The Impact of Deep Energy Renovations on Indoor Air Quality and Ventilation in Irish Dwellings

Hala Hassan[1], Asit Kumar Mishra[2], Hilary Cowie[3], Emmanuel Bourdin[4], Brian McIntyre[5], Marie Coggins[*1]

*Corresponding author: marie.coggins@universityofgalway.ie

1 School of Natural Sciences & Ryan Institute, University of Galway, Galway, H91TK33, Ireland

2 School of Public Health, University College Cork, College Road, Cork, Ireland

3 Institute of Occupational Medicine (IOM), Edinburgh, EH14 4AP, UK

4 Climate Action Policy and Construction Industry Regulation Unit, Department of Housing, Local Government and Heritage, Custom House, Dublin 1, D01 W6X0, Ireland

5 Sustainable Energy Authority of Ireland, Three Park Place, Hatch Street Upper, Dublin 2, D02 FX65, Ireland

ABSTRACT

Achieving energy-efficient dwellings has become a vital part of the global climate action plan to reduce energy usage and carbon emissions. Deep energy retrofits (DER) can help reduce residential energy use significantly. However, evidence on how DER impacts on indoor air quality (IAQ), and consequently, occupant health, is scarce. More in-depth analysis of IAQ data before and after energy retrofits is essential to understand the indoor environmental challenges of adopting energy efficiency measures. DER will be required to achieve the EU target of zero emission building stock by 2050, and such studies can inform policy as retrofit strategies evolve. This study evaluates the IAQ in a sample of domestic dwellings (n=12) in Ireland before and after undergoing DER, as part of the SEAI funded research project (ARDEN). IAQ pollutants, including $PM_{2.5}$, carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde, radon, nitrogen dioxide (NO_2), and BTEX (Benzene, toluene, ethylbenzene, and xylenes) were measured over a period of 48 hours to three months (depending on the pollutant) using continuous and passive sampling methods. This study further assesses the performance of the mechanical ventilation systems installed in the homes post DER. The results show that higher concentrations of $PM_{2.5}$ were recorded in some homes post-retrofit compared to pre-retrofit. This was likely due to a combination of factors – increased air tightness (i.e., reduced infiltration), the new mechanical ventilation systems not achieving design flow rates, and varied occupant activities during measurement period. Overall, formaldehyde concentrations significantly increased (p <0.001) post-retrofit, most likely due to the use of building materials, paints, and furnishings during retrofitting. Radon levels measured post-retrofit were below the Irish national reference level (i.e., <200 Bq m^{-3}) for most homes sampled (n=26), except for four homes which were in high radon areas. Results suggest that more emphasis is needed on improving the design, installation, commissioning and maintenance of ventilation systems, along with raising homeowner's awareness regarding IAQ, and how to operate and maintain their ventilation systems in an efficient and effective manner. This would support good IAQ in the energy efficient homes, ensuring health and wellbeing.

KEYWORDS

Indoor air quality, Deep energy retrofit, Ventilation, $PM_{2.5}$, Formaldehyde

1 INTRODUCTION

Ireland plans to halve its greenhouse emissions by 2030 and achieve net zero emissions by 2050. Towards this goal, the Irish programme for Government and Climate Action Plan (CAP23) have set targets to design and construct all new dwellings to Zero Energy Building (ZEB) and retrofit 500,000 existing dwellings to a building energy rating (BER) of B2 or cost-optimal equivalent by 2030. The Deep retrofit multi-annual pilot programme (DER) was introduced in 2017 and managed by the Sustainable Energy Authority of Ireland (SEAI) aiming to upgrade homes to, at least, an A3 BER by adopting a whole-house retrofit, including the requirement for a high performing fabric, reduced thermal bridging, improved air tightness ($\leq 5\ m^3\ h^{-1}\ m^{-2}$ @ 50 Pa), use of renewable fuels, and installation of mechanical ventilation to support air quality.

Ventilation is a vital component of energy efficient homes, to ensure healthy indoor air quality for occupants. Increased building air tightness, post retrofit, in the absence of proper ventilation has been shown to compromise the quality of indoor air for its occupants (Wang et al., 2022). Increased concentration of pollutants, often above recommended guidelines, of particulate matter, carbon dioxide, formaldehyde, and radon have been frequently observed in homes post energy renovations (Du et al., 2019; Földváry et al., 2017). Poor indoor air quality, mainly due to inadequate ventilation, has been shown to be the most influential risk factor associated with respiratory conditions in the household (Wimalasena et al., 2021). Issues of mould growth and noise from the mechanical ventilation systems have also been reported post retrofit (Elsayed et al., 2022).

The lack of occupant knowledge on how to operate and maintain newly installed ventilation systems is another factor that will impact on indoor air quality. Coggins et al. (2022) study on indoor air quality, in deep energy retrofitted dwellings in Ireland, found that air quality was negatively impacted by improper handover and inadequate cleaning and maintenance of ventilation systems. Similarly, in the study of Pedersen et al. (2021), although tenants perceived better ventilation post renovations, many tenants were not adequately informed regarding how the ventilation systems in their homes operated.

Healthy indoor air quality in highly efficient homes can be achieved by ensuring sufficient air change rates through properly installed and maintained ventilation systems (Dovjak et al., 2022), as well as raising occupants awareness regarding IAQ and promote positive engagement with building ventilation systems.

In this study, we evaluate the IAQ in a sample of Irish dwellings (n=12), pre and post energy renovations. Furthermore, we assess the performance of the mechanical ventilation systems installed as part of the retrofit.

2 METHODOLOGY

Ethical approval for this study was obtained from the Research Ethics Committee of the University of Galway. Homes which had participated in the SEAI DER programme were recruited to participate in this study. Twelve dwellings were selected to assess the IAQ and thermal comfort pre-retrofit. The participating dwellings were located across Ireland in both urban, sub-urban and rural locations. All homes underwent a deep energy retrofit between 2019 and 2020, and were > 36-months post retrofit at the time of this study. The pre-retrofit

IAQ measurements were collected in 2019 and 2020. However, due to the COVID19 restrictions, to ensure the safety of the homeowners and the researchers, sampling was suspended during the pandemic. Post-retrofit measurements resumed in winter of 2022 and through the summer of 2023, after the pandemic restrictions had been lifted.

2.1 Indoor Air Quality Monitoring

The following IAQ parameters were measured in the bedrooms and living rooms of the recruited homes over a period of 48-72 hours: particulate matter ($PM_{2.5}$), total volatile organic compounds (TVOCs), carbon monoxide (CO), carbon dioxide (CO_2), temperature (T ºC), and relative humidity (RH%). Concentrations were measured at 1-minute ($PM_{2.5}$) or 5 minute intervals (TVOCs, CO_2, CO, T, and RH). Passive samplers were used to collect formaldehyde samples (over a period of 72 hours) for the same rooms. Additionally, radon was measured for a period of 3 months in 3 homes pre-retrofit and all the 12 homes post retrofit.

Occupants were asked to complete an activity diary to trace occupant's activities during the sampling periods, and a questionnaire form to obtain feedback on the dwellings energy consumption, cleaning and cooking routines, and ventilation systems. Bedroom ventilation rates [Air Change Rates (h^{-1}) and l/s per person] were calculated using the steady-state method and night-time CO_2 concentrations, based on number of occupants and average CO_2 generation rate for sleeping occupants (Batterman, 2017; Persily & de Jonge, 2017).

3 RESULTS AND DISCUSSION

Post retrofit, all homes were upgraded to a post building energy rating (BER) of A3 or better, with post building air tightness values of between 2.7 – 5.0 $m^3\ hr^{-1}\ m^{-2}$, as shown in Figure 1. The BER provide an indication of the energy performance of the dwelling (SEAI, 2023). Each rating corresponds to an energy use per unit floor area per year [EUI = kWh/m^2 year]. Eleven dwellings had oil-fired boilers and one dwelling had a gas-fired boiler as primary space heating pre retrofit. In addition, all dwellings had either an open fire or solid multi-fuel stove as secondary heating. All the retrofits involved the substitution of the previously used fossil fuel based heating systems with an air to water (A2W) heat pump.

Mechanical ventilation systems were installed in all homes. Homes either had demand control ventilation (DCV) where airflow volume was adjusted based on humidity (n = 10), or mechanical ventilation with heat recovery MVHR (n = 2). Ventilation rates, calculated using night-time CO_2 concentrations, were considerably lower in retrofitted homes (1.6 – 8.2 l/s per person; avg. = 4.0 l/s per person) compared to before the retrofit (1.4 – 32.2 l/s per person; avg. = 8.2 l/s per person). During the field surveys, many problems were observed with the newly installed ventilation systems (i.e. low pressure below design flow rates, and dust deposits on the vents).

$PM_{2.5}$ concentrations were higher in some homes post retrofit. The 24-hr $PM_{2.5}$ average concentration (n=24) ranged from 5.5 $\mu g\ m^{-3}$ to 56.7 $\mu g\ m^{-3}$ pre retrofit, and from 4.6 $\mu g\ m^{-3}$ to 353.8 $\mu g\ m^{-3}$ post retrofit. The maximum median concentration was recorded (3 day median = 245 $\mu g\ m^{-3}$) in a bedroom (Home 5). This home also had the lowest measured bedroom ventilation (1.6 l/s per person) of all homes studied. Home 5 was most likely under ventilated during the sampling period. In this home, only one of the wet rooms had an extract vent (bathroom), while the extract vent in the other wet rooms (kitchen) was removed by the homeowner post retrofit due to issues related to noise and draught. Figure 2 shows a time series profile of the $PM_{2.5}$ concentrations in the same bedroom. There were several peak concentrations (up to 1980 µg m^{-3}) during the sampling period. According to the homeowner, the bedroom door was closed during 2nd night-time, and pets were present in the room overnight.

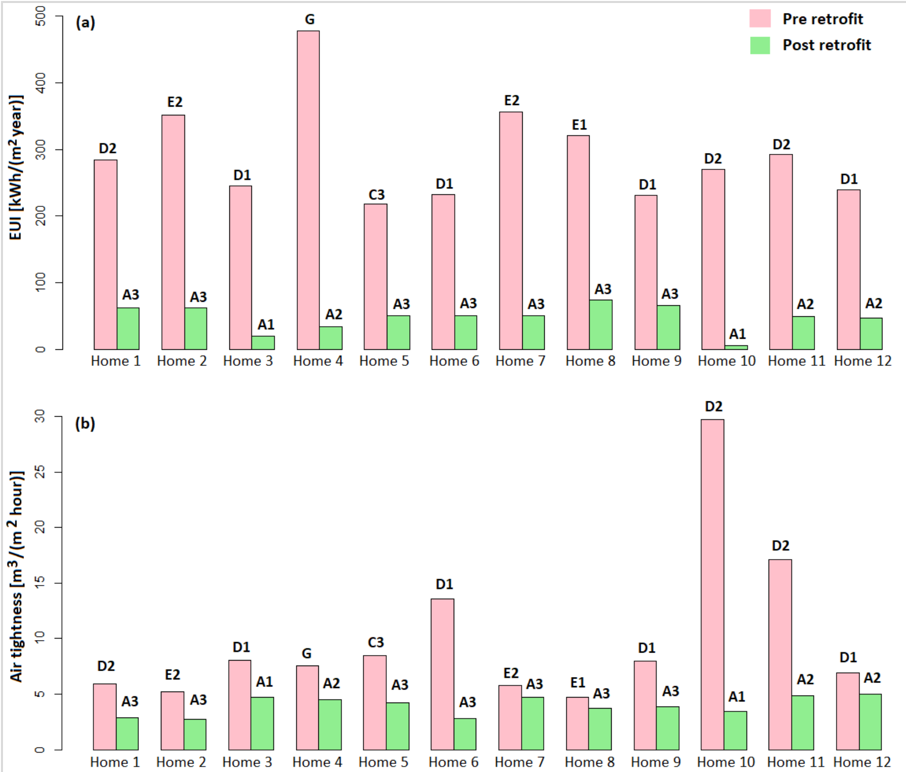

Figure 1 (a) Energy use intensity (EUI) and (b) Air tightness, pre and post retrofit for the studied homes. Each home is labelled by its BER rating for each retrofit status

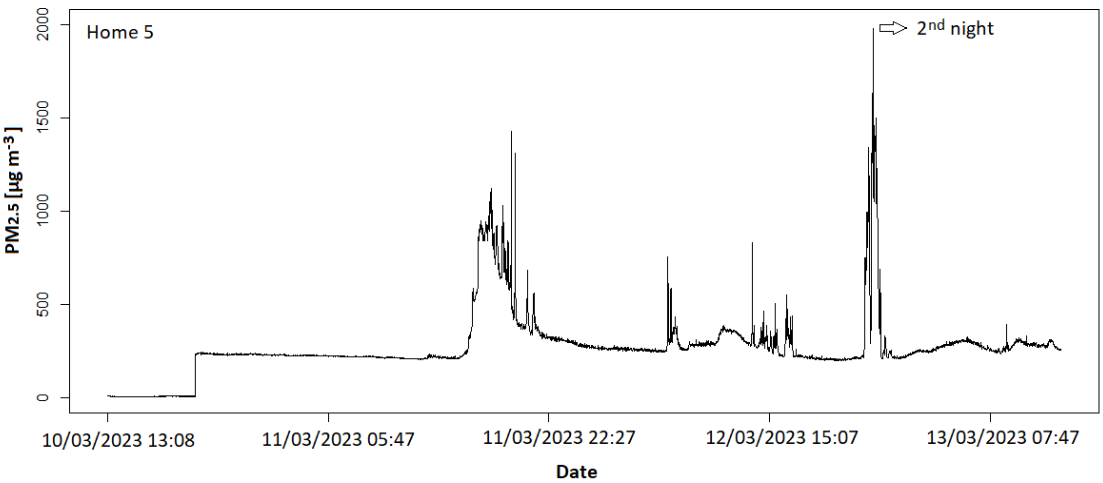

Figure 2 Time series of $PM_{2.5}$ bedroom concentrations in Home 5 over a 3 days sampling period

Overall, there was a significant increase in Formaldehyde concentrations (72-hr average) post retrofit (p <0.001) compared to pre retrofit values, with post retrofit concentrations exceeding the ATSDR annual long-term health-based guideline value of 10 µg/m^3, which is also recommended by Public Health England (ATSDR, 2005; PHE, 2019). The materials used in the renovation works including furnishings, paints, and insulation materials, are major sources of formaldehyde and could be contributing to these high levels in the homes.

Radon levels were measured post-retrofit in 26 homes (14 extra homes in addition to the 12 homes in this study). Radon levels exceeding the national guideline level (i.e., 200 Bq m^{-3}) were recorded in four of the homes located in high radon areas, as per EPA's radon risk map (EPA, 2023).

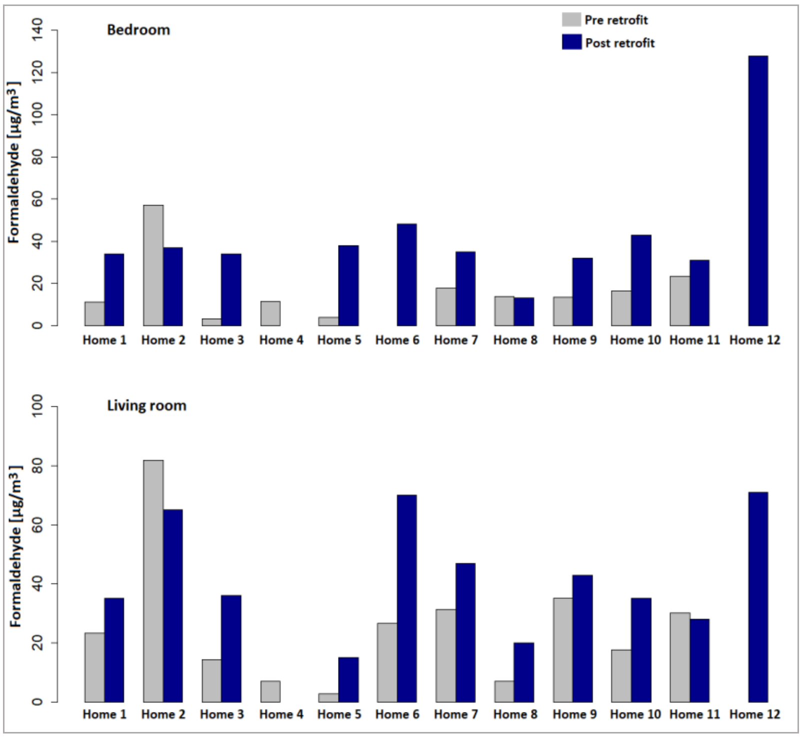

Figure 3: Formaldehyde concentrations [μg m^{-3}] in bedrooms and living areas over a 3 day period pre and post retrofit

4 CONCLUSIONS

Post deep energy retrofit assessments showed significant increases in some indoor air pollutants. Estimated ventilation rates were lower (on average) post energy renovations, which, along with occupant activity, are likely to impact on measured pollutant levels. In most of the homes, problems with ventilation systems and/or visible signs of underperformance and lack of maintenance (i.e. low pressure or dust deposits on the vents) were observed. Future work will include a statistical analysis to investigate possible associations between pollutant concentrations and factors associated with the retrofit.

5 ACKNOWLEDGEMENTS

The Government of Ireland through the Sustainable Energy Authority of Ireland's Research, Development and Demonstration Funding Programme 2018 funds this project (RDD204).

6 REFERENCES

ATSDR. (2005). *Agency for Toxic Substances & disease Registry, USA.* https://www.atsdr.cdc.gov/mrls/mrllist.asp

Batterman, S. (2017). Review and Extension of CO_2-Based Methods to Determine Ventilation Rates with Application to School Classrooms. *Int J Environ Res Public Health*, *14*(2). https://doi.org/10.3390/ijerph14020145

Coggins, A. M., Wemken, N., Mishra, A. K., Sharkey, M., Horgan, L., Cowie, H., Bourdin, E., & McIntyre, B. (2022). Indoor air quality, thermal comfort and ventilation in deep energy retrofitted Irish dwellings. *Building and Environment*, *219*, 109236. https://doi.org/https://doi.org/10.1016/j.buildenv.2022.109236

Dovjak, M., Vene, O., & Vaupotič, J. (2022). Analysis of Ventilation Efficiency as Simultaneous Control of Radon and Carbon Dioxide Levels in Indoor Air Applying Transient Modelling. *Int J Environ Res Public Health*, *19*(4). https://doi.org/10.3390/ijerph19042125

Du, L., Leivo, V., Prasauskas, T., Täubel, M., Martuzevicius, D., & Haverinen-Shaughnessy, U. (2019). Effects of energy retrofits on Indoor Air Quality in multifamily buildings. *Indoor Air*, *29*(4), 686-697. https://doi.org/https://doi.org/10.1111/ina.12555

Elsayed, M., Romagnoni, P., Pelsmakers, S., Castaño-Rosa, R., & Klammsteiner, U. (2022). The actual performance of retrofitted residential apartments: post-occupancy evaluation study in Italy [Article]. *Building Research and Information*. https://doi.org/10.1080/09613218.2022.2121908

EPA. (2023). *Radon risk map. https://gis.epa.ie/EPAMaps/Radon?&lid=EPA:RadonRiskMapofIreland. [accessed July 2023]*

Földváry, V., Bekö, G., Langer, S., Arrhenius, K., & Petráš, D. (2017). Effect of energy renovation on indoor air quality in multifamily residential buildings in Slovakia. *Building and Environment*, *122*, 363-372. https://doi.org/https://doi.org/10.1016/j.buildenv.2017.06.009

Pedersen, E., Borell, J., Li, Y., & Stålne, K. (2021). Good indoor environmental quality (IEQ) and high energy efficiency in multifamily dwellings: How do tenants view the conditions needed to achieve both? *Building and Environment*, *191*, 107581. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.107581

Persily, A., & de Jonge, L. (2017). Carbon dioxide generation rates for building occupants. *Indoor Air*, *27*(5), 868-879. https://doi.org/https://doi.org/10.1111/ina.12383

PHE. (2019). *Public Health England, Air Quality: UK guidelines for selected volatile organic compounds in the UK.* https://www.gov.uk/government/publications/air-quality-uk-guidelines-for-volatile-organic-compounds-in-indoor-spaces

SEAI. (2023). *Sustainable energy authority of Ireland building energy rating certificate (BER) [Online]. https://ndber.seai.ie/pass/ber/search.aspx. [accessed July 2023]*

Wang, C., Wang, J., & Norbäck, D. (2022). A Systematic Review of Associations between Energy Use, Fuel Poverty, Energy Efficiency Improvements and Health. *Int J Environ Res Public Health*, *19*(12). https://doi.org/10.3390/ijerph19127393

Wimalasena, N. N., Chang-Richards, A., Wang, K. I., & Dirks, K. N. (2021). Housing Risk Factors Associated with Respiratory Disease: A Systematic Review. *Int J Environ Res Public Health*, *18*(6). https://doi.org/10.3390/ijerph18062815