Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT

This project has been funded by the Sustainable Energy Authority of Ireland under the SEAI Research, Development & Demonstration Funding Programme 2018, Grant number 18/RDD/204

SECTION 1: PROJECT DETAILS

Project Title	Indoor **A**ir, ventilation and occupant comfo**R**t in Irish domestic dwellings pre and post **DE**ep Energy re**N**ovations (ARDEN)
Lead Grantee (Organisation)	University of Galway
Lead Grantee (Name)	Dr. Marie Coggins
Final Report Prepared By	Dr. Marie Coggins and Dr. Hala Hassan
Report Submission Date	13th September 2024

	Organisation	
Project Partner(s)	University of Galway	
Collaborators	Department of Housing, Local Government and Heritage	
External Consultant(s)	Institute of Occupational Medicine IOM – Edinburgh	

Project Summary (max 500 words)

The objective of the ARDEN research project was to evaluate indoor air quality (IAQ), thermal comfort and ventilation performance in a sample of Irish domestic dwellings pre- and post-deep energy retrofit. All dwellings were participants of the SEAI deep retrofit pilot programme and received energy upgrades to a minimum building energy rating (BER) of A3, achieving a post-retrofit airtightness value of ≤5 $m^3\ h^{-1}\ m^{-2}$ @ 50 Pa.

Twenty-six homes were recruited to participate in the ARDEN project (12 homes for pre-post retrofit assessment, and additional 14 homes for post-retrofit assessment only). Indoor air pollutants including: $PM_{2.5}$, CO_2, CO, TVOC, formaldehyde, radon, NO_2, BTEX, as well as temperature and relative humidity were measured in the main bedroom and living area of the homes. Diaries and questionnaires were used to obtain information on occupant's activities during the measurement period and to collect their feedback regarding the energy retrofit.

Occupants reported a high level of satisfaction with thermal comfort post-retrofit, with only a small number of reported issues regarding overheating in summer.

Indoor carbon dioxide (CO_2) concentrations are often used as a proxy for ventilation. In some cases, retrofit improved indoor CO_2 concentrations particularly in living areas, indicating a positive impact on ventilation. However, many bedrooms were under-ventilated post-retrofit. Concentrations of formaldehyde increased across all homes post-retrofit, while concentrations of $PM_{2.5}$ increased in some homes. Radon concentrations exceeding the Irish National reference level were recorded post-retrofit in homes located in high radon areas.

Higher concentrations of most pollutants (CO2, TVOC, $PM_{2.5}$) were observed in bedrooms. Although underperforming ventilation was likely to have played a role in the observed increasing trend in pollutant concentrations post-retrofit, it is unlikely to be wholly responsible. The introduction of new building materials as part of retrofit is likely to have contributed to higher formaldehyde levels. Occupant behaviour within a more airtight home (e.g. the use of wood burning stoves, candle and incense burning) and the ingress of outdoor air pollution are also possible sources of $PM_{2.5.}$

Given the ambitious Climate Action Plan targets of retrofitting 500,000 homes to B2 or cost optimal equivalent, it is very important that there is more emphasis on pollutant source control and proper installation and maintenance of mechanical ventilation systems during retrofit. Making homes more energy efficient should lead to more sustainable healthy homes. Occupants of mechanically ventilated homes also need to become more aware of the important role of ventilation in an energy efficient dwelling and should ensure that their systems are serviced and maintained regularly.

Since the SEAI Deep Energy Retrofit pilot in 2018, additional guidance and ventilation requirements in the Irish Building Regulations Technical Guidance Document, TGD Part F have been introduced for major renovations, which requires independent third-party inspection and validation checks on ventilations systems to ensure that the required design flow rates are met.

Keywords (min 3 and max 10)	Indoor air quality, Deep energy retrofit, Ventilation, Thermal Comfort, CO_2, $PM_{2.5}$, Formaldehyde, Radon

1 Hassan et al. (2024). *Building and Environment*, 2024. 259: p. 111637 DOI: https://doi.org/10.1016/j.buildenv.2024.111637
2 Coggins et al. (2022). *Building and Environment*, 2022. 219: p. 109236 DOI: https://doi.org/10.1016/j.buildenv.2022.109236.
3 European Union, Directive (EU) 2018/844, *Official Journal of the European Union*: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02010L0031-20210101
4 'Why you need proposal ventilation in your home': https://www.gov.ie/pdf/?file=https://assets.gov.ie/234808/63f05795-f067-41c0-a559-b8ab030f0297.pdf#page=nul

SECTION 2: FINAL TECHNICAL REPORT

2.1 Executive Summary

Twenty-six homes, participants of the SEAI Deep Energy Pilot programme were recruited to participate in the ARDEN study (12 homes had pre- and post-retrofit assessments completed, and an additional 14 homes had post-retrofit assessments only). The 26 homes were located across Ireland in both urban, sub-urban and rural locations. Measurements of eleven indoor air pollutants (IAPs) including: particulate matter ($PM_{2.5}$), carbon monoxide (CO), carbon dioxide (CO_2), total volatile organic compounds (TVOCs), nitrogen dioxide (NO_2), benzene, toluene, ethylbenzene and xylene (BTEX), formaldehyde, radon and the thermal parameters temperature (°C) and relative humidity (%RH) were made in participating homes. All pre-retrofit surveys took place from May 2019 to January 2020, just 25 homes participated in the post retrofit measurements which were completed between 12-36 months after retrofit completion.

During the surveys, occupants were asked to complete:

(1) an activity diary to record any activities during the sampling period that may have impacted on indoor air quality in the home (e.g., burning scented candles, presence of pets, opening windows and doors …etc.),
(2) a questionnaire to provide information on demographics, occupant behaviour, the heating and cooking appliances used in the home, ventilation strategy, energy use and occupant feedback on the retrofit and their perception of IAQ. Participants were asked to rate their thermal comfort on a seven-point thermal comfort scale and to consider their comfort in winter and summer (if relevant). They were also asked to reflect on how their thermal comfort had changed since the retrofit.

IAQ data was collated using Microsoft Excel and analysed using R statistical software. Data was filtered into daytime (7 a.m. – 10 p.m.) and night-time periods (10 p.m. – 7 a.m.), based on the expected usage pattern of the room, it was assumed that living rooms (including the adjacent kitchen and dining area) are likely to be occupied during the daytime while bedrooms are occupied during the night-time. IAQ parameters which were recorded as a time series, were entered into a linear mixed effects (LMEs) model in R, to examine the impact of the retrofit. Some IAPs were analysed by performing a t-test to compare concentrations at pre and post retrofit stage.

Daytime CO_2 levels in the living rooms reduced post retrofit, however many of the bedrooms surveyed were under-ventilated. Mechanical ventilation systems in 19 of the 25 homes surveyed homes did not meet performance requirements in the Irish Code of Practice for the Energy efficient retrofit of dwellings (S.R. 54:2014) and the Irish Building Regulations-Part F. Under performing ventilation systems along with frequent reporting of closed bedroom doors and windows at night most likely resulted in the low bedroom ventilation rates.

Our data analysis showed that $PM_{2.5}$ increased significantly ($p < 0.0001$) post retrofit in both the living areas and bedrooms. This increase is most likely caused by a combination of factors including inadequate ventilation, ingress from outdoors via open windows or doors (during wintertime), presence of a wood burning stove and other occupant activities e.g. candle and incense burning.

Figure 1 shows the formaldehyde concentrations (72-hr average) across the 25 homes post retrofit. Formaldehyde concentrations increased following the retrofit, exceeding the ATSDR 1- year long-term health-based guideline value of 10 µg m^{-3}, (a limit which is also recommended by Public Health England), in all rooms. The concentration of one formaldehyde bedroom sample (128 µg m^{-3}) exceeded the WHO (30-minute) guideline of 100 µg m^{-3}, a limit recommended to prevent sensory irritation in the general population. This sample was collected during the summer period, and therefore could be impacted by the increased air temperatures recorded during the same period. Increased concentrations of formaldehyde post retrofit have been reported by several studies and attributed to the use of new building materials during retrofit coupled with sometimes reduced air change rate post retrofit.

1 Hassan et al. (2024). *Building and Environment*, 2024. 259: p. 111637 DOI: https://doi.org/10.1016/j.buildenv.2024.111637
2 Coggins et al. (2022). *Building and Environment*, 2022. 219: p. 109236 DOI: https://doi.org/10.1016/j.buildenv.2022.109236.
3 European Union, Directive (EU) 2018/844, *Official Journal of the European Union*: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02010L0031-20210101
4 'Why you need proposal ventilation in your home': https://www.gov.ie/pdf/?file=https://assets.gov.ie/234808/63f05795-f067-41c0-a559-b8ab030f0297.pdf#page=nul

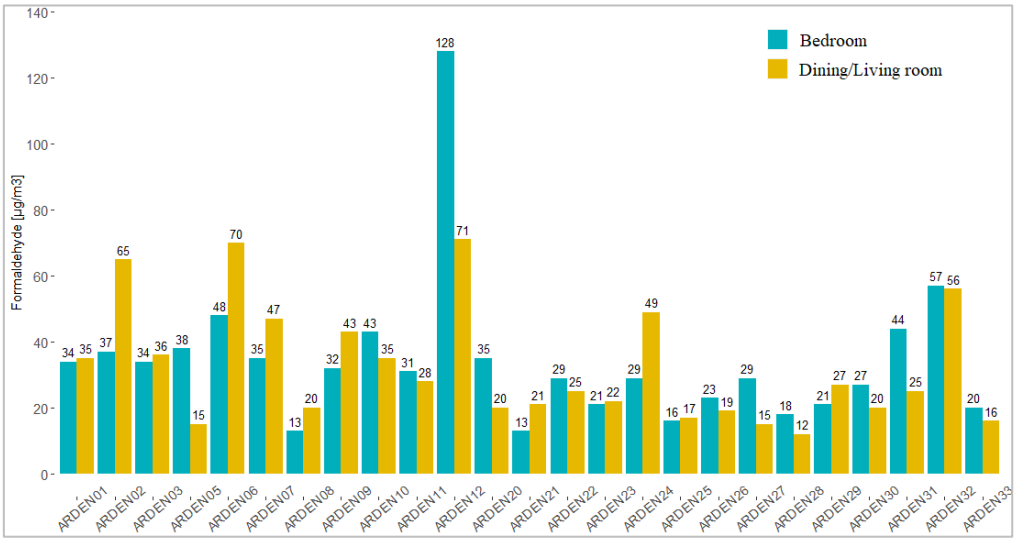

Figure 1 Formaldehyde air concentrations [µg m^{-3}] in the bedrooms and living rooms of participant homes post-retrofit

Radon was measured in 19 homes, at post-retrofit stage only. The overall average concentration across the measured homes (107.6 Bq m^{-3}) exceeded the Irish indoor average for residential buildings (77.0 Bq m^{-3}). Three homes, located in high radon areas had radon concentrations between 200-320 Bq m^{-3}, which exceeds the Irish EPA national reference level of 200 Bq m^{-3}. Increased airtightness above ground level and reduced ventilation could cause radon concentrations to increase.

2.2 Introduction to Project

Irelands National Retrofit programme sets out ambitious targets to retrofit 500,000 homes by 2030. Many of these homes will adopt a deep retrofit, and research studies such as ARDEN are required to ensure co-benefits to indoor environmental quality are prioritised alongside energy efficiency.

Deep Energy renovation (DER) adopts a whole building approach involving a high performing fabric, reduced thermal bridging, improved air tightness (≤ 5 m^3 h^{-1} m^{-2} @ 50 Pa), use of renewable fuels and mechanical ventilation. DER achieves much larger energy savings than conventional energy renovations.
In this research project the air concentration of eleven priority pollutants for health have been measured in a sample of Irish homes participated in SEAI's DER Pilot programme.

Further details regarding project methodologies and study findings can be obtained in study publications [1,2].

The impact of energy efficient measures such as DER on indoor air quality (IAQ) is largely understudied internationally. Although research shows that improving the energy efficiency of a building improves indoor temperature and occupant comfort, the impact on IAQ is inconclusive. The Energy Performance of Buildings Directive (EPBD)[3] identifies improved indoor environmental quality along with better health and wellbeing of occupants as key goals of the European retrofit programme. Post retrofit data on exposure to indoor air pollutants is required to help evaluate the impact of energy retrofit on health via health impact assessment methodologies. Post occupancy assessments such as those completed in ARDEN can also help identify unintended consequences of retrofit that require corrective action via amendment of current policy or guidance.

2.3 Project Objectives

1 Hassan et al. (2024). *Building and Environment*, 2024. 259: p. 111637 DOI: https://doi.org/10.1016/j.buildenv.2024.111637
2 Coggins et al. (2022). *Building and Environment*, 2022. 219: p. 109236 DOI: https://doi.org/10.1016/j.buildenv.2022.109236.
3 European Union, Directive (EU) 2018/844, *Official Journal of the European Union*: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02010L0031-20210101
4 'Why you need proposal ventilation in your home': https://www.gov.ie/pdf/?file=https://assets.gov.ie/234808/63f05795-f067-41c0-a559-b8ab030f0297.pdf#page=nul

(1) To complete a comprehensive assessment of the air concentration of eleven indoor air pollutants, assess ventilation performance and measure thermal comfort parameters in a sample of Irish domestic dwellings before and after deep energy renovations
(2) Using the data above, combined with the results from building occupant surveys, assess occupant comfort regarding thermal and indoor air quality parameters post deep energy renovations.
(3) Using statistical analysis tools, investigate the impact of the deep energy renovation measures on indoor air quality in domestic dwellings.

2.4 Summary of Key Findings/Outcomes

- *Innovation 1: Provide a full analysis of the impact of deep energy retrofit on IAQ, thermal comfort, and ventilation in Ireland.*

  This study provides a unique Irish dataset characterising indoor air quality (IAQ) parameters, thermal comfort, and ventilation performance pre and post deep energy retrofit in homes in Ireland. It suggests a positive impact of deep energy upgrades on thermal comfort and variable impacts on indoor pollutant concentrations. Our study highlighted poor compliance with then (NSAI S.R. 54 -2017-2019) ventilation requirements for retrofit.

- *Innovation 2: This study provides valuable insights on the role of occupant behaviour on IAQ in energy efficient homes. Although many of the homes were under ventilated post-retrofit, occupant activities also made a significant contribution to post-retrofit indoor air quality.*

2.5 Project Impact

Societal

The average European spends upwards of 70% of their time indoors, therefore indoor air plays a significant role in human health. There is an urgent need to educate society at large regarding what constitutes good indoor air and the importance of ventilation in achieving this goal. By increasing public awareness via projects like ARDEN, regarding the importance of IAQ, we will empower individuals to seek to improve their living conditions by engaging more with IAQ and measures such as ventilation in their home following retrofit. The research team participated in many outreach activities (print, and broadcast media) and contributed to the creation of outreach materials on indoor air e.g. an outreach video and leaflet for homeowners developed by the Department of Housing, Local Government and Heritage.[4]

Economic

It is currently estimated that the economic costs of poor indoor air quality in Europe are approximately €200 billion. Energy retrofits can help reduce such costs if managed correctly both at design, construction and post occupancy stage offering many an opportunity to not only improve the energy performance of their dwelling but also to improve their living conditions through improved indoor environmental quality. The study could encourage and inform the development of new or modified technical interventions, such as modified ventilation technologies to tackle specific indoor pollutant sources, and greener cleaner construction products and household furnishings.

Policy-Oriented

Regulators and policy makers within the Department of Housing, Local Government and Heritage and SEAI can use the project data to inform the direction of the future Deep Retrofit programme as part of Ireland's Renovation Strategy. The results of this study support the new requirements in Building Regulations 2019, Technical Guidance Document (TGD) Part F for third party compliance checks of ventilation systems and the provision for control indicators to be in a located in place visible to the occupant.

1 Hassan et al. (2024). *Building and Environment*, 2024. 259: p. 111637 DOI: https://doi.org/10.1016/j.buildenv.2024.111637
2 Coggins et al. (2022). *Building and Environment*, 2022. 219: p. 109236 DOI: https://doi.org/10.1016/j.buildenv.2022.109236.
3 European Union, Directive (EU) 2018/844, *Official Journal of the European Union*: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02010L0031-20210101
4 'Why you need proposal ventilation in your home': https://www.gov.ie/pdf/?file=https://assets.gov.ie/234808/63f05795-f067-41c0-a559-b8ab030f0297.pdf#page=nul

Scientific

This project provides the first Irish dataset evaluating the impact of deep energy retrofit on IAQ, thermal comfort and ventilation. The dataset has been presented at several international conferences, including the International Energy Agency, Annex 5- AIVC conferences and workshops, also study results have been published in two peer-reviewed scientific papers. The work also provides recommendations for further research in this area. A follow-on study has now commenced also funded by SEAI the BEVENT project will explore the role of occupant behaviour in IAQ and ventilation performance. Project data will also be analysed as part of a larger project within the International Energy Agencies Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings.

2.6 Recommendations

- To maximise the benefits of energy retrofit to Indoor air quality post energy retrofit, greater compliance with the ventilation guidance set out in the Irish Building Regulations 2019 TGD Part F and also the NSAI S.R. 54 guidance is required. A ventilation strategy needs to be part of the retrofit strategy.

- To achieve good IAQ in energy retrofits, a greater emphasis needs to be placed on pollutant source control indoors, for example well designed cooker hood extraction, and the use of low emitting VOC products. The introduction of a harmonised EU VOC labelling scheme, to allow designers and homeowners select low emitting products is essential to support the European renovation wave. Further studies are required to evaluate the impact of using biomass burning wood stoves, on IAQ in energy efficient homes.

- As many of the indoor pollutant sources are not always related to moisture, the industry needs to consider performance based mechanical ventilation systems based on IAQ indicators other than CO_2

- A radon risk assessment should be performed as part of any energy retrofit, but especially where pre-retrofit data indicates that the home is in a high-risk radon area.

- More research incorporating learning from real world case studies is required to fully understand the complex interactions between energy efficient buildings and occupant behaviours, preferences and needs. Such research can help address some of the technical interface challenges encountered in practice and promote the development of more human centric building controls which can be successfully used by the building occupants.

2.7 Conclusions and Next Steps

The ARDEN project investigated the impact of deep energy retrofit measures on IAQ concentrations, thermal comfort, and ventilation in a sample of Irish domestic dwellings. More emphasis on pollutant source control and proper installation and maintenance of mechanical ventilation systems during retrofit is required to ensure DERs lead to more sustainable healthy homes. Occupants of mechanically ventilated homes also need to become more aware of the important role of ventilation in an energy efficient dwelling and should ensure that their systems are serviced and maintained regularly.

1 Hassan et al. (2024). *Building and Environment*, 2024. 259: p. 111637 DOI: https://doi.org/10.1016/j.buildenv.2024.111637
2 Coggins et al. (2022). *Building and Environment*, 2022. 219: p. 109236 DOI: https://doi.org/10.1016/j.buildenv.2022.109236.
3 European Union, Directive (EU) 2018/844, *Official Journal of the European Union*: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02010L0031-20210101
4 'Why you need proposal ventilation in your home': https://www.gov.ie/pdf/?file=https://assets.gov.ie/234808/63f05795-f067-41c0-a559-b8ab030f0297.pdf#page=nul