



# Sustainable Energy Authority of Ireland

## National Energy Research, Development & Demonstration Funding Programme

### FINAL REPORT

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#### SECTION 1: PROJECT DETAILS

<b>Project Title</b>	ALIVE - Assessing Indoor Environmental Quality and Energy Efficiency In a range of Naturally-Ventilated Buildings: A Multi-Disciplinary Approach
<b>Lead Grantee (Organisation)</b>	University of Galway
<b>Lead Grantee (Name)</b>	Dr. Miriam Byrne
<b>Final Report Prepared By</b>	Miriam Byrne, James McGrath, James O'Donnell, Divyanshu Sood, Ibrahim Alhindawi
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	<b>Name</b>	<b>Organisation</b>
<b>Project Partner(s)</b>	Dr James O'Donnell Dr James McGrath	UCD Maynooth University
<b>Collaborators</b>	Dr Eleni Mangina	UCD

#### Project Summary

In the ALIVE project, an assessment was carried out of the capability of natural ventilation to reduce energy consumption and avoid overheating while simultaneously maintaining indoor environmental quality (IEQ) within Irish buildings. Remotely-operated sensors continuously collected IEQ data in naturally-ventilated buildings, amassing an estimated 40 million data points, which are to be stored in an open-repository and accessible to all relevant stakeholders. Gathering complementary thermal comfort, building characteristics, utility bills, occupancy/activity schedules was also a critical component of the integrated approach as novel applications of data analytics and machine-learning tools were deployed to identify temporal data trends that accounted for the above features. A complementary indoor air quality assessment was carried out for key pollutants of concern. The combined database was analysed in terms of WHO and CIBSE guidelines to identify occupants' air pollution exposure and thermal comfort. The approach deployed and validated Building Energy Performance Simulation models that integrated IEQ and energy components for domestic and non-domestic locations to evaluate the approach in real-world conditions. These integrated models were used to determine the impact of natural ventilation on IEQ and overheating for each archetype selected and potential impacts on BER and NEAP ratings were evaluated. The impact of specific recommendations on the national building stock were also

assessed and additional meteorological conditions, current/future climate conditions, occupancy scenarios and emission profiles were also assessed through simulation.

Overall, this project conducted a comprehensive and scientifically-robust assessment of the effectiveness of natural ventilation in Irish dwellings.

**Keywords (min 3 and max 10)**

Indoor Environmental Quality,  
Energy Efficiency,  
Natural Ventilation,  
Thermal Comfort,  
Building Simulation,  
Longitudinal IEQ data

## SECTION 2: FINAL TECHNICAL REPORT

### 2.1 Introduction to the Project

#### (a) Context

In recent years, the global drive towards improving building standards to reduce energy consumption has emerged as a critical response to the dual challenges of climate change and future sustainability goals. These advancements in energy efficiency often involve enhancements in thermal and insulation properties, and increased airtightness. The International Energy Agency (IEA) acknowledges the pivotal role of enhancing energy efficiency in realising a low-carbon future for the built environment while also emphasising its importance in sustaining health and well-being benefits. However, in recent European history, the focus on building energy efficiency promotion has been on energy consumption reduction during winter, as temperate climates did not need to consider cooling, which is now a challenge due to increasing global temperatures. Natural ventilation (NV) offers significant benefits, including passive cooling, but a consequence of NV is uncontrolled heat loss through airflow during winter, which can impact occupant comfort and evoke energy-conservation behaviours, including reduced window opening. As a result, there is potential for indoor air pollutants and moisture to accumulate, thus negatively impacting occupant health and comfort. Numerous studies have evaluated IAQ in naturally ventilated dwellings, however, most of this research has concentrated on conventional buildings, with higher air leakage rates, and few have studied energy consumption in parallel. While there is a growing trend toward mechanical ventilation (MV) or mechanical ventilation with heat recovery systems (MVHR), these options are not always viable due to budget constraints, space limitations, and other practical considerations. While airtight energy-efficient dwellings employing NV strategies are considered viable within current building standards, evaluation of the performance of this ventilation strategy is less well documented, and this provides the context for the ALIVE project.

#### (b) Monitoring Study: Indoor Air Quality and Thermal Status of Dwellings

House selection criteria focused on a cohort of semi-detached dwellings, which represent 40.7% of the total naturally-ventilated energy-efficient houses in Ireland. These dwellings have an 'A' Building Energy Rating (BER) (seven A2, two A3), denoting a maximum primary energy consumption of up to 50 (A2) and 75 (A3) kWh/m<sup>2</sup> per year; the air permeability of the specific dwellings was not available. Bedrooms, living rooms, and kitchens were monitored for a one-week long period during both summer and winter using research grade instrumentation, to measure PM<sub>2.5</sub>, CO<sub>2</sub>, TVOCs, NO<sub>2</sub>, CO, and temperature and relative humidity. These measurements were complemented by a longitudinal study of CO<sub>2</sub>, temperature and humidity in bedrooms and living rooms, which spanned one year. In all cases, hourly energy consumption (kWhr) was continuously

monitored over the same year-long period, using Ziggytec sensor technology. Bedroom air exchange rates were extrapolated based on the metabolic CO<sub>2</sub> method (winter mean: 0.21 hr<sup>-1</sup>; summer mean: 0.33 hr<sup>-1</sup>; annual mean: 0.28 hr<sup>-1</sup>). Longitudinal monitoring was also carried out in selected apartment and office buildings.

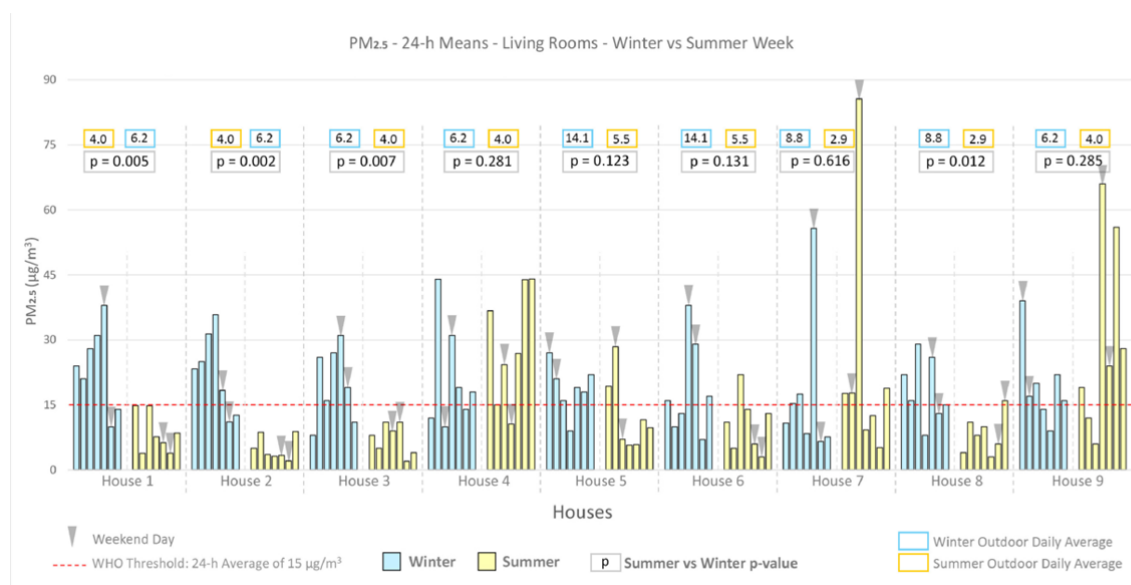


Figure 1. Summer and winter 24-hour mean PM<sub>2.5</sub> concentrations in nine monitored dwellings, with weekend days indicated.

Figure 1 shows an example of the summer vs winter PM data. Specific attention was given to PM, as a substantial body of research, including epidemiological studies and controlled human exposure experiments, has highlighted the health risks associated with PM exposure. However, it must be emphasised that research grade measurements of PM concentration (as opposed to consumer grade monitoring from which trends can be established) was conducted over a week-long period only in each season. A comparison of PM<sub>2.5</sub> concentrations monitored in kitchens to the 24-hour WHO guideline of 15 µg/m<sup>3</sup>, reveals that 93% of the daily averages exceeded this threshold in winter compared to 49% in summer. In living rooms, fewer exceedances were observed, with 68% of days exceeding the guideline in winter and 28% in summer, suggesting the dispersion of kitchen PM into living rooms; high correlation values ( $r = 0.61$ – $0.96$  in winter,  $0.56$ – $0.91$  in summer) between PM<sub>2.5</sub> in kitchens and living rooms indicate that kitchen activities, particularly cooking, are the primary sources of PM emissions. This conclusion is supported by activity diaries, which reported infrequent vacuuming and minimal use of candles and incense burners. Survey responses provide qualitative evidence that house occupants routinely utilised cooker hoods during cooking events.

Similar trends to the above were observed regarding some other pollutants, i.e. that greater challenges regarding indoor air pollution control existed in winter. This contrasts to some extent with observations regarding thermal status of the monitored rooms, as shown in Table 1. While temperature and humidity were broadly within acceptable limits during the months when heating was actively used (i.e. Oct–Apr), there was evidence that up to half of the rooms monitored did not meet the CIBSE TM59 criterion for overheating risk (which requires that the internal temperature does not exceed a defined comfort temperature by 1 °C for more than 3% of the occupied hours over the monitoring period; occupancy was determined from CO<sub>2</sub> concentration profiles). This was the case during some summer months (May–Sept), when heat pumps, which were constantly operating, were not generally heating the houses, and was considered to be associated with building orientation, with south and west-facing bedrooms emerging as being particularly vulnerable.

Table 1– Monthly Data Summary of Mean Temperature

Bedrooms	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
House 1	18.7	19.4	20.2	21.6	24.0	25.0	24.1	24.4	24.8	22.4	20.0	19.7
House 2	21.0	21.1	21.2	21.7	23.1	24.5	23.3	24.1	25.0	22.6	22.0	21.3
House 3	21.5	21.9	21.9	21.3	22.6	24.3	24.1	23.7	23.5	22.0	21.7	21.9
House 4	19.8	19.5	19.7	19.9	21.0	22.7	22.5	21.9	21.9	21.0	20.2	20.4
House 5	20.8	20.4	20.3	19.7	21.6	23.6	21.6	22.0	22.0	21.3	20.7	21.7
House 6	16.6	18.0	21.0	20.8	21.7	24.0	21.5	21.5	22.3	21.9	21.8	18.9
House 7	18.6	21.5	21.5	21.5	22.7	24.2	22.6	23.0	23.5	21.5	21.0	20.8
House 8	19.4	20.7	21.7	21.4	22.0	24.3	22.0	22.5	23.2	20.7	20.2	19.5
House 9	21.8	22.1	21.9	21.8	23.8	25.1	24.5	24.7	24.5	22.5	22.1	21.5
BRs Avg	19.8	20.5	21.0	21.1	22.5	24.2	22.9	23.1	23.4	21.8	21.1	20.6

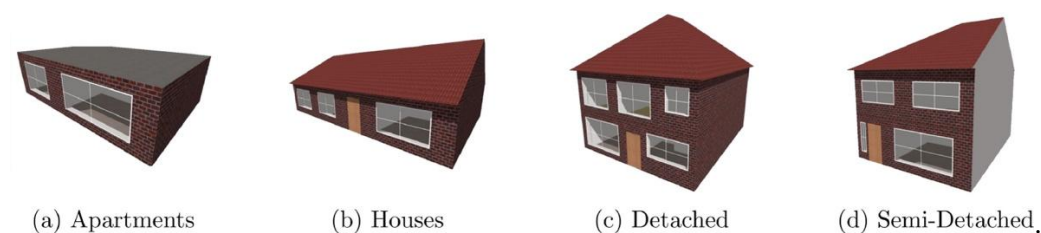
Living Rooms	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
House 1	17.3	17.8	18.3	19.2	21.3	22.4	22.0	22.4	22.4	20.9	19.0	18.9
House 2	21.3	21.2	21.3	21.7	22.3	23.3	23.0	23.4	23.4	22.1	21.8	21.5
House 3	19.8	20.3	20.4	19.8	21.0	22.8	22.4	22.1	22.0	20.5	20.2	20.1
House 4	21.9	21.5	21.5	21.3	21.2	22.6	22.3	21.8	22.0	21.9	22.0	22.8
House 5	17.4	17.2	19.9	19.4	21.2	22.5	20.5	21.0	20.6	21.6	20.2	18.6
House 6	18.1	19.8	20.8	21.0	21.7	24.2	21.7	21.6	21.1	21.5	20.7	19.1
House 7	19.7	20.9	21.1	21.2	22.2	24.3	22.1	22.6	23.2	21.4	20.9	20.8
House 8	18.8	19.5	21.5	21.8	23.3	25.5	23.2	23.5	24.0	21.2	19.7	19.1
House 9	22.1	21.7	21.3	19.6	22.8	23.9	23.9	23.9	23.6	22.4	21.7	21.9
LRs Avg	19.6	20.0	20.7	20.6	21.9	23.5	22.3	22.5	22.5	21.5	20.7	20.3

While details of the monitoring campaign may be found in the publications resulting from this research (notably Alhindawi *et al*, Building and Environment, Vol 276, 2025), a summary of the key findings are as follows:

- A novel hybrid methodology has allowed for an accurate, longer-term representation of IEQ, capturing a combined 40 million data points.
- A marked variation in day-to-day IEQ concentration confirms the need for longer-term monitoring to elucidate the monthly and annual exposure patterns.
- Natural ventilation provided air change rates, with marked observed differences between summer and winter, and a corresponding improvement in IAQ during the summer period. Cooking was a major source of indoor PM, even when cooker hoods were employed
- While CO<sub>2</sub> was utilised to determine air change rates, it is considered to be an indicator of ventilation status only, and not an IAQ metric.

### (c) Model Development

The monitoring results highlight the important impact of building occupant behaviour upon IAQ influence, ventilation usage and energy consumption. These factors can be most accurately and comprehensively analysed via a computational approach and this was successfully adopted within the ALIVE project. The first of several aspects involved the development of a deterministic occupancy model, as a representative of a large number of dwellings, using Time Use Survey (TUS) data to generate day-wise occupancy schedules. The model is based on a predefined set of rules, considering dwelling type, number of occupants, month of the year and day of the week. This approach enables a detailed assessment of how different occupancy patterns influence the performance of archetypes in estimating energy consumption at various spatial and temporal scales. Figure 2 shows archetypes that were developed for EnergyPlus simulations, to represent the Irish building stock, and Figure 3 provides an example of yearly occupancy profiles corresponding to defined activity levels



*Figure 2. Developed archetypes for the model*

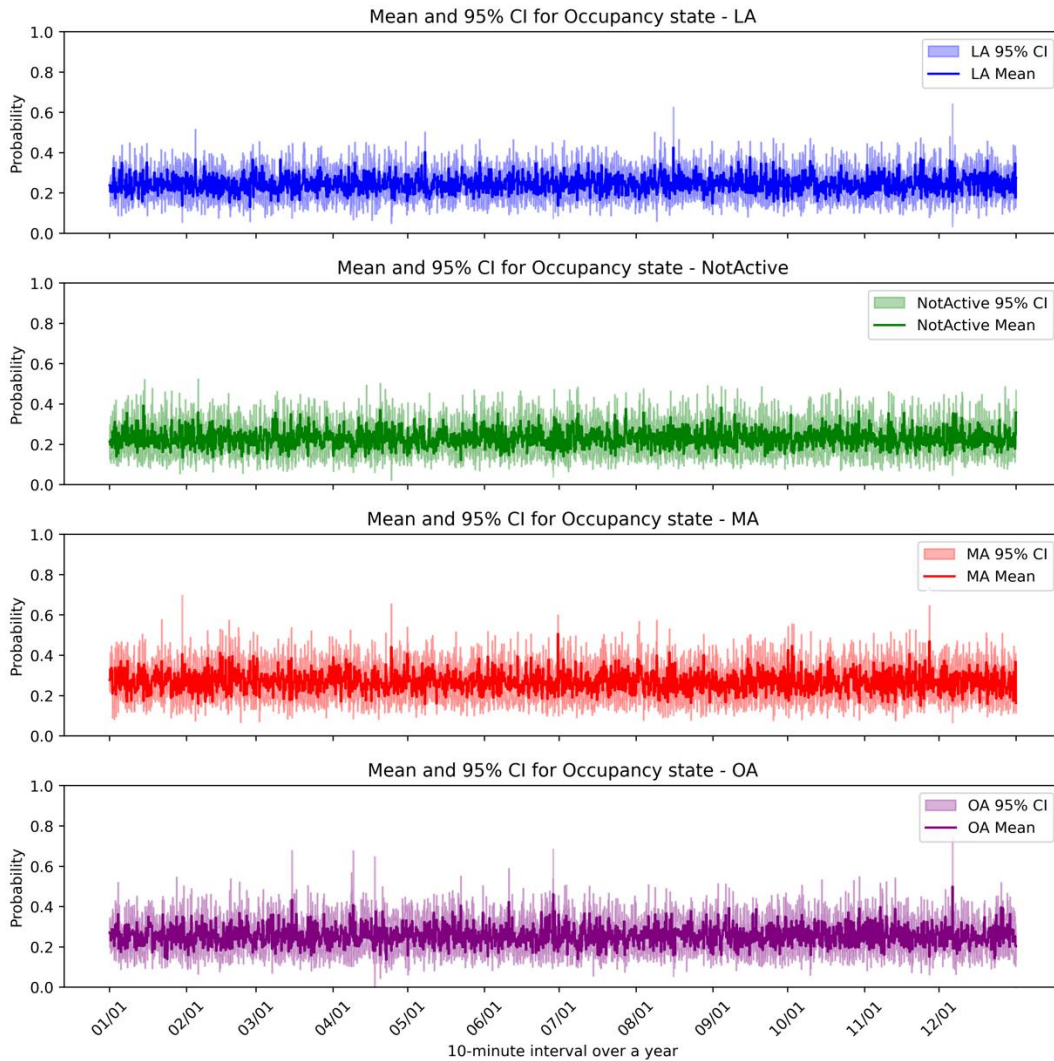


Figure 3: Mean and 95% confidence interval for each class (Light Activity (LA), Medium Activity (MA), NotActive and Outside Activity (OA)) at 10-minute intervals for a year.

A further model development involved the generation of a low-computational methodology based on a metamodel approach tailored for rapid prediction and optimisation of heating energy consumption (kWh), thermal discomfort, and elevated CO<sub>2</sub> levels (hours) under the influence of occupancy-related parameters. Figure 4 demonstrates how these predicted parameter values closely align with data collected during the measurement campaign.

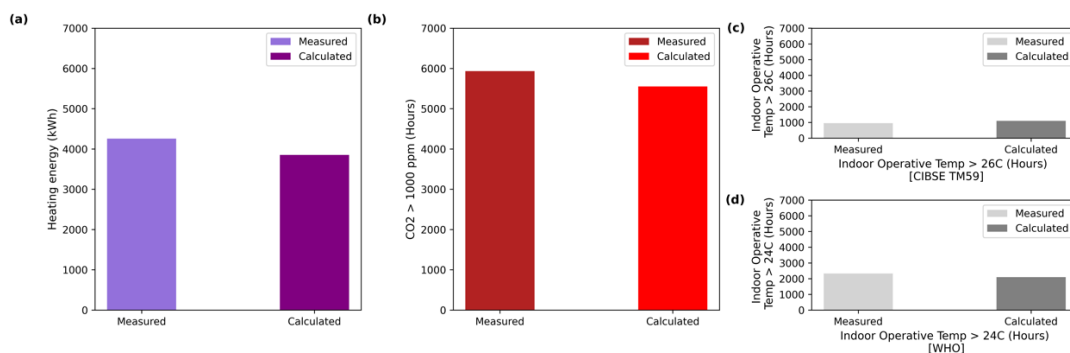


Figure 4: Comparison of annual heating energy consumption (kWh), CO<sub>2</sub> concentration > 1000 ppm (Hours) and indoor operative temperature based on CIBSE TM59 standard and WHO guidelines with measured and calculated values to validate the base case.

While the details of the modelling developments can be found in the publications resulting from this work (notably <https://doi.org/10.1016/j.buildenv.2024.112255> ) the key computational achievements can be summarised as follows:

:

- *A synthetic large dataset (1 million datapoints) for residential buildings for Irish building energy rating labels has been generated.*
- *A customised framework based on the metamodel approach for rapid prediction and optimisation of heating energy consumption, thermal discomfort, and CO<sub>2</sub> concentration in energy-efficient naturally ventilated homes has been constructed.*
- *A substantial difference in parameter impact and ranking when comparing individual versus collective outcomes, reflecting the interrelated nature of the outputs, has been observed.*
- *High prediction accuracy using machine learning algorithms (XGBoost, Support Vector Machines, RandomForest), with XGBoost being the most effective, has been achieved.*
- *An 80% reduction in optimisation completion time with a high correlation coefficient of 0.98 compared to traditional physics-based approach has been achieved.*

## 2.2 Project Objectives

Overall, this project contributed significantly to filling an international knowledge gap as it aligns directly to research needs. This project set out to achieve the following:

- Assess natural ventilation capabilities to improve energy performance while maintaining IEQ within buildings
- Determine the exposure of dwelling occupants to indoor air pollution exposure based on longitudinal data in various microenvironments
- Evaluate the NEAP/DEAP methodologies and identify the potential to map results to the current BER, improving overall building stock rating
- Disseminate the findings in the scientific literature, engage with policymakers and inform the general public

## 2.3 Summary of Key Findings/Outcomes

### ***Innovation 1: Development of Occupancy-based buildings archetypes for energy analysis at various spatial and temporal scales***

This study develops occupancy-based building archetypes using Time Use Survey (TUS) data to generate realistic, dynamic occupancy profiles. These profiles capture variations by occupant count, dwelling type, and time of year, enabling more accurate energy analysis across spatial and temporal scales.

### ***Innovation 2: Identification of influential factors for combined energy consumption and indoor environmental quality in residential buildings***

This work presents a novel simulation framework integrating occupancy-based archetypes, parametric simulation, and machine learning to identify key factors influencing both energy consumption and IEQ in residential buildings. It reveals that parameter importance and selection vary by target, offering valuable insights for accurate and efficient building performance analysis.

***Innovation 3: Machine learning based prediction and multi-objective optimisation of heating energy consumption, thermal comfort and CO<sub>2</sub> concentration in energy-efficient naturally ventilated residential dwellings***

This research introduces a novel low-computational metamodel-based approach to simultaneously predict and optimise heating energy use, thermal discomfort, and CO<sub>2</sub> levels in naturally ventilated residential buildings. The method offers a fast, reliable path to designing energy-efficient dwellings with improved indoor environmental quality (IEQ).

***Innovation 4: Development of a Probabilistic Occupancy Model (POM) for Multi-Scale Energy Analysis***

This study presents a robust methodology to develop a Probabilistic Occupancy Model (POM) using Time Use Survey data based on Bayesian Neural Networks, capturing stochastic occupancy patterns across spatial scales. The model achieved high accuracy in predicting occupancy states and heating energy use, enhancing the precision of urban-scale energy analyses. ***Innovation 5: Assessing indoor environmental quality in naturally-ventilated energy-efficient Irish dwellings and other buildings***

An outcome of the study is a comprehensive mapping of the trends for key IAQ parameters and thermal comfort, as well as evaluating overheating frequency, all based on natural ventilation effectiveness for maintaining adequate ventilation rates within selected houses, apartments and office buildings. The range of air pollutants that are monitored and the extent of the study is novel from an Irish built environment perspective, and also internationally, where naturally ventilated energy efficient buildings have been under-studied.

## **2.4 Project Impact**

*Clearly position the impact of your project with reference to the needs of the Irish Energy Sector, national and international policy objectives, and SEAI's remit.*

### **Societal**

As the average European spends upwards of 90% of their time indoors, there is a need to educate society regarding the utilising of ventilation systems, especially in domestic settings, to secure good air quality. The ALIVE project focuses on the important 36% of energy efficient dwellings in Ireland that are naturally ventilated. By liaison with selected dwelling occupants and via public engagement and outreach (print and broadcast media) regarding the project findings from year-long experimental monitoring and computational tool development, the research team has empowered occupants to improve their living conditions by understanding the likely timing of the ventilation vs thermal comfort challenges throughout the year. This approach encourages building occupants to optimise ventilation in their homes, while recognising the impact upon air pollutants and energy usage.

### **Economic**

It is currently estimated that the economic costs of poor indoor air quality in Europe are approximately €200 billion, and it is imperative that a drive towards increased building airtightness, motivated by energy efficiency considerations, does not elevate this. The ALIVE project provides a computational framework that identifies the key factors – both occupant and design related- in securing good indoor air quality, specifically in naturally ventilated buildings. A longitudinal monitoring study complements the modelling outputs and confirms that, in certain seasons and with certain building design typologies, it is possible to maintain adequate indoor air quality and appropriate thermal comfort in buildings without the need for mechanical ventilation.

### **Policy-Oriented**

The complex correlation between energy consumption, Indoor Environmental Quality (IEQ) and occupancy is significant for residential buildings but often overlooked in design and operation phases. The computational methodology developed in this research is based on a metamodel approach tailored for rapid prediction and optimisation of heating energy consumption (kWh), thermal discomfort (hours), and elevated CO<sub>2</sub> levels (hours) under the influence of occupancy. The framework, operating with unprecedented computational efficiency, highlights that variables such as occupancy density, metabolic rate, and window operations significantly influence heating consumption, thermal discomfort, and CO<sub>2</sub> levels. Including occupancy-related variables ensures that predicted results and optimised parameters are resilient and within WHO and CIBSE TM59 limits, while aligning heating consumption with energy-efficient standards and improving the reliability of the results; this can assist policymakers, local authorities and urban planners in modifying, updating and implementing energy recommendations.

### **Scientific**

This project provides the first longitudinal dataset in Ireland evaluating IEQ in naturally ventilated, energy efficient dwellings, and a computational framework that links IEQ to occupancy and energy usage complements this. Various aspects of the monitoring and modelling data have been presented at numerous international conferences, including the International Energy Agency, Annex 5- AIVC conferences and workshops, and the results have been published in seven peer-reviewed scientific papers, with two further papers under review. The work also provides recommendations for further research in this area, with aspects of the work being addressed by members of the project team in the SEAI-funded ENABLE and ALIGN projects. Project data are also contributing to dissemination activity within the International Energy Agencies (IEA) Energy in Buildings and Communities (EBC) Programme Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings.

## **2.5 Recommendations**

Indoor cooking has been identified as a key contributor to indoor PM<sub>2.5</sub> concentrations, necessitating a greater emphasis on source control and removal at source. While current building regulations require extraction fans, only qualitative data were collected regarding their use and it can be considered that a lack of clarity pertains to both the ventilation systems' operational performance and the occupants' willingness to use them. Therefore, a detailed investigation is necessary. This would include positioning and flow rates of fans, fan capture efficiencies across different particle size ranges, an assessment of the acoustic and vibrational aspects of the technology that might hinder adoption, and an exploration of behavioural factors influencing usage.

This research integrates experimental data with computational energy simulations and indicates a divergence between designed and real-world building performance. Consequently, the tools developed

in this project offer considerable potential to enhance future analytical approaches by explicitly accounting for the interdisciplinary nature of energy consumption, IEQ and ventilation.

The increased thermal performance of buildings has led to improved thermal comfort during winter; however, challenges arise with indoor air quality. Conversely, the summer months present a scenario in which better indoor air quality exists, but maintaining comfortable indoor temperatures becomes challenging. This underscores the inherent conflict between optimising thermal comfort and ensuring healthy indoor air quality in residential buildings throughout the year. This highlights the need for extended, multifaceted monitoring to capture trade-offs among different metrics (energy consumption, thermal comfort and IEQ). Additionally, the research findings highlight the need for future investigation into the resilience of the current building stock to future climate conditions and the need to consider implementing cooling strategies and solar shading techniques to adapt to rising global temperatures.

## **2.6 Conclusions and Next Steps**

The findings from this research project collectively underscore the complexities of designing and operating naturally ventilated energy-efficient dwellings. While these buildings offer significant energy-saving potential, they present unique challenges in maintaining optimal IAQ and thermal comfort, especially during seasonal transitions. The future of energy-efficient housing will depend on the ability to adapt ventilation and thermal comfort systems to meet the evolving needs of occupants and the changing climate.

This research calls for a holistic approach that integrates robust ventilation solutions, passive cooling strategies, and occupant education to enhance both indoor environmental quality and energy efficiency, for which the measurement and computational methodologies that were developed in this project are ideal.