive) homes (n=113) and these groups were both compared to reference homes with no efficiency upgrades. This work, which measured radon levels over one year, ventilated Passive Homes had statistically less radon than energy renovated homes.

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48 Stanley FK, Irvine JL, Jacques WR, Salgia SR, Innes DG, Winquist BD, Torr D, Brenner DR, Goodarzi AA. Radon exposure is rising steadily within the modern North American residential environment and is increasingly uniform across seasons. Scientific reports. 2019 Dec 3;9(1):1-7.

49 Khan SM, Gomes J, Krewski DR. Radon interventions around the globe: A systematic review. Heliyon. 2019 May 1;5(5):e01737.

50 Honig, P. Radon and a Passive House. Green Builder Advisor. Feb 15, 2015. available at http://www.greenbuildingadvisor.com/blogs/dept/guest-blogs/radon-and-passive-house#ixzz5DKrjx7pZ accessed Sept 9 2022; Poffijn, A. et al. A Pilot Study on the Air Quality in Passive Houses with Particular Attention to Radon. 2022 https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.371.8052&rep=rep1&type=pdf accessed Sept 9 2022

51 Meyer W. Impact of constructional energy-saving measures on radon levels indoors. Indoor Air. 2019 Jul;29(4):680-5.

Similar work was undertaken in Switzerland by Yang et al.[52] This study compared energy renovated homes (new and old) to green-certified homes (Minergie) which provide more ventilation than standard homes. This work determined that all renovated homes (older homes and newer builds) had significantly higher radon levels than Minergie homes. In this research, homes that undertook the most renovation strategies (insulation, double glazed windows, and sealing) and those that did not add ventilation had the highest radon levels. A strong and significant correlation was also found between the presence of mechanical ventilation and lower radon levels.

Research in Ireland[53] has confirmed that Passive House designed homes have statistically lower radon levels. This research also found that radon levels tended to be more consistent between floors of such homes. Non-passive homes tend to have a gradient, with lower levels of homes having higher levels than upper floors.

There appears to be no reason in principle that high-performance homes cannot address even very high radon risks (e.g. radon levels for which mechanical ventilation would be unable to sufficiently dilute). Sub-slab depressurization systems can be built as 'passive systems' --without a fan and so requiring no post-installation energy use (except for modest incidental changes to insulation levels). Some building codes, such as in British Columbia, specify an 'extended rough-in' which includes a vent pipe, but allow for curves in the pipe or horizontal runs that make these different from well-built passive systems. The addition of the fan is in some measure to compensate for allowances to builders. Ideally, a carefully built passive system could be installed from the get-go, and then radon tested to assess whether a fan is needed (e.g. upgrading to an active system).[54] When fans are added there are techniques for reducing fan size—such as ensuring proper materials are in place under the building slab (e.g. course gravel that allows for airflow) and proper pressure measurements.

Even in post-construction mitigation scenarios, proper pressure measurements can reduce the needed fan size to 20 watts or less.[55] Specialized products or structural materials that increase air flow under the slab may also reduce how much fan strength is needed.[56] Research from Natural Resources Canada in Prince George, British Columbia[57] shows very good results for both the use of heat recovery ventilators (e.g. which

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[52] Yang S, Goyette Pernot J, Hager Jörin C, Niculita-Hirzel H, Perret V, Licina D. Radon investigation in 650 energy efficient dwellings in western Switzerland: impact of energy renovation and building characteristics. Atmosphere. 2019 Dec;10(12):777.

[53] Mc Carron B, Meng X, Colclough S. An investigation into indoor radon concentrations in certified passive house homes. International Journal of Environmental Research and Public Health. 2020 Jan;17(11):4149.

[54] CAN/CGSB-149.11-2019 ibid.

[55] Health Canada.Reducing Radon Levels in Existing Homes, 2010. ibid.

[56] Hers, I, and Hood, E. Sustainable Approaches for Soil Gas Mitigation Systems. 2012. https://cupolex.ca/downloads/Technical%20Reports/HERS2012Mitigation.pdf last accessed Sept 20 2022

[57] Zhou LG, Berquist J, Li YE, Whyte J, Gaskin J, Vuotari M, Nong G. Passive soil depressurization in Canadian homes for radon control. Building and Environment. 2021 Jan 15;188:107487.

incorporate balanced mechanical ventilation) and passive sub-slab depressurizations systems that were carefully built (such as ensuring insulation through the attic and a straight pipe).[58] The study examined fifteen new construction homes, of which 5 had an HRV, ten did not have an HRV, and all had a carefully built passive sub-slab depressurization system (PSD). With the stack 'closed' (e.g. the PSD rendered inoperative) all those with an HRV (carefully calibrated by the researchers) had indoor radon concentrations below 200 Bq/m^3 whereas three of ten homes operating without an HRV had indoor radon concentrations above 200 Bq/m^3. As well, when the stack was open, and the PSD functioning, all ten new construction homes without an HRV successfully reduced the indoor radon concentration below about 100 Bq/m^3 during both the winter and shoulder seasons, and in those with HRVs to below 80 Bq/m^3 during the shoulder season. There still remains considerable room for more research on how to optimize radon reduction and energy efficiency.

Conclusion

Good evidence has existed for almost 40 years that sealing homes up with the aim of reducing energy use can increase radon gas levels. The relationship between energy efficiency renovations and increased radon gas levels is clear and consistent across different countries and housing types. As houses become more airtight, radon levels can increase, and the magnitude of this problem increases in regions where radon levels are elevated. As such, researchers across multiple disciplines (engineering, building sciences, architecture, health sciences and public health) are stressing the importance of radon testing when energy retrofits are undertaken. Adding ventilation may offer partial solutions, although more research needs to be done on this topic given the mixed results from studies in the US.

The recognition that renovations can alter indoor radon levels needs to be translated broadly to building trades and science professionals, the construction industry, government energy efficiency leaders and energy auditors. The US EPA's *Energy Efficiency Plus Health* guidelines are a good first step for engaging more broadly about the public health impacts of energy renovations. It is also important for the public to know more about this topic. The message needs to be spread that even basic steps - replacing windows or adding weatherstripping- can reduce indoor ventilation and make indoor air quality worse. A broader awareness program—and better government policies—are needed to ensure energy efficiency does not sacrifice health.

Lung cancer remains the more significant cause of cancer death in Canada, and efforts to reduce radon, an important lung carcinogen, maybe inadvertently frustrated by

[58] Ibid.

strategies that reduce energy loss. Testing for radon in inexpensive and easy and mitigation using sub-slab depressurization systems is very effective. Changes to Canada's existing housing stock are necessary to meet our climate targets, however, these solutions should not be at the expense of residents' health. It is time that governments and the energy efficiency sector take steps to prevent lung cancer from being an unintended consequence of climate adaptation.