NLC Sensor Performance Measurement of Housing Stock: Evaluation

Nicholas Harrington (1), Tim Sharpe (2), Mohammed Zaeem Farooq (2), and Kenneth Gibb (3)

UK Collaborative Centre for Housing Evidence

August 2026

(1) Formerly of the University of Glasgow/UK Collaborative Centre for Housing Evidence, now UK Government, Department for Energy Security and Net Zero

(2) University of Strathclyde, Department of Architecture

(3) University of Glasgow, UK Collaborative Centre for Housing Evidence

Economic and Social Research Council

Arts and Humanities Research Council

UK COLLABORATIVE CENTRE FOR HOUSING EVIDENCE

Contents

Executive Summary

Context and Aims

North Lanarkshire Council constructed 19 Net Zero homes within a new housing programme of 150 council properties. These homes were built with fabric efficiency measures and technologies beyond standard new-build requirements, including triple glazing, additional insulation, photovoltaic panels, battery storage, and heat pumps. An array of environmental sensors was installed in these homes, and additional monitoring and property data were available across a wider group of homes, creating an opportunity to examine how these homes are performing in use.

Project stakeholders were interested in understanding the extent to which the homes appear to deliver improved environmental performance and what practical lessons can be learned from the monitored data. In particular, the project sought to examine how far available sensor, monitoring, and related data could be used to understand differences between housing types, identify patterns in indoor environmental conditions and energy use, and interpret these findings considering household routines and behaviours.

This research brings together environmental sensor data, available energy and property data, construction cost information for the Net Zero homes, and behavioural research with residents to understand how monitored conditions relate to the everyday use of homes. The study also intended to provide practical learning on the opportunities and limitations of this type of data-led approach for future housing evaluation.

Methods Adopted

The research required a mixed-methods approach combining quantitative monitoring data with qualitative and survey-based behavioural evidence. In practice, the project drew on four main categories of data:

- Monitored/environmental data: relating primarily to indoor environmental conditions, including temperature and CO_2, alongside available monthly energy and property data where accessible.
- Economic data: relating to construction cost information for the Net Zero homes.
- Contextual/property data: relating to dwelling type, housing cohort, heating system, and basic property characteristics.
- Behavioural data: relating to occupier experiences, heating and ventilation practices, comfort, satisfaction, and everyday household routines.

Data Shortcomings

One project aim was to explore whether the installed sensor array and related data could support calculation of household heat demand. In practice, this proved more limited than originally envisaged. While the sensors provided useful information on indoor environmental conditions, there was much more limited access to household energy consumption. Access to fiscal metered consumption data was not included at the outset and was subsequently delayed and incompletely accessible. At the point of project commencement, the number of homes with fully installed and operational sensors was much lower than originally anticipated and access to complete datasets was constrained. This reduced the number of households available for recruitment to the behavioural research cohort and limited the volume and quality of environmental monitoring data available for analysis.

As a result, the project could not produce a robust heat-demand calculation for all the homes as originally intended. The monitored data has been used more cautiously: to examine patterns in environmental conditions, to compare relative performance across cohorts where possible, and to assess the practical strengths and limitations of the available monitoring approach. In this sense, the project provides learning about the feasibility of using sensor-based data within housing evaluation, while also identifying the additional metered and contextual data that would be required for more complete heat-demand modelling in future.

Availability of sub-metered data to identify space and water heating demands was very limited and information on household gas consumption data was also delayed for several months due to the time required to obtain the necessary permissions for data sharing. While the research team continued work on other elements of the project during this period, the absence of complete energy consumption data meant that the heat demand calculations originally envisaged could not be undertaken. The environmental sensors installed within the homes measure conditions such as temperature and CO_2 levels was more complete but relied on a secondary data source which limited comparison across the cohorts.

Whilst the monitored data was incomplete, the data potentially can provide valuable insights into the in-use performance of dwellings. Whilst this project identified challenges with data collection these can undoubtedly be addressed.

Findings

Overall, the results indicate that effective housing improvement programmes need to address both the physical performance of homes and the circumstances and practices of households. Combining fabric and system upgrades with household-centred advice, appropriate financial support, and post-installation follow-up is likely to be necessary to achieve reliable improvements in comfort, affordability, and energy performance across the housing stock.

The monitoring data largely confirm the patterns identified in the behavioural analysis. In well-insulated Net Zero homes, where residents reported leaving the heating on steadily and experiencing good comfort, the sensor data show stable indoor temperatures achieved with relatively low energy use. This reinforces the behavioural finding that continuous, low-level heating can work well when the building fabric supports it.

In contrast, in several existing homes where residents expected very warm indoor conditions, the monitoring data show higher energy use without correspondingly higher indoor temperatures. This helps explain why residents in these homes reported dissatisfaction and reliance on coping strategies and confirms that higher energy input does not always translate into better comfort when buildings or heating systems limit performance.

The sensor data also distinguishes between different reasons for cooler indoor temperatures. Where residents reported turning heating off to manage costs, the data show lower temperatures alongside lower energy use, indicating deliberate under-heating. Where residents reported low comfort despite leaving the heating on, the data show low temperatures without low energy use, pointing instead to building or system constraints. This distinction is not clear from either dataset on its own.

Patterns in indoor CO_2 levels further support the behavioural findings. Homes where residents reported frequent window opening generally show lower CO_2 concentrations, but often at the cost of higher energy use, confirming that ventilation habits affect both air quality and heating demand. Similarly, homes with heat pumps in existing buildings show higher energy use and only moderate comfort, supporting residents' concerns that low-carbon technologies do not automatically deliver good outcomes without suitable building conditions and user support.

Finally, the monitoring data confirm that households reporting similar levels of comfort often achieve this through very different combinations of heating use, energy consumption, and ventilation. This reinforces the behavioural conclusion that comfort is shaped by both the physical characteristics of the home and how people live in it, rather than by energy use alone.

In sum, the behavioural and sensor data provide a more complete picture than either could on its own. The behavioural data explain why households use energy in specific ways, while the monitoring data show how those choices play out in practice, strengthening confidence in the findings and helping to identify where different types of housing or household may need different forms of support or intervention.

There are five take-aways for local authorities considering wider use of sensors:

- Sensor data are most powerful when combined with an understanding of household behaviour.
- Similar buildings and technologies can perform very differently in practice.
- Sensors can help distinguish between affordability-driven under-heating and building or system limitations.
- Whole-stock sensor deployment should be designed around learning and targeting, not simple benchmarking.
- Strategies for sensor deployment need to manage scale and granularity and prioritise data access and robustness.

Broader Reflections

Despite the data challenges, there are some important findings from this study. First and foremost is the need for a clear research design to identify achievable objects and control for variables. Given the variability and complexity of housing, a much bigger dataset would be needed to generate sufficient statistical power to provide quantitative analysis.

However, case studies can also provide vital insights into real world performance, and detailed monitoring, but also occupancy and use can be used to identify individual performance, and this data can be used to generate detailed dynamic modelling for larger cohorts. Despite the limited dataset, some useful and interesting indicators are present. These include indications of improvements in environmental conditions in the improved homes, well above the existing homes, with the net-zero homes providing best performance in terms of improved temperature and ventilation, both of which have important health impacts.

Whilst detailed energy data is largely constrained to the new-zero homes, this data also clearly illustrates the range of energy use between homes. Given that this group has the least diversity in terms of location and built form, this may be ascribed to patterns of occupancy and behaviour. There is also good evidence of the contributions of the PV renewables.

The project also illustrates the challenges of management and analysis of large datasets. Both providers provide excellent portals for access to data, but these are not designed to statistical analysis or cross comparison across a range of dwellings or variables, and significant effort was required to collect and collate this data which limited detailed analysis. Nevertheless, there is an interesting and useful dataset which might be used to undertake more detailed analysis of individual dwellings, especially if further contextual and behaviour data can be obtained.

Whilst there were significant problems with the availability of data, the project does clearly illustrate the value of both monitored data on performance, but also contextual data. Monitored data will tell you 'what', contextual data will tell you 'why'.

In the context of the non-regulated energy use, some further insight is needed here to understand whether this results in 'rebound' effects. A concept that there is 'free' electricity may lead to higher use. Moreover, the choice of systems and technologies tends to be driven by imperfect modelling. SAP is not a predictive tool and makes several assumptions about patterns of use which will not reflect real life.

With new technologies there is a need to consider performance over time, cost of maintenance, and with a lifespan of 20 years, replacement, especially for roof integrated systems.

This type of evaluation would benefit from a more strategic research design – a large cohort of dwellings gathering simpler overall consumption data is likely to be more successful in generating statistical data in support of the hypothesis. Identification of case studies within this then may allow more detailed monitoring and evaluation to identify causality. Whilst this monitoring programme had limitations, these technologies are advancing and provide vital insights that inform current and future use. They also become useful tools for asset management and support for occupants in terms of risk factors.

Investment and follow-up operational recommendations

- Prioritise fabric-first retrofit in existing homes.
- Combine heat pump installations with fabric upgrades and system commissioning.
- Identify and support households likely to be rationing heat.
- Provide post-installation advice and simple user guidance.
- Undertake regular, systematic post-occupancy surveying of tenants in the properties.
- Consider household composition and occupancy when planning upgrades.
- Address hot water and appliance efficiency alongside space heating.

Further Practice implications

- Embedded environmental and energy monitoring is vital to inform outcomes of policy initiatives and resultant changes in standards and regulations.
- There is a significant performance gap that exists between design stages and performance in use. The latter is more important as this determines progress toward policy targets and objectives.
- Regulation and standards should be driven by in-use, rather and expected performance. Consideration should be given to elements of control, usability and information as critical drivers for performance.
- Performance needs a systems approach, considering dwellings rather than component pieces

1. Introduction

The Scottish Government has put forward an ambitious target of net zero emissions of all greenhouse gases by 2045. Integral to the success of Scotland's net zero strategy will be the decarbonisation and improved energy efficiency of its housing stock. Homes account for a substantial share of national energy use and emissions, with space heating making up the largest proportion of household energy demand. For local authorities, this creates a strong policy and delivery interest in understanding how low-energy and Net Zero homes perform in practice, how residents use them, and what lessons can be drawn for wider housing programmes.

North Lanarkshire Council has constructed 19 Net Zero homes within a new housing programme of 150 council properties. These homes were built with fabric efficiency measures and technologies beyond standard new-build requirements, including triple glazing, additional insulation, photovoltaic panels, battery storage, and heat pumps. An array of environmental sensors was installed in these homes, and additional monitoring and property data were available across a wider group of homes, creating an opportunity to examine how these homes are performing in use.

Because of the additional investment associated with the Net Zero homes, project stakeholders were interested in understanding the extent to which the homes appear to deliver improved environmental performance and what practical lessons can be learned from the monitored data. In particular, the project sought to examine how far available sensor, monitoring, and related data could be used to understand differences between housing types, identify patterns in indoor environmental conditions and energy use, and interpret these findings in light of household routines and behaviours.

This research is therefore an evaluation of the use of monitoring and behavioural evidence within a live local authority housing programme. It brings together environmental sensor data, available energy and property data, construction cost information for the Net Zero homes, and behavioural research with residents in order to understand how monitored conditions relate to the everyday use of homes. The study is also intended to provide practical learning on the opportunities and limitations of this type of data-led approach for future housing evaluation.

Research Questions

1. How far can the available monitoring and sensor data be used to understand the in-use performance of the homes included in this study?

   a. What does the available data allow us to say about relative patterns of environmental performance and energy use across the main housing cohorts?

   b. What are the main practical and analytical limitations of the available sensor and monitoring data for assessing housing performance?

2. What can the available cost information tell us about the construction costs of the Net Zero homes, and what are the implications for understanding their potential value within a local authority housing programme?

3. What can monitored environmental conditions tell us about thermal comfort, ventilation, and the lived experience of the homes, and how far can these findings be interpreted alongside resident-reported experiences?

4. How does occupant behaviour shape the use and performance of the monitored homes?

   a. What factors appear to influence differences in household comfort, heating practices, ventilation, and energy-related routines?

   b. What is the relationship between occupant behaviour and the monitored data?

   c. What practical lessons can be identified for local authorities interested in wider use of sensors and monitoring in housing?

Methods

Answering these questions required a mixed-methods approach combining quantitative monitoring data with qualitative and survey-based behavioural evidence. In practice, the project drew on four main categories of data:

- Monitored/environmental data: relating primarily to indoor environmental conditions, including temperature and CO_2, alongside available monthly energy and property data where accessible.
- Economic data: relating to construction cost information for the Net Zero homes.
- Contextual/property data: relating to dwelling type, housing cohort, heating system, and basic property characteristics.
- Behavioural data: relating to occupier experiences, heating and ventilation practices, comfort, satisfaction, and everyday household routines.

The research design was refined in response to the data that became available over the course of the project. At the point of commencement, the number of homes with fully operational sensor installations was lower than initially anticipated, which reduced the potential behavioural cohort and limited the number of properties for which monitored data could be directly interpreted alongside resident evidence. In addition, access to some household energy data was delayed, and the installed sensors did not themselves function as smart meters or provide direct measures of household energy consumption.

For these reasons, the study focused primarily on:

1. describing and comparing monitored environmental and available energy patterns across housing cohorts;
2. analysing household behaviour through preliminary surveys, periodic winter surveys, and case-study comparison; and
3. identifying what this combined evidence can and cannot tell us about the in-use performance of Net Zero and comparable homes.

Heat demand calculation and data shortcomings

At the outset of the project, one aim was to explore whether the installed sensor array and related data could support calculation of household heat demand. In practice, this proved more limited than originally envisaged. While the sensors provided useful information on indoor environmental conditions, there was much more limited access to household energy consumption. Access to fiscal metered consumption data was not included at the outset and was subsequently delayed and incomplete for part of the study period.

At the point of project commencement, the number of homes with fully installed and operational sensors was much lower than originally anticipated and access to complete datasets was limited. This reduced the number of households available for recruitment to the behavioural research cohort and limited the volume and quality of environmental monitoring data available for analysis. As a result, the behavioural cohort was smaller than initially envisaged.

As a result, the project was not able to produce a robust heat-demand calculation for all the homes as originally intended. Where reliable data exists indications of delivered heat in kWh/m2 can be estimated. The monitored data has been used more cautiously: to examine patterns in environmental conditions, to compare relative performance across cohorts where possible, and to assess the practical strengths and limitations of the available monitoring approach. In this sense, the project provides learning about the feasibility of using sensor-based data within housing evaluation, while also identifying the additional metered and contextual data that would be required for more complete heat-demand modelling in future work.

The project also uses available monitoring and property data to explore broad differences between four housing conditions: Net Zero homes, standard new-build homes, retrofit homes, and existing homes. However, given the limited data, these comparisons are interpreted carefully, recognising that differences in dwelling type, household composition, occupancy, and system operation can all influence observed outcomes.

Availability and veracity of sub-metered data to identify space and water heating demands was very limited and information on household metered energy data was also delayed for several months due to the time required to obtain the necessary permissions for data sharing. While the research team continued work on other elements of the project during this period, the absence of complete energy consumption data meant that the heat demand calculations originally envisaged could not be undertaken. The environmental sensors installed within the homes measuring conditions such as temperature and CO_2 levels was more complete, but relied on a secondary data source which limited comparison across the cohorts. The need to extract and clean data also introduced some uncertainties. Without reliable energy usage data to complement these measurements, it was not possible to derive robust estimates of household heat demand.

Whilst the monitored data was incomplete, it is clear that the data can provide valuable insights into the in-use performance of dwellings. Whilst this project identified challenges with data collection these can undoubtedly be addressed.

Cost-Benefit Analysis / Business Case

The project originally intended to compare construction and running costs across multiple housing types. In practice, reliable and consistent construction cost data was available only for the Net Zero homes. The economic component of this report therefore focuses on the construction costs associated with these homes and considers these in the context of their intended performance and policy rationale.

While this does not amount to a full comparative cost-benefit analysis across all cohorts, it does provide an initial contribution to understanding the investment profile of the Net Zero homes within the North Lanarkshire Council programme. The findings should therefore be read as a focused cost review rather than a complete economic appraisal of all housing types included elsewhere in the report.

Health Impact

The project also considered whether monitored environmental conditions and resident evidence could contribute to understanding health-related aspects of housing performance, particularly ventilation and thermal comfort. In principle, indicators such as temperature and CO_2 can provide useful information about conditions relevant to indoor environmental quality, which are indicators, but not measurements of health.

However, self-reported health information collected through the behavioural strand was limited in consistency and was difficult to match robustly to the monitored environmental data. Reported issues often appeared to relate to underlying health conditions rather than to housing or recent energy-efficiency changes. For this reason, the report does not attempt a formal health-impact evaluation. Instead, it uses environmental indicators and resident accounts more cautiously, focusing on comfort, ventilation, and lived experience rather than claiming direct health outcomes.

Occupant Behaviour

Occupant behaviour is a central part of this study. The behavioural strand draws on preliminary household surveys, periodic winter surveys, earlier interview material from Phase 1, and comparative case-study analysis. Together, these provide evidence on how households use heating systems, manage ventilation, experience comfort, and respond to energy costs and everyday domestic routines.

This part of the project became especially important because behavioural evidence provided the strongest means of interpreting monitored conditions. While sensor data can show patterns in temperature, ventilation, and, where available, energy use, it cannot by itself explain why households use their homes differently. The behavioural research therefore allows the report to examine how occupancy patterns, comfort expectations, family composition, and everyday practices shape the performance observed in the monitored homes.

Additional focus groups were not undertaken in this phase. Given the questions being addressed and the evidence already gathered through Phase 1 interviews and repeated surveys, it was considered that focus groups were unlikely to add substantial new insight beyond the behavioural data already available.

Process Evaluation

The project also provides practical learning from implementing monitoring and behavioural research within a live local authority housing programme. This includes lessons relating to sensor installation coverage, data access and permissions, the timing and completeness of metered data, and the challenges of combining different types of data within a single evaluation framework.

These process findings are important in their own right. They help to clarify what can realistically be achieved through this kind of housing monitoring project, what forms of evidence are most useful in practice, and what additional data or design choices would strengthen future studies.

The data collected and the inputs from occupants have followed strict ethical guidelines. The project sits within CaCHE's ethical approval procedures. Households were contacted by the Council about participation and were fully briefed in relation to consent, privacy, and the purpose of the research. All materials and data have been de-identified using consistent researcher codes that do not link back to individual households or addresses.

The data collected and the inputs from occupants have followed strict ethical guidelines. The project's sits within CaCHE's ethical approval procedures, interviewees were contacted by the council about participation and were fully briefed in terms of consent, privacy and information as to the project and the use of their data. All materials and data have been de-identified using consistent researcher codes that do not link back to the households or addresses.

The report is in the following sections. After the introduction, we start by examining the behavioural research component, followed by a series of six matched case studies which combine behavioural and quantitative data analysis. This is followed by a detailed evaluation of the data generated through sensor and metering and operational practicalities of using it. The penultimate section is the economic evaluation of the cost-effectiveness of net zero homes in the study, before the report's conclusions and recommendations. An annex summarises preliminary research for the project that measured heat loss which is discussed at various points in this report.

2. Behavioural Research

This section presents findings from the behavioural strand of the study, which explores how households use and experience their homes, and how everyday practices shape comfort, energy use, and energy costs. It complements the technical monitoring and sensor-based analysis presented elsewhere in this report by providing insight into the lived experience behind measured data.

While sensor data can show how temperatures, humidity, and energy use vary over time, they cannot explain why these patterns occur. The behavioural research addresses this gap by examining household routines, preferences, and constraints, including heating operation, thermostat settings, ventilation habits, hot water use, laundry practices, and the use of coping strategies such as extra clothing or blankets.

Together, these findings help to interpret the quantitative results, identify mechanisms behind observed patterns, and highlight the ways in which building characteristics and household practices interact. This combined perspective supports a more complete understanding of housing performance, with direct relevance for retrofit design, technology deployment, and support for households within North Lanarkshire Council's housing stock.

Methods

This section of the report draws on three primary data sources: preliminary household surveys and interviews, monthly periodic household surveys, and information on dwelling archetype and heating system type. The cohort consists of 13 homes, all drawn from North Lanarkshire Council's social housing stock (while 15 homes were originally recruited, two households provided incomplete periodic survey data and are therefore excluded from some analyses). The preliminary household surveys and interviews were undertaken in September 2024, and the periodic household surveys were administered monthly between December 2024 and March 2025, with each survey capturing responses about the preceding month (November 2024 to February 2025). Information on dwelling archetype and heating systems was compiled at the outset of the project.

Analysis focused on descriptive and comparative approaches rather than formal statistical modelling, reflecting the modest sample size and exploratory nature of the study. Periodic survey responses were plotted by month and labelled by HOME ID and housing archetype to visualise distributions, ranges, and within- and between-group variation. Results were examined both at the level of the whole cohort and by archetype (Net Zero, New Build, Retrofit, Existing), with attention paid to median tendencies, clustering, and outliers.

To aid interpretation, results from different survey domains (e.g. comfort, thermostat settings, turning heating off, energy spend, laundry, bathing, ventilation, and coping strategies) were compared with one another to identify recurring associations and contrasting patterns. Preliminary household profiles were used as contextual information to explore how household size, composition, and occupancy patterns might help explain observed variation, particularly for hot water use, appliance activity, and heating practices.

Six homes were additionally selected as case studies and grouped into three comparability clusters based on shared physical characteristics (discussed in the next section). For these homes, monthly survey responses were presented as heatmaps to support visual comparison of temporal stability, co-occurrence of behaviours, and contrasts between physically similar dwellings.

Interpretation of findings was iterative and triangulated across figures, tables, and case studies. Emphasis was placed on identifying consistent themes, plausible mechanisms, and patterns that appeared repeatedly across multiple indicators, while recognising uncertainty associated with self-reported data and the absence of direct metered energy measurements. The analysis is therefore intended to provide a grounded, exploratory account of relationships and tendencies rather than definitive causal claims.

The following limitations should be considered when interpreting the findings of this research:

1. Small, non-representative sample. The cohort consists of 13 homes and is not statistically representative.
2. Reliance on self-reported data. Findings are based primarily on self-reported survey responses, which may be subject to recall error.
3. Unverified energy cost data. Reported energy costs are not directly verified against metered consumption and may reflect different tariffs, payment methods, or estimation practices.
4. Exploratory, descriptive analysis. The analysis is descriptive and exploratory, with no formal statistical testing.
5. Seasonally limited data collection. The periodic surveys cover winter months only (November–February), and patterns will differ seasonally.
6. Non-standard orientation of behavioural frequency scales. Behavioural frequency questions used a consistent 1–10 scale where lower values indicated higher frequency (1 = constantly, 10 = never). This direction was chosen to align higher numerical values with lower occurrence of potentially undesirable conditions or behaviours (and to maintain consistency across multiple behavioural items, but it differs from some conventional Likert formats.

Despite these limitations, repeated monthly surveys, household profiling, and case-study comparisons provide a consistent and informative picture of lived experience within the participating homes.

Cohort archtypes

Our data is organised into four cohorts.

Net Zero Homes

Net Zero homes are recently constructed dwellings (2023–24) designed with an enhanced specification intended to support low-carbon performance and reduce operational emissions. While there is no single formal "Net Zero" construction standard, these homes incorporate measures that go beyond prevailing new-build requirements, including high levels of fabric efficiency and airtightness, typically delivered through timber-frame construction with substantial mineral wool and loft insulation to minimise heat loss. Space and water heating are provided by air source heat pumps rather than fossil-fuel systems, and all homes include roof-mounted solar photovoltaics (PV) and battery storage to support on-site generation and reduce reliance on grid electricity. Collectively, these measures are intended to improve energy efficiency, lower emissions, and support stable indoor temperatures with reduced running costs relative to conventional housing.

New Build Homes

New build homes are also recently constructed (2023–24) and meet contemporary Scottish building standards, but do not incorporate the enhanced low-carbon specification and additional measures applied in the Net Zero homes. They generally have good levels of insulation and modern fabric performance, typically using timber-frame construction with mineral wool insulation and substantial loft insulation. Heating is provided by modern gas central heating systems rather than heat pumps. Some new build homes include solar PV, but this is not universal. Compared with Net Zero homes, new builds are assumed to have lower fabric and system performance, but substantially better thermal characteristics than most older housing stock.

Retrofit Homes

Retrofit homes are older properties (generally mid-20th century) that have received partial fabric upgrades over time. These upgrades typically include cavity wall insulation and, in some cases, additional loft insulation or solar PV. However, they have not undergone comprehensive, whole-house retrofit to modern energy efficiency standards. Heating is usually provided by gas central heating systems. As a result, retrofit homes occupy an intermediate position: they are assumed to perform better than untreated existing homes, but remain significantly less thermally efficient than new build or Net Zero homes.

Existing Homes

Existing homes are older properties (mostly 1940s–1970s) that have not received major fabric upgrades beyond basic or historic measures such as early cavity wall insulation or modest loft insulation. They generally lack external wall insulation and advanced airtightness measures. Heating is predominantly provided by gas central heating, although one (i.e., HOME ID 13) has a heat pump installed without accompanying fabric improvements. These homes are expected to exhibit higher heat loss and lower baseline thermal performance than the other categories of home in the cohort.

Further details on cohort energy efficiency can be found in the heat loss analysis annex.

Preliminary behavioural surveys of household profiles

A preliminary household survey was undertaken in September 2024, approximately two months before the start of the periodic surveys, to establish a baseline profile for each participating household. The survey was designed to capture contextual information about who lives in each home and how the home is typically used, providing essential background for interpreting later monitoring and survey results.

The preliminary survey also gathered information about heating systems, typical thermostat settings, perceived warmth and comfort, and general attitudes towards energy efficiency. These surveys were supplemented with short interviews, which allowed participants to clarify responses, describe routines in more detail, and highlight any specific issues with their home or heating system. Together, the household profile for each dwelling, enabled the project to explore how differences in household composition, occupancy, and everyday practices relate to the patterns observed in the periodic surveys and sensor data.

The survey period ran from November 2024 to February 2025 (inclusive), providing four months of data covering the 2024/25 heating season. The survey contained approximately 30 questions and was designed to take around 10–15 minutes to complete. It was structured to capture a broad picture of how households experience warmth, use energy, and manage everyday practices over time. Households were asked to report their most recent gas and electricity bills (where available), and to compare both costs and energy use with the same time last year. They were also asked whether people were at home more or less than usual, and to estimate the frequency of energy-related activities such as washing, tumble-drying, natural drying of clothes, and the number of showers or baths. Together, these questions provide contextual information on overall energy use, occupancy patterns, and routine household activities that influence energy demand.

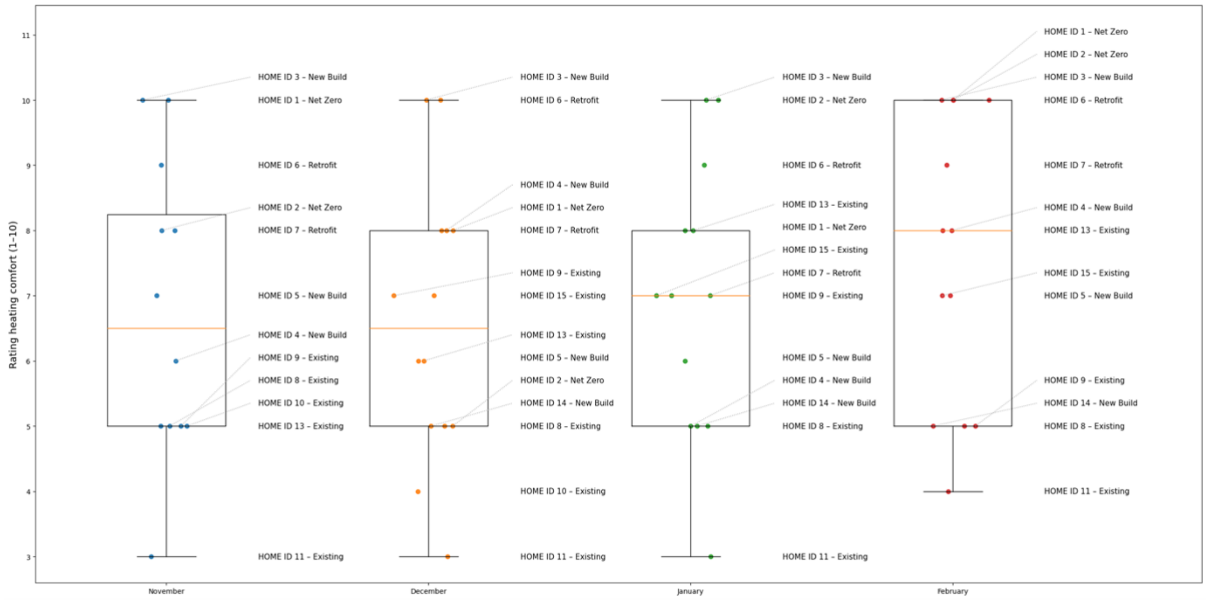
The survey also includes a set of questions focused on comfort, heating system use, and everyday thermal practices. Many of these use simple rating scales (for example 1–10 scales or Likert-style options such as "never" to "always") to capture perceived comfort, heating system performance, and the frequency of specific behaviours. Households report their usual thermostat setting and how often they turn heating off, alongside ratings of coping strategies such as wearing extra clothes, using hot water bottles, using extra blankets, or plugging in portable heaters. The survey also includes questions on ventilation-related practices, including opening windows, closing internal doors, and closing blinds or curtains. Finally, a short set of health-related questions asks about general wellbeing and symptoms such as coughing, headaches, nausea, and itching, as well as doctor calls or visits. Using standardised scales and simple response formats supports consistency across months and enables comparison between households while remaining accessible to non-technical participants.

Heating comfort

Figure 1 shows how each participating household rated their heating comfort during November, December, January, and February of the 2024/25 heating season, using a simple scale from 1 (terrible – cold most of the time) to 10 (perfect – always comfortable). Each point represents a household's monthly self-reported comfort score, labelled by a unique HOME ID and the archetype of home they live in. The distribution shown for each month illustrates both typical comfort levels and the range of experiences across the cohort.

Results

Figure 1. Monthly self-reported heating comfort by household during the 2024/25 heating season (1–10 scale).



Key findings

- The results show a meaningful spread of responses each month, suggesting considerable variation in comfort levels across the cohort.
- Homes classified as Net Zero and New Build are consistently clustered toward the higher end of the comfort scale (generally 8–10), indicating that occupants in these homes are more likely to report being comfortably warm throughout the heating season.
- Retrofit homes tend to report mid-to-high comfort scores, but with greater dispersion than Net Zero and New Build homes, suggesting that fabric improvements reduce cold-related discomfort but do not eliminate variation between households.
- Existing (untreated) homes display the widest range of comfort scores, including most of the lowest ratings observed across all months, indicating a higher risk of occupants experiencing insufficient warmth. Several households in Existing homes repeatedly report comfort levels around or below the midpoint of the scale (≈5), implying that feeling "sometimes cold" is a persistent experience rather than an isolated occurrence.

Interpretation

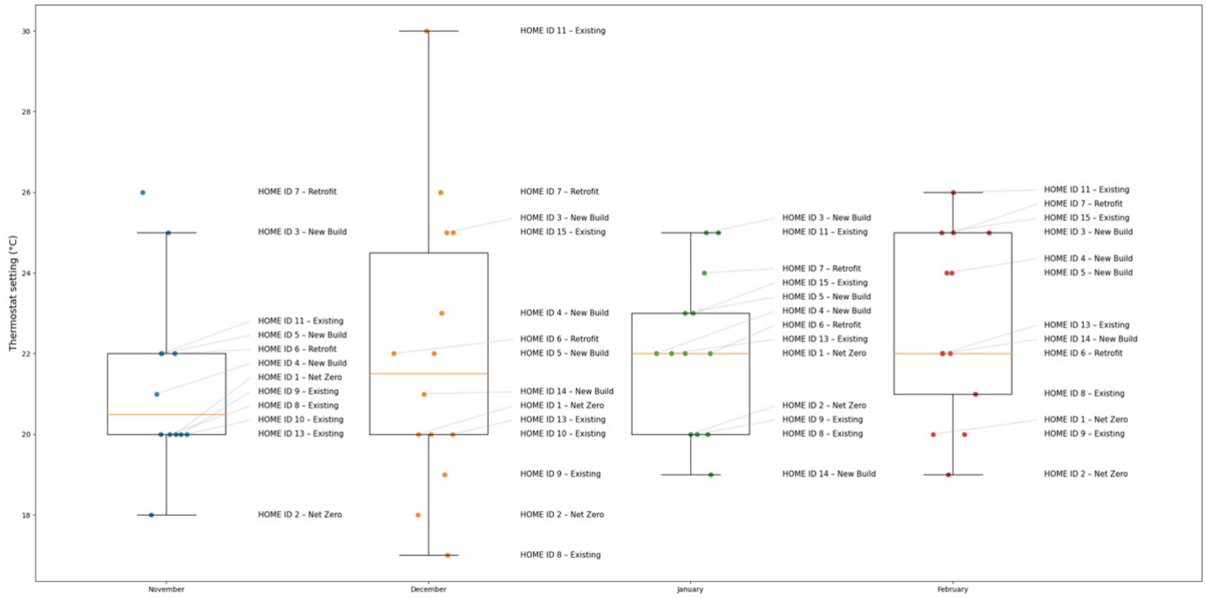
Overall, the results show that while more thermally efficient homes are generally associated with higher comfort, household-level factors also play a significant role in shaping lived thermal experience. The slight rise in median comfort from November to February suggests that some households adjust their heating regimes as winter progresses or increase heating use in response to colder conditions. At the same time, substantial variation between households living in the same type of home indicates that building fabric alone does not determine experienced comfort.

A small group of households report consistently very high comfort across multiple months, pointing towards stable thermal conditions that may reflect a combination of efficient building fabric and effective system operation. Conversely, a small group report consistently low comfort, suggesting persistent under-heating that may relate to financial constraints, system performance issues, or both.

Thermostat settings

Figure 2 shows the temperature at which each household reported setting their thermostat for each month of the 2024/25 heating season. Each point represents a household's self-reported thermostat setting, labelled by HOME ID and home archetype, allowing comparison across months and between households. It is important to note that households do not all have the same type of heating system: HOME IDs 1, 2, and 13 use air source heat pumps, while the remaining homes use gas boilers. As a result, heating technologies cut across housing types, including one air source heat pump installed in an otherwise untreated existing home. The link between thermostat setting and heating energy consumption is well established—higher thermostat settings generally correspond to higher energy use, all else being equal. At the same time, thermostat settings reflect both heating need and personal preference, and households differ in how they judge what feels comfortable. The distribution shown for each month illustrates both the typical thermostat setting across the cohort and the extent of variation between households.

Figure 2. Monthly self-reported thermostat settings by household during the 2024/25 heating season (°C).



Key findings

- The temperature at which a household set their thermostat varies considerably, from around 17 °C to 30 °C in each month, indicating large differences in heating preferences and/or perceived heating needs.
- A small number of households consistently report very high thermostat settings (24–26 °C or above), while others consistently report much lower settings (around 17–19 °C), indicating pronounced differences in heating demand, comfort expectations, and/or constraints on heating use.
- Most households cluster between approximately 20 °C and 23 °C in all months, suggesting this range represents a common band of preferred or tolerated indoor temperature.
- Median thermostat settings increase slightly from November to February, indicating that some households raise their target temperatures over winter.
- Considerable variation exists between households within the same housing archetype, suggesting that thermostat setting is strongly influenced by household-level factors rather than building type alone.
- Homes with different heating technologies (gas boilers and air source heat pumps) appear across the full range of thermostat settings, indicating no obvious clustering by heating system type alone.
- Patterns of thermostat setting appear strongly shaped by household behaviour: some households maintain stable set-points througout, reflecting habitual heating practices, while others adjust settings more frequently, indicating more responsive or adaptive approaches to managing warmth.

Interpretation

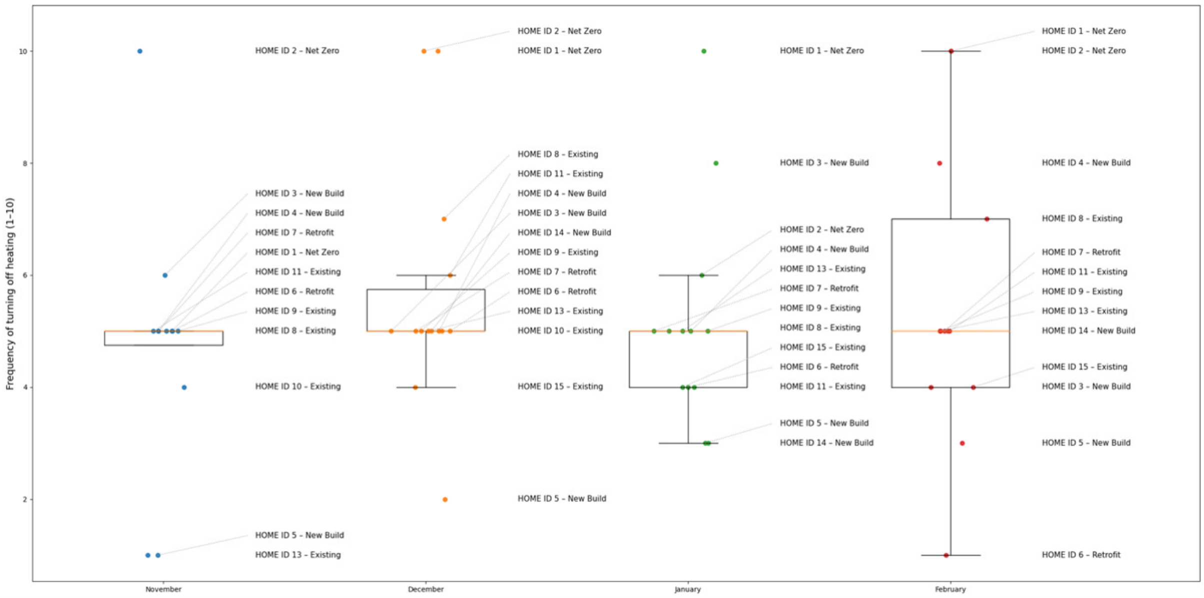
Linking thermostat settings (Figure 2) with household composition indicates that higher set-points are more common in larger households and those with children. HOME ID 11 (three adults, one teenager, one child) reports among the highest thermostat settings in the cohort, while HOME ID 1 (two adults, two teenagers), HOME ID 5 (one adult, two teenagers, one child), and households with two adults and one child such as HOME ID 4 and HOME ID 9 also tend to appear in the mid-to-upper range of set-points. In contrast, single-adult households such as HOME ID 12 and HOME ID 8 generally report lower thermostat settings, while HOME ID 13 (single adult on weekdays, children at weekends) sits toward the lower-to-middle range. Overall, these patterns suggest thermostat setting is associated with household size and the presence of children, but with substantial variation remaining that points to the importance of individual preferences and household practices.

In addition to household composition, variation in thermostat settings may also reflect differences in everyday energy-related practices that shape how households achieve thermal comfort. Some households may rely more heavily on non-heating strategies—such as wearing extra clothes, using hot water bottles, or adding blankets—which could allow lower thermostat set-points without compromising comfort. Conversely, households reporting higher thermostat settings may place less emphasis on these coping strategies or may prioritise achieving warmth primarily through space heating. Similarly, practices such as frequently opening windows, keeping internal doors open, or leaving blinds open could increase heat loss and prompt higher thermostat settings, while more consistent door-closing and blind-closing may support lower set-points.

Turning heating system off

Figure 3 presents households' self-reported frequency of turning their heating system off during November, December, January, and February of the 2024/25 heating season. Households rated their behaviour on a scale from 1 (constantly – heating is turned off most of the time) to 10 (never – heating is on all the time, day and night), with intermediate values indicating occasional or situational switch-off (e.g., at night or when heating is not needed). Each point represents a household's monthly response, labelled by HOME ID and housing archetype. Turning heating off can reflect a range of influences, including financial pressure, energy-saving practices, perceived adequacy of warmth, or established routines. For households with heat pumps, these responses also provide an indication of whether systems are being operated in line with best-practice guidance, which typically recommends continuous low-level operation rather than frequent switching off.

Figure 3. Monthly self-reported frequency of turning heating off (1–10 scale) by household during the 2024/25 heating season.



Key findings

- Most reported values across all months cluster around the mid-range of the scale, indicating that many households report turning heating off "sometimes" (around 4–6), regardless of housing archetype.
- The two Net Zero homes show slightly different patterns: one consistently reports "never" turning heating off (10) in all the surveyed months, while the other reports "sometimes" (around 5) in two months and "never" (10) in the remaining months.
- New Build homes are widely distributed across the scale, with reports ranging from "rarely" turning heating off (around 2–3) through to "never" (around 8–10), indicating substantial diversity in practice.
- Retrofit homes also span a broad range, from "constantly" or very frequently turning heating off (around 1–3) to "sometimes" (around 6–7), with no consistent clustering.
- Existing homes similarly occupy most of the scale, including low, mid, and high frequencies, and show substantial overlap with Net Zero, New Build, and Retrofit homes in each month.
- Overall, Net Zero homes tend to sit toward the top end of the distribution (predominantly "never" turning heating off), while New Build, Retrofit, and Existing homes cover a much wider range, overlapping in the mid-range.
- Individual households do not always report the same response each month; some show noticeable shifts between "sometimes," "rarely," and "never,".

Interpretation

The reported patterns suggest that decisions about turning heating off are shaped by a combination of household routines, perceptions of comfort, and financial considerations, rather than by dwelling archetype alone. Given that all participants are social housing tenants and many are likely to be on fixed or constrained incomes, mid-range responses indicating that heating is turned off "sometimes" may reflect active management of heating to control costs, for example by switching systems off at night or when rooms are unoccupied. At the same time, the wide spread of responses within New Build, Retrofit, and Existing homes indicates that similar dwelling types can be associated with very different heating practices, underscoring the importance of behaviour and household circumstances alongside building characteristics. The tendency for Net Zero homes to report that heating is "never" turned off aligns with recommended best practice for air-source heat pump operation, which favours continuous low-level operation rather than frequent on–off cycling, and may indicate effective handover and guidance from installers (or successful self-education). A degree of month-to-month variation even within this small group suggests that occupants may still be adapting their behaviour, stressing the role of learning and lived experience alongside technical performance.

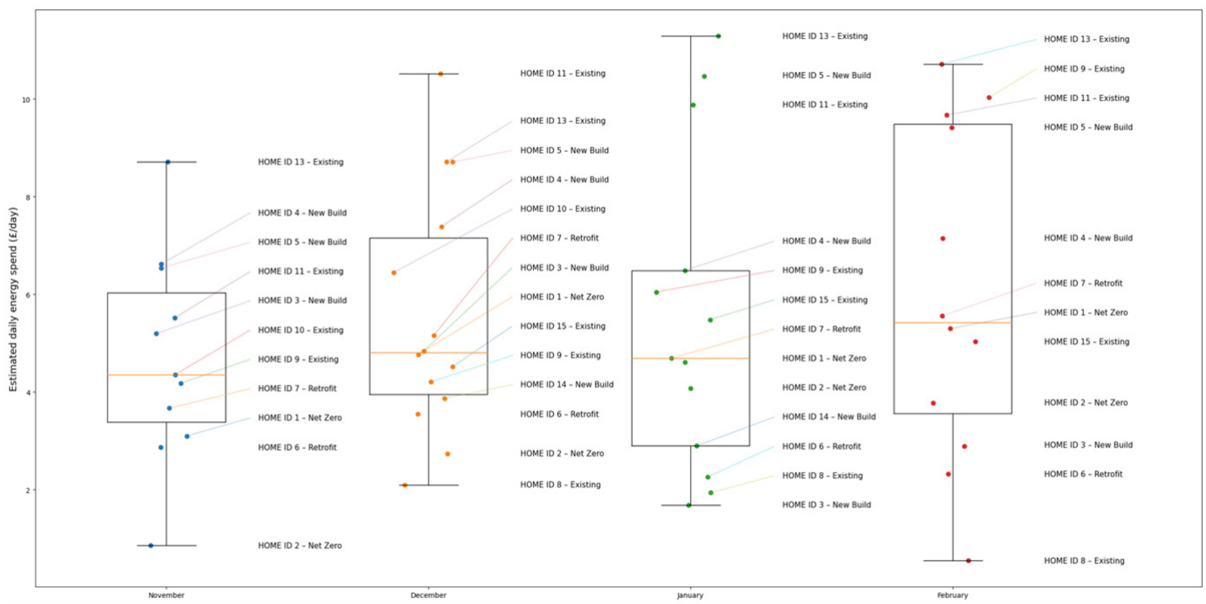
Comparing Figure 3 (turning off heating) with Figure 1 (heating comfort) shows a small number of cases where lower heating comfort coincides with turning the heating off more often, which may indicate financial constraint. For example, HOME ID 11 (Existing) reports low comfort (around 3–5) in several months alongside responses suggesting heating is turned off "sometimes" to "often," and HOME ID 6 (Retrofit) reports low comfort in February together with more frequent turning off. In contrast, there are also cases where lower comfort coincides with heating that is rarely or never turned off, which may instead point to limitations in building fabric or system performance rather than cost-driven restriction; for example, HOME ID 8 (Existing) reports moderate-to-low comfort while also indicating that heating is generally kept on most of the time or "rarely" turned off. For the two Net Zero homes (HOME ID 1 and HOME ID 2), high reported heating comfort coincides with heating being rarely or never turned off, suggesting that the combination of high-performance building fabric and heat pump systems enables comfortable conditions to be maintained through steady, continuous operation rather than frequent switching

Energy expenses

Figure 4 presents each household's self-reported total energy expenditure for gas and electricity, expressed as an estimated daily cost (£/day) for November, December, January, and February of the 2024/25 heating season. Households were asked to provide monthly totals for gas and electricity use (combined or separately), drawing on bills where available, and these figures were converted to daily values based on the number of days in each month to enable comparison across time and between households. Each point represents a household's daily estimate for the month, labelled by HOME ID and housing archetype. Reported expenses should be interpreted with caution, as they have not been independently verified.

While total household energy spend reflects more than space heating alone, the figure provides a provisional indicator of relative household energy costs. Some background electricity uses (e.g. lighting and small appliances) are likely to be broadly similar across households, but higher-variability activities such as hot water use, laundry, and appliance use can make a substantial contribution to these values and are considered later in the report.

Figure 4. Self-reported household energy expenses for gas and electricity, converted from monthly estimates to £/day.



Key findings

- Reported daily household energy costs vary substantially across the cohort and across months, ranging from under £1/day in some cases to over £11/day in others, indicating large inter-household differences in overall energy use and/or tariff arrangements.
- The Net Zero dwellings exhibit consistently low-to-moderate reported daily energy costs relative to the wider cohort (generally below ~£5.50/day), with one showing exceptionally low November costs (below £1/day) and both remaining among the lowest reported values through December–February.
- Existing dwellings are more frequently represented at the upper end of reported daily energy costs, with several showing sustained values above £8–£10/day, suggesting that some older properties are associated with higher overall energy expenditure.
- New-build homes exhibit a wide spread of reported costs, ranging from relatively low to among the highest in the dataset, indicating substantial variability that cannot be attributed solely to building age or construction standard.
- Retrofit homes tend to cluster within the low-to-mid range of daily energy costs, suggesting more moderate overall energy expenditure relative to the highest-spending existing dwellings.
- A general seasonal rise in energy costs from November through January/February is evident for many households, consistent with increased winter energy demand, though these values reflect total household energy use rather than space heating alone.

Interpretation

Daily energy spend shows an indicative association with household occupancy, with larger households and those containing children or teenagers (e.g., HOME ID 5, HOME ID 9, HOME ID 11, HOME ID 13) more often appearing in the mid-to-upper range of reported costs, while smaller and single-adult households (e.g., HOME ID 2, HOME ID 6, HOME ID 8, HOME ID 12) more commonly fall toward the lower end. However, this relationship is not linear: some multi-person households report moderate costs (e.g., HOME ID 7 and HOME ID 4), and some smaller households report relatively high costs (e.g., HOME ID 13), suggesting that occupancy contributes to—but does not determine—overall energy expenditure, which is also shaped by building characteristics, heating system type, and everyday practices.

The three homes known to use air-source heat pumps span different cost profiles. The two Net Zero dwellings with ASHPs (HOME ID 1 and HOME ID 2) show low-to-moderate daily energy costs across the heating season, whereas the ASHP installed in an existing dwelling (HOME ID 13) is associated with comparatively high reported costs. This contrast highlights the importance of broader building performance and usage context alongside heating system type.

Homes with Solar PV appear across the full range of reported daily energy costs, from low (e.g., HOME ID 2, HOME ID 6) to high (e.g., HOME ID 5, HOME ID 9, HOME ID 13), indicating that while on-site generation may contribute to lower purchased electricity under certain usage patterns, its impact on total household energy expenditure is strongly mediated by overall demand, occupancy, and behaviour rather than acting as a uniform cost-reduction measure.

Finally, changes in occupancy show a weak and inconsistent relationship with month-to-month changes in daily energy cost. In some cases, households reporting being “home a bit more” or “home a lot more” coincide with rising costs (e.g., HOME ID 5 and HOME ID 7), but substantial cost increases also occur where households report being “at home the same amount” (e.g., HOME ID 9 and HOME ID 13). This suggests that changing occupancy may contribute to variation in some households but does not reliably explain the observed month-to-month cost changes.

Overall, the findings indicate that household energy costs emerge from the interaction of occupancy, building performance, heating system type, and everyday practices, with no single factor alone sufficient to explain the observed patterns.

Washing and dryer loads

Figure 5 presents each household’s self-reported number of washing machine loads per month, and Figure 6 shows the self-reported frequency of electric clothes dryer use per month, for November, December, January, and February of the 2024/25 heating season. Each point represents a household’s monthly estimate, labelled by HOME ID and housing archetype. Not all households own or use an electric clothes dryer; therefore, zero values may reflect the absence of a dryer, exclusive use of line-drying, or use of alternative appliance functions (e.g. washer–dryer combinations). Washing and drying are relatively energy-intensive activities, and differences in the frequency of these practices are expected to contribute to variation in overall household electricity consumption and total energy costs. Presenting these data allows comparison of laundry-related practices across households and months, and supports interpretation of the wider patterns observed in reported energy use and expenditure.

Figure 5. Self-reported washing machine loads per month for each household.Figure 5. Self-reported washing machine loads per month for each household.

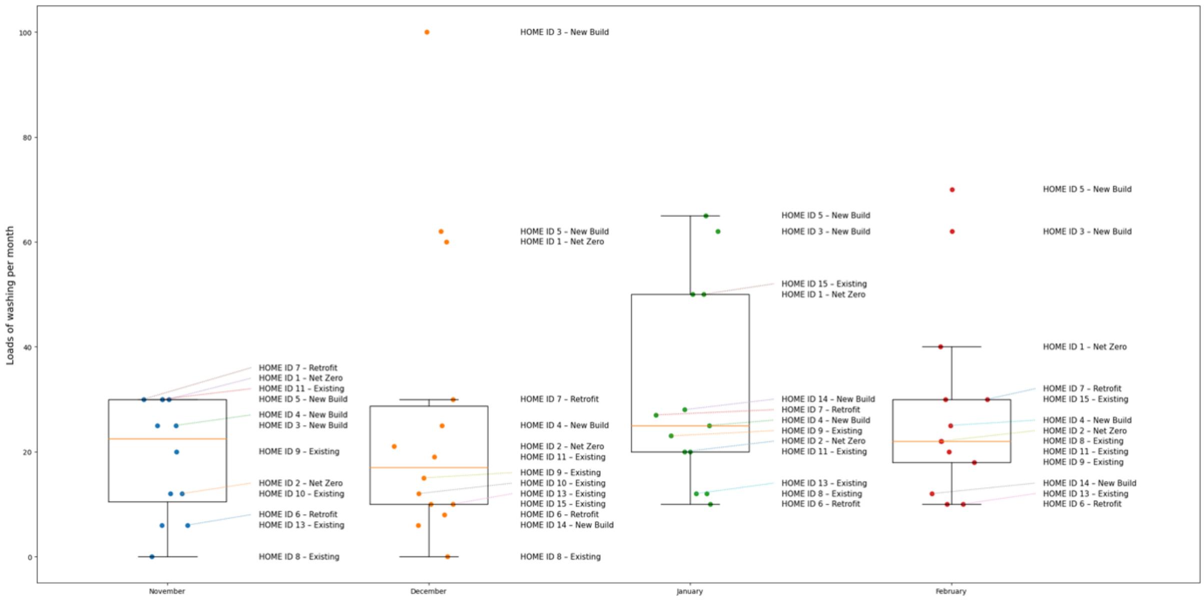
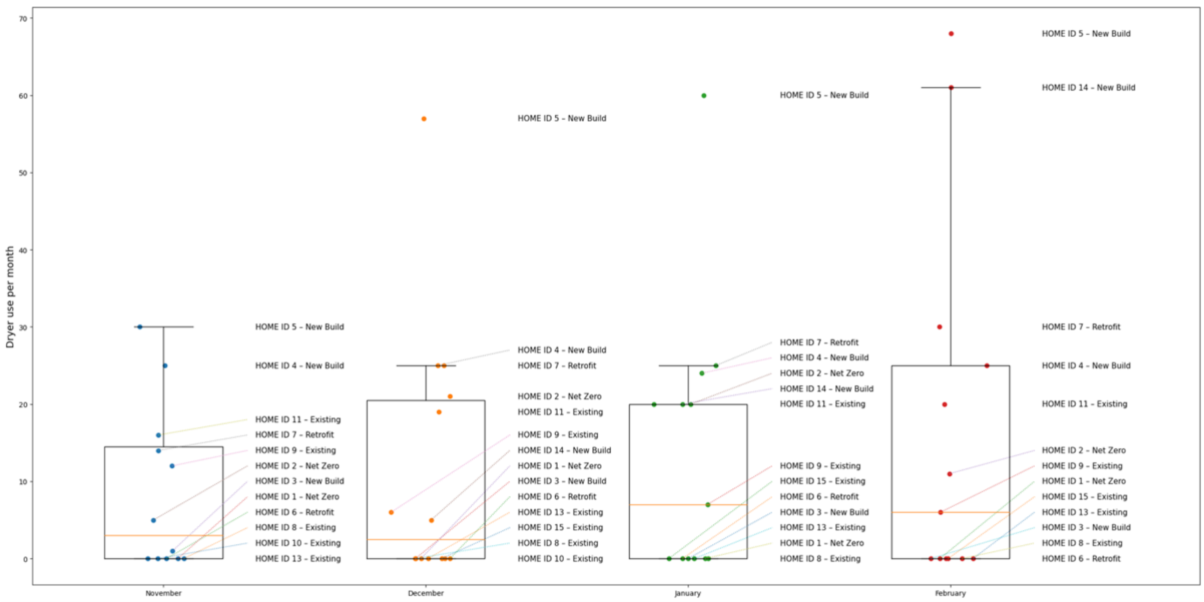


Figure 6. Self-reported electric clothes dryer use per month for each household.



Key findings

Overall, washing machine and electric dryer use vary widely between households and across months, with no clear or consistent differences by housing archetype, indicating substantial diversity in laundry practices across the cohort.

- Reported washing loads span a very wide range across the cohort, from close to 0 loads per month in some households to around 100 loads per month in the highest cases, indicating substantial differences in washing frequency between households.
- Large variation is visible both between households and within households over time, with some homes showing monthly changes of 10–30 loads per month.
- No systematic pattern is evident by archetype: Net Zero, New Build, Retrofit, and Existing homes all appear across low (≈0–10 loads/month), medium (≈15–30 loads/month), and high (>40 loads/month) washing-use ranges.
- Several New Build homes appear among the highest reported washing loads in some months (around 60–100 loads/month), but other New Build homes report moderate or low use, indicating substantial variation within this archetype.
- Electric dryer use also varies widely, ranging from 0 uses per month in some households to approximately 60–70 uses per month in the highest cases.
- A notable number of households report zero or near-zero dryer use across multiple months.

- As with washing machine use, no strong clustering by archetype is apparent: Net Zero, New Build, Retrofit, and Existing homes are all represented among both low (0–5 uses/month) and high (>20 uses/month) dryer-use households.
- Considerable month-to-month variability is visible for several households, with changes of 10–30 dryer uses per month in some cases.

Interpretation

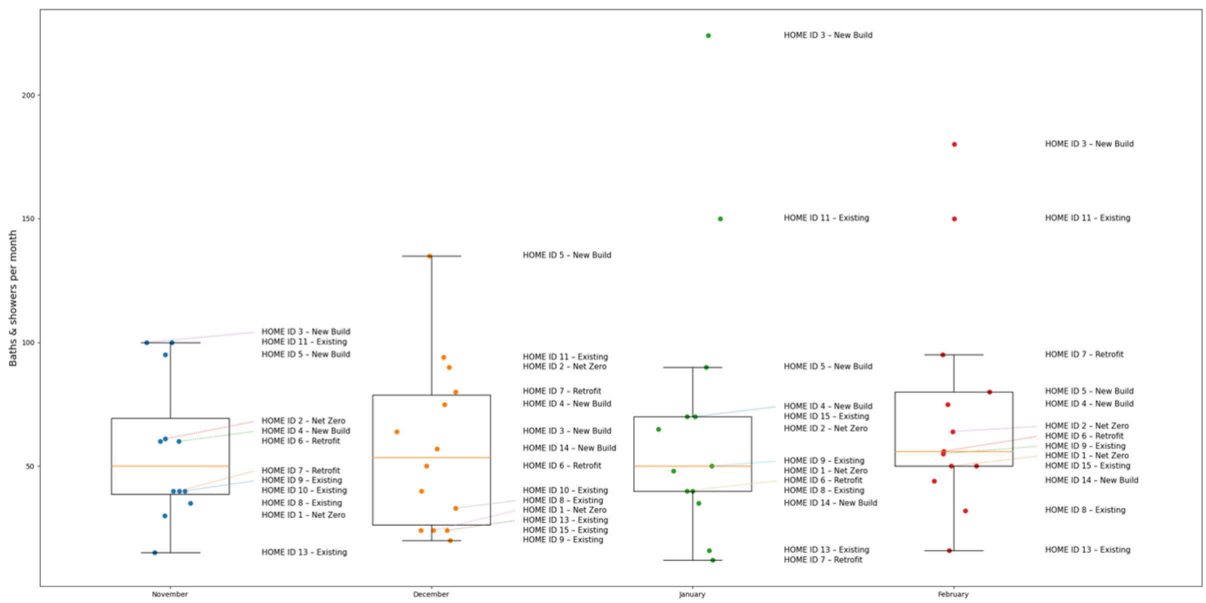
The wide variation in washing machine and dryer use appears to align, in part, with known differences in household composition. Households with more occupants and/or children or teenagers, such as HOME ID 11 (three adults, one teenager, one child) and HOME ID 5 (one adult, two teenagers, one child), tend to appear among the higher ranges of washing loads and dryer use, consistent with greater overall laundry demand. Single-adult households such as HOME ID 12 and HOME ID 8 are more often found toward the lower end of reported use. However, important exceptions are evident. HOME ID 3, which consists of two adults, reports by far the highest washing machine use in the cohort, indicating that laundry frequency cannot be explained by household size alone. Taken together, these patterns suggest that while household composition may contribute to differences in laundry-related energy use, the results should be treated with caution and likely also reflect variation in routines, appliance practices, and inherent uncertainty with self-reported data.

Comparison of Figures 5–6 (washing machine and dryer use) with the results of Figure 5 (daily energy spend) suggests no strong or consistent relationship between reported laundry activity and total daily household energy costs. Overall, this weak alignment indicates that laundry practices are only one of many contributors to total household energy expenditure, and suggests that building fabric, heating system type, the presence or absence of Solar PV, and a range of other behavioural factors also influence overall household energy consumption.

Hot water (baths and showers)

Figure 7 presents each household's self-reported number of baths and/or showers taken per month for November, December, January, and February of the 2024/25 heating season. Households were asked to estimate how many baths and showers were taken across the household in each month, with each point representing a household's monthly estimate and labelled by HOME ID and housing archetype. Bathing and showering are relatively energy- and hot-water-intensive activities and therefore constitute an important component of overall household energy demand. The reported results provide a useful basis for exploring differences and variability in hot water–related practices between households across the heating season.

Figure 7. Monthly self-reported number of baths and/or showers per household.



Key findings

- Reported numbers of baths and/or showers per month span a wide range across the cohort in all months, from around 10–15 per month at the low end to well over 100 per month at the high end. Substantial variability is evident between households and within individual households across months, with some homes showing large month-to-month changes.
- New Build homes appear across the full range of reported values, including some of the highest monthly totals (e.g., above 150–200 in January and February) as well as moderate and lower values.
- Existing homes also span a broad range, from relatively low monthly totals (around 15–30) to high values (above 100 in some months).

- Retrofit homes are distributed mainly within the low-to-mid range, but also include some higher monthly totals (e.g., around 80–95 in February).
- Net Zero homes generally fall within the low-to-mid range across months, but still show month-to-month variation and overlap with other archetypes.

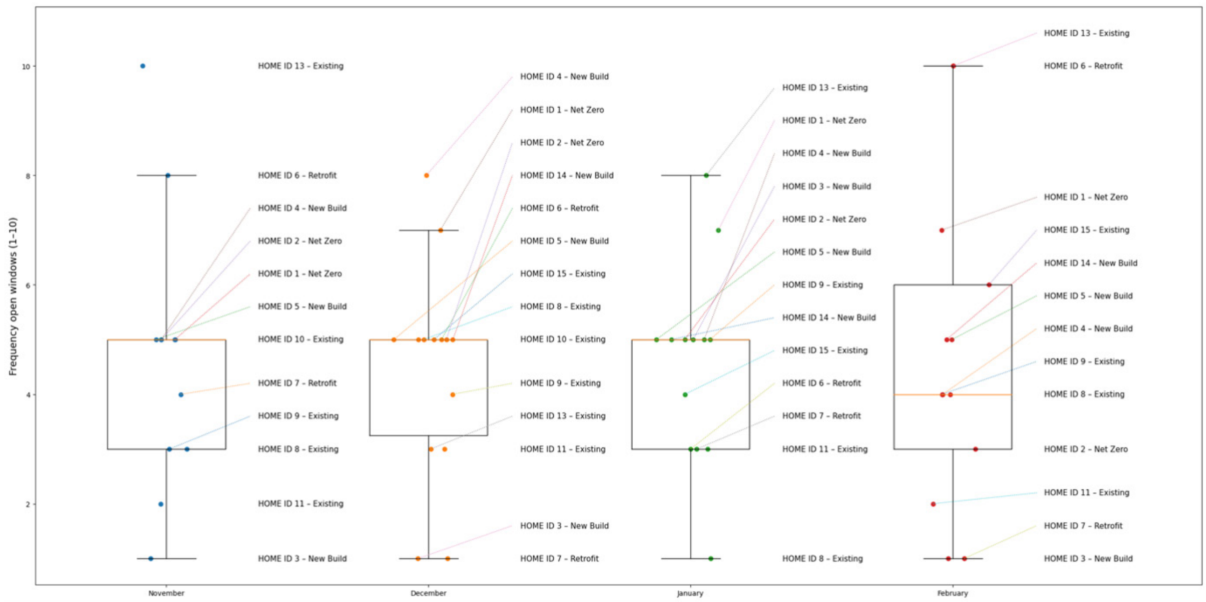
Interpretation

As with laundry, hot water use shows pronounced heterogeneity across households and weak clustering by archetype. Higher monthly totals of baths and showers tend to align with households that include multiple occupants and/or children, while lower totals are more often reported by smaller or single-adult households. This broadly corresponds with patterns observed for washing machine use, where larger households generally report higher laundry frequencies, although notable exceptions exist. Taken together, the bathing/showering data and washing machine results (i.e., hot water use and laundry) are likely to represent the largest non-heating contributors to variation in household energy consumption across the sample. One thing to note is that bathing and showering will feature in the energy use for hot water demand, but laundry will not. This underscores the importance of considering everyday water- and appliance-related practices alongside space-heating behaviour when interpreting patterns of household energy demand.

Ventilation routine

Figure 8 presents each household's self-reported frequency of opening windows for November, December, January, and February of the 2024/25 heating season, using a 1–10 scale (where 1 indicates windows are open constantly, 5 indicates windows are opened sometimes, and 10 indicates windows are never left open). Households were asked to reflect on their typical window-opening behaviour across each month, with each point representing a household's monthly response and labelled by HOME ID and housing archetype. Window-opening is a key ventilation-related practice that can influence indoor air quality, thermal comfort, and space-heating demand, and the figure therefore provides insight into how ventilation behaviours vary between households and across the winter period.

Figure 8. Monthly self-reported frequency of opening windows (1–10 scale) for each household.



Key findings

- Reported values span almost the full scale in every month, from households indicating windows are opened constantly to households indicating windows are never opened, demonstrating substantial variation between households.
- Across all months, most households cluster around sometimes opening windows (values around 4–6), with fewer households at the extremes of constantly (values around 1–2) or rarely/never opening windows (values around 8–10)New Build homes appear across the full range, including households reporting windows are opened constantly, sometimes, and rarely/never, with no clear clustering.
- Net Zero homes are mainly located in the sometimes to rarely/never range across months, but do not form a distinct cluster separate from other archetypes.
- Retrofit homes span low, mid, and high parts of the scale, including constantly, sometimes, and rarely/never opening windows in different months.
- Existing homes also occupy most parts of the scale, with households reporting windows opened constantly, sometimes, and rarely/never, overlapping with all other archetypes.

- Individual households do not always report the same category each month; some move between sometimes and rarely/never, or between constantly and sometimes, contributing to the month-to-month spread visible in the figure.

Interepration

The wide spread of reported window-opening frequencies across all archetypes reinforces earlier findings that ventilation practices are primarily shaped by household routines and preferences rather than dwelling type alone. Comparing window-opening frequencies with laundry practices suggests some alignment between low dryer use, higher washing loads, and more frequent window opening in certain households, consistent with indoor air-drying of clothes. These patterns support the interpretation that, for some households, window opening may be linked to moisture management associated with clothes drying, although this relationship is not universal across the sample. Comparison with heating comfort indicates a small number of cases where lower comfort coincides with windows being opened sometimes or more frequently, which may contribute to heat loss and reduced perceived warmth. Conversely, some households report moderate-to-high comfort while also opening windows sometimes, suggesting that window opening does not necessarily translate into discomfort and may reflect short, purposeful ventilation rather than prolonged heat loss.

Taken together, the results indicate that ventilation regimes form part of a complex set of everyday practices that interact with laundry routines, comfort perceptions, and heating behaviour. While more frequent window opening could plausibly contribute to higher space-heating demand and therefore higher energy costs in some households, the absence of a consistent pattern suggests that ventilation is only one of several interacting factors shaping overall household energy expenditure.

Heat management and coping strategies

The following section examines five specific heat management and coping strategies that were explicitly tested through the periodic household survey: wearing extra clothes (Table 1), using a hot water bottle or heat pack (Table 2), using extra blankets (Table 3), closing internal doors to retain heat (Table 4), and closing blinds or curtains to reduce heat loss (Table 5). These strategies were selected because they are commonly identified in the literature as everyday, low-cost ways households attempt to maintain thermal comfort, particularly under conditions of constrained energy use. Households were asked to report how often they used each strategy over the previous month. Together, these questions provide insight into the extent to which households rely on coping practices to manage warmth and comfort, complementing earlier analyses of heating system operation, reported comfort, and household energy use.

Table 1. Monthly self-reported frequency of wearing extra clothes to maintain warmth (1–10 scale) for each household.

[1 = Constantly (I always put on extra clothes to keep warm); 5 = Sometimes (every now and again I'll put extra clothes on to stay warm); 10 = Never (I never put extra clothes on to keep warm)]

HOME ID	Archetype	Nov	Dec	Jan	Feb
1	Net Zero	3	10	5	8
2	Net Zero	10	10	10	10
3	New Build	10	10	10	1
4	New Build	5	5	5	10
5	New Build	10	7	5	6
6	Retrofit	10	10	10	10
7	Retrofit	10	9	4	3
8	Existing	5	6	5	5
9	Existing	3	3	7	4
10	Existing	4	5	–	–
11	Existing	2	1	3	1
12	Existing	–	–	–	–
13	Existing	3	4	8	9
14	New Build	–	5	5	5
15	Existing	–	8	5	5

Table 2. Monthly self-reported frequency of using hot water bottle/heat pack to maintain warmth (1–10 scale) for each household.

[1 = Constantly (I always use a hot water bottle); 5 = Sometimes (every now and again I'll use a hot water bottle); 10 = Never (I never use a hot water bottle)]

HOME ID	Archetype	Nov	Dec	Jan	Feb
1	Net Zero	10	10	10	10
2	Net Zero	10	10	10	10
3	New Build	10	10	10	10
4	New Build	10	10	5	10
5	New Build	9	10	8	10
6	Retrofit	10	10	10	10
7	Retrofit	2	5	10	10
8	Existing	10	10	10	10
9	Existing	6	10	8	7
10	Existing	5	10	–	–
11	Existing	10	9	7	10
12	Existing	–	–	–	–
13	Existing	3	4	10	10
14	New Build	–	1	10	4
15	Existing	–	6	6	6

Table 3. Monthly self-reported frequency of using extra blankets to maintain warmth (1–10 scale) for each household.

[1 = Constantly (I always use extra blankets to keep warm); 5 = Sometimes (every now and again I used extra blankets to stay warm); 10 = Never (I never used extra blankets to keep warm)]

HOME ID	Archetype	Nov	Dec	Jan	Feb
1	Net Zero	10	10	10	10
2	Net Zero	10	10	10	10
3	New Build	10	10	10	10
4	New Build	5	5	5	7
5	New Build	2	4	4	6
6	Retrofit	10	10	10	10
7	Retrofit	10	2	3	10
8	Existing	10	10	10	10
9	Existing	10	10	10	10
10	Existing	3	5	–	–
11	Existing	2	3	1	1
12	Existing	–	–	–	–
13	Existing	10	4	8	10
14	New Build	–	5	1	5
15	Existing	–	4	6	6

Table 4. Monthly self-reported frequency of closing internal doors to maintain warmth (1–10 scale) for each household.

[1 = Constantly (doors are always closed to keep the room at temperature); 5 = Sometimes (every now and again doors are closed to keep rooms warm); 10 = Never (doors are never closed in the home because of temperature)]

HOME ID	Archetype	Nov	Dec	Jan	Feb
1	Net Zero	8	10	10	8
2	Net Zero	1	1	5	10
3	New Build	10	10	10	10
4	New Build	5	4	5	8
5	New Build	1	1	1	1
6	Retrofit	5	3	2	10
7	Retrofit	2	2	3	5
8	Existing	5	1	1	2
9	Existing	3	3	3	2
10	Existing	1	2	–	–
11	Existing	3	2	5	5
12	Existing	–	–	–	–
13	Existing	1	10	1	5
14	New Build	–	5	10	10
15	Existing	–	9	5	6

Table 5. Monthly self-reported frequency of closing blinds/curtains to maintain warmth (1–10 scale) for each household.

[1 = Constantly (blinds or curtains are always closed to keep rooms warm); 5 = Sometimes (every now and again blinds or curtains are closed to keep rooms warm); 10 = Never (blinds or curtains are never closed to keep rooms warm)]

HOME ID	Archetype	Nov	Dec	Jan	Feb
1	Net Zero	10	8	5	5
2	Net Zero	5	5	5	10
3	New Build	10	10	10	10
4	New Build	5	5	5	5
5	New Build	5	8	4	5
6	Retrofit	10	8	5	10
7	Retrofit	9	5	7	10
8	Existing	5	5	5	5
9	Existing	3	3	2	3
10	Existing	1	3	–	–
11	Existing	5	5	5	2
12	Existing	–	–	–	–
13	Existing	1	6	5	8
14	New Build	–	5	1	7
15	Existing	–	5	5	6

Key findings

- The data do not reveal any clear or systematic pattern between housing archetype (Net Zero, New Build, Retrofit, Existing) and the types of heat management or coping strategies reported; instead, households within the same archetype use different combinations of strategies. Reported use of all five strategies spans from constantly to never across the cohort, indicating substantial variation between households.
- For extra clothes, households across all archetypes report values ranging from constantly to never, with many households positioned around sometimes. For hot water

bottles / heat packs, responses range from constantly to never in all archetypes, with several households in each archetype reporting frequent use and others reporting no use. Extra blanket use similarly spans the full range across Net Zero, New Build, Retrofit, and Existing homes.

- Reported frequency of closing internal doors varies from constantly to never across households in all archetypes, with many reporting sometimes closing doors. Reported frequency of closing blinds or curtains also covers the full range from constantly to never across all archetypes.

- Net Zero homes report a mixture of sometimes and never for several coping strategies, alongside occasional reports of constant use for specific items in some months. New Build homes show wide dispersion across all strategies, including households reporting constant, sometimes, and never use.Retrofit homes also display variation across the full range for most strategies. Existing homes collectively occupy all parts of each scale, with no consistent pattern unique to this archetype.

- Several individual households change category between months (e.g., from sometimes to rarely/never, or from sometimes to frequently/constantly) for one or more strategies, contributing to visible month-to-month spread in the data.

Interpretation

The reported patterns suggest that the use of heat-management and coping strategies is shaped less by housing archetype and more by long-standing habits, cultural norms, and individual or household histories. Practices such as wearing extra clothes, using hot water bottles, or adding extra blankets are often learned behaviours that people carry from earlier life experiences, including what they grew up doing in their family home, rather than strategies adopted solely in response to current dwelling characteristics. Similarly, behaviours such as closing internal doors or closing blinds and curtains are familiar, everyday actions that some households appear to perform routinely and others rarely, independent of dwelling type.

At the same time, the data indicate that some households may be using these strategies primarily to manage costs. For example, some Existing and Retrofit homes (e.g., HOME ID 11 and HOME ID 6) report both greater use of coping strategies and more frequent turning off heating in certain months, which may point to cost-conscious management of warmth rather than comfort-driven sufficiency. In contrast, the Net Zero homes (HOME ID 1 and HOME ID 2) generally report high heating comfort alongside relatively low reliance on kinetic coping strategies, and also tend to report that heating is rarely or never turned off. This combination is consistent with high-performance building fabric and continuous low-level heating, where additional coping behaviours are less necessary.

Cross-checking with heating comfort ratings further supports this distinction. Households such as HOME ID 11 (Existing), which report lower comfort in several months, also tend to report using coping strategies more frequently, suggesting these practices may compensate for unmet warmth needs. Conversely, households reporting high comfort (e.g., the Net Zero homes HOME ID 1 and HOME ID 2, and one New Build home, HOME ID 3) generally show lower or more moderate use of coping strategies, indicating less need to rely on supplementary measures.

Overall, the findings suggest that coping and heat-management practices reflect a mix of ingrained habit, efficiency-oriented behaviour, and financial constraint, with their meaning varying by household context rather than aligning systematically with housing archetype.

Summary

Across all homes in the study, people's day-to-day experiences of warmth, energy use, and comfort are shaped by a combination of the building itself and how households live within it. Broadly, the new build and net zero homes tend to offer more consistent and comfortable indoor conditions, while existing homes show the widest range of experiences, including a greater risk of colder conditions and poor ventilation. Retrofit homes often sit between these two, suggesting that improvements can help but do not guarantee good outcomes on their own.

The results of the periodic surveys suggest that households' energy-related behaviours—such as how warm people choose to keep their homes, when and for how long heating is used, how often windows are opened, and how frequently appliances like washing machines, tumble dryers, baths, and showers are used—are extremely varied and play a considerable role in shaping a home's eventual energy consumption patterns. Some households maintain steady indoor temperatures and run heating continuously through colder periods, while others regularly switch heating off for parts of the day, rely more on additional clothing or blankets, or adjust ventilation to manage moisture and air quality.

At the same time, no housing type shows a single "typical" pattern of behaviour: thermostat settings, heating schedules, ventilation habits, and everyday practices such as laundry and bathing vary widely within every archetype. This means that while building design and construction quality set important limits on what is possible, household needs, routines, and constraints—such as family size, health, working patterns, financial pressures, and personal comfort preferences—play a major role in determining actual comfort, energy use, and costs.

The preliminary household profiles help explain some of the variation observed in the periodic survey results, particularly for activities linked to hot water and appliance use. Homes with more occupants, including those with children or teenagers, generally report more frequent bathing, showering, and laundry, which aligns with periodic survey findings showing higher non-heating energy demand in some of these households. At the same time, this relationship is not straightforward: some smaller households also report relatively frequent washing and bathing, while some larger households report more moderate levels. This helps to explain why the periodic surveys show wide spreads in hot water and appliance use even among homes with similar numbers of occupants.

Household composition and occupancy patterns also appear to influence heating practices, but again in varied and overlapping ways. Homes with low weekday daytime occupancy are more likely to report turning heating off when occupants are out, while homes that are occupied throughout the day more often report leaving heating on for longer periods. Larger households and those with children sometimes report higher preferred temperatures, but high thermostat settings are also found in smaller households, and moderate or low settings are found in larger ones. Similarly, lower comfort is reported in both single-person and multi-person households. Overall, the periodic surveys suggest that household composition and occupancy provide useful context for interpreting patterns of comfort, heating use, and energy demand, but they interact with many other factors—such as building performance, heating system characteristics, and individual preferences—meaning they cannot reliably predict outcomes on their own.

Reported energy spend shows some broad differences by housing archetype, with net zero homes generally clustered at the lower end of daily costs and existing homes more often appearing at the higher end, while new build and retrofit homes span a wide range. This suggests that building fabric and system specification influence the overall level of energy demand, but do not determine costs on their own. Household profile also appears to matter: homes with more occupants, particularly those with children, tend to report higher energy spend, consistent with greater hot water use, laundry, and longer periods of occupancy. However, there is substantial overlap between household types, with some small households reporting relatively high costs and some larger households reporting moderate costs. Together, these patterns indicate that both archetype and household composition shape energy spend, but their effects are strongly mediated by everyday practices, heating operation, and other contextual factors such as tariffs and system performance.

Overall, these cases reinforce three messages from the periodic survey results:

1. Low comfort can arise from both heating rationing and technical limitations.

2. Low-carbon technologies on their own do not guarantee low costs or high comfort.

3. Household composition and occupancy shape demand, but do not reliably predict outcomes.

Together, these outliers show why periodic survey results must be interpreted alongside household context and building characteristics, and why archetype-level averages alone are insufficient for targeting interventions.

3. Matched Case Studies

Six homes were selected as case studies to enable more detailed, like-for-like comparisons of household experiences, behaviours, and outcomes (Table 6). These homes were grouped into three comparability clusters based on shared physical characteristics such as age, dwelling type, size, and heating system, so that differences in results could be explored with a broadly similar baseline of building physics. Two homes were selected within each cluster, allowing attention to focus on how household practices, preferences, and circumstances interact with comparable dwellings, rather than being dominated by major differences in building form or specification. Together, these clusters span net zero new-build homes, conventional new-build homes, and older existing homes, providing a structured way to examine both technological and behavioural influences on comfort, energy use, and costs.

Table 6. Case study comparability clusters and baseline building characteristics.

Cluster	Home IDs	Construction period	Dwelling type	Heating system	Specification / archetype	Bedrooms
I	1; 2	2020s	Semi-detached	Heat pump	Net Zero specification	3
II	4; 5	2020s	End-terrace	Gas boiler	New build (conventional)	3
III	9; 11	1940–1970	Mid-terrace	Gas boiler	Existing housing	3

Visualising monthly patterns using heatmaps

To support comparison across the case study homes, the monthly survey responses for each household have been presented as heatmaps. In these charts (Figures 9 to 14), each row represents a different aspect of household experience or behaviour (such as comfort, heating operation, window opening, or use of coping strategies), and each column represents a month. The colour shading shows the reported value, allowing patterns to be seen immediately rather than requiring readers to compare multiple tables of numbers.

This visual approach helps to highlight three main features of the data. First, it shows which aspects of experience are relatively stable over time and which fluctuate from month to month within the same home. Second, it makes it easier to see relationships between different measures, such as whether lower comfort tends to coincide with greater use of coping strategies or more frequent heating-off behaviour. Third, when heatmaps are viewed side by side for physically comparable homes, they illustrate how households living in similar dwellings can display very different patterns of behaviour, comfort, and coping. Overall, the heatmaps provide an accessible way to explore how building characteristics and everyday practices combine to shape lived experience, complementing the summary statistics presented elsewhere in the report.

Net Zero homes (cluster I)

These two homes share the same construction period, dwelling type, size, and heat pump–based Net Zero specification. Both net zero homes show generally high levels of comfort and strong satisfaction with their heating systems, supporting the wider finding that high-performance new-build homes can provide stable and comfortable indoor conditions. HOME ID 1 reports consistently high ratings for heating system performance and comfort across all months, with only modest variation. HOME ID 2 also reports high comfort in most months, although a dip occurs in December, alongside a lower rating of the heating system and comfort for that month.

Heating operation patterns are similar in both homes. Each household reports rarely or never turning heating off in most months, indicating a tendency towards continuous or near-continuous heating, which aligns with best-practice operation for heat pump systems. Window opening remains at low-to-moderate levels in both homes, suggesting limited reliance on ventilation that would significantly undermine indoor temperatures during colder periods.

Figures 9 & 10. Heatmaps of monthly comfort, heating operation, and coping behaviours for HOME IDs 1 & 2.

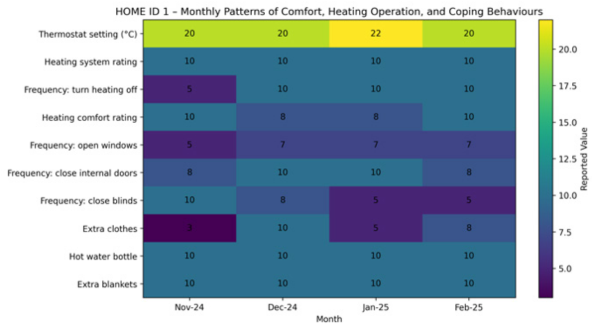


Fig. 9 (HOME ID 1).

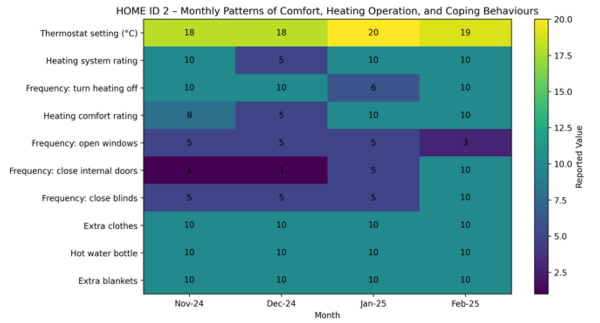


Fig. 10 (HOME ID 2).

Despite these similarities, the two homes differ in their use of coping strategies. HOME ID 1 shows generally low reliance on extra clothing, while HOME ID 2 reports consistently high use of extra clothes, hot water bottles, and blankets, even when comfort ratings are high. This suggests different personal comfort practices or habits, rather than large differences in building performance. Overall, the comparison shows that physically similar net zero homes can deliver similarly good thermal conditions, but households may still adopt distinct comfort and coping routines, reinforcing the importance of considering both building performance and household behaviour when interpreting results.

New build homes (Cluster II)

These two homes share the same construction period, dwelling type, size, gas heating and new build specification. The two new build homes display moderate and variable comfort and satisfaction with their heating systems, with neither showing the consistently high ratings seen in the net zero cluster. HOME ID 4 reports heating system ratings that are generally high, but comfort ratings fluctuate across months, including a dip in January. HOME ID 5 reports steady, mid-range comfort scores across all months, alongside consistently moderate ratings of the heating system.

Heating operation differs between the two homes. HOME ID 4 reports moderate, increasing frequency of turning heating off by February, whereas HOME ID 5 reports very low frequencies of turning heating off, indicating a more continuous heating pattern. Despite this difference, both homes report similar overall comfort levels, suggesting that heating schedules alone do not explain comfort outcomes.

Figures 11 & 12. Heatmaps of monthly comfort, heating operation, and coping behaviours for HOME IDs 4 & 5

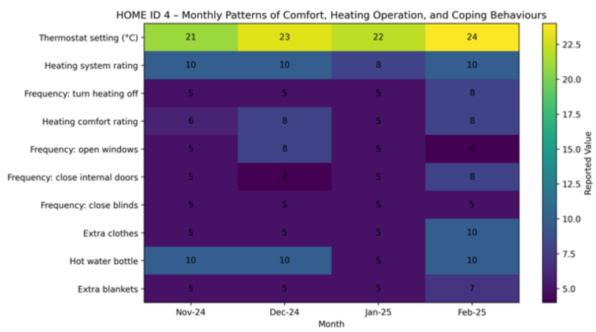


Fig. 11 (HOME ID 4).

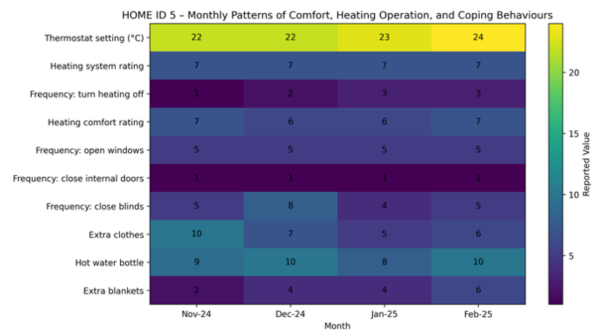


Fig. 12 (HOME ID 5).

Differences are also evident in everyday practices and coping strategies. HOME ID 5 reports consistently high use of extra clothes and hot water bottles across all months, while HOME ID 4 shows lower and more variable use of these strategies, but a marked increase in extra clothes in February. Window opening and closing of internal doors are broadly similar in both homes, remaining low-to-moderate.

Overall, the comparison suggests that even within physically similar new build homes, households can adopt different heating and coping practices while experiencing broadly comparable comfort. This reinforces the wider finding that new build status alone does not guarantee uniformly low-effort warmth, and that household routines and preferences play an important role in shaping lived experience.

Existing homes (Cluster III)

These two homes share the same construction period, dwelling type, size, gas heating and untreated fabric specification (Table 6). The two existing homes show consistently lower comfort and satisfaction with their heating systems than the net zero and new build clusters, but they also differ noticeably from one another. HOME ID 9 reports moderate heating system ratings and mid-range comfort scores, with comfort improving slightly in December and January before falling again in February. In contrast, HOME ID 11 reports very low heating system ratings and very low comfort across all months, indicating persistent dissatisfaction and ongoing difficulty achieving comfortable conditions.

Heating operation patterns are broadly similar in that both households report turning heating off at moderate frequencies, rather than leaving it on continuously. However, these similar heating schedules lead to very different outcomes: HOME ID 9 achieves moderate comfort, while HOME ID 11 remains uncomfortable. This suggests that building condition and/or system performance plays a stronger role than heating schedules alone in explaining the contrast between the two homes.

Figures 13 & 14. Heatmaps of monthly comfort, heating operation, and coping behaviours for HOME IDs 9 & 11.

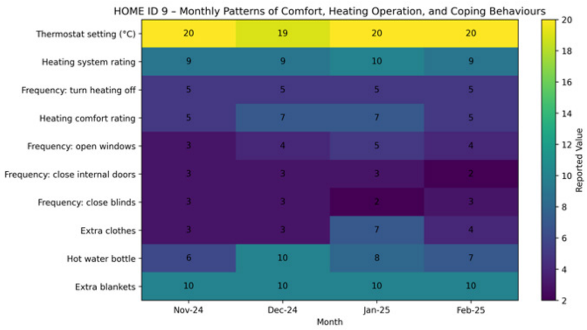


Fig. 13 (HOME ID 9).

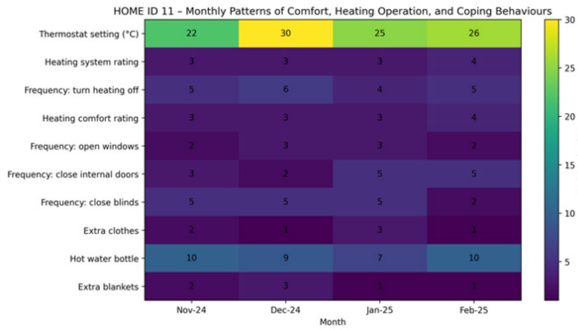


Fig. 14 (HOME ID 11).

Coping strategies are more prominent in HOME ID 11. Hot water bottle use is very high in all months, and some use of extra blankets and extra clothes is also reported, reflecting ongoing attempts to manage low comfort without relying solely on the heating system. HOME ID 9 also reports high use of hot water bottles and extra blankets, but comfort levels are generally higher than in HOME ID 11, indicating that coping in this home may be more supplementary rather than essential.

Overall, this comparison highlights the wide range of experiences within existing housing. Two physically similar older homes can produce very different comfort outcomes, even with similar heating schedules, reinforcing the importance of dwelling condition, system effectiveness, and potentially past maintenance or retrofit history in shaping lived experience.

Across the three clusters, the case studies demonstrate that physical similarity reduces some sources of variation, but does not remove large differences in comfort, coping, and heating practices, reinforcing the central finding that outcomes are co-produced by buildings and households.

Key findings

- Net zero homes deliver the most stable comfort, with consistently high heating system ratings and comfort scores, whereas new build and especially existing homes show greater fluctuation and lower average comfort. *Implication*: High-performance fabric and system integration significantly reduce the risk of poor thermal experience.

- Physically similar homes can show very different lived experiences. Within each cluster, households display distinct heating practices and coping behaviours despite comparable building characteristics. *Implication*: Building physics influence, but do not determine outcomes.

- Continuous or near-continuous heating is common in higher-performing homes, while moderate heating-off behaviour appears more often in existing homes. *Implication*: System type and building performance influence how feasible it is to maintain steady warmth.

- Low comfort arises from different mechanisms. In some homes it aligns with frequent heating-off behaviour (suggesting rationing), while in others it occurs despite heating being left on (suggesting fabric or system limitations).*Implication*: Interventions need to distinguish between affordability issues and technical shortcomings.

- Coping strategies are widespread across all clusters, including net zero homes, but tend to be most intense and persistent in the lowest-comfort existing home. *Implication*: Coping behaviours can act as a useful indicator of unmet comfort needs.

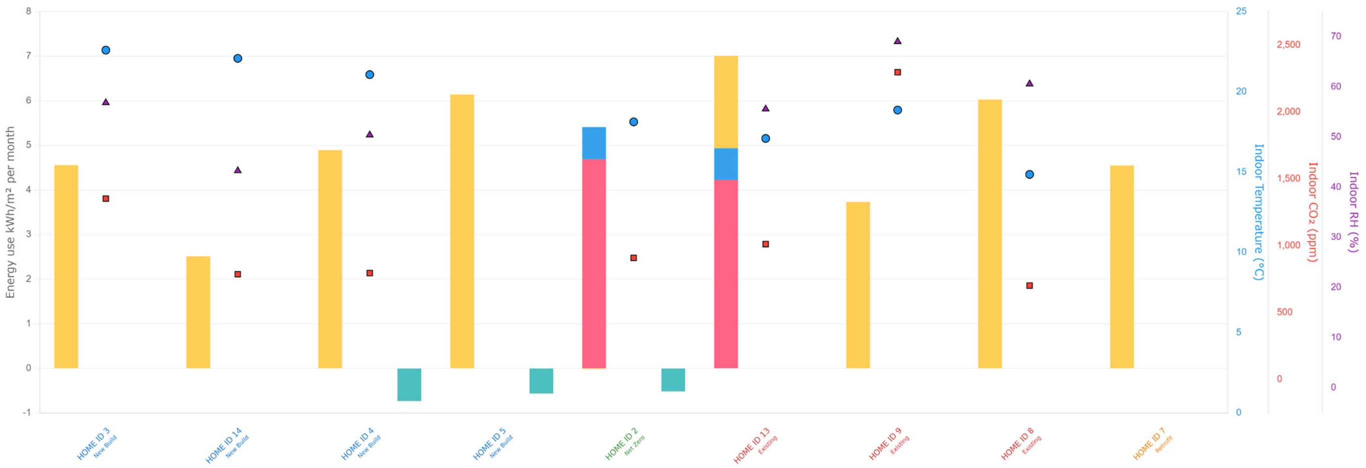
- High thermostat settings do not guarantee high comfort, particularly in existing housing. *Implication*: Raising setpoints is not an effective substitute for improving building or system performance.

- Household practices shape demand even in efficient homes. Some new build and net zero homes show high reliance on extra clothes or hot water bottles despite good comfort.*Implication*: Occupant routines and preferences remain important alongside technical solutions.

4. Comparing the Behavioural & Sensor Data

The following chart is used to examine whether expectations identified in the behavioural analysis are reflected in monitored energy use and indoor environmental conditions. Figure 15 brings together data on energy use, indoor temperature, and indoor air quality for each monitored home during November 2024. Energy use is shown as stacked bars, with different colours indicating how energy is used: pink represents space heating, blue represents hot water, yellow represents appliances and other household electricity use, and teal (shown below zero where present) represents on-site solar electricity generation, which reduces energy drawn from the grid. Average indoor temperature and indoor carbon dioxide (CO_2) concentration are overlaid as symbols and read against the axes on the right-hand side of the chart. Taken together, the chart allows comparison between homes in terms of both energy use and the indoor conditions achieved and provides a basis for assessing whether behavioural expectations are visible in the quantitative monitoring data.

Figures 15. Monthly energy use intensity by end use, indoor temperature, and indoor CO2 concentration across monitored homes (November 2024).



Data coverage and interpretation note

The energy data shown in this chart should be read with some care, as not all energy measurements are available for every home. While the behavioural research covered a wider group of households, only a subset have sufficiently complete and reliable monitoring data to be included in this figure. We have checked the available data for each property against the energy systems known to be installed, including electricity use, space heating, hot water, and on-site solar panels where present.

For November 2024, only HOME ID 2 and HOME ID 13 have a complete and internally consistent set of energy data that allows their total energy use to be fully assessed. In the later winter months, HOME ID 13 is the only property with consistently complete energy data across all energy uses. Other households discussed in the behavioural section are not shown in the chart because key elements of their monitored energy data are missing or incomplete.

Several homes are known to have solar panels but do not show the expected reduction in energy use associated with on-site generation or export. These include HOME ID 9, HOME ID 7, HOME ID 4, and HOME ID 5. In these cases, the absence of negative energy values reflects missing or incomplete solar data rather than the absence of solar panels. Homes without solar panels would not be expected to show this pattern.

In addition, some other energy measurements are incomplete across the wider group of homes. Indoor temperature and CO_2 data are more complete and are included primarily to provide context on indoor conditions, rather than to support detailed comparisons of energy performance between properties.

Overall, the chart is intended to illustrate broad patterns and relationships between energy use and indoor environmental conditions, rather than to support precise comparison of total or net energy use across individual homes. Similar patterns were observed in December 2024, January 2025, and February 2025. While absolute energy use and indoor temperatures vary seasonally, the relative differences between homes and the behavioural pathways identified in November remain consistent.

Linking behavioural expectations with monitored energy and environmental outcomes

This section brings together what residents told us about how they use their homes with what the monitoring equipment recorded about energy use, indoor temperature, and air quality. The aim is to check whether patterns identified in the behavioural research are also visible in the monitored data.

We first analysed the survey and interview findings to understand household routines, expectations, and constraints, such as how people use their heating, how warm they expect their homes to be, and how they manage ventilation. From this, we developed a set of clear expectations about how different homes might appear in the monitoring data in terms of energy use, indoor temperature, and CO_2 levels. We then used the sensor and smart meter data to see whether these expectations were reflected in practice.

This section is not intended to prove cause and effect. Instead, it looks at whether different behavioural patterns identified in the qualitative research can also be seen in the monitored data. This helps explain why homes that are physically similar can perform very differently, and why similar levels of comfort can be achieved through different combinations of energy use and ventilation. Including this section strengthens the report by showing how the behavioural findings and monitoring data support one another. It also highlights why energy and sensor data on their own are not enough to fully understand housing performance, and why residents' lived experience is an essential part of interpreting energy use, indoor temperature, and air-quality data.

Based on the behavioural analysis, seven expectations were identified about how different homes would appear in the quantitative monitoring data. The tables that follow set out these expectations and show how they are reflected in the monitored energy and indoor environmental conditions.

Expectations based on how households use their homes:

1. Homes with high levels of insulation and airtightness, where residents leave the heating on most of the time (Net Zero homes), were expected to maintain steady indoor temperatures while using relatively low amounts of energy.

2. Existing homes where residents expect very warm indoor conditions were expected to use more energy but not necessarily achieve higher indoor temperatures.

3. Homes where residents frequently turn the heating off to manage costs were expected to have cooler indoor temperatures and lower overall energy use.

4. Some homes with low reported comfort were expected to have low indoor temperatures even though the heating is usually left on, suggesting building or system limitations rather than deliberate under-heating.

5. Homes where residents frequently open windows for fresh air or to deal with moisture were expected to show lower indoor CO_2 levels, but potentially higher heating demand.

6. Existing homes fitted with heat pumps were expected to use more energy and deliver only moderate comfort compared with Net Zero homes using the same technology.

7. Homes reporting similar levels of comfort were expected to achieve this in different ways, using different combinations of energy use, indoor temperature, and ventilation.

1. Expectation: Net Zero homes: steady heating and lower energy use

What residents told us	What the monitoring data show	What this tells us
Residents in Net Zero homes (HOME ID 1 and HOME ID 2) reported that they were generally comfortable, rarely turned their heating off, and did not rely much on coping strategies such as extra clothing or blankets. Based on this, we expected these homes to maintain steady indoor temperatures while using relatively little energy.	The chart shows that HOME ID 2 maintains indoor temperatures within a narrow and comfortable range, while using less energy per square metre than most other homes. CO_2 levels are moderate, suggesting that comfort is not being achieved by closing the home off or reducing ventilation.	The data support the expectation that in well-insulated homes, leaving the heating on at a steady level can provide good comfort efficiently, without high energy use or poor air quality.

2. Expectation: Existing homes with high warmth expectations: higher energy use, limited comfort

What residents told us	What the monitoring data show	What this tells us
In HOME ID 11 (an existing home), residents reported very high thermostat settings and strong expectations of warmth, but still experienced low comfort and relied on coping strategies. This suggested that high energy use might not translate into higher indoor temperatures.	HOME ID 11 shows relatively high energy use, but indoor temperatures remain modest compared with some homes that use less energy. CO_2 levels are sometimes high, indicating high occupancy and limited effective ventilation.	The data confirm that higher energy use does not always lead to better comfort in existing homes, and that building condition or heating system limitations can restrict what residents are able to achieve.

3. Expectation: Heating turned off to manage costs: cooler homes and lower energy use

What residents told us	What the monitoring data show	What this tells us
Some households, such as HOME ID 6 (Retrofit) and HOME ID 9 (Existing), reported frequently turning the heating off to manage costs and relying on coping strategies. We expected these homes to have cooler indoor temperatures and lower energy use.	HOME ID 9 has lower indoor temperatures than the Net Zero homes and uses less energy overall. CO_2 levels suggest the home is occupied and not being overheated to compensate.	Lower temperatures in these homes appear to reflect deliberate decisions to limit heating, rather than problems with the building or heating system.

4. Expectation: Low comfort despite heating being left on

What residents told us	What the monitoring data show	What this tells us
In HOME ID 8 (Existing), residents reported low comfort even though the heating was rarely or never turned off. This suggested that low temperatures might persist despite ongoing energy use.	HOME ID 8 has lower indoor temperatures than many other homes, without particularly low energy use. CO_2 levels indicate that the home is occupied.	This supports the view that low comfort in this case is linked to building or system limitations, rather than residents choosing to under-heat their home.

5. Expectation: Window opening and ventilation: lower CO_2, higher energy use

What residents told us	What the monitoring data show	What this tells us
Residents in homes such as HOME ID 3 (New Build) reported opening windows frequently, often to manage fresh air or drying laundry. We expected this to result in lower CO_2 levels, but potentially higher heating demand.	HOME ID 3 has lower CO_2 levels than some other homes, alongside moderate to high energy use. Indoor temperatures are maintained, but at a higher energy cost.	The data support the idea that ventilation habits affect air quality and energy use, regardless of the age or type of the building.

6. Expectation: Heat pumps in existing homes would not automatically deliver low-energy outcomes

What residents told us	What the monitoring data show	What this tells us
In HOME ID 13 (an existing home with a heat pump), residents reported moderate comfort, concerns about running costs, and frequent switching of the heating. We expected energy use to be higher than might be assumed for a low-carbon system.	HOME ID 13 shows relatively high energy use without correspondingly high indoor temperatures. CO_2 levels suggest periods of high occupancy.	The data confirm that heat pumps do not automatically lead to low energy use in existing homes, and that performance depends on building condition and how the system is used.

7. Expectation: Similar comfort achieved in different ways

What residents told us	What the monitoring data show	What this tells us
Across the study, many households reported similar levels of comfort despite very different behaviours, expectations, and constraints.	Homes with similar indoor temperatures often have very different energy use and CO_2 levels, showing that comfort can be achieved through different combinations of heating, energy use, and ventilation.	Comfort is shaped by both the building and how people live in it. There is no single "right" pattern of energy use that delivers comfort across all homes.

Taken together, these seven expectations set out the different ways in which household practices, expectations, and constraints were expected to be reflected in monitored energy use, indoor temperature, and air-quality outcomes. We next draw these strands together and consider how the behavioural and sensor data relate to one another in explaining the observed variation between homes.

5. Evaluationg Monitored Data

Aims

The outline intention of the monitoring campaign was a quantitative comparison of the four groups, to identify any performance improvements for the 'net-zero' approaches in terms of energy use and environmental performance.

The installation of the monitoring equipment had been untaken prior to this study and included a range of energy and environmental sensors. These include the iOpt installations which included sensors for temperature, relative humidity and CO2, and a range of energy monitoring devices, depending on the technologies installed in the properties. Space heating was either by gas boilers in the existing properties (although one property had a heat pump), the standard new-build and the retrofit properties, and with heat pumps provided in the net-zero homes. The standard new-build and net zero homes had photovoltaic panels (PV) to generate electricity, and the net-zero homes had Tesla batteries for electrical storage from the PV.

Energy consumption monitoring included electricity use, and heat flow sensors from the boilers and heat pump. The devices use measurements of temperature and flow rates to estimate the energy consumption in kWh, which would indicate space and water heating loads. In theory this would enable a calculation of space heating, and hot water consumption, but would not account for system losses, such as boiler efficiencies. Non-regulated electrical use (that is electricity not used for space and water heating) is measured in the houses with gas boilers. In the case of dwellings with heat pumps, the heat flow consumption can be deducted from the overall electrical consumption to identify non-regulated (ie space and water heating) electrical consumption. Data was also available on the electrical generation from the PV panels.

Long term reliable collection from multiple data points is challenging in domestic environments. It was clear early on in the project that significant data was missing. Additional data was made available from AICO sensors which provide data on temperature, relative humidity and CO2.

Both organisations have portals which enable interrogation of data. The interfaces are designed to provide a temporal overview of insights into overall performance of the NLC stock, with a system of alerts and an ability to view data from individual dwellings. Multiple data (for example environmental and energy data) cannot be viewed concurrently, and selecting a different metric, for example energy or environmental data, requires that the date range is reselected. The units vary in some cases, for example, hot water demand is shown as temperature rather than energy use. It is not possible to select and save data from this study cohort or apply forms of comparative analysis.

The need to combine data across these data, along with data from the AICO sensors, led to the need for data export to allow the data to be collated. Data exports from the portal were provided by iOpt and AICO which were grouped by month and dwelling in the cohort. In both cases data was downloaded by the host organisation and shared via .csv files which enabled the data to be collated and cleaned. This data has been collated for analysis but has also been developed into a portal for further visualisation and analysis. Information on fiscal meter consumption for the period Oct 2024 – Nov 2025 was also provided separately via spreadsheet summaries.

Data Availability and Limitations

General availability of the data lacked completeness where not all properties had records for all circuit. For example, water heater data was zero or missing for most homes, and off-peak electricity usage data was incomplete. This showed a wider issue of structural heterogeneity in the energy exports. "Mains" electricity channels such as on-peak incoming were typically present, technology-relevant circuits (e.g., PV production, battery discharge, or ASHP-related heating) were only available for a subset of homes and were often dominated by missing or zero values. This created a recurring ambiguity between low consumption and channels that were not metered, not configured, or encountered missed logging. This led to inconsistent cross-property comparisons.

Several parameters in the imported files were not self-evident such as "heating" vs "heating-ashp", "waterheater", "onpeakincoming"/"offpeakincoming", "pvproduction" and "batterydischarge". Further to this, the monthly available data for energy consumption had discrepancies, as months with incomplete data were available and at the same time files with complete data were also available, which caused confusion in the validity of the data and the appropriate basis for reporting. Beyond monthly inconsistencies, time-series inspection also indicated that data completeness issues were not limited to missing months. In some instances, there were clear logging gaps within otherwise "covered" periods. As a result, robust analysis required explicit completeness screening (e.g., minimum expected records per day/month) and careful boundary handling to avoid artefacts being interpreted as true behavioural or technical signals.

A full year of data was difficult to find as most of the properties had 2 to 3 months of missing data while 4 properties only had 6-7 months of data. Narrowing further, this data then missed energy type usage and environmental data. In practice, this meant we could only compare homes when they had both enough months of data and the right metered channels, so any technology-specific analysis ended up using a smaller subset of properties.

The environmental data was available from two different sensor providers and hence further data formatting was necessary to enable the data to be analysed in a comparable manner. In addition to provider-to-provider harmonisation, there were practical data handling complications associated with timestamps and identifiers. Environmental time series were broadly regular (e.g., 15-minute measurements), but timestamps were not always perfectly aligned to an exact reporting grid, which complicates direct joining with other datasets unless consistent rounding/flooring rules are applied. Property and room identifiers also required standardisation (e.g., differences in naming conventions, casing, or label formats), which introduced additional mapping and quality-assurance steps before metrics could be aggregated by property, room, or month.

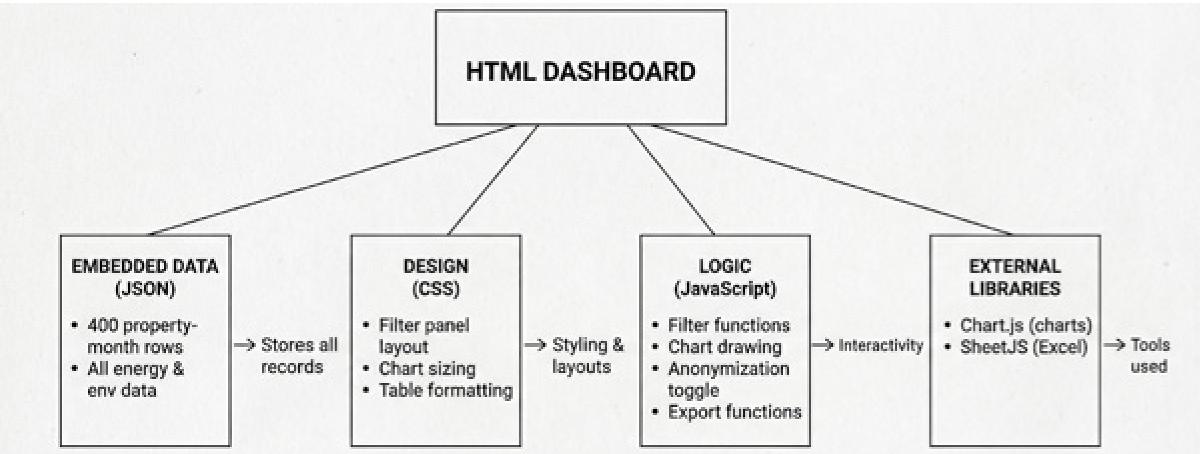
In some cases, it was difficult to interpret data as various months showed low energy consumption figures leading to the assumption that not all calendar days were logged. To overcome this, if there were two datasets found for the same month, the higher number was taken for the analysis. A related reliability issue was that completeness alone did not guarantee validity, particularly for environmental parameters. Although missing values were limited in the core exported fields, inspection identified occasional spurious extremes (e.g., implausibly high CO_2 or temperature/dewpoint spikes) and duplicate records. These anomalies are typical of real-world sensor deployments and can materially bias monthly averages, percentiles, and “bad IAQ” flags if not addressed. Consequently, it wasn’t enough to see that the dataset was complete; it was also required to clean it by removing duplicate rows and filtering out unrealistic spikes, because even a few faulty readings could distort the results.

Dashboard development

The structure and patterns in the data were studied with the help of a developed dashboard which allowed side by side comparison with the help of filter feature. This feature allowed the user to filter for specific months, energy data, category and technology equipped. It further allowed the user to filter the properties by name and then anonymise the data. The filtered data plots in real time and user could download the plot with the data file with one click.

The dashboard is built as a self-contained HTML file that functions like a mini application. Fundamentally, all 400 property-month records are embedded directly into the file as JSON data which is essentially a static database built right into the document. The design layer (CSS) controls how everything looks which includes the layout of filter panels, chart dimensions, table formatting, and the colour scheme. The logic layer (JavaScript) allows to filter data, draw charts, toggle anonymisation, and generate exports. Finally, two external libraries i.e., Chart.js to create interactive charts, and SheetJS to generate Excel files; which are loaded from the internet when first opened but then work offline. This architecture means everything needed to run the dashboard lives in one file, making it completely portable and requiring no server, database, or installation. This allowed seamless sharing between project partners.

Figure 16. HTML Dashboard data structure



When you interact with the dashboard, click a checkbox or select a filter option, JavaScript comes into action and scans through all 400 records in the browser’s memory to identify which ones match your selected criteria. For example, if you filter for “Net Zero” properties with “Heat Pump” technology in “Winter months,” the code quickly finds about 45 matching records from the original 400. These filtered records are then passed to the Chart.js library, which calculates bar heights, positions scatter points, and applies the category-specific colour coding to labels. In the meantime, the statistics boxes recalculate (showing “45 records” instead of “400”), and the property table shows only the matching properties. This process of scanning, filtering, calculating, redrawing, and updating happens instantly.

Throughout this chapter, the individual data is anonymised, noting that the figures use different coding from elsewhere in this report.

Figure 17. javascript search functions.

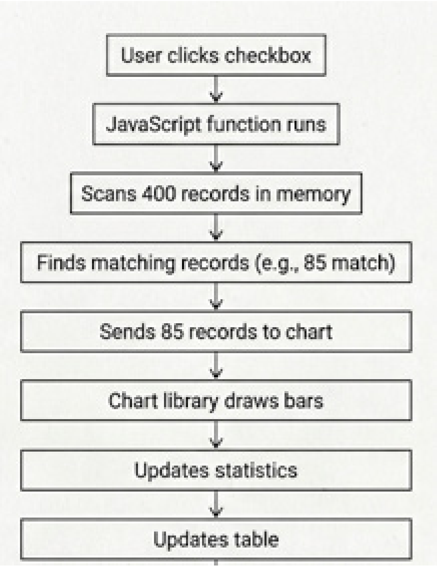


Figure 18. Energy and Environmental Performance Dashboard – Graphical Data

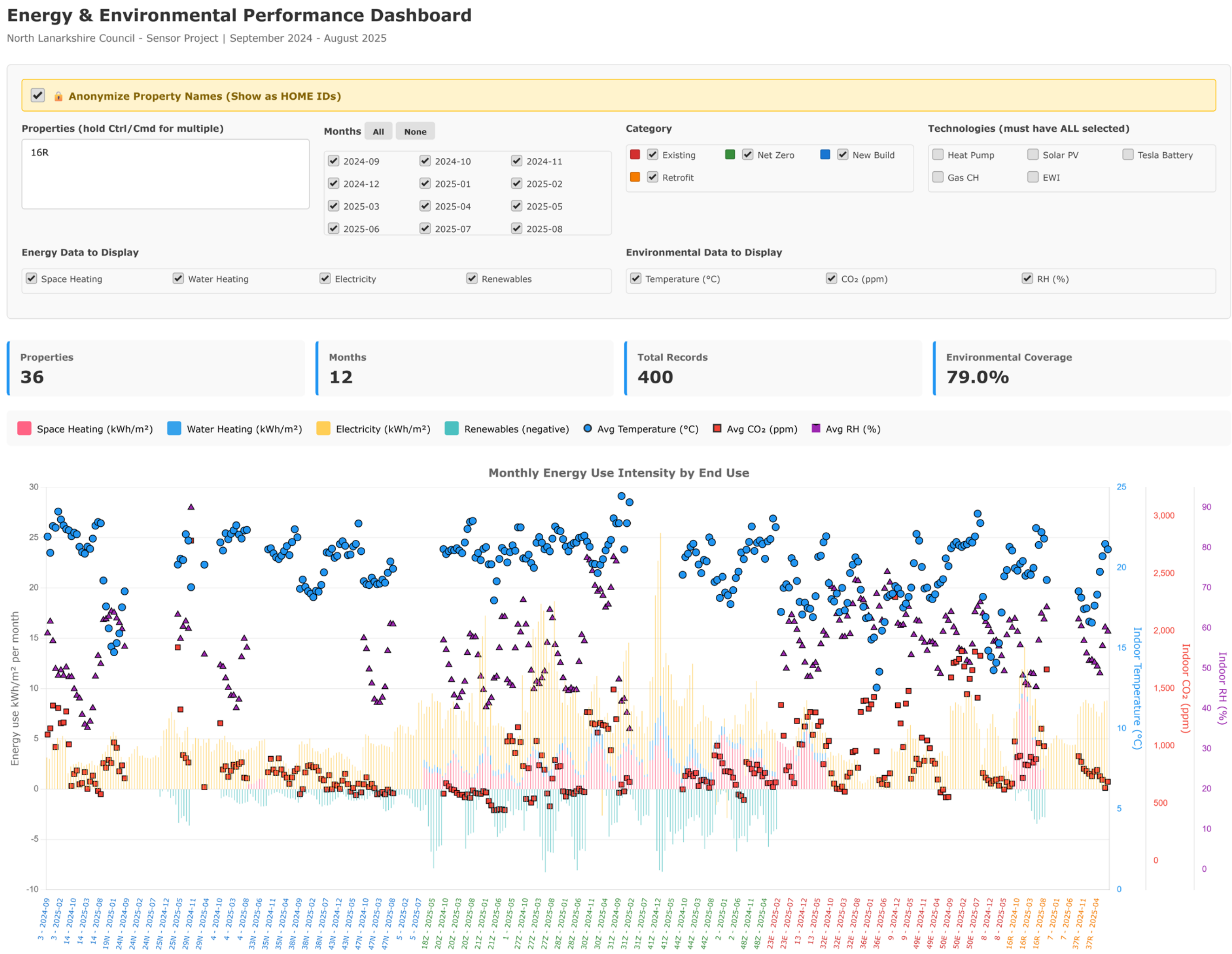


Figure 19. Energy and Environmental Performance Dashboard – Building Summary Data

Property Attributes - All Properties

Property	Category	Bedrooms	Floor Area (m²)	Heat Pump	Solar PV	Tesla Battery	Gas CH	EWI
3	New Build	2	63	○	○	○	●	○
14	New Build	3	73	○	○	○	●	○
19N	New Build	3	76	○	○	○	●	○
24N	New Build	3	73	○	○	○	●	○
25N	New Build	3	96	○	●	○	●	○
29N	New Build	3	73	○	○	○	●	○
4	New Build	4	104	○	●	○	●	○
33N	New Build	3	96	○	●	○	●	●
35N	New Build	3	96	○	●	○	●	○
38N	New Build	3	96	○	●	○	●	○
43N	New Build	2	72	○	●	○	●	○
47N	New Build	2	56	○	●	○	●	○
5	New Build	4	104	○	●	○	●	○
18Z	Net Zero	3	72	●	●	●	○	●
20Z	Net Zero	3	96	●	●	●	○	○
21Z	Net Zero	3	96	●	●	●	○	○
1	Net Zero	4	116	●	●	●	○	○
27Z	Net Zero	3	72	●	●	●	○	○
28Z	Net Zero	3	72	●	●	●	○	○
30Z	Net Zero	4	116	●	●	●	○	○
31Z	Net Zero	4	116	●	●	●	○	○
41Z	Net Zero	4	104	●	●	●	○	○
44Z	Net Zero	3	96	●	●	●	○	○
2	Net Zero	4	96	●	●	●	○	○
48Z	Net Zero	3	104	●	●	●	○	○
23E	Existing	4	79	○	○	○	●	○
13	Existing	3	83	●	○	○	○	○
32E	Existing	3	72	○	○	○	●	○
36E	Existing	4	93	○	○	○	●	○
9	Existing	4	91	○	●	○	●	○
49E	Existing	4	81	○	○	○	●	○
50E	Existing	4	81	○	○	○	●	○
8	Existing	4	81	○	○	○	●	○
16R	Retrofit	2	47	●	●	●	○	●
7	Retrofit	3	67	○	●	○	●	●
37R	Retrofit	2	46	○	○	○	●	●

The data lacks contextual information. The size of the property and number of bedrooms were available, but number of occupants and their use of building was initially unknown

Data Analysis

The data is available in the form of time series as well as monthly averages. In practice, the analysis relied mainly on the time-series exports so that the same rules could be applied across all properties and months, rather than depending on supplier-produced monthly files which were sometimes inconsistent. The time series included multiple columns indicating property identifiers (address/property reference) and metered channels such as space heating electricity, and grid electricity import split into peak and off-peak tariffs. Where available, the files also contained additional technology-related channels such as PV production and battery discharge, although these were not consistently present across the full cohort.

For pre-processing, the csv files were read in Python with explicit date-time parsing. Timestamps were then standardised and mapped onto a consistent sampling grid by assigning each record to a standardised time step. This step was important because some files were not perfectly aligned to a clean time grid, and in some cases a small number of duplicate timestamp rows were present. Once the data were on a standard time base, completeness checks were carried out by comparing the number of records per day and per month against the expected number based on the sampling interval. This allowed identification of partial days, truncated end-of-period records, and logging gaps within otherwise "covered" months. These checks were necessary because low monthly totals could sometimes reflect under-logging rather than genuinely low energy use.

Monthly aggregation was then performed for each property by summing energy channels over each calendar month. Total grid import and space heating electricity were calculated for each month, and these monthly totals were assembled into a monthly averaged dataset anchored by property identifiers. Where two versions of monthly data existed for the same period, the time-series based aggregation was treated as the primary reference, and anomalies were flagged so that results were not driven by incomplete logging. In addition, circuit-level availability was reviewed because not all properties had the same metered channels (for example, off-peak import, water heating, PV production, battery discharge, or ASHP-related heating), and many technology-specific channels were dominated by missing or zero values. This meant that technology-specific analysis required clear inclusion criteria and, in practice, reduced the sample size for some comparisons.

Environmental data from the two difference sources underwent similar processing. The environmental time series were imported, timestamps were parsed and standardised, and then monthly averages were computed for key parameters (e.g., CO2, temperature, humidity, dewpoint) before being added into the same master monthly csv. Additional formatting was required because environmental data were available from more than one sensor provider and therefore had differences in naming conventions and structure. Basic validity screening was also applied to ensure that occasional unrealistic spikes (for example, extreme CO2 or temperature/dewpoint values) did not distort monthly averages, and duplicate entries were removed where the same property/room/timestamp combination appeared more than once.

The monthly averages were then compared with sensor company provided averages for verification. It is important to note that, in different version of the data files, company provided averages throughout the monitoring period varied amongst themselves for some properties. Hence cross-checked data was used where available.

The final master csv therefore combined monthly energy metrics, monthly environmental metrics, and property attributes including category, number of bedrooms, and installed technologies. The energy data was divided by floor area for normalisation (kWh/m^2/month) to allow fairer comparisons across properties of different sizes, and the workflow retained flags for missing channels and incomplete periods so that results could be interpreted with the appropriate level of confidence.

In practice, the separation between the installation and monitoring, and analysis campaigns has led to a disconnect in the understanding of the nature and purpose of the data as the label categories in the .csv files are unclear. Consequently, the task of refining and collating this very disparate dataset has been onerous.

Some comparisons can be made across similar dwellings, as a quasi-case study approach, but lack of contextual data, such as occupancy numbers, behavioural insights and detailed construction data limits the ability to draw robust conclusions. However, there are some illustrations about the relative performance of broadly similar house categories.

To describe the construction process of the dashboard, it is a self-contained html file with embedded data so no server is required and could be shared seamlessly between the research partners. It holds 400 months of data and normalises energy values by floor area for a fair comparison. Stacked bars for energy components are clearly identifiable, scatter overlays depict CO2 and temperature while colour coded axis labels are available as per category. Three y-axes are part of the visualisation where energy is on the left while temperature is on the right and CO2 on the far right. It works offline and one file is shareable for full access. However, its static data and for any new data, the file will need to be reconstructed.

Results

The outline aim of the project was as to use the available monitored data for energy use and environmental conditions and augment this with additional contextual data about the construction of the homes, patterns of occupancy and use, and variations in building form to identify the following:

- Whether the sensor data can provide sufficient granularity to determine relative energy performance of the four main design conditions (New-build Standard, New-build Zero-Carbon, Existing as existing, existing retrofitted) and insights into patterns of energy use for space and water heating, unregulated energy, incidental gains, and energy generation.
- Utilise the available data to identify contexts that explain variations in performance, for example different locations and dwelling types, family size, patterns of occupancy, variations in heating and ventilation.
- Evaluate the data to identify performance issues that may affect health and well-being, for example thermal comfort, moisture levels, ventilation, and other impacts (e.g. noise, light).

As discussed in the previous section, there is a very constrained dataset available from the original cohort of 50 homes:

- 17 New build homes in the sample, but data only available from 13 properties and none of these have a complete dataset.
- 12 Homes in the new-build Net-zero group, with 12 reporting data, none with complete energy use. Environmental data is available for limited periods for 9 of these properties.
- 14 Homes in the standard new build category, but with an incomplete energy dataset in all these properties, with only one providing space heating consumption and none providing water heating consumption. Of these eight properties have consistent environmental data.
- 7 Homes in the existing category, only one providing a complete dataset, although all providing environmental data.

A graph that visually summarises the available data is contained in Figure 19. This show the selected dwellings, the energy and environmental data that is available over the period Sept – 24 to Aug 25.

Restricting the data range to individual months improves coverage to a small degree but still does not provide comprehensive data. Comparing individual months is also less robust as it increases risks of atypical variations, for example absences or holidays which limit comparative analysis. However, observations are made here for the period Nov 25 – Feb 25 which provides the most complete dataset, during the heating season.

The limitations on available energy data across the four categories are such that comparative quantitative analysis of energy consumption across the four cohorts is generally not possible, but the remaining data does provide some insights for a series of case studies, although analysis and insight are constrained by lack of contextual data. The aim was that this would have been provided by the qualitative/behavioural analysis described in the previous sections. Unfortunately, there is a minimal overlap between the qualitative cohort and data from the monitored dwellings. There are only two properties that have complete energy data that includes space, water and electricity use during the survey period. One is HOME ID 13, which is an existing property (but is also the one existing property with a heat pump so not representative of this group), and a net-zero home, HOME ID 2, but this latter is missing electrical consumption in some months.

Whilst comparison of the relative energy performance of the four dwelling types is not possible, there is more comprehensive data on the net-zero homes, and there are some observations that can be made between the relative performance of these homes.

Figure 20. Existing Energy Use and Environmental Conditions Nov 24 – Feb 25

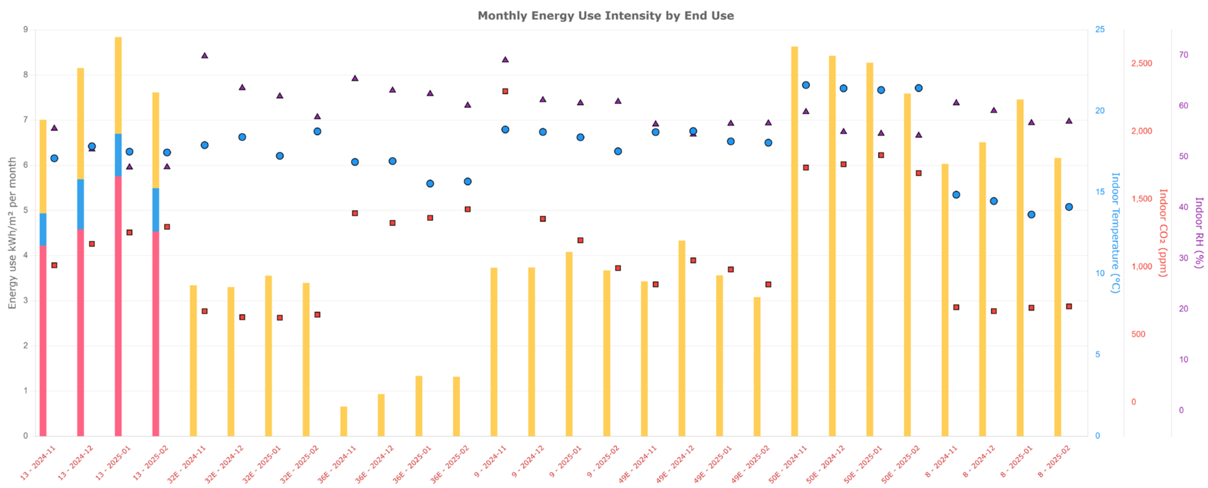


Figure 21. Retrofit Energy Use and Environmental Conditions Nov 24 – Feb 25

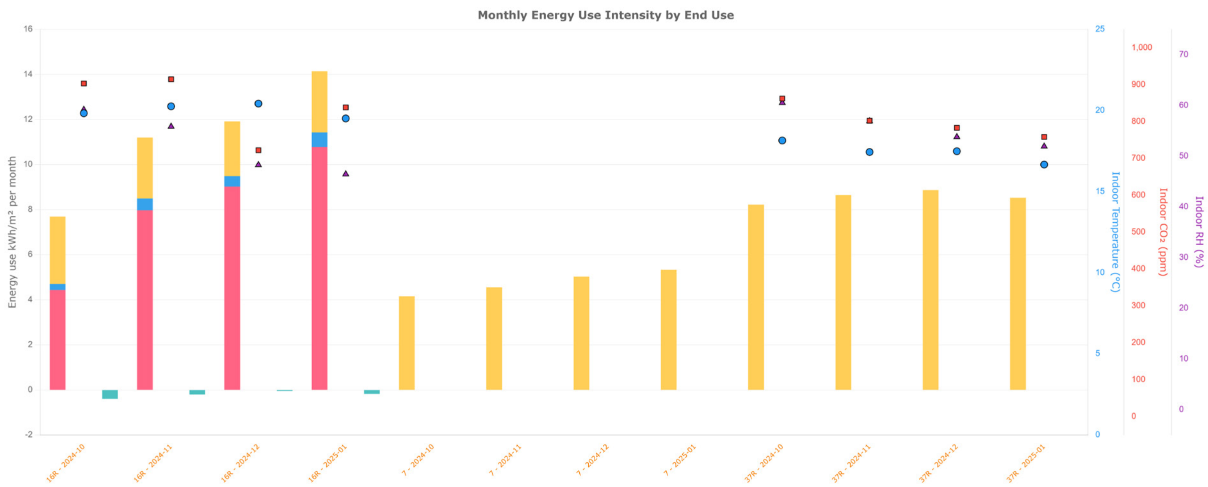


Figure 22. New-Build Energy Use and Environmental Conditions Nov 24 – Feb 25

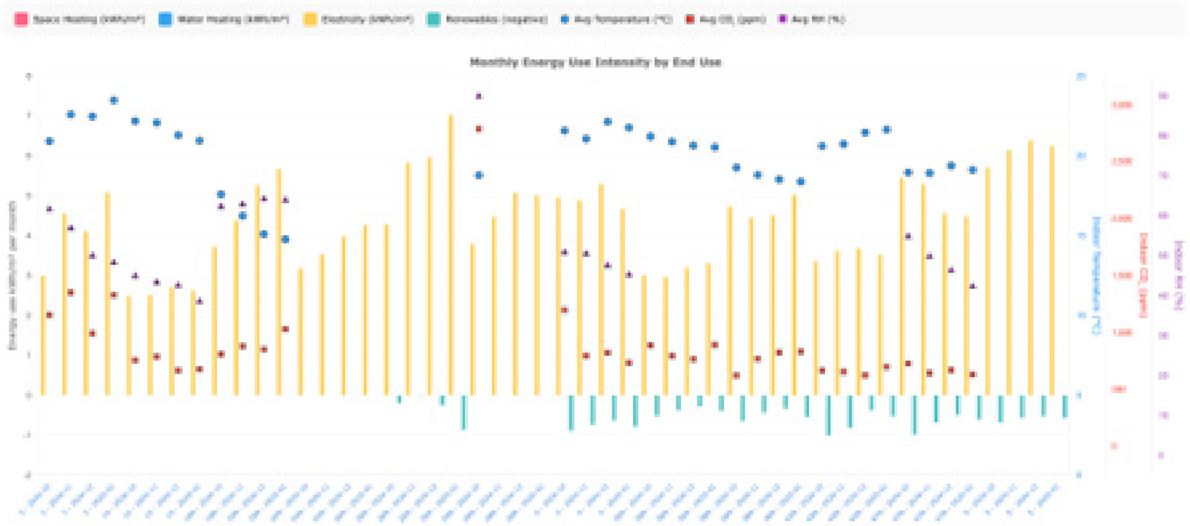
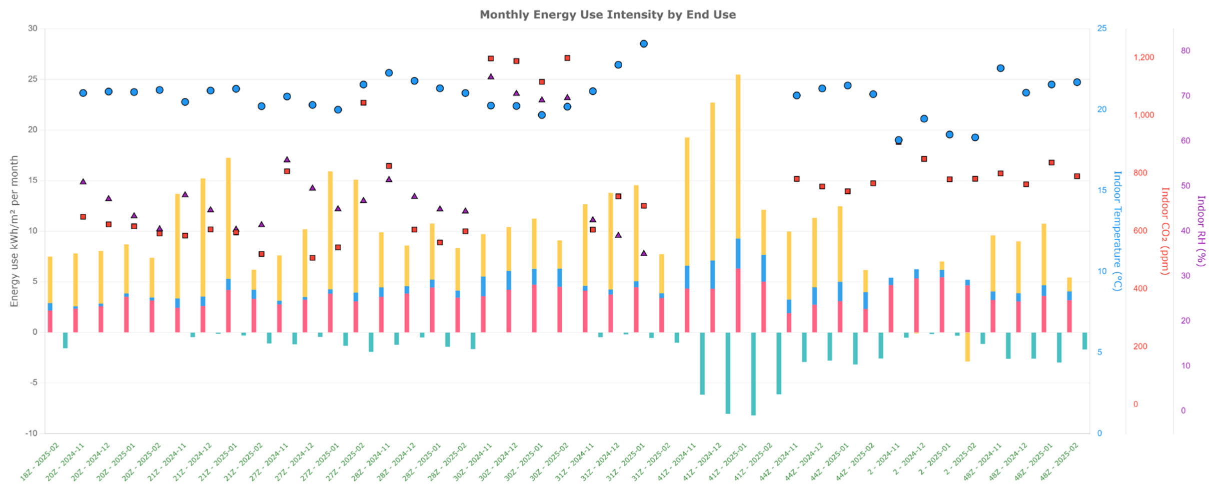


Figure 23 Net-Zero Energy Use and Environmental Conditions Nov 24 – Feb 25



Energy Use

As noted above, there is limited data for space and water heating, with data available from 10 Net-zero homes, 1 existing home and 1 retrofit home.

For the net-zero homes, during this period the average space heating consumption is 3.7 kWh/m2 for the Net-zero homes, 7.97 kWh/m2 for the retrofit home and 4.22 kWh/m2 for the existing home, but clearly the data from the retrofit and existing home is not representative and the limitation of data from single homes is illustrated by the spread of energy consumption across the net zero homes from the lowest at 1.90 kWh/m2 against the highest at 4.68 kWh/m2 more than twice the consumption.

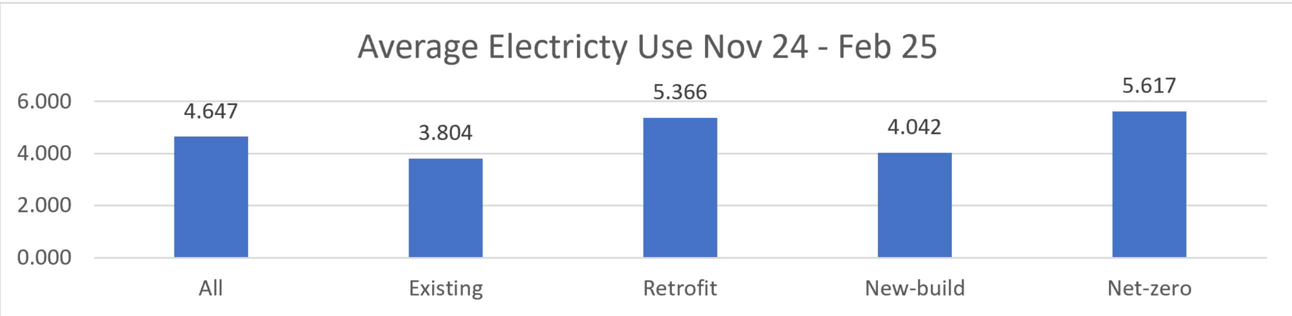
An important observation is that in this data the non space heating electrical consumption in the net zero homes appears to be higher than space heating consumption, with an average of 6.27 kWh/m2, nearly more than double the average for space heating (3.30 kWh/m2). Within this there is a wide variation, with the lowest at 4.18 kWh/m2 against the highest, nearly three times as much 12.6 kWh/m2. Patterns of occupancy are likely to be a major factor – these are all 3 and 4 bedroom homes, but the actual levels daily occupancy are not known. It may be reasonably speculated that more people in the home may result in higher demand, for example laundry, appliances, etc. but there may be particular demands – for example large TV's, gaming, etc. which may be driving use.

Table 7

Location	Space Heating (kWh/m²)	Water Heating (kWh/m²)	Electricity Residual (kWh/m²)
20Z	2.905	0.282	4.799
21Z	3.141	0.961	8.989
27Z	3.230	0.475	8.502
28Z	3.812	0.782	4.809
30Z	4.259	1.784	4.073
31Z	3.934	0.511	7.742
41Z	4.996	2.663	12.233
44Z	2.512	1.664	5.807
2 (Z)	5.033	0.725	-0.540
48Z	3.275	0.890	4.529
Average	3.710	1.074	6.094

Comparing available data on electricity use across all house types, both the existing and net-zero house types had the highest non-regulated energy use, but in the case of the net-zero homes this was offset to a significant degree by PV generation.

Figure 24. Average Electricity Use Nov 24 – Feb 25



An important consideration here is whether these incidental loads are impacting on space heating loads. Incidental gains become a much more important factor in well-insulated homes which retain heat better, and this was supported by an analysis of heat loss from the various homes during a cold night which shows much improved heat retention on the Net Zero homes. In this analysis, the drop in temperature overnight was observed for different levels of insulation.

Figure 25. Normalised Temperature Loss across insulation levels

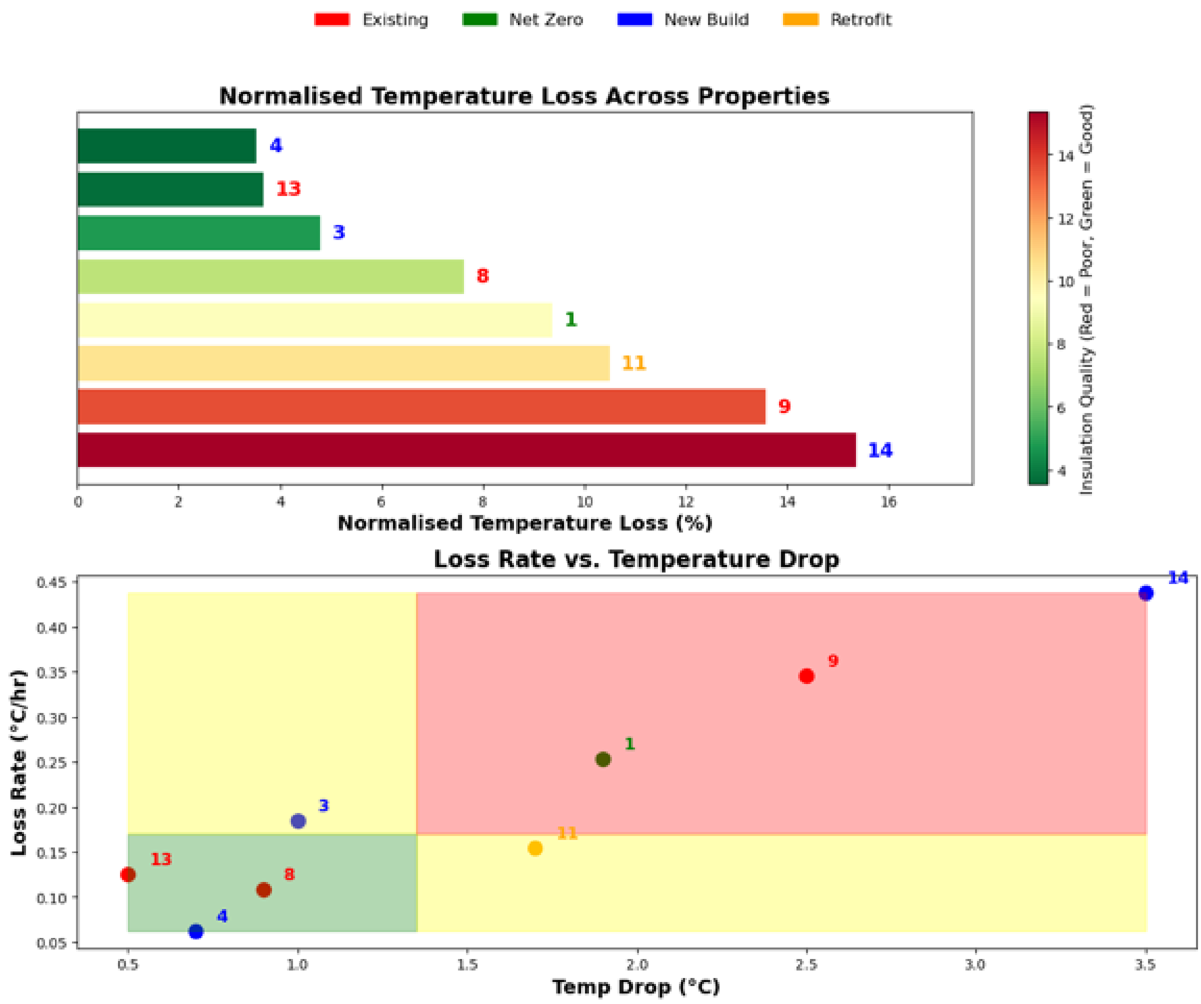
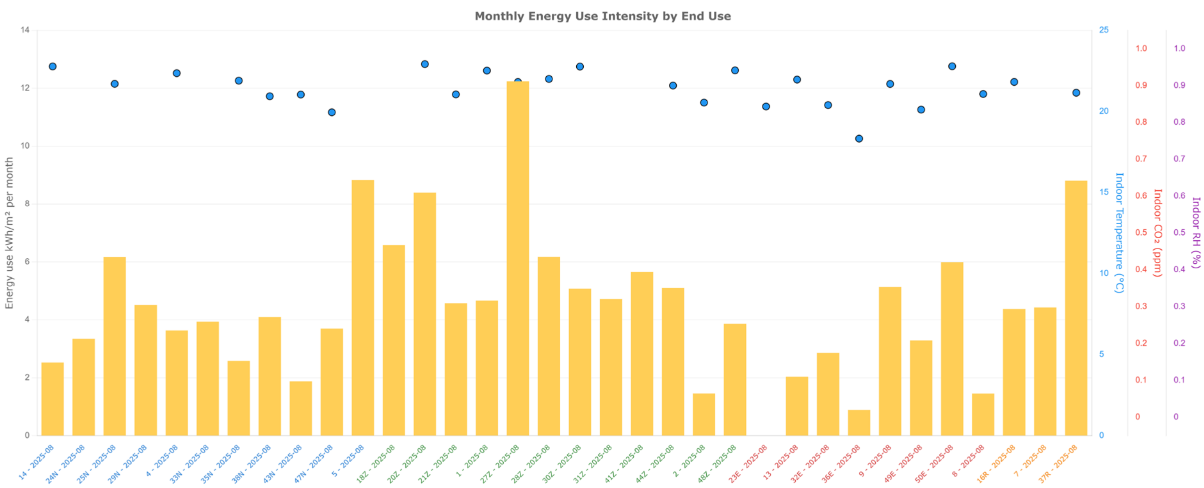
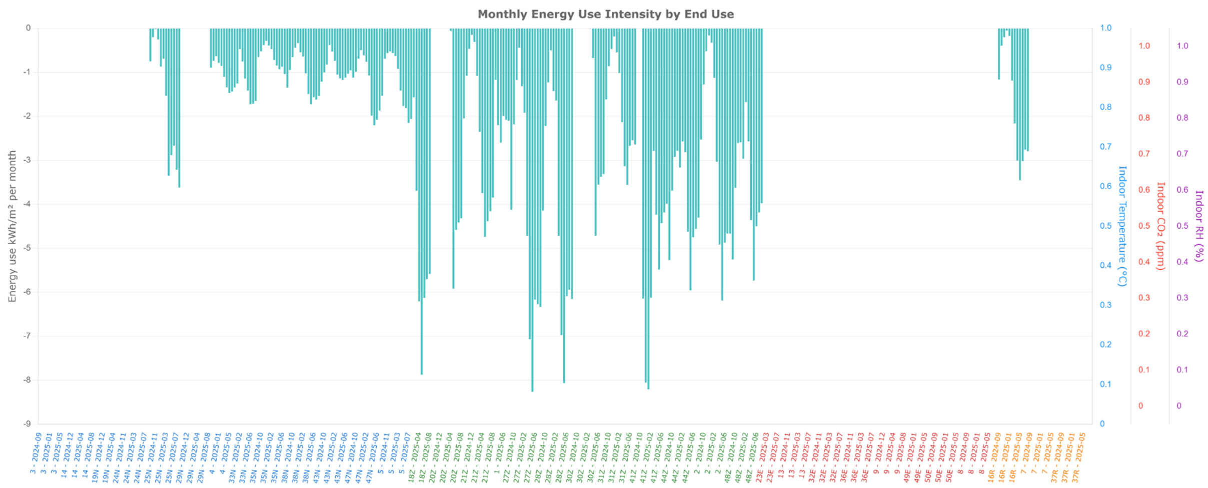


Figure 26. Electrical Consumption and Average Monthly Temperature Aug 2025



Overall, there appears to be a meaningful contribution from PV generation across the monitored homes. All dwellings in the site include PV; however, output is consistently higher in the Net Zero homes, likely reflecting differences in system scale and/or specification. Taking July 2025 as an example, the average output is 399 kWh for the Net Zero homes, compared with 158 kWh for the standard new-build homes. We do not have sufficient contextual data to determine the extent to which this difference is driven by system size, panel type, orientation, or roof pitch. In general, generation follows a clear seasonal profile, with higher output in summer months, and appears to make a significant contribution to overall household energy demand. However, we do not have a detailed understanding of the temporal distribution of this generation or the extent to which battery storage influences its utilisation. It is assumed that the PV data represents generated output rather than delivered or self-consumed energy.

Figure 27. Nominal monthly PV production for New Build and Net Zero



Environmental Performance

There is a more complete, but not comprehensive, environmental performance with data from 26 properties (8 Standard New-build, 8 Net-zero, 8 existing, and 2 retrofit) during this period. This allows some comparison between relative performance of the groups.

Temperature

Taking a sample month (Nov 24 as an example), there is a clear distribution of average monthly temperatures, with the net-zero homes achieving the highest and most stable temperatures, with the existing dwellings performing the worst. Average temperatures in the new-build standard home are good, but the average is slightly lower and the range is greater. Lack of range indicates greater temperature stability.

Figure 28. Monthly Average Internal Temperature Distribution Nov 24 – Feb 25

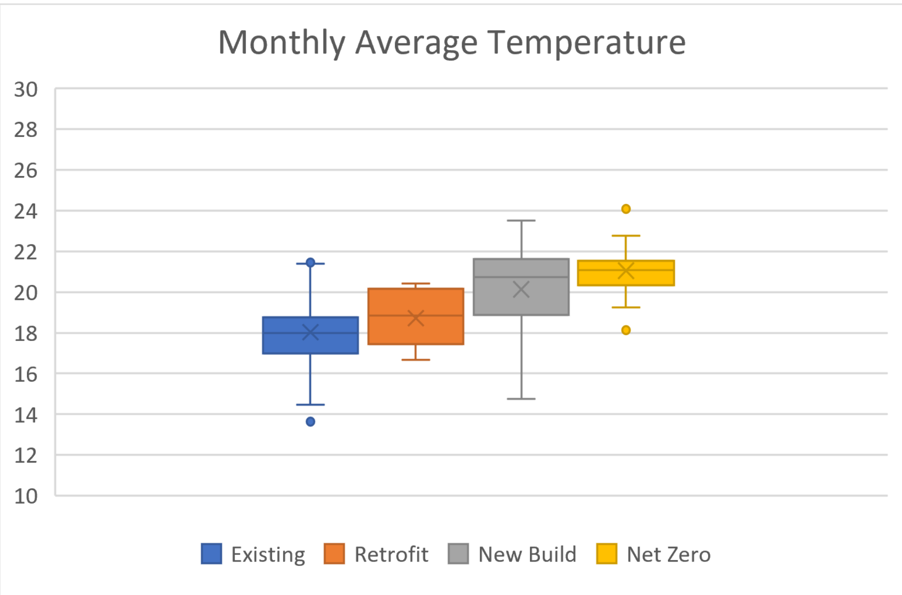
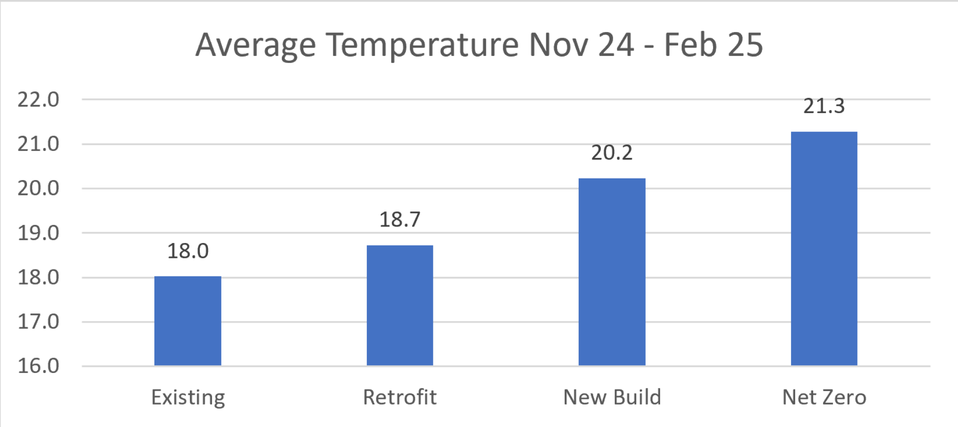


Figure 29 Monthly Average Internal Temperature Nov 24 – Feb 25



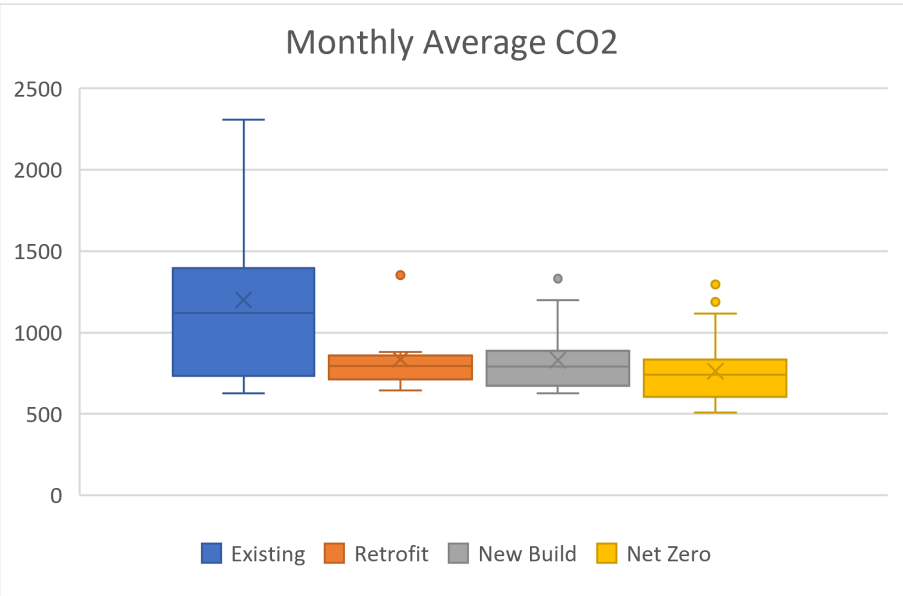
However, monthly average temperature of over 21oC may also suggest that demand temperatures and set points become higher when temperature of more easily – and more affordably – achieved.

Ventilation

Data for Carbon Dioxide (CO2) also shows a similar positive outcome. CO2 is used as a proxy for ventilation, with CO2rates below 1000ppm being broadly recognised as good ventilation and having positive impacts on health, so lower values indicate better ventilation rates.

In this case average CO2levels are much higher in the existing homes and also more variable. Performance in the improved homes appears much better. A characteristic of many existing homes is that they are poorly insulated and hard to heat, and ventilation is frequently constrained to attempt to manage comfort and energy use. Improved and new homes will have better thermal standards so impacts of more liberal ventilation may be smaller in terms of effect on comfort and energy consumption.

Figure 30 Monthly Average CO2 levels Nov 24 – Feb 25



Some caution is needed with these data as we do not have data on occupancy patterns or numbers of people in the home during this period, which heavily influence CO2 levels in the home.

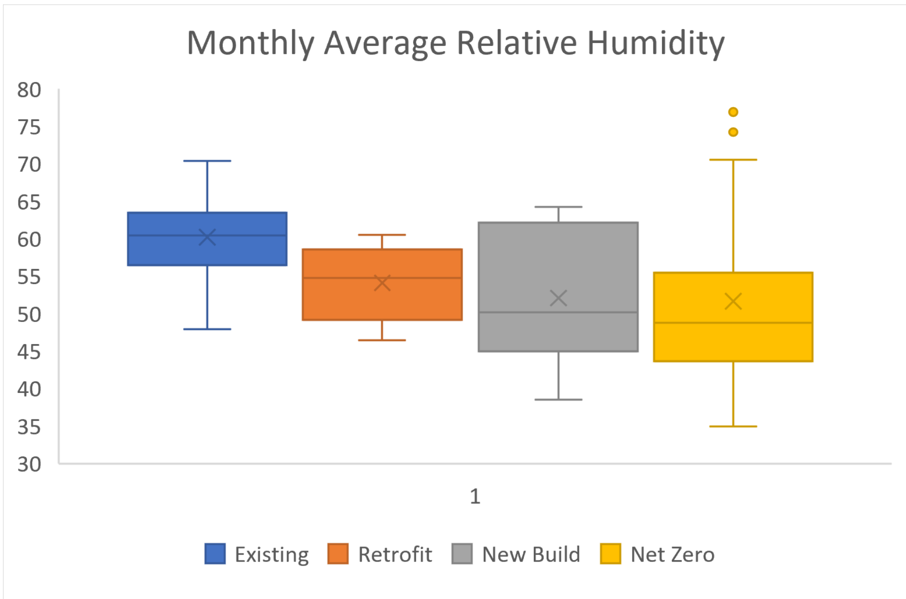
Relative Humidity

Moisture levels impact significantly on health, with high relative humidity impacting on incidences of dampness and mould.

Comparative analysis of relative humidity across the four cohorts is shown in Fig. 31. Again, some caution is needed here, with limited numbers with reliable data, including only

2 retrofit properties and RH will be significantly affected by occupancy levels. However, this shows that the Net Zero homes have the lowest average RH, with averages below 60% RH, and existing homes the highest.

Figure 31. Monthly Average Relative Humidity Distribution Nov 24 – Feb 25



Fiscal meter data

A further dataset was provided which is the fiscal meter readings for 47 properties in the study for the period between September 2024 and August 2025. These are meter reading for kWh consumption electricity and gas. Some caution is needed with this data as some readings are estimates rather than measured consumption. This data is also total energy consumption which does not split out space and water heating, although for the gas properties this will be the primary use, cooking being the other possible use. It is also assumed that the electricity readings are net of any PV production, i.e. excess generation may reduce the meter readings.

Analysis of this data provides some interesting insights and is summarised in Figure 32 and 33.

Figure 32 Energy Consumption and Average Energy use/m2.

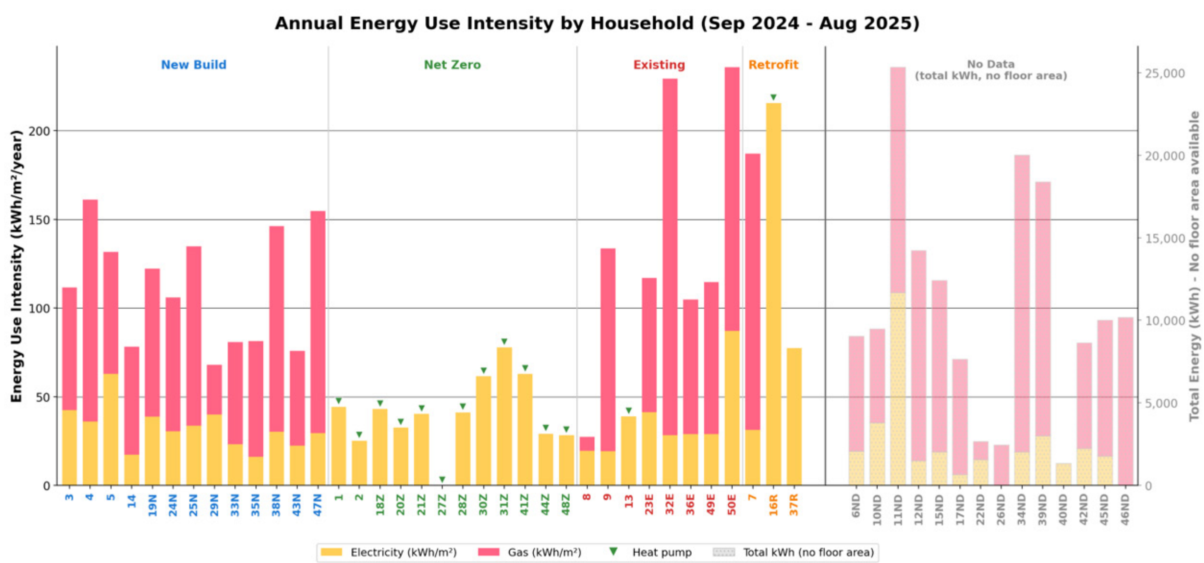
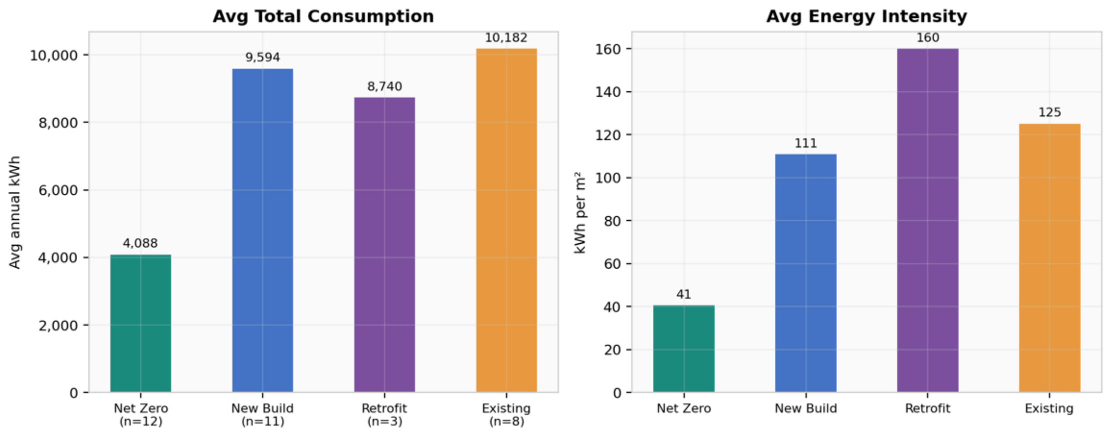
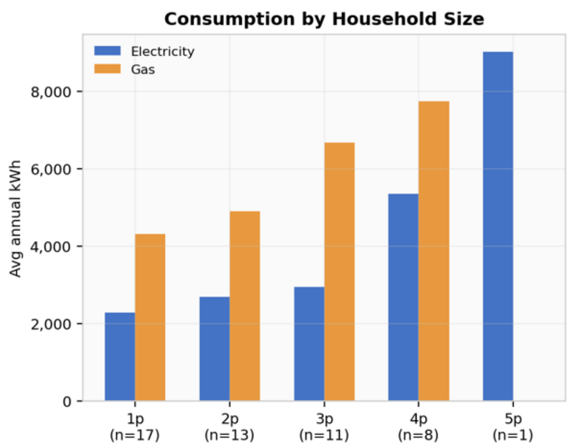


Figure 33. Average Total Energy Consumption and Average Energy use/m2 for the four cohort types.



This appears to show that the Net Zero homes have significantly lower total consumption. This is likely to be a mix of improved fabric performance, but potentially the larger contribution of the PV generation. This data also included some indication of family size during this period and analysis of family size against consumption shows a clear relationship (Figure 34).

Figure 34. Total annual energy use by family size.



This clearly illustrates the importance of this contextual data in understanding patterns of energy consumption – similar houses may have different levels of consumption due to numbers of occupants and their heating patterns

Summary

The overall picture here is that the Net-Zero homes appear to be delivering the best overall performance, both in terms of overall energy consumption, but also thermal comfort, ventilation and moisture. Performance gains in terms of temperature against the new-build were marginal, but taking account of energy use, appear to be cost-effective.

Key findings

Whilst there were significant problems with the availability of data, the project does clearly illustrate the value of both monitored data on performance, but also contextual data. Monitored data will tell you 'what', contextual data will tell you 'why'.

- Within this limited dataset there is a clear indication of improved performance, with the net zero homes having the best overall performance. They lose heat more slowly, achieve higher temperatures and improved ventilation with lower energy use.
- PV production in the net-zero homes was much higher than in the equivalent standard new build homes and has the potential to make significant contributions to overall energy use.
- In the context of the non-regulated energy use, some further insight is needed here to understand whether this results in 'rebound' effects. A concept that there is 'free' electricity may lead to higher use.
- Clearly, the way that the homes are occupied and used is a critical driver of overall energy use. Advice and guidance, especially for new technologies is important.
- Choice of systems and technologies tends to be driven by imperfect modelling. SAP is not a predictive tool and makes several assumptions about patterns of use which

will not reflect real life.

- With new technologies there is a need to consider performance over time, cost of maintenance, and with a lifespan of 20 years, replacement, especially for roof integrated systems.

- This type of evaluation would benefit from a more strategic research design – a large cohort of dwellings gathering simpler overall consumption data is likely to be more successful in generating statistical data in support of the hypothesis. Identification of case studies within this then may allow more detailed monitoring and evaluation to identify causality.

- Whilst this monitoring program had limitations, these technologies are advancing and provide vital insights that inform current and future use. They also become useful tools for asset management for landlords, and support for occupants in terms of risk factors and mitigations

- With monitoring systems there are diminishing returns in respect for the complexity of monitoring and risk of data loss.

- Extreme caution is needed about the use of this data. This information provides an intimate picture of occupancy in private environments. Strong controls are needed concerning the access, use and ownership of such data.

- Despite the limitations, without this data there would be no information about the in-use energy and environmental performance of the dwellings.

Policy implications

- Given the degree of innovation needed to achieve Net-Zero standards embedded environmental and energy monitoring is vital to inform outcomes of policy initiatives and resultant changes in standards and regulations.

- There is a significant performance gap that exists between design stages and performance in use. The latter is more important as this determines progress toward policy targets and objectives.

- Regulation and standards should be driven by in-use, rather and expected performance. Consideration should be given to elements of control, usability and information as critical drivers for performance.

- Performance needs a systems approach, considering dwellings rather than component pieces.

6. Economic Evaluation: Cost-Effectiveness of Net Zero New Build

Introduction

The study originally intended to compare construction and running costs across multiple housing types based on the archetypes used across other parts of the work. In fact we were only able to examine ten comparable net zero new build homes. focusing on the construction costs associated with these homes and considers these in the context of their intended performance and policy rationale. This does not amount to a full comparative cost-benefit analysis across all cohorts, but it does provide an initial contribution to understanding the investment profile of the Net Zero homes within the North Lanarkshire Council housebuilding programme. The findings should therefore be read as a focused cost review rather than a complete economic appraisal of all housing types included elsewhere in the report.

In practice what we did is estimate the numbers for the ten new build net zero homes – they are comparable from a technology point of view (heat pumps, solar PV, and battery; no gas CH). The object is to generate a sense of the relative cost effectiveness measured by energy cost and emissions, on a per metre squared basis for the ten properties in-scope. Of course, we could extend this to other archetypes – but here we wanted to look at comparable properties in terms of archetype and energy model (even if they vary by size and property type) and get a sense of the scope of the available data to do such cost-effectiveness work in principle.

Method

The calculations we will do for the ten properties are based on the following assumptions and values.

- Electricity prices for the time period used were found from Ofgem price cap figures found here: https://www.ofgem.gov.uk/energy-price-cap)
- UK GRID EMISSIONS FACTORS used to calculate the emissions levels were found here: https://www.itpenergised.com/new-2024-uk-grid-emissions-factors)
- Electricity prices were therefore based on the following figures: Rate per kWh for electricity: 27.03 pence/kWh; and Daily standing charge for electricity: 53.80 pence/day
- The carbon emission factor for electricity used was: 0.22535 kg CO2e/kWh
- The electricity based energy consumption for each property consisted of the sum of: space heating, water heating, electricity, electricity residual minus renewable generation.

Table 8 below looks at the ten in-sample properties (rows), identifying (across columns) their type, bed room size, floor space and their calculated total energy consumption for the four months November 2024 to February 2025, inclusive. Using the assumptions above we then calculate total electricity cost, total carbon emissions, and then divide each of the later variables by the floor size of the species property to arrive at per metre squared ratios of the energy cost per square meter and the carbon emissions per square metre. Finally, the last three columns display the individual build cost per m2, these vary from £1908 m2 to £2218 m2.The energy cost ratio and the carbon ratio which utilise the build cost per m2 for each property as denominator. These indicate operational performance relative to construction cost (lower ratios = better cost-effectiveness).

Findings

There were ten properties sampled, all with comparable energy profiles (no gas, heat pump, PV solar and battery), all new build net zero – six 3 beds and four 4 beds, with two terraced and eight semi-detached, varying in size from 72m2 (two examples – both terraced) to two at 116m2, with four at 96m2 and two at 104m2. The modal property therefore was a semi-detached 3 bed property with 96m2 floorspace.

Total energy consumption for the four months recorded varied by a factor more than three for the most to the lowest energy consumption (12475.72 kWh to just 3525.04 kWh) bit with the six of the others more grouped together between 4846.32 kWh and 6546/29 kWh). Total energy (all electricity) reflected the pattern of energy consumption varying from a low of £1022.38 or £257 a month to a high of £3436.75 or £859 a month). Three had total energy costs between £1643.25 and £1693.06 and two were in the range of £2378.23 and £2530.47.

Energy cost (per m2) for the total four months fluctuated between £10.65 and £33.04, with 5 properties paying less than £20 and 4 paying between £20.50 and £26.36. The lower the ratio the less the household for energy per unit of build costs. If the ratio is higher, it means the home is more expensive to run and less energy efficient.

Emissions (per m2) for the total period of four months varied from 8.27 to 27.03, with five other properties between 12.65 and 16.63; the remaining three clustered between 20.49 and 22.28. A lower ratio means that for each unit of construction cost, the home is producing fewer carbon emissions, which is better for the environment and suggests greater energy efficiency. Conversely a higher ratio, indicates that that the home is generating more carbon emissions relative to its build cost, which is less environmentally friendly. It is not surprising that we such variation in these cost-effectiveness numbers given that we have already identified and stressed the importance of occupancy type, property usage, energy preferences and the potential for rebound effects.

Turning to the energy cost and carbon ratios (defined here as operational energy cost or emissions per m^2, divided by construction cost per m^2), lower values indicate better cost-effectiveness, as they represent lower running costs or emissions relative to the initial build investment. These ratios are calculated only for the ten Net Zero homes in the sample and are therefore used to compare performance within this group, rather than against other housing archetypes. For example, NZ9 shows the lowest ratios in the dataset for both energy cost and carbon emissions (0.00503 and 0.00392, respectively), indicating strong operational performance relative to its build cost. In contrast, NZ7 shows the highest ratios (0.01732 for energy cost and 0.01417 for carbon emissions), suggesting higher operational impacts relative to its construction cost.

Table 8 Cost Effectiveness Analysis : Comparable Net Zero Properties

Address code	Type	Beds	Floor area (m^2)	Energy (kWh)	Electricity cost (£)	Carbon (kg CO_2e)	Energy cost /m^2	Emissions /m^2	Build cost (£/m^2)	Energy cost ratio	Carbon ratio
NZ1	Mid terrace	3	96	6024.79	1693.06	1357.69	17.64	14.14	2109	0.00836	0.00670
NZ2	End terrace	3	96	9492.83	2630.47	2139.21	27.40	22.28	2109	0.01299	0.01056
NZ3	Semi detach	3	72	6546.29	1834.02	1475.21	25.47	20.49	2218	0.01148	0.00924
NZ4	Semi detach	3	72	4846.33	1374.52	1092.12	19.09	15.17	2218	0.00860	0.00684
NZ5	Semi detach	4	116	8559.63	2378.23	1928.91	20.50	16.63	2076	0.00987	0.00801
NZ6	Semi detach	4	116	10815.88	2988.09	2437.36	25.76	21.01	2076	0.01241	0.01012
NZ7	Semi detach	4	104	12475.72	3436.75	2811.40	33.05	27.03	1908	0.01732	0.01417
NZ8	Semi detach	3	96	5929.73	1667.37	1336.26	17.37	13.92	2109	0.00824	0.00660
NZ9	Semi detach	4	96	3525.04	1017.38	794.37	10.60	8.27	2109	0.00503	0.00392
NZ10	Semi detach	3	104	5840.52	1643.25	1316.16	15.80	12.66	1908	0.00828	0.00663

Figure 35 Cost Effectiveness Comparisons across the New Build Net Zero Properties

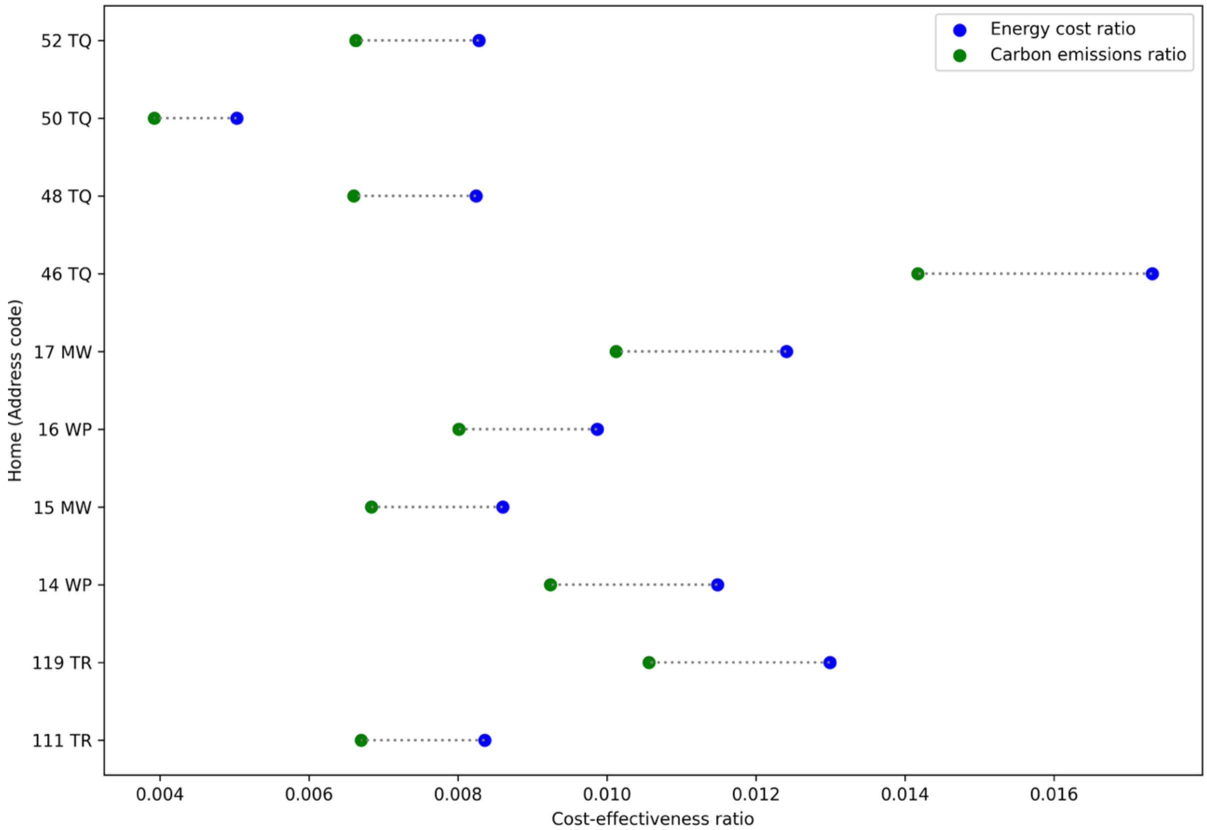


Figure 35 contrasts the energy cost and carbon ratios to build costs for each property graphically showing the low (NZ9) and high (NZ7) outliers, as well as indicating that the carbon ratio is always lower that than the energy cost ratio but there are narrow and wider divergences for specific properties.

This exploratory exercise show that it is perfectly possible to make meaningful cost-effectiveness analyses of the new build net zero properties, but that these are better understood in the round by contextualising them in terms of occupancy, behavioural preferences and household size, as well as the characteristics of energy or property fabric. It would be straightforward to incorporate gas-based energy consumption to undertake similar exercises with the non-net-zero new build though we have not done this here, recognising the absence of data and heterogeneity across that part of the sample.

7. Conclusions

This research was made possible by the experiment of different archetypes produced by the North Lanarkshire council new build programme (net zero and standard new homes, alongside retrofitted and unimproved existing properties). This creates a great opportunity to test and contrast different such archetypes in terms of adding data on the individual properties to their energy consumption, comfort and cost. This was then in principle greatly enhanced by the possibility of collecting sensor, metred and phone app data with which to monitor such performance. This was the context within which this research took place.

Two important additional elements have made this research somewhat different from what we originally anticipated when the proposal was constructed. First, we all thought that an important triangulation in our understanding would come from behavioural evidence from occupiers (i.e. the council's tenants living in these archetypes). It is not just the fact that the home in question is three or four bed and has for example triple glazing, modern insulation and specific kinds of energy systems – it is the household's composition, their occupancy levels, how they use the property during the day and across seasons, and their fundamental preferences (and constraints) in how they approach warmth, comfort and energy use. We have found this behavioural dimension to be essential to helping us understand outcomes.

Second, it has proven in practice difficult to collect, assemble the data and to organise it in such a way that multiple data from different sources can be used consistently. There were also significant delays and requirements to change track with the data we were trying to source and to recognise that not all households had the same kinds of data (such as varying use of smart meters). This both delayed the project and also meant we could not answer all the questions we wanted to, or were able to study all of the homes in the sample on a consistent basis. But we remain capable of being able to say a lot about the evidence we do have. We return to the evaluative learnings later in this conclusion.

Core findings are found in section 2 through 6 of this report. Here we return to key points and reflect a little further on them.

Behaviour Matters

This section examined how households use and experience their homes, and how everyday practices influence comfort, energy use, and energy costs. It provides insight into the lived experience behind measured temperatures and energy consumption. The results show that building type matters, but it does not determine outcomes on its own. Net zero homes generally provide more consistent comfort and lower energy costs, while existing homes show greater risk of cold and higher costs. However, large differences are observed between households living in physically similar homes.

Household routines, preferences, and constraints play a major role in shaping comfort and energy use alongside building performance.

Two different routes to low comfort are evident. In some homes, low comfort is linked to households turning heating off frequently and relying on coping strategies, suggesting cost-related rationing. In others, households report low comfort even when heating is rarely or never turned off, indicating technical or fabric limitations. These situations require different responses. Low-carbon heating technologies do not automatically lead to low-cost or high-comfort outcomes. Heat pumps perform well in high-performance homes, but in existing housing they can be associated with high costs and only moderate comfort. Non-heating energy uses—particularly hot water, bathing, and laundry—also make a substantial contribution to overall energy spend and help explain why similar homes can have very different bills.

The case-study analysis strengthens these conclusions by showing how different outcomes arise in comparable homes. Heatmaps and paired comparisons indicate stable household "signatures" of comfort, heating operation, and coping, and reveal how similar buildings can support different lived experiences. A mixed-methods approach provides a richer understanding than building metrics alone.

The term 'behaviour' can be thought of as a loaded term, particularly in the context of landlord/tenant relationships. The is a danger that differences in performance are characterised as 'bad' behaviour with a tendency to apportion blame. However, critical dimensions of this are usability, knowledge and agency. Many heating and ventilation systems are complex and unfamiliar, and lack of intuitive accessible controls can exacerbate this issue. Systems which rely on active intervention by occupants have inherent weaknesses which may impact their performance. People have frequently developed habits to address familiar systems, such as heating controls. Some aspects, such as indoor air quality, cannot be readily perceived by occupants which limits their ability to mitigate them. Many systems and devices are poorly explained and demonstrated. Ensuring that innvovate systems are designed to be be understood and used is therefore an important element of the design of low energy homes.

Overall, the results indicate that effective housing improvement programmes need to address both the physical performance of homes and the circumstances and practices of households. Combining fabric and system upgrades with household-centred advice, appropriate financial support, and post-installation follow-up is likely to be necessary to achieve reliable improvements in comfort, affordability, and energy performance across the housing stock.

Evaluating Monitored Data

The overall aim of this part of the project was to use monitored data to quantify the energy and environmental performance benefits of energy reduction strategies for retrofit of existing dwellings, and to compare relative performance of homes with 'net-zero' technologies against homes built to standard building regulations. Fifty homes were originally included in the project, which included:

- 17 existing homes including a mixture of houses, four-in-a-block, flats, semi-detached, terraced and mid-terraced homes, with 3 or 4 bedrooms
- 7 retrofitted homes, including a mixture of mid and end terraced houses, flats and one four-in-a block, with 2, 3 and 4 bedrooms
- 14 standard homes, including semi-detached houses and bungalows, mid and end terraced houses, and flats, with 2, 3 and 4 bedrooms
- 12 net-zero homes, which included semi-detached bungalows, mid and end terraced houses, with 3 or 4 bedrooms.

The Challenges

These groups represent a wide variation of house types, sizes and locations, with a high-variance sample. This introduces a range of confounding variables which may affect the dwelling performance. In addition, varying patterns of occupancy and occupant behaviour introduce further variables which may affect performance. Previous studies have shown wide variation in consumption and use across identical houses, but in this case this variation is further exacerbated by a range of locations, sizes and built form.

It also became apparent early in the project that the dataset was significantly incomplete. It was based on an ambitious monitoring campaign which sought to gather several sources of data related to the varying space and water heating technologies, including heat pumps, gas boilers, photovoltaic panels, battery storage. It also included environmental monitoring collecting data on temperature, relative humidity and CO_2.

Detailed monitoring in domestic environments is very challenging due to difficulties in getting access, maintaining data connections and power sources, undertaking maintenance and replacement, and the management of the large quantities of data that are produced. Overall, a very small proportion of the dwellings were able to provide consistent energy data. Additional environmental data was obtained through a different sensor provider. Further complexity was due to difficulties accessing the data. Although the monitored data can be accessed through an online portal, this has limited capacity for multivariate analysis. These challenges, along with the need to include data from another provider led to data being exported as .csv files for independent collation and analysis, and this introduced further uncertainties about data sources and reliability. Due to these complexities, the lack of data has meant that robust conclusions about the relative performance of the varying dwelling types cannot be reliably drawn from this dataset.

Cost-Effectiveness

The uneven nature of the data meant that it was only possible to contrast the ten new build net zero homes that had comparable energy set-ups. It was a comparatively straightforward job to use the energy consumption and expenditure on it to link that to the size and type of homes and to create ratios that can tell us about relative cost and emissions efficiencies. We do this in the penultimate section but it s worth stressing that even within this set of simialr properties there is conservable variation in outcomes suggesting that this may in part be to do with specific homes, energy systems and how they are operated, but also that it is likely to be down to the occupants' behaviour, incentives and preferences, reiterating the importance of good or smart guidance, effective on-going support and post occupancy surveys.

How the behavioural and sensor data work together

The behavioural research was used to develop clear expectations about how different households were likely to use energy and what indoor conditions they might achieve, based on how residents described their routines, expectations, and constraints. The sensor and smart-meter data then provided an independent way to check whether these expectations were visible in practice.

Overall, the monitoring data largely confirm the patterns identified in the behavioural analysis. In well-insulated Net Zero homes, where residents reported leaving the heating on steadily and experiencing good comfort, the sensor data show stable indoor temperatures achieved with relatively low energy use. This reinforces the behavioural finding that continuous, low-level heating can work well when the building fabric supports it.

In contrast, in several existing homes where residents expected very warm indoor conditions, the monitoring data show higher energy use without correspondingly higher indoor temperatures. This helps explain why residents in these homes reported dissatisfaction and reliance on coping strategies and confirms that higher energy input does not always translate into better comfort when buildings or heating systems limit performance.

The sensor data also distinguishes between different reasons for cooler indoor temperatures. Where residents reported turning heating off to manage costs, the data show lower temperatures alongside lower energy use, indicating deliberate under-heating. Where residents reported low comfort despite leaving the heating on, the data show low temperatures without low energy use, pointing instead to building or system constraints. This distinction is not clear from either dataset on its own.

Patterns in indoor CO_2 levels further support the behavioural findings. Homes where residents reported frequent window opening generally show lower CO_2 concentrations, but often at the cost of higher energy use, confirming that ventilation habits affect both air quality and heating demand. Similarly, homes with heat pumps in existing buildings show higher energy use and only moderate comfort, supporting residents' concerns that low-carbon technologies do not automatically deliver good outcomes without suitable building conditions and user support.

Finally, the monitoring data confirm that households reporting similar levels of comfort often achieve this through very different combinations of heating use, energy consumption, and ventilation. This reinforces the behavioural conclusion that comfort is shaped by both the physical characteristics of the home and how people live in it, rather than by energy use alone.

In sum, the behavioural and sensor data provide a more complete picture than either could on its own. The behavioural data explain why households use energy in specific ways, while the monitoring data show how those choices play out in practice, strengthening confidence in the findings and helping to identify where different types of housing or household may need different forms of support or intervention.

There are four take-aways for local authorities considering wider use of sensors:

A. Sensor data are most powerful when combined with an understanding of household behaviour.

The monitoring data alone show differences in energy use, temperature, and air quality, but the behavioural evidence explains why those differences occur. Without insight into residents' expectations, routines, and constraints, sensor data risk being misinterpreted—for example, confusing deliberate heating reduction for technical under-performance.

B. Similar buildings and technologies can perform very differently in practice.

The findings show that homes of similar type, including those using the same heating technologies, can have very different outcomes depending on how they are used and the constraints residents face. Sensors make these differences visible, but meaningful interpretation requires recognising that performance is shaped by both building fabric and household practices, rather than technology alone.

C. Sensors can help distinguish between affordability-driven under-heating and building or system limitations.

By examining energy use, indoor temperature, and CO_2 data together, sensors can help distinguish between different reasons for low indoor temperatures. In some homes, lower temperatures occur alongside lower energy use, indicating that residents are deliberately limiting heating to manage costs. In other cases, low indoor temperatures persist despite ongoing energy use, pointing instead to building or heating system limitations rather than behavioural under-heating. Homes showing patterns consistent with affordability-driven under-heating may benefit most from financial support, advice, or engagement with residents, while homes showing constrained performance despite energy use are more likely to require physical interventions such as fabric improvements or heating system checks. Using sensors in this way allows local authorities to move beyond one-size-fits-all responses and focus resources effectively.

D. Whole-stock sensor deployment should be designed around learning and targeting, not simple benchmarking.

The evidence suggests that sensors are best used to reveal patterns and pathways rather than to rank homes or residents by "performance." When paired with behavioural insight, sensor data can support more tailored interventions—such as identifying where retrofit is needed, where system settings or user support may help, and where wider affordability issues are shaping outcomes.

Overall Reflections

Despite the data challenges, there are some important findings from this study. First and foremost is the need for a clear research design to identify achievable objects and control for variables. Given the variability and complexity of housing, a much bigger dataset would be needed to generate sufficient statistical power to provide quantitative analysis.

However, case studies can also provide vital insights into real world performance, and detailed monitoring, but also occupancy and use can be used to identify individual performance, and this data can be used to generate detailed dynamic modelling for larger cohorts. Despite the limited dataset, some useful and interesting indicators are present. These include indications of improvements in environmental conditions in the improved homes, well above the existing homes, with the net-zero homes providing best performance in terms of improved temperature and ventilation, both of which have important health impacts.

Whilst detailed energy data is largely constrained to the new-zero homes, this data also clearly illustrates the range of energy use between homes. Given that this group has the least diversity in terms of location and built form, this may be ascribed to patterns of occupancy and behaviour. There is also good evidence of the contributions of the PV renewables.

The project also illustrates the challenges of management and analysis of large datasets. Both providers provide excellent portals for access to data, but these are not designed to statistical analysis or cross comparison across a range of dwellings or variables, and significant effort was required to collect and collate this data which limited detailed analysis. Nevertheless, there is an interesting and useful dataset which might be used to undertake more detailed analysis of individual dwellings, especially if further contextual and behaviour data can be obtained.

Whilst there were significant problems with the availability of data, the project does clearly illustrate the value of both monitored data on performance, but also contextual data. Monitored data will tell you 'what', contextual data will tell you 'why'.

In the context of the non-regulated energy use, some further insight is needed here to understand whether this results in 'rebound' effects. A concept that there is 'free' electricity may lead to higher use. Moreover, the choice of systems and technologies tends to be driven by imperfect modelling. SAP is not a predictive tool and makes several assumptions about patterns of use which will not reflect real life.

With new technologies there is a need to consider performance over time, cost of maintenance, and with a lifespan of 20 years, replacement, especially for roof integrated systems.

This type of evaluation would benefit from a more strategic research design – a large cohort of dwellings gathering simpler overall consumption data is likely to be more successful in generating statistical data in support of the hypothesis. Identification of case studies within this then may allow more detailed monitoring and evaluation to identify causality. Whilst this monitoring programme had limitations, these technologies are advancing and provide vital insights that inform current and future use. They also become useful tools for asset management and support for occupants in terms of risk factors.

Investment and follow-up recommendations

- Prioritise fabric-first retrofit in existing homes.
- Combine heat pump installations with fabric upgrades and system commissioning.
- Identify and support households likely to be rationing heat.
- Provide post-installation advice and simple user guidance.
- Undertake regular, systematic post-occupancy surveying of tenants in the properties.
- Consider household composition and occupancy when planning upgrades.
- Address hot water and appliance efficiency alongside space heating.

Further Practice implications

- Embedded environmental and energy monitoring is vital to inform outcomes of policy initiatives and resultant changes in standards and regulations.
- There is a significant performance gap that exists between design stages and performance in use. The latter is more important as this determines progress toward policy targets and objectives.
- Regulation and standards should be driven by in-use, rather and expected performance. Consideration should be given to elements of control, usability and information as critical drivers for performance.
- Performance needs a systems approach, considering dwellings rather than component pieces.

Annex 1 - Preliminary Qualitative Heat Loss Analysis

Between August and November 2024, fifty (50) homes in North Lanarkshire were fitted with an array of environmental and energy sensors by the Council. These sensors collect data for temperature, CO2, humidity, as well as energy consumption (gas and electricity). These data (when combined with other sources) can be used to determine heat demand calculations, running costs, and well as CO2 emissions.

The following is a summary of a preliminary report based upon initial findings of a research programme investigating heating regimes and energy efficiency across these 50 homes in North Lanarkshire Council. Although the broader research programme includes both qualitative and quantitative methods, this report details only those findings derived from the qualitative data.

Table A1. Thirteen Sensor Homes Participating in Qualitative Research with Select Information

Home ID	EE Category[1]	Archetype	Beds	Period
1	Net Zero (new build)	Semi-detached	3	2020s
2	Net Zero (new build)	Semi-detached	3	2020s
3	New build	Flat	1	2020s
4	New build	End-terrace	3	2020s
5	New build	End-terrace	3	2020s
6	Retrofit	Flat	2	1950s
7	Retrofit	End-terrace	2	1960s
8	Existing	Flat	3	1960s
9	Existing	Mid-terrace	3	1940s
10	Existing	Flat	2	1960s
11	Existing	Mid-terrace	3	1960s
12	Existing	Semi-detached	2	1960s
13	Existing	Mid-terrace	2	1960s

In November 2024, North Lanarkshire Council sent letters to all 50 of the sensor homes, inviting households to participate in a qualitative research programme. Follow-up phone calls were made and messages sent to aid recruitment. Households were offered a £100 Amazon voucher incentive to participate. Ultimately, thirteen (13) households agreed to participate in the qualitative research which included both surveys and interviews.

Given the small sample size (n=13), the research adopts a case study approach. Rather than seeking statistically significant findings derived from a large survey, this approach enables the generation of detailed insights into the complex interactions between household profiles, occupant behaviours, and heat and energy consumption. The case study method is particularly valuable for local authorities, as it provides nuanced data that more effectively highlights linkages between these insights and tenant-related policy considerations.

1 EE Category (or Energy Efficiency Category) identifies the four distinct types of home in the study: (1) new homes built to a Net Zero standard; (2) new homes built to a New Build standard; (3) existing homes that have undergone a Council retrofit; and, (4) existing homes that have not undergone a Council retrofit.

Table A2. Comparability Clusters (baseline building physics)

Cluster	Home IDs	Comparable characteristics
I	1; 2.	2020s, semi-detached, Net Zero specification, heat pump, 3 bedrooms.
II	4; 5.	2020s, end-terrace, gas boiler, 3 bedrooms.
III	9; 11.	1940-1970, mid-terrace, gas boiler, 3 bedrooms.
Un-clustered	3; 6; 7; 8; 10; 12; 13.	Mixed

To enhance the validity of the case study method, comparability clusters were identified so that behavioural differences could be isolated while the building physics were controlled. Based on period of construction, building archetype, fabric specification, and number of bedrooms, three (3) clusters were created (as detailed in Table A2):

I. 3-bedroom semi-detached homes constructed in the 2020s to Net Zero specifications (incl. heat pumps, PV & battery storage)

II. 3-bedroom end-terraces constructed in the 2020s to prevailing new build standards (incl. modern gas boilers)

III. 3-bedroom mid-terraces constructed between 1940 and 1970 to prevailing building standards

Principal findings

There is no discernible correlation between the level of insulation and building fabric and the household energy efficiency rating (EER). Occupancy of a Net Zero, new build, or retrofit home does not directly encourage or discourage energy-efficient behaviour. Equally, occupancy of an untreated home does not significantly influence household energy efficiency behaviour.

1. There is a correlation between the level of insulation and building fabric and the risk of under-heating across the cohort. Occupancy of Net Zero, new build, or retrofit homes significantly reduces or eliminates household under-heating indicators. In contrast, occupancy of untreated homes increases under-heating.

2. There is a likelihood of "rebound effects" when households have their homes retrofitted with improved fabric and clean heat technologies. The rebound effect may result in actual reductions in CO_2 emissions for treated homes being less than anticipated, based solely on modelling using housing physics or heat demand calculations.

3. Variations in household profiles influence energy consumption in either direction. Occupant behaviour could account for performance gaps that emerge in the quantitative data.

4. Due to variations in household profiles, heat demand calculations may not be consistent across similar housing archetypes within the thirteen case study homes, or within the three identified comparability clusters. Occupant behaviour could account for these inconsistencies across heat demand calculations.

5. Living in a Net Zero home has considerable economic and health co-benefits for tenants. Occupants have more disposable income, sleep better, have fewer health complications, and enjoy better mental health than if they lived in an untreated home.

6. The Council handover process left tenants unsure about the operation and control of their clean heating systems. Tenants found the booklets and instructions they were given challenging to use and learned little from them. There is an information transmission barrier related to written material alone.

Key recommendations for North Lanarkshire Council

1. Anticipate rebound effects following retrofitting of existing homes. All homes in the sample that have not undergone a Council retrofit are occupied by households showing medium or high incidence of under-heating indicators. There is a likelihood that after these homes receive fabric and heating system upgrades, the reduction in energy consumption may fall short of estimations based on modelled thermal and system efficiency improvements.

2. Anticipate performance gap concerning reductions in CO_2 emissions. Many tenants are currently heating their homes less than they would like due to financial constraints. If, as expected based on these findings, tenants increase their heating levels after the retrofit, the reductions in CO_2 emissions estimated based on current heat demand calculations may not accurately reflect real-world outcomes.

3. Improve energy efficiency awareness across housing stock. Lowering thermostat settings, shorter shower durations, reduced frequency of washing machine and dryer use, and using doors and curtains for insulation could lead to meaningful energy savings. Easy-to-understand infographics illustrating actions to reduce

household costs and increase disposable income—without compromising comfort and lifestyle—are recommended.

4. Scrutinise heat demand calculations as primary basis for heating system design. Due to under-heating indicators reported by many Council tenants and considerable variation in household profiles within similar housing stock, heat demand calculations alone may be an unreliable basis for clean heat system design. It is recommended that heating systems be designed based on the highest band of heat demand calculations for a given housing archetype across the sample.

5. Further investigate the mental and physical health co-benefits that the Net Zero homes may be generating. If improvements to tenant health were quantified, the cost-benefit case for investing in Net Zero homes would be strengthened. Data concerning quality-adjusted life years gained and reduced NHS financial burdens are likely to be revealed through a difference-in-differences (DiD) analysis comparing Net Zero homes with a matched control group of untreated homes.

6. Improve interpersonal and mixed-media handover process for clean heat technology. In addition to the written materials provided to tenants, the Council could consider offering information workshops for tenant groups, particularly in larger Net Zero development schemes. When tenants are housed in properties with new technology, a walkthrough with an informed professional is recommended.

7. The sensors have provided a significant level of insight into the actual in-use performance of the homes and are a useful tool for asset management. General monitoring of environmental conditions and overall energy use can provide a cost-effective indication of use and consumption over a large number of homes. The introduction of elements of sub-metering, particularly separation of space and water heating is technically possible, but introduces additional levels of cost and complexity in terms of the monitoring requirement (e.g. heat flow meters) and risks of data loss at scale.