# Radon Levels and Indoor Air Quality in Northern Ireland Passive House Buildings

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## Abstract

The international passive house standard is primarily a building standard that delivers high thermal comfort based on excellent building fabric and balanced mechanical heat recovery ventilation. Indoor air quality and overheating prevalence are topics that have attracted increasing research attention across Europe, however post occupancy monitoring of indoor radon concentrations particularly in the Ireland and the UK is a much less studied.

This research investigates radon levels and indoor air quality in Northern Ireland certified passive house buildings. The initial findings of this research suggest that in principle buildings built to the passive house standard correspond with lower indoor radon gas concentrations. The research also demonstrates a correlation with excellent indoor air quality in the same buildings over the monitoring period.

**Keywords** Certified Passive House, EnerPHit, Radon, IAQ Indoor Air Quality

## 1.0 Introduction

Implementation of the new legally binding Paris climate change agreement has now reinforced the need to reduce energy consumption in buildings. Currently European buildings account for 40% of the total energy consumption in the European Union (EU) [1]. The energy performance in buildings directive (EPBD) mandates all EU member states to build near zero energy buildings (NZEB) by 2021[2].

To meet the passive house standard the air tightness of a building must achieve an air change per hour rate of less than 0.6 at 50 Pascal's of pressure (n50), and have ventilation provided by a balanced mechanical heat recovery system. The international passive house standard offers a proven methodology to achieve this goal [3]. While recent studies have focused on Indoor Air Quality (IAQ) and, in particular, overheating risks in Ireland and the U.K. [4], none have investigated the relationship between the unique characteristics of certified passive house buildings and indoor radon concentrations.

The World Health Organization (WHO) has identified radon as a known human carcinogen, because of the wealth of biological and epidemiological evidence and data showing the connection between exposure to radon and lung cancer in humans

[5]. It is estimated to cause 30 deaths per year in Northern Ireland and is the second largest identified cause of lung cancer after smoking [6]. Public Health England (PHE) estimates that some 155,000 homes, or about 1 in 5 in Northern Ireland, are now in ‘affected areas’: these are places where some householders are exposed to radon at a level where protective action is recommended [7]. Radon is a naturally occurring radioactive gas that results from the decay of uranium in rocks and soils and is the major source of ionising radiation exposure to the UK population [7]. The gas is colourless, odourless and tasteless and can only be measured using special equipment. When radon surfaces in the open air, it is quickly diluted to harmless concentrations, but when it enters an enclosed space, such as a house or other buildings, it can sometimes build up to unacceptably high concentrations. Radon from the ground enters buildings chiefly through cracks in floors or gaps around pipes or cables. Radon decays to form tiny radioactive particles, some of which stay suspended in the air. When these particles are inhaled into the lungs, they give a radiation dose that may damage cells in the lung [8].

Radon is measured in Becquerel’s per cubic metre of air ($Bq/m^3$). Radon measurements are normally made with two passive integrating detectors in each home - one in the main living area and the other in a regularly used bedroom. This reflects the parts of the home that are most occupied. The detectors are left in place for three months. The government has recommended an ‘action level’ for radon in homes in the UK. This level is 200 $Bq/m^3$. Above this level it is recommended that householders take action to reduce their radon levels [6]. HPA advises that homes with smokers or ex-smokers should also seriously consider reducing radon levels where concentrations are measured above the target level because of the substantial risks associated with smoking and radon exposure combined. [7]

The objective of this study is to assess if a certified passive house building with much higher air tightness than other standards coupled with mechanical ventilation will produce reduced indoor radon gas concentrations and provide excellent indoor air quality. This paper will present the initial research findings from a Northern Ireland sample for a larger PhD study investigating if Irish and UK certified passive house buildings have lower indoor radon concentrations. The coloured areas in the map below have a 1% or greater probability of the radon level in a dwelling exceeding the Action Level these are known as radon affected areas [8].

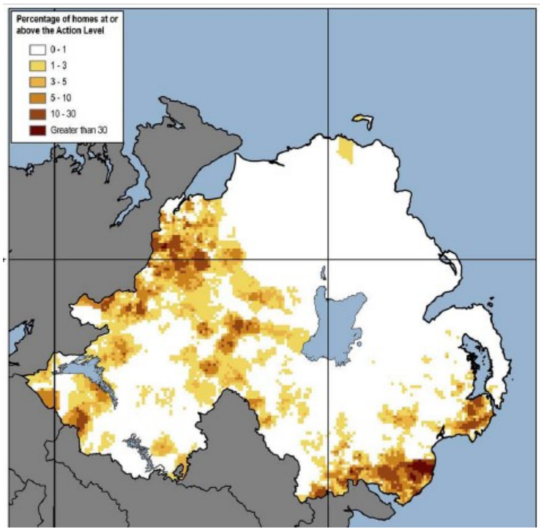



**Figure 1 – Northern Ireland map of radon affected areas.**

## 2.0 Radon Testing

The sample used in this paper is from five certified passive house buildings located in Northern Ireland. Table 1 below provides details on these buildings including the size, year of construction, construction type, the certification of passive house standard and the air tightness level (n50).

| ID | Postcode | Year | Size $M^2$ | Construction | Type | Building | N50 |
|---|---|---|---|---|---|---|---|
| 2474 | BT78 5 | 2012 | 127 $M^2$ | Timber | New Build | Detached | n50 = 0.51/h |
| 2856 | BT19 1 | 2013 | 185 $M^2$ | Timber | New Build | Detached | n50 = 0.58/h |
| 4749 | BT92 6 | 2014 | 287 $M^2$ | Masonry | EnerPHit | Detached | n50 = 0.7/h |
| 4751 | BT71 6 | 2014 | 144 $M^2$ | Timber | New Build | Detached | n50 = 0.6/h |
| 5185 | BT74 4 | 2014 | 455 $M^2$ | Timber | New Build | Campus | n50 = 0.6/h |

**Table 1 – Details of selected buildings for the initial sample**

The building characteristics and materials are of significance [8], the most common sources of radon are from the soil gas and off gassing from building materials containing radon [9].Building material emissions, are much lower than pollution from the soil gas and only applies to certain building materials such as sand, soil, cement and rock, etc. originating from different rocks and earth's crusts. Concentrations of radon present in these building materials will vary depending upon the geological origin [10]. Timber frame construction is the dominant form of construction in this sample. It is also worth noting that building ID: 2474 is equipped with a ground air heat exchange system. There could be a concern for increased radon levels if there were leaks or direct air intake from the soil in this system.

Studies have shown that energy retrofitting of homes may reduce ventilation in the home, thereby, increasing radon levels, particularly where a number of retrofitting measures are installed at the same time [11]. It also has to be noted that when retrofitting to the passive house standard (EnerPHit) such as existing house ID: 4749 where perhaps the existing floor does not include radon protection it may prove difficult to seal properly across the full footprint of the building. Therefore, it is difficult to predict the effect of applying passive house techniques to existing buildings as on one hand failing to completely seal the building envelope could increase the radon level and on the other hand a properly installed and operating mechanical heat recovery ventilation system could reduce the radon level [12].

Building ID: 5185 is non-residential so in this case the two most occupied rooms were chosen for testing. In accordance with Public Health England guidelines if a radon level in any part of a workplace exceeds 300 $Bq/m^3$ as an annual average, the employer is then obliged to take radon mitigation action to ensure staff safety. Just over 24,000 radon measurements were conducted in homes in Northern Ireland in the period between 1983 and 2015 [13]. Table 2 presents the arithmetic and geometric average of the measured radon levels in each postcode area corresponding to passive house building are located in Northern Ireland [14].

| ID | Postcode | Homes | Homes Tested | Arithmetic Average | Geometric Average | Highest Result |
|---|---|---|---|---|---|---|
| 2474 | BT78 5 | 3,200 | 93 | 50 **Bq m$^{-3}$** | 40 **Bq m$^{-3}$** | 190 **Bq m$^{-3}$** |
| 2856 | BT19 1 | 6,400 | 6 | 32 **Bq m$^{-3}$** | 20 **Bq m$^{-3}$** | 93 **Bq m$^{-3}$** |
| 4749 | BT92 6 | 530 | 63 | 65 **Bq m$^{-3}$** | 37 **Bq m$^{-3}$** | 540 **Bq m$^{-3}$** |
| 4751 | BT71 6 | 4,900 | 56 | 38 **Bq m$^{-3}$** | 29 **Bq m$^{-3}$** | 180 **Bq m$^{-3}$** |
| 5185 | BT74 4 | 1,600 | 17 | 47 **Bq m$^{-3}$** | 37 **Bq m$^{-3}$** | 110 **Bq m$^{-3}$** |

**Table 2 – Reference levels from Radon in Dwellings in Northern Ireland 2009**

The indoor radon levels were measured by CR-39[3] alpha track diffusion radon gas detectors placed in the main living area (Room 1) and the main bedroom (Room 2) for just over 3 months from October 2017 to January 2018. The numerical radon results are presented as: arithmetic average and geometric average. The test results will also be compared with the existing data on radon in Northern Ireland. In 2010 the Health Protection Agency (HPA) updated its advice on the limitation of human exposure to radon, maintaining the national action level at 200 Bq/m$^3$ and introducing the concept of a target level at 100 Bq/m$^3$ [12].

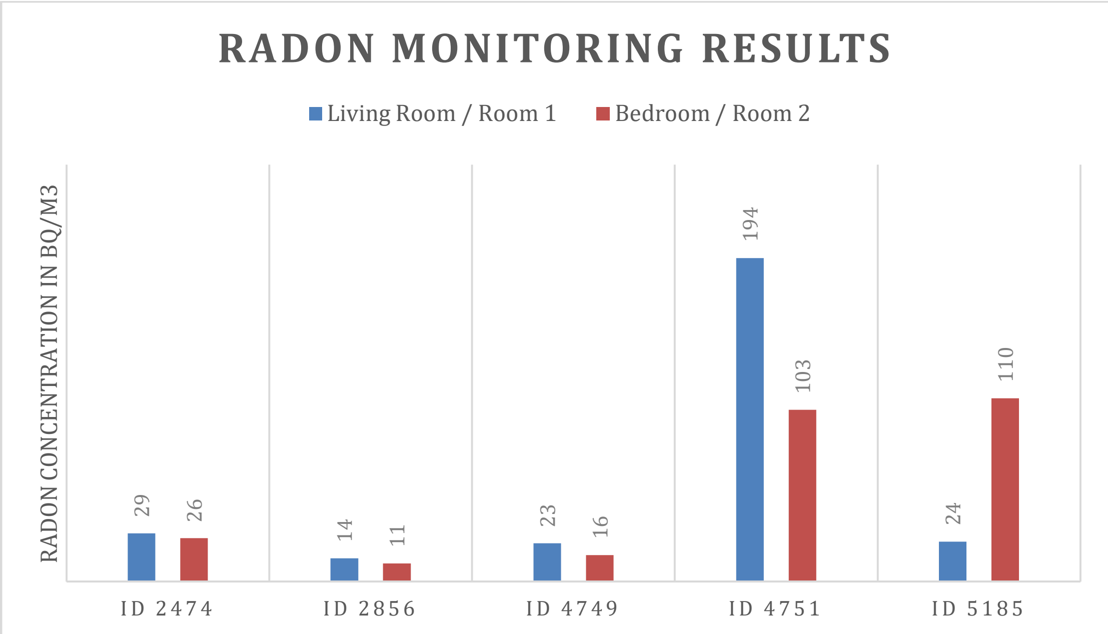



**Figure 2 – Radon Monitoring Results**

Figure 2 shows the initial results for radon concentration in certified passive house buildings. Figure 2 displays the results of radon detectors located in both the living room (room 1) and the main bedroom (room 2). In building ID: 5185 which is a commercial building the rooms selected were the two most frequently occupied and are labelled Room 1 and Room 2.

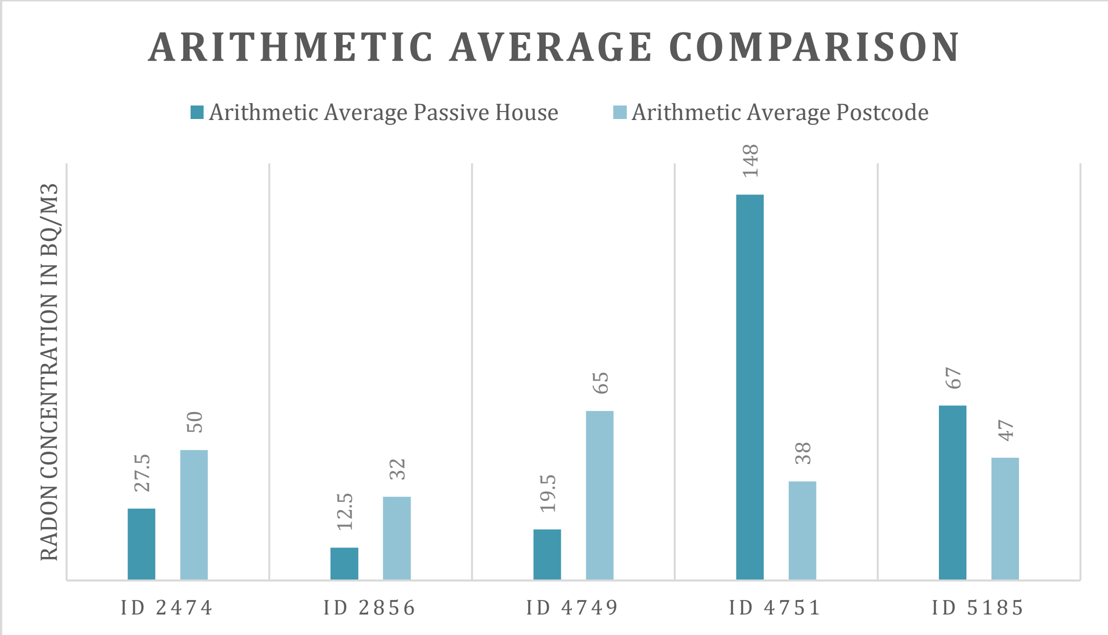



**Figure 3 – Radon Monitoring Results Arithmetic Average Comparison**

Figure 3 shows the arithmetic average comparison of passive house monitoring results and the most recent figures in Northern Ireland by corresponding postcode reference level from Public Health England. We can see that all results indicate levels below the action level (AL) of 200 Bq/m$^3$. ID: 4751 however is above the target level (TL) of 100 Bq/m$^3$.

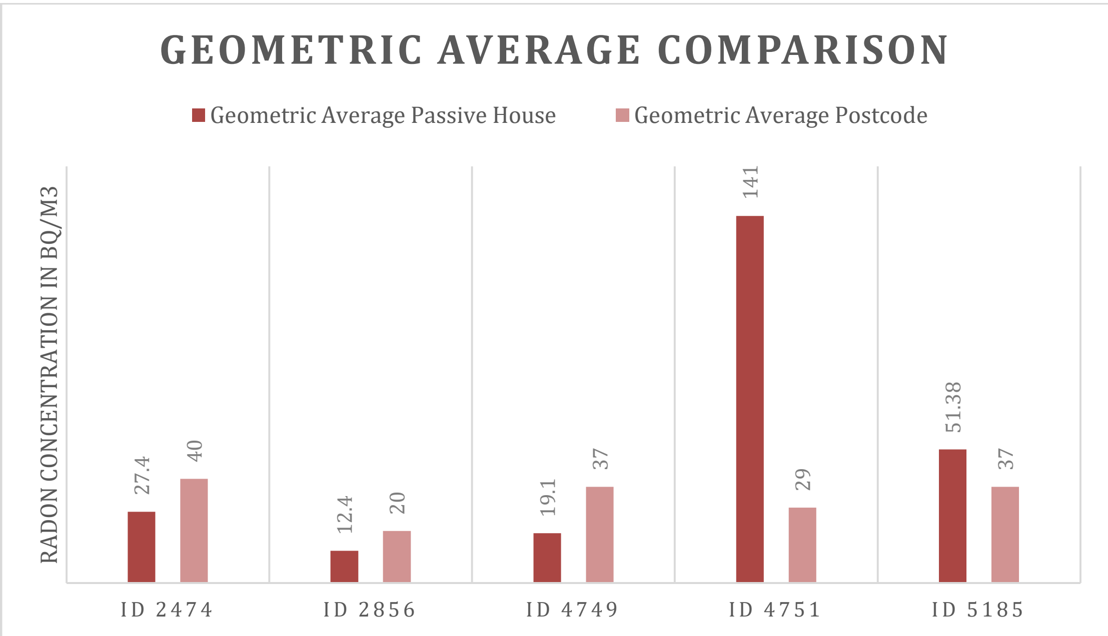



**Figure 4 – Radon Monitoring Results Geometric Average Comparison**

Figure 4 shows the geometric average comparison of the house monitoring results of passive house buildings when compared to the corresponding postcode reference level. We can see again that all results indicate levels below the action level (AL) of 200 Bq/m$^3$. ID: 4751 again however is above the target level (TL) of 100 Bq/m$^3$.

The building ID: 4751 is a two story domestic dwelling located it an area with a maximum radon potential is 3-5 %. The monitoring result in both rooms is higher than the radon level for the corresponding postcode.

The building ID: 5185 is a large single storey educational facility, despite being built to the passive house standard within the same parameters as the other buildings in the sample. The monitoring result is higher than the radon level for the corresponding postcode. We can see from Figure 1 that room 1 in this building produced a low reading consistent with the rest of the sample and that room 2 produced a reading that was much higher. Indeed the result for room 2 was above the target level (TL) of 100 Bq/m$^3$ recommended by Public Health England. There are various potential reasons as to why this may have occurred such as mechanical ventilation problems [15]. The cause of this elevated value will be investigated further with the building inhabitants.

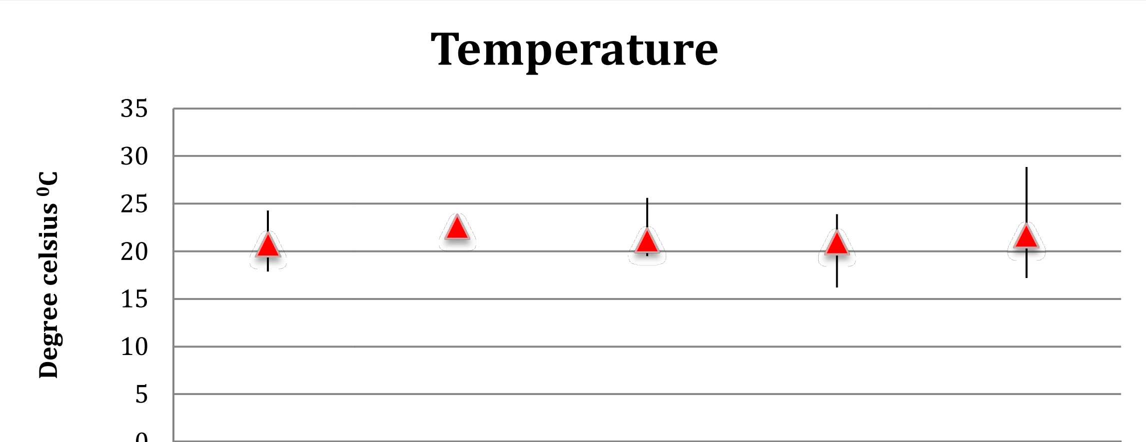
The other results however do provide consistently low readings of indoor radon concentrations from the monitoring period. It is acknowledged however that this sample is particularly small and that the initial findings need to be handled with caution. A much bigger sample will provide conclusive evidence if results follow this pattern. This however does add weight to the similar existing pilot studies carried out Austria and Belgium [12, 15].

## 3.0 Indoor Air Quality Monitoring

Temperature, relative humidity and carbon dioxide were monitored over the same three month period during the radon testing. Data was collected at five-minute intervals from outdoor and indoor monitoring units in the five certified passive house buildings in the sample. Initial findings are reported below:

A. Indoor air temperature
B. Indoor relative humidity
C. Indoor carbon dioxide concentrations

### *3.1 Indoor Air Temperature*



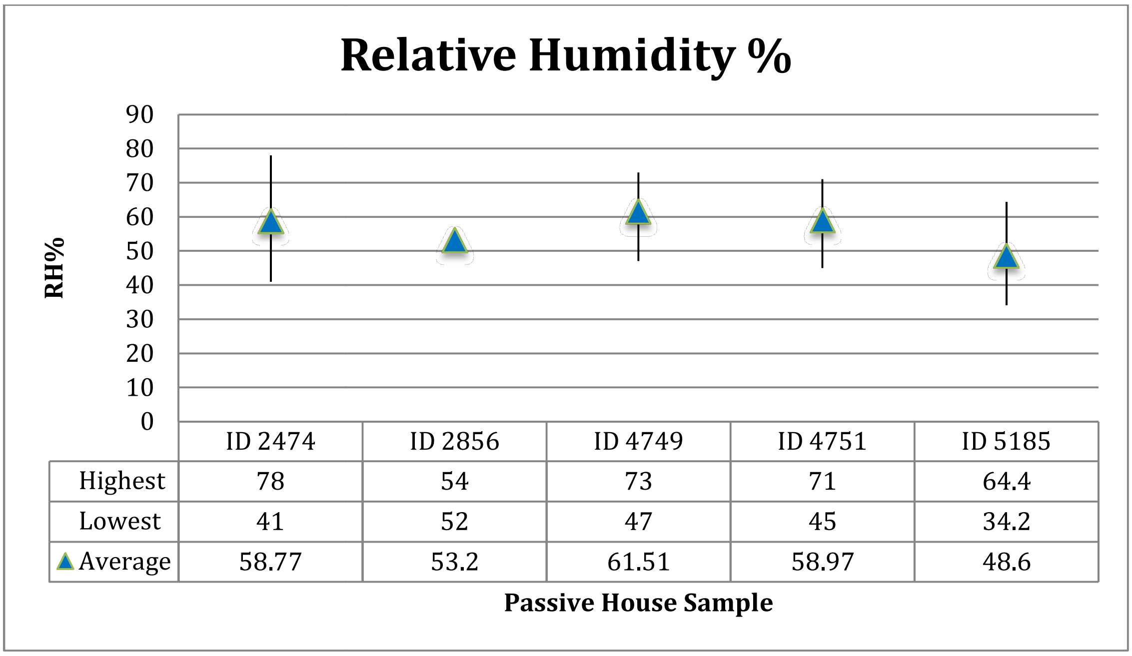

| | ID 2474 | ID 2856 | ID 4749 | ID 4751 | ID 5185 |
|---|---|---|---|---|---|
| Highest | 24.3 | 23.6 | 25.6 | 23.9 | 28.82 |
| Lowest | 17.9 | 21.8 | 19.5 | 16.2 | 17.2 |
| ▲ Average | 20.73 | 22.58 | 21.18 | 20.96 | 21.69 |

**Figure 5 – Temperature monitoring data**

The results of monitoring over three months from October 2017 to January 2018 produced the data presented in Figure 5 demonstrating that all five buildings are on average at a very comfortable temperature of 20.73°C to 22.58°C. The highest and lowest figures recorded in the data were 28.82°C and 16.2°C.

The design temperature in a certified passive house is 20°C [16]. Thermal comfort is achieved when the (average) temperature of the coldest surface in the room is no greater than 4.2 degrees below the room temperature. Uncomfortable cold air descent and radiant heat deprivation can occur in case of a larger temperature difference. The Passive House standard requires that a temperature in excess of 25°C cannot occur for more than 10% of the year. When compared to this standard, on average the dwellings are not showing an overheating risk.

### *3.2 Indoor relative humidity*




| | ID 2474 | ID 2856 | ID 4749 | ID 4751 | ID 5185 |
|---|---|---|---|---|---|
| Highest | 78 | 54 | 73 | 71 | 64.4 |
| Lowest | 41 | 52 | 47 | 45 | 34.2 |
| ▲ Average | 58.77 | 53.2 | 61.51 | 58.97 | 48.6 |

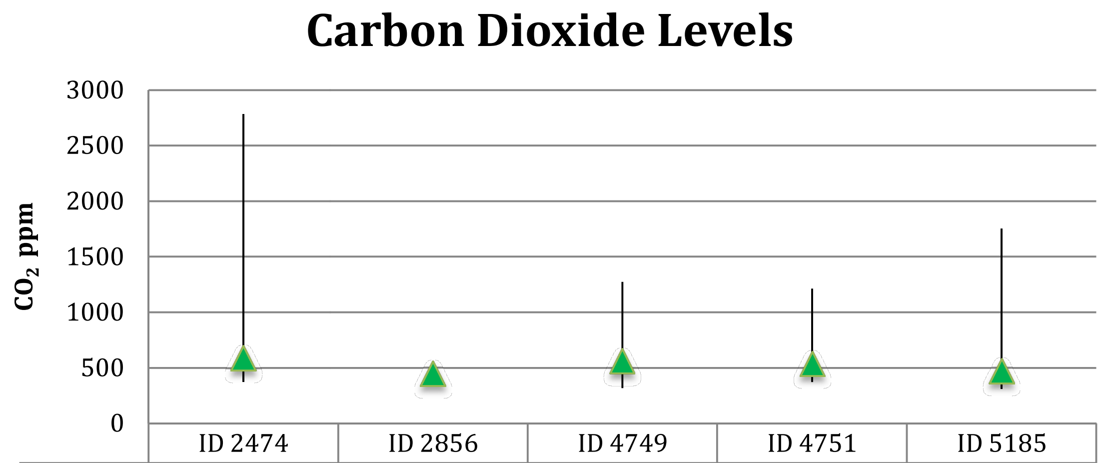
**Figure 6 – Relative Humidity (RH %) monitoring data**

Comfortable levels of relative humidity can be within a wide range depending on the temperature, typically from 40% to 70%, but ideally between 50% and 60%.[17] Very low humidity can create discomfort, respiratory problems, and aggravate allergies for some individuals. In the winter, it is considered advisable to maintain relative humidity at 30% or above.

Relative humidity varies considerably depending on climate and location, Ireland's temperate maritime climate contributes to high relative humidity compared with other countries [16]. The level of RH% achieved is a function of moisture generation with the home but also is dependent on the outside air temperature and humidity. The colder it is outside the lower the internal (RH%) can be. Outside the heating period the (RH%) inside can exceed 80% because of minimal temperature difference between inside and outside [17].

The monitoring data in Figure 6 indicates that all buildings are performing well in relation to indoor relative humidity levels. The average range 48.6% - 61.51% and the highest and lowest figures recorded were 78% and 41%. These figures are well within the acceptable 30% to 80% RH range.

### 3.3 Indoor carbon dioxide concentrations




| | ID 2474 | ID 2856 | ID 4749 | ID 4751 | ID 5185 |
|---|---|---|---|---|---|
| Highest | 2787 | 500 | 1274 | 1214 | 1752 |
| Lowest | 376 | 413 | 318 | 372 | 308 |
| ▲ Average | 586.83 | 446.06 | 558.21 | 534.26 | 469.17 |

**Figure 7 – Carbon Dioxide (Co2) monitoring data**

Indoor air degrades due to the accumulation of gas compounds, dust and mites, moulds and bacteria. The concentration of $CO_2$ produced by human activity indoors is a good indicator of the confinement of the indoor air and of this accumulation. Normal and excessive $CO_2$ levels can be characterised as follows:

- Normal outdoor level: *350 - 450 ppm*
- Acceptable levels: < *600 ppm*
- Complaints of stiffness and odours: *600 - 1000 ppm*
- ASHRAE and OSHA standards: *1000 ppm*
- General drowsiness: *1000 - 2500 ppm*
- Adverse health effects may be expected: *2500 - 5000 ppm*
- Maximum allowed concentration within an 8 hour working period: *5000 - 10000 ppm[17]*

Taking into account the general classification of air quality in relation to $CO_2$ levels, the air quality can be classified as good, a good functioning balanced ventilation system should guarantee a sufficient air exchange rate and avoid the accumulation of indoor air pollutants including radon. A number of recent studies highlight the issue of the importance of balanced mechanical heat recovery system being designed commissioned and maintained properly [18, 19, 20]. The studies have also observed elevated $CO_2$ levels, especially in the bedrooms [18, 20].

In Figure 7 $CO_2$ data is presented from the monitoring period which produced a range from 446ppm to 586ppm. The highest figure recorded was 2787ppm and the lowest was 308ppm. The figure of 308ppm is lower than the ambient carbon dioxide, and reflects a reading which occurred during the device calibration.

## 4.0 Conclusions

In conclusion this paper presents the initial findings of a larger research project. The main results are consistent with the hypothesis that certified passive house buildings perform better in respect of indoor radon concentrations compared to postcode averages. In Figure 8 both the arithmetic and geometric averages from the study are compared against the overall averages for Northern Ireland. This clearly shows lower indoor radon concentrations in the passive house sample. As the number of houses investigated in this research was very small, the results should be treated with caution, however they correlate with results in similar pilot studies [9, 12, 15].

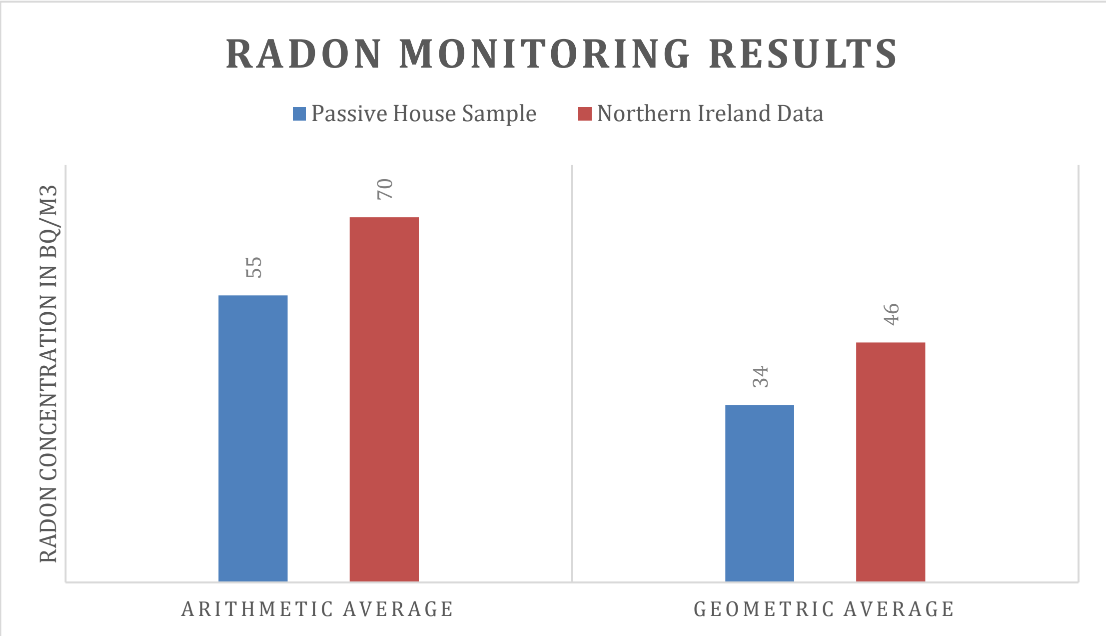



**Figure 8 – Northern Ireland Arithmetic and Geometric average comparison**

The study also provides some indications for what should be investigated in a more detailed way. Previous research outlines that off gassing from certain building materials could be a contributory factor to elevated indoor radon concentrations, therefore consideration to the construction types such as timber construction and masonry construction comparisons along with new build and retrofit comparisons is required.,. As the study progresses the corresponding amount of data will increase which will improve the s statistical validity of the results.

ID: 2474 is equipped with a ground source intake for the mechanical heat recovery ventilation system has demonstrated no negative effect on indoor radon concentrations. This would suggest that this system was installed correctly and this could be taken as an indication of quality assurance.

ID: 4749 is a building retrofitted to the passive house standard called EnerPHit, shows no indication of elevated radon levels for a retrofitted building. It is also the only building in the sample which is constructed from masonry construction which would suggest that the off gassing effect could be more prevalent, nevertheless no elevated indoor radon concentrations.

ID 4751 and ID 5185 which produced individual indoor radon concentration results above the target level of 100 Bq/m$^3$, requires further analysis into the ventilation system and its current operation. The correlation between radon, and the corresponding N50 level in these passive house buildings was also evaluated. No significant correlation was found. These sub sections will be explored in detail in the larger study.

Despite the small sample size of five passive houses, some clear trends are emerging in relation to the indoor air quality metrics of temperature, relative humidity and carbon dioxide experienced in the dwellings. Taking into account the general classification of air quality in relation to $CO_2$ levels the average air quality readings recorded qualified as good. This was as expected as a good functioning balanced ventilation system should guarantee a sufficient air exchange rate and avoid the accumulation of indoor air pollutants. Proper maintenance of the ventilation systems is also a critical point.

It is acknowledged that the 2787ppm figure recorded in ID: 2474 is significantly high however this was elevated for only a short period of time and was directly linked to occupancy. Regarding temperature, the average figures recording during the three month monitoring period maintain excellent thermal temperatures within a 20.7°C to 22.5°C although ID: 5185 had a peak recording 28°C above the threshold the figures are well within the limit of 26°C for 10% of the year specified by the Passive House Institute.

Finally in relation to relative humidity all the buildings display excellent readings consistent with good indoor air quality. Based on the results of this monitoring period the conclusion is that the Passive House standard achieves its stated objective providing occupant comfort and indoor air quality.

The work carried out over the three month period of this pilot study has proven to be valuable in assessing the performance of certified passive houses in Northern Ireland. Future work will produce a local comparative study of the certified Passive House standard buildings and buildings built to the prevailing building regulations in the UK and Ireland with respect to radon, and the differences quantified.
Building characteristics such as construction type, airtightness levels and also the retrofitted home will be tracked to ascertain any statistical correlation between these factors, radon levels and indoor air quality.

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