PLEA 2024 WROCŁAW
(Re)thinking Resilience

Balancing Energy-Efficiency and Health in Retrofitted Dwellings to the EnerPHit Standard

Achieving Optimal Indoor Environmental Quality

ALEJANDRO MORENO-RANGEL[1], TIM SHARPE[1]

[1]University of Strathclyde, Glasgow, UK

ABSTRACT: It is widely known that the UK has the least energy-efficient building stock in Europe, which contributes to over 30% of total greenhouse gas emissions. To improve the energy performance of both new and existing buildings, the UK is implementing policies to improve performance. One of the retrofit solutions, EnerPHit, has been applied in a tradiational stone tenement building in Glasgow as a test of this approach.

The findings to date indicated that the project has been effective in providing comfortable, healthy dwellings with low energy usage and high levels of occupant satisfaction. but some individual dwellings are exceeding targeted consumption levels. Despite this, the dwellings maintain good indoor temperatures, generally within the EnerPHit performance targets, without sacrificing thermal comfort. The indoor air quality and ventilation targets were met with CO2 levels below 1,000ppm throughout the monitoring period, and there was no evidence to suggest that the MVHR systems were switched off or malfunctioning. Currently, there are no apparent concerns regarding interstitial moisture in the construction.

There are valuable lessons to be learned from this retrofit program, particularly the significance of occupant behaviour, expectations, and their engagement with building systems, but the project has also highlighted the need for construction skills to enable delivery and proper maintenance and operation of new building systems.

KEYWORDS: Energy, Comfort, EnerPHit, net zero retrofit, indoor environment.

1. INTRODUCTION

In order to tackle Climate Change, new net zero targets have been implemented by several countries. When considering the complete life of a building, the built environment is responsible for over 50% of the carbon emissions [1]. Many countries have started looking at the Passivhaus Standard to meet these commitments [2], for instance, Scotland.

The UK has Europe's worst energy-efficient building stock, contributing over 30% of total greenhouse gas emissions [3]. In a determined push towards net zero, the UK government introduced the Future Homes Standard in England, while Scotland established the Domestic Building Environmental Standards (2025) Bill, akin to the renowned Passivhaus standard. These policies represent significant milestones, but at present, a substantial number of existing buildings still heavily rely on natural gas for heating, hot water, and cooking. Thus, retrofitting existing buildings emerges as the foremost challenge. While evidence of the performance of new builds to the Passivhaus in Scotland is available [4], little is available about retrofits.

Approaches to retrofit pose different challenges; without holistic measures to ensure that both energy and environmental measures are improved, unintended consequences may occur.

While the Passivhaus principles are still applicable for EnerPHit [5], there are some key differences in terms of heating and cooling demand, 25kWh/m2/year instead of the 15kWh/m2/year for Passivhaus Classic, as well as the airtightness level (n50) of 1.0 h-1 @ 50 Pa compared to the 0.6 h-1 @ 50 Pa for new builds. These considerations recognise the changes associated with working with existing buildings. Beyond the operational carbon emissions, EnerPHit buildings have other benefits, such as adequate ventilation and indoor air quality (IAQ), improved thermal comfort and a low risk of internal condensation [6]. However, challenges related to limitations associated with the refurbishment of existing buildings still exist [7]. Some of these challenges are related to the building occupants' behaviours; others may be related to the refurbishment process and skills in the construction sector. While the key driver for retrofitting is the reduction of carbon emissions, we should also consider other aspects of the indoor environment that can impact occupants' health and energy use. Hence, the risk of overheating, mould and condensation, should be considered alongside IAQ and ventilation, particularly in Passivhaus dwellings [8].

This work presents the energy monitoring and indoor environmental conditions (thermal comfort and indoor air quality) of one of the largest deep energy residential retrofits to the EnerPHit Standard in a historic tenement building in Scotland.

2. METHOD

The building's energy retrofit design and construction happened between 2020 and 2022, with the first occupants moving in November 2022. This paper presents the indoor environmental (temperature, relative humidity and carbon dioxide) analysis between the 9th of February and the 26th of June 2023 of 6 of the 8 one-bedroom flats. Energy reading were taken directly from the electricity and gas meters during the installation of the sensors and a further visit was scheduled in August 2023 to collect the second readings. The retrofitted building is a traditional pre-1919 4-storey red sandstone tenement consisting of eight one-bedroom social housing flats and a communal close and backcourt (see Figure 1).

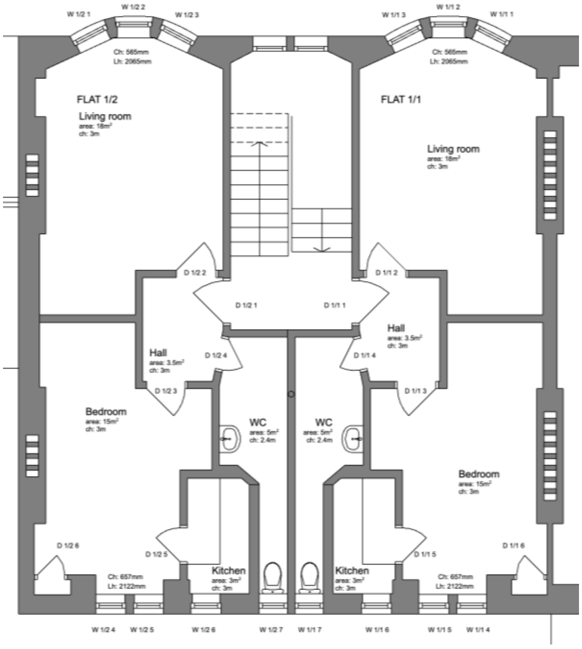

Figure 1: Floor plan of the building. Source: John Gilberts Architects.

The data was collected using a commercial monitoring kit (Gateway - AICO Ei1000G SmartLINK, sensors - AICO Ei1025 SmartLINK). The sensors were installed in each of the flats' living room, kitchen and bedroom. Data were collected at 15-minute intervals for each of the parameters [Temp -10 to 40; Relative humidity 15-95%RH; Carbon dioxide 0-5000ppm]. Energy consumption was collected through manual meter readings.

Stone tenements have a unique structure and appearance that makes installing external wall insulation (EWI) on stone facades difficult. Although in this case EWI could be placed on the brick elevations on the sides and rear, improving U-values on the stone facade requires internal insulation. However, adding internal insulation may make the stonework colder and wetter, which can pose a risk to timber elements such as floor joists that protrude into the stonework. To investigate this interstitial moisture sensors were installed in beams during construction to assess this risk. These sensors use an OmniSense G-4-NBIOT-EU Gateway with 4G Cellular Data, which wirelessly connects with temperature and moisture sensors embedded in the construction. The wireless-powered gateway is located in the loft space, and the sensors for interstitial condensation were placed during construction at the bottom front side and top back of the building.

Individual air source heat pumps (ASHP) are used to heat four of the flats (ground and first floor flats), extracting heat from the external air to provide hot water for radiators and domestic use. Modern and efficient combi gas boilers heat the remaining four upper flats. Each of the eight flats is equipped with a mechanical ventilation heat recovery unit (MVHR) located above the bathroom ceiling. These units remove moist and stale air from the kitchens and bathrooms while simultaneously bringing in fresh air from the outside. By utilising a heat exchanger, the MVHR system transfers heat from the stale air to the fresh air, minimising heat loss and reducing the overall heating demand. The six upper flats also have wastewater heat recovery units installed in the bath/shower systems. This allows the captured heat from the wastewater to be recirculated back into the hot water system, effectively reducing the demand for water heating.

3. RESULTS

3.1 Energy use

To date energy use has been collected through meter readings. During the periods – February 2023 to August 2023. The readings collected were used to determine the annual electricity demand of each flat and the building as a whole. The annual estimation was based on a simple extrapolation between the days when meter readings were taken, the estimation of the space heating demand for the electric heating flats (second and third floors) was also extrapolated based on the heating demand for those using gas.

The average electricity demand for the six flats was 23.94 kWh/m^2. However, there was a variation in this figure when comparing the flats that used electricity as a source of heating via the heat pump versus those that used gas. For the flats that used electric heating, their electricity consumption between February and August 2023 was 29.62 kWh/m^2, while for those that used gas for space and water heating, it was 18.26 kWh/m^2. Additionally, for the flats using gas heating, the average consumption during this period was 33.20 kWh/m^2.

the average estimated annual electricity demand for all the flats is 39.81 kWh/m^2year, which is lower than the average home in Scotland, estimated at 43.4

kWh/m²year by Ofgem. By comparing the electricity consumed by the gas and heat pump flats, we can estimate the energy required for space and water heating for flats that use electricity as a source of heating via the heat pump. This indicates an estimated annual demand of 19.89 kWh/m²year for heat pump flats. Assuming a figure of 15 kWh/m²year for water heating, this would indicate a space heating demand of 4.89 kWh/m²year, which is below the EnerPHit target of 25 kWh/m²year.

However, the annual space and water heating consumption for flats with gas heating is estimated to be 51.91 kWh/m²year. Taking into account an assumed 15 kWh/m²year for water heating gives a space heating load of 36.91 kWh/m²year, which is higher than the EnerPHit target of 25 kWh/m²/year. Based on these numbers, the estimated average annual heating demand for the building is 20.90 kWh/m²year.

The readings collected were used to determine the annual electricity demand of each flat and the building as a whole. The estimation was based on a simple extrapolation from days when meter readings were taken. The average estimated annual electricity demand for all the flats is 39.81 kWh/m²year, which is lower than the average home in Scotland, estimated at 43.4 kWh/m²year by Ofgem. By comparing the electricity consumed by the gas and heat pump flats, we can estimate the energy required for space and water heating for flats that use electricity as a source of heating via the heat pump. This indicates an estimated annual demand of 19.89 kWh/m²year for heat pump flats. Assuming a figure of 15 kWh/m²year for water heating, this would indicate a space heating demand of 4.89 kWh/m²year, which is below the EnerPHit target of 25 kWh/m²year.

However, the annual space and water heating consumption for flats with gas heating is estimated to be 51.91 kWh/m²year. Taking into account an assumed 15 kWh/m²year for water heating gives a space heating load of 36.91 kWh/m²year, which is higher than the EnerPHit target of 25 kWh/m²/year. Based on these numbers, the estimated average annual heating demand for the building is 20.90 kWh/m²year (Figure 2).

Based on the annual estimations, the flats that use electricity as a source of heating via the heat pump would meet the EnerPHit target. However, these figures do not include any measurement of the effectiveness of the WWHR system, so caution is required. If effective, it may reduce hot water energy consumption, which would then impact the space heating loads. Based on the data to date, this would appear to be less impactful on the heat pump flats.

The EnerPHit standard for space heating in cold temperate climates, like the UK, is to be below 25 kWh/m²year, and the total annual energy demand should not exceed 60 kWh/m²year. The former standard is being met, but the latter is at an aggregate figure of 65.77 kWh/m²year. However, this number appears to be inflated by gas consumption and higher electrical use in one of the heat pump flats. There are several possible explanations for these variances, including incomplete data, patterns of use and consumption, the ability of a gas system to oversupply, and a relatively cool spring that increased demand. Clearly, some flats are using significantly more energy than others, and further investigation is necessary to understand this. Several potential issues are raised later in the report, such as a lack of information about system usage, extended occupancy periods, varying expectations for thermal comfort, and control issues. Additionally, the two missing flats may affect averages once their figures are known. All these figures are estimated, and once complete data is available, there is a need for further verification. However, based on the evidence so far, the flats appear to be on target to meet the EnerPHit standards, suggesting a successful retrofit.

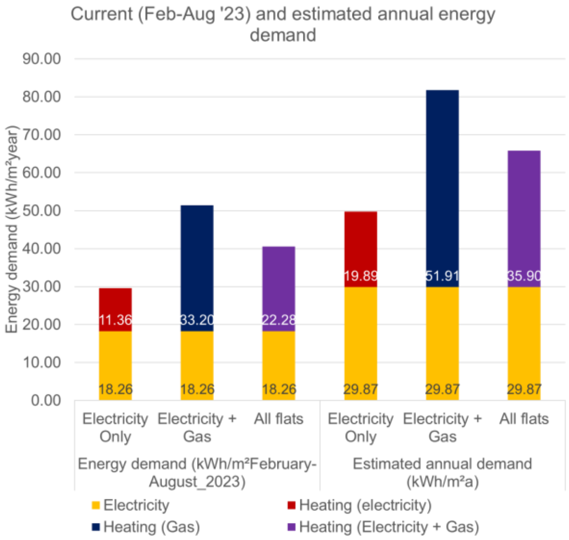

Figure 2: Mean annual energy demand for different flats (estimated from consumption between 28/January to 23 of August 2023). Source Authors.

3.2 Indoor temperatures

During the monitoring period, the indoor temperature in all flats remained within the acceptable range according to the EnerPHit standard, which is between 20°C to 25°C. However, the H2 flat had indoor temperatures above 25°C for more than 10% of the time. The rest of the flats had an acceptable level of overheating according to the Passivhaus standard, which allows for temperatures above 25°C for 10% of the time. The overheating temperatures, as defined by the Passivhaus standard, were mostly observed during the heat waves in June. The temperature ranges are shown in Table 1.

The upper flats had lower indoor temperatures compared to the lower flats – a potential explanation could be the type of heating. However, during the 2022 heating season, the H2 flat experienced some temperature problems. Despite this, the occupant reported that the flat was easy to heat to a desired temperature and were comfortable with the warm temperatures.

Typical daily average indoor temperature levels in the different rooms of the flats were [daily average mean (daily average min - daily average max)]:

- Bedroom: 21.8°C (18.0 – 26.4°C)
- Kitchen: 21.8°C (15.2 – 30.8°C)
- Living room: 20.7°C (17.0 – 25.9°C)

Table 1: Temperature ranges in the different households between 27/01/2023 and 26/06/2023. Source: Authors.

Home		<20°C (%)	20°C-25°C (%)	>25°C (%)
	Bedroom	1%	96%	3%
H1	Kitchen	Data lost		
	Living	51%	48%	1%
	Bedroom	4%	67%	30%
H2	Kitchen	3%	53%	44%
	Living	2%	61%	37%
	Bedroom	0%	90%	10%
H3	Kitchen	5%	89%	6%
	Living	21%	74%	5%
	Bedroom	34%	66%	0%
H4	Kitchen	38%	62%	1%
	Living	38%	62%	1%
	Bedroom	22%	70%	9%
H5	Kitchen	13%	85%	2%
	Living	59%	38%	3%
	Bedroom	20%	78%	2%
H6	Kitchen	33%	60%	8%
	Living	62%	35%	3%

3.3 Relative humidity

The indoor relative humidity levels in the building were mostly within the recommended range of 40%RH to 60%RH, which was confirmed by occupant satisfaction surveys. This indicates that the occupants were generally satisfied with the levels, and there were low levels of mould problems. However, it is worth noting that there were frequent occurrences of levels below 40%RH, particularly in March and April, with the H2 flat having significantly higher occurrences of humidity levels below 40%RH, driven by the higher temperatures. Extended periods of time with humidity levels below 40%RH can cause dry skin, itchy skin, and dry eyes. Despite this, the H2 occupants reported feeling comfortable as they were used to these levels.

The indoor relative humidity levels were lower in the lower flats compared to the upper flats. This could potentially be explained by the fact that temperature levels could mask the real humidity levels, as warmer air can hold a higher moisture level. Warmer temperatures were more frequent on the lower floors.

Typical daily average indoor relative humidity levels in the different rooms of the flats were [daily average mean (daily average min - daily average max)]:

- Bedroom: 43.61%RH (29.4 – 62.5%RH)
- Kitchen: 44.4%RH (25.4 – 50.8%RH)
- Living room: 46.5%RH (33.1 – 61.4%RH)

3.3 Carbon dioxide

Carbon dioxide (CO_2) is a commonly used indicator of ventilation in environmental monitoring. CO_2 levels are an effective indicator of occupancy and/or ventilation levels . Generally, keeping CO_2 levels below 1000 ppm is considered a good measure of ventilation, as it is broadly equivalent to a ventilation rate of 10 l/s/person. It is worth noting that there are significant associations between ventilation and health, and some energy efficiency measures in retrofitting may potentially reduce ventilation levels.

However, it should be noted that the flats in question are relatively small and have low occupancy rates, so it is unlikely that CO_2 levels would be excessive under normal conditions. The flats are equipped with a Mechanical Ventilation with Heat Recovery (MVHR) system, which mechanically extracts air from kitchens and bathrooms and supplies air with recovered heat into the occupied space. Therefore, if CO_2 levels are elevated, it may indicate that the system is disabled or not functioning properly.

The monitoring carried out showed that indoor carbon dioxide levels remained below 1,000 ppm most of the time. This indicates good ventilation and indoor air quality levels, which was corroborated by the occupant satisfaction surveys.

Typical daily indoor carbon dioxide levels in the different rooms of the flats were [daily average mean (daily average min - daily average max)]:

- Bedroom: 527 ppm (418 - 1,013 ppm)
- Kitchen: 515 ppm (356 - 899 ppm)
- Living room: 506 ppm (419 - 992 ppm)

3.4 Interstitial condensation

Moisture issues can arise when interstitial condensation occurs within an enclosed wall, roof or floor cavity structure. This type of condensation happens when moisture-laden air vapour permeates through a building's fabric elements, encountering temperature variations along the way, and condenses within the building rather than on the surface. Wood moisture equivalent (WME) is a measurement of the (theoretical) percentage of moisture content that would be attained by a piece of wood in contact with, or in close proximity to, a moisture equilibrium across a host of materials. We can use the %WME to determine how fast a wall is drying and the risk for the occurrence of rot and fungus. Based on the WME levels, the wall was drying up between February and mid-March and then stayed relatively stable until June, when it started to get some moisture. However, the levels remain below recommended for dry rot, cellar fungus, white pore or mini fungus (>25 %WME). The recommended WME levels are below 15%WME. Measured WME levels are constantly below 15%WME – the recommended levels to avoid any risk of rot, although common furniture beetle may proliferate above 12%WME. There was a high variability on one of the internal sensors, however it is likely that the variability here is due to proximity to central heating pipes.

4. DISCUSSION

It should be noted that these are early findings, without complete data, and with a number of estimations. While this energy and indoor environment monitoring demonstrate a good performance of the building, there were some issues with the operation and maintenance of the building which indicate that there are still lessons to be learned in retrofitting buildings.

One of the main issues with the flats was related to the heat pumps. During winter, one of the occupants was left without heating for about 1.5 weeks due to a broken heat pump. The engineers had to visit three times to diagnose the problem, and then once more to fix it. They searched for the problem next to the system or inside the building, but the outdoor pipes were frozen, causing further issues. This occurred on some of the coldest days in December, leaving the occupants very disappointed. It suggests that there may be a skills gap related to the proper maintenance and operation of heat pumps, which must be addressed as the uptake in the region develops. Unfortunately, there is no monitored data during this period to identify the effect on internal temperatures.

Another issue was occupant behaviour. For example, some occupants did not turn off heating, possibly due to higher comfort expectations and low energy prices. One instance of this was when the heating was left on for a couple of days during winter, causing discomfort to the surrounding flats as it was too hot. Although this may be expected in such cases, and in other buildings, this ‘free’ heat may be beneficial, the external fabric is designed to keep the heat inside but there is little thermal barrier between adjacent flats. The occupants suggested that there should be a safety feature to prevent such mishaps in the future. The only solution they had was to reach the housing association to mediate.

5. CONCLUSION

This paper presents the energy and indoor environmental quality of a deep energy retrofit to the EnerPHit standard carried in a sandstone tenement in Glasgow. The following are the key lessons learned from the monitoring of this building:

Energy Consumption and targets. From an energy perspective, the dwellings appear to be performing well above the targeted levels of consumption, with an estimated annual consumption for space of 33.20 kWh/m² year for the gas flats and 11.36 kWh/m² year for the heat pump flats. The estimated annual consumption for the whole block is 35.90 kWh/m² year.

Good thermal environmental performance. During the monitored period, the low energy consumption did not seem to compromise the thermal comfort of the dwelling. The average indoor temperatures were within the Enerphit performance targets. Additionally, the house did not seem to be negatively affected by a period of hot weather during early summer. However, one dwelling was an exception, but it was confirmed that the occupant had a preference for a different level of comfort.

Good IAQ/Ventilation. The dwellings remained below 1,000 ppm CO_2 throughout the monitoring period, and there was no evidence of the MVHR systems being switched off or failing.

Interstitial condensation risks in timber. There are no obvious concerns regarding the presence of interstitial moisture at this stage. However, ongoing monitoring is necessary due to changing conditions and potential adverse weather.

Overall performance. From a technical perspective, based on the data available to date, the retrofit appeared to be very successful in providing very low energy, comfortable, healthy dwellings with high degrees of occupant satisfaction.

ACKNOWLEDGEMENTS

The authors would like to thank the building occupants, John Gilbert Architects and Southside Housing Association for their support in this project.

REFERENCES

[1] IPCC, Chapter 9: Buildings, in *Climate Change 2022: Mitigation of Climate Change*, 2022, pp. 9–1 to 9–168. [Online]. Available: https://www.ipcc.ch/report/ar6/wg3/

[2] A. Moreno-Rangel, E. Tsekleves, P. Young, M. Huenchunir, and J. M. Vazquez, Design research role on supporting net-zero buildings, in *PLEA 2022 Will cities survice?*, Santiago, Chile: PLEA, Nov. 2022.

[3] ONS, *Greenhouse gas emissions, UK: provisional estimates: 2021,* Nov. 2022.

[4] A. Moreno-Rangel, Passivhaus, *Encyclopedia*, vol. 1, pp. 20–29, 2021, doi: 10.3390/encyclopedia1010005.

[5] A. Moreno-Rangel, T. Sharpe, G. McGill, and F. Musau, Indoor Air Quality and Thermal Environment

Assessment of Scottish Homes with Different Building Fabrics, *Buildings*, vol. 13, no. 6, p. 1518, Jun. 2023, doi: 10.3390/buildings13061518.

[6] P. Leardini and M. Manfredini, Modern housing retrofit: Assessment of upgrade packages to enerphit standard for 1940-1960 state houses in Auckland, *Buildings*, vol. 5, no. 1, pp. 229–251, 2015, doi: 10.3390/buildings5010229.

[7] B. Dorota Hrynyszyn and L. Cornelia Felius, Upgrading of a Typical Norwegian Existing Wooden House According to the EnerPHit Standard, in *Cold climate HVAC 2018 Sustainable Buildings in Cold Climates*, D. Johansson, H. Bagge, and A. Wahlström, Eds., Kiruna, Sweeden: Sringler, Mar. 2018, pp. 183–193. doi: https://doi.org/10.1007/978-3-030-00662-4_16.

[8] A. Moreno-Rangel, T. Sharpe, G. McGill, and F. Musau, Indoor air quality in passivhaus dwellings: A literature review, *Int J Environ Res Public Health*, vol. 17, no. 13, pp. 1–16, 2020, doi: 10.3390/ijerph17134749.