

Electricity consumption in net zero ready homes with ASHP and PV and its effect on power networks. A case study in the UK

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ABSTRACT

Low-carbon homes with enhanced insulation and airtightness, heat pumps and renewables are expected to be more energy-efficient. However, their real operational performance remains uncertain until inhabited. The performance gap between modelled and implemented energy systems is well documented. There is relatively little work showing the performance gap in practice for operational domestic heat pumps, particularly when combined with PV generation. This study examines the performance of 7 low-carbon homes constructed according to the UK's Future Homes Standard. It offers a comprehensive assessment of the operational impacts of low carbon dwellings on local power infrastructures, representing some of the earliest implementations of these new building regulations for future homes in the UK. A whole year of energy consumption data is analysed using a combination of regression techniques, graphical representations, and tabular data analysis to investigate operational energy performance, heat pump efficiency, peak power demand, and renewable energy utilization, providing novel insight to the implications of heat pumps on local power networks. The study reveals that measured diversified peak demand was just 14.6% of the total design capacity. Heating and cooking accounted for more than 80% of the peak power. While an average of 65% of solar energy generated was utilized within the homes, there remains scope to enhance PV energy integration by expanding the area of PV panels. These findings underscore that relying solely on theoretical or installed capacity could significantly overestimate actual network requirements and reinforces the importance of diversity-based planning and the role of occupancy patterns in shaping peak demand.

1. Introduction

Governments across the world have pledged to limit global reach net-zero CO₂ emissions globally by 2050 [1]. The building and construction sector is responsible for 37 % of global energy related emissions [2], with 17 % of energy emissions coming from residential buildings [3]. To address this problem, policies in different countries are being devised and implemented to improve energy efficiency of homes and reduce carbon emissions. The UK government plans to implement from 2025 the Future Homes Standard, a new building regulation intended to ensure all new homes built from 2025 will produce 75–80 % less carbon emissions than homes built previous 2013 regulations [4], providing net-zero ready homes that will become net zero when the grid is decarbonised.

These low carbon homes will have higher levels of insulation, airtightness and adopt low carbon heating systems, such as heat pumps. They will be powered only by electricity, therefore not connected to the gas grid. The expectation is that these houses will save more energy, and therefore be more cheaper to run, than conventional homes heated by fossil fuels, such as gas boilers. However, although low-carbon buildings are considered to consume less energy [5], there is compelling evidence of performance gap, where real consumption is higher than expected

[6,7]. Performance gap has been attributed to different factors, including accuracy of models [8] and occupant behaviour [9,10,11]. There is a need to better understand occupant behaviour and motivations so energy efficiency predictions can be optimized [12,13,14]. This makes real performance testing critical for ensuring expected energy savings on electricity consumption are met and power grids are correctly designed.

While electricity can be decarbonised at transmission level networks, the decarbonisation of heat is much harder as it requires higher building efficiency. Heat pumps are often quoted as a method for decarbonising heat, though can become an issue for local power networks as they add additional demand on local infrastructure. Some studies have tried to analyse the impact of the electrification of heat in power networks. You [15] presents a control model to potentially reduce the impact of heat pumps on local power networks, based on an economic market driver. Although they do not demonstrate a high economic value in heat pump flexibility, they identify a potential 15 % decrease in peak demand through fiscal penalties. Huty [16] presents an agreeing study, focused on peer to peer trading of heat and power. Bampoulas [17] presents a similar study, focused on heat pump flexibility, as does David Kröger [18]. Pinto [19] provides a linear optimisation, based on a cost optimised dispatch model for France and Spain. These models offer

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important insight into the electrification of heat, but they all rely on simulated and assumed heat pump usage profiles, which can introduce error into the final conclusion.

With regards to the contribution from renewables, Tian provides a model to maximise the photovoltaic (PV) utilisation within buildings [20], as does Rahdan [21], who shows significant benefit to the local distribution network in reduced costs attributed to peak reduction from solar PV. Meunier [22] presents a method to determine grid reinforcement requirement under different heat pump and PV scenarios. Damianakis [23] expands on this using a bottoms-up approach to demonstrate 300 % increase in system over-loading with high heat pump penetration, which is not significantly reduced with introduction of PV. They recommend focusing on integration of heat pumps with high performance homes. Sommerfeldt [24] demonstrates the value of PV-heat pump systems where there is high disparity between the cost of heat and the cost of power, showing a novel case where PV does not financially benefit electrified systems. Efkarpidis [25] makes similar conclusions through a dispatch optimisation of heat pumps, storage, and PV. Most of these studies rely heavily on modelled and assumed data to assess the impact of heat pumps, while very few utilise directly measured data.

There are many works which explore the efficacy of heat pumps in general. Conte [26] presents a paper which compares CO₂ heat pumps with propane heat pumps. Benchamma [27] discusses hybrid expansion solar-air heat pumps for building level applications, while others such as Dai [28] discusses hybrid heat pumps for space heating. These papers add significant value to the field of thermal engineering. However, this area of research is outwith the scope of this paper. The work presented here will focus on the direct application of commercially available heat pumps, rather than the refrigeration cycle being used.

This study analyses in-practice data of operational domestic heat pumps combined with on-site renewable generation of 7 net zero ready homes located in the UK. This demonstration site was selected to understand the potential real energy savings of houses built under the proposed Future Homes Standards, powered 100 % by electricity, and their impact on the power grid. Each home is fitted with an energy meter which records the consumption of electricity from each circuit breaker in the consumer unit.

The objectives of this study are:

1. Present a detailed analysis of measured heat pump utilisation for high efficiency dwellings.
2. Critically assess the importance of solar electricity generation in reducing peak demand from air source heat pumps.
3. Present a critical assessment of energy utilisation within highly electrified dwellings.

The work will present results on (i) the imported energy analysed using linear regression and Structural Equation Modelling in order to show the correlation with different energy usage and the relationship to outdoor and indoor temperature, (ii) the electricity consumption over a year in different properties to show the variability and differences revealing the demand for heating, (iii) the heat consumption over a year in different houses to show how it drives energy consumption, (iv) the peak electricity consumption and timing in different houses to show the impact on the network, and (v) the impact of PV generation in different houses to provide an insight into seasonal effects and the potential mismatches between energy supply from PV and consumption patterns. The discussion challenges some of the assumptions on system design and the impact on networks. The work concludes with statements about the importance of occupant behaviour and the lower levels of peak demand.

2. Methods

2.1. Case study

The case study is a set of 7 homes within the West Midlands region of England, United Kingdom (Fig. 1). The dwellings are a mix of two, three, and four bedroom homes, built to improved fabric performance over the existing building regulations. The design goal for these dwellings was to develop homes in line with the UK's Future Homes Standard as proposed in 2019, which mandate 80 % reduction in carbon emissions for new homes by 2025 when compared with the 2013 regulations [29]. As the development was an early adopter of Future Homes Standard, being the first of its kind in the UK, it didn't have any gas connection, only electricity supply. Although the development consisted on 12 homes, only 7 houses accepted to participate in the study.

Given the availability of three house types, the decision was made to trial three different cost-effective specifications to explore a range of technologies to meet the standard (Table 1). There was the expectation that this approach would ensure the demonstrator project to provide data and have a greater opportunity for learning including how a traditional architectural design and a traditional masonry form of construction can be adapted to meet the challenges of climate change.

To assist with rising future energy costs, each of the 12 homes was fitted with 2.2kWp of PV panels (Fig. 2a), exceeding the standard requirements. Moreover, each type of house implemented a distinct strategy for achieving airtightness and ensuring proper ventilation:

- Type 1: A four-bedroom unit, designed with a 7 kW space and domestic hot water heating air source heat pump (Fig. 2b), lower air permeability, and heat recovery (MVHR) systems.
- Type 2: A two-bedroom unit with minimal space load, featuring a water-only heat pump and electric panel radiators, along with lower air permeability and MVHR systems.
- Type 3: A three-bedroom unit, equipped with a 5 kW space and domestic hot water heating air source heat pump, and spot mechanical extract fans in the kitchen and bathrooms, with a low background rate and humidity or pull cord activated boost.



Fig. 1. Layout of the case study.

Table 1
Summary of Dwelling characteristics.

Element	Type 1	Type 2	Type 3
Floor	75 mm screed, 150 mm PIR, beam and block floor	75 mm screed, 150 mm PIR, beam and block floor	75 mm screed, 150 mm PIR, beam and block floor
External wall	Facing brick, 150 mm PIR, aircrete block, airtight polymer spray, plasterboard on dabs and skim	Facing brick, 150 mm PIR, aircrete block, airtight polymer spray, plasterboard on dabs and skim	Facing brick, 150 mm PIR, concrete block, plasterboard on dabs and skim
Roof	150 mm PIR between rafters, 90 mm PIR below rafters, plasterboard on dabs and skim	400 mm mineral wool roll	150 mm PIR between rafters, 90 mm PIR below rafters, plasterboard on dabs and skim
Window	1.2 W/m ² K double glazed unit, with 0.45 G-value	1.2 W/m ² K double glazed unit, with 0.37 G-value	1.2 W/m ² K double glazed unit, with 0.45 G-value
Lintel	Thermally Broken Hytherm	Thermally Broken Hytherm	Thermally Broken Hytherm
Heating	7 kW ASHP, 210L unvented cylinder, compact radiators	Panel heaters and 200L hot water heat pump	5 kW ASHP, 200L unvented cylinder, compact radiators
Ventilation	MVHR	MVHR	extractor fan
PV	2.2 kW	2.2 kW	2.2 kW

2.2. Metering

The electricity consumption was metered using an Emporia energy monitoring system. The system recorded how much energy was being consumed in real time, and was configured to record data either at 15 min or 30 min intervals. One emporia sensor was fitted to the main input to the dwelling consumer unit with further sensor installed on each circuit including input from solar PV. The system monitors within $\pm 2\%$ accuracy and provides download from the cloud or continuous connection via an API to a server.

2.3. Data quality

As mentioned, the study originally included all 12 dwellings. However, the occupants of several dwellings declined to take part in the study, while in other instances metering issues led to a loss of data. The following plots were chosen as they had the best data quality for a consistent period of time. The plots which will be discussed in the study are: 1a, 2b, 2c, 3d, 3e, 3f, and 3 g. Although additional data was available, a single year (2023) has been chosen to provide a fair and consistent comparison across different dwellings. The available data found very little missing data, showing a good data quality throughout the study. The key measurements are the mains, and heat related measurements. For all plots, with the exception of Plots 3e and 3 g, the measured data covered close to 100 % of the chosen period (typically less than 0.01 % missing), Plot 3e was missing measurements for the immersion heater for 50 % of the time, while Plot 3 g was missing mains and heat data for 6.7 % of the time. This is not expected to significantly impact the study due to the low consumption of electricity from immersion heating. Data interpolation methods such as linear interpolation have been used to fill these small gaps to improve the data quality.

2.4. Multiple linear regression model

Multiple linear regression (MLR) was used to identify the importance of factors influencing the imported energy. The MLR model with statistical significance was developed as the following Equation (1) for quantitative analysis of influencing factors on the import energy demand:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \dots + \beta_p X_p + \epsilon \quad (1)$$

Where:

- Y = predicted import energy
- β_0 = constant term
- $\beta_1, \beta_2, \dots, \beta_p$ = regression coefficients for each predictor



Fig. 2. Photographs of installed (a) solar PV array, (b) heat pumps and (c) hot water cylinders.

- $X_1, X_2, \dots, X_p$ = independent variables (e.g., heat pump energy)
- ε = error term (residuals)

The MLR model included eight core variables affecting import energy demand: heat pump, cooker, cooker, lights, PV, outdoor temperature, indoor temperature and month of year. As the goal is to understand the contribution of the heat pump to electricity import, winter months data (2023–12, 2024–01 and 2024–02) from House 1a was used to avoid diluting the signal with summer periods when the heat pump is idle or barely used.

3. Results

3.1. Import energy

3.1.1. Influencing factors analysis with MLR

MLR was used to analyse the electricity consumption over a year in different properties to show the variability and differences revealing the demand for heating. The model demonstrates a strong ability to predict electricity import, with an R^2 value of 0.986. This high explanatory power indicates that nearly 99 % of the variation in import energy is accounted for by the selected predictors. The F-statistic is 42,860 on 8 and 4,867 degrees of freedom, with a p-value less than 0.001 except form one variable ‘month’, indicating strong overall model significance.

Among these, the heat pump stands out as a dominant contributor, with a coefficient of approximately 0.99, indicating that nearly every additional kilowatt of heat pump consumption corresponds directly to an equivalent increase in imported electricity. The statistical significance of this relationship, coupled with a low variance inflation factor ($VIF \approx 1.23$), supports the reliability and independence of this predictor within the model. Other appliances such as cookers and lights also exhibit notable impacts on energy import during winter, whereas PV output shows a negative relationship, consistent with its role in reducing grid dependency. Overall, the model based on winter data offers a representative view of heating related energy use, making it particularly suitable for assessments of energy performance and demand-side management strategies during the heating season.

Table 2 shows the regression coefficients, indicating that heat pump power consumption has the strongest positive contribution to import energy ($\beta = 0.989$), followed by cooker ($\beta = 1.057$), lights ($\beta = 1.710$), and sockets ($\beta = 0.737$), all statistically significant with $p < 0.001$. PV generation is negatively associated with import energy ($\beta = -0.864$), as expected. Both indoor and outdoor temperatures show small but significant effects, while the month variable, although statistically significant ($p = 0.010$), has a relatively small magnitude, suggesting limited seasonal drift in import energy after accounting for other variables. These results support the robustness and interpretability of the model.

3.1.2. Validity evaluation and coefficient interpretation

The model validity tests can be summarized as follows: (1) The model appeared well specified based on diagnostic checks, with the

Durbin-Watson statistic of 1.57 indicating no severe autocorrelation in residuals. Additionally, Fig. 3 shows no pattern between predicted values and residuals, which is a good indication of model adequacy and that the assumptions of the Ordinary Least Squares (OLS) regression are reasonably met. (2) The average value of the residuals is close to zero, and their standardized distribution approximates normality. Though the distribution exhibits some right skewness (skew of 3.60) and moderate kurtosis (kurtosis of 30.76) from the Jarque-Bera test, the deviations are not considered severe enough to violate normality. (3) The model can be regarded as not having a multicollinearity problem, in view of the results of the variance inflation factors (VIF) being less than 2, with heat pump (1.23), cooker (1.10), sockets (1.15), lights (1.35), PV (1.57), outdoor temperature (1.71), indoor temperature (1.62) and month (1.23).

3.2. Electricity consumption

Total electricity consumption was analysed to understand energy demand patterns and compare against typical household estimates. Fig. 4a shows the total electricity consumption for each plot. Plot 3 g has the highest total consumption, while Plot 1a and 2c also consume annual energy over 8000 kWh. Annual energy consumption varies in buildings, even in the same types of dwellings. Plot 2b and Plot 2c are the same type but still show a 19 % difference in overall energy consumption. Plots 3d–3 g are also the same type but show around 47 % difference between the largest and smallest consumptions. This shows that even with buildings of the same typology constructed to the same specification, in-life usage can greatly vary the energy consumption in practice.

Different types can be compared by normalising the consumption to the respective floor area, as shown in Fig. 4b. When the demand is normalised to the floor area, the Type 2 plots (2b and 2c) now become the largest energy consumers. Plot 2c stands out with the highest value of 121 kWh/m², which might suggest a higher density or intensity of mains data usage or generation in this particular plot. This is to be

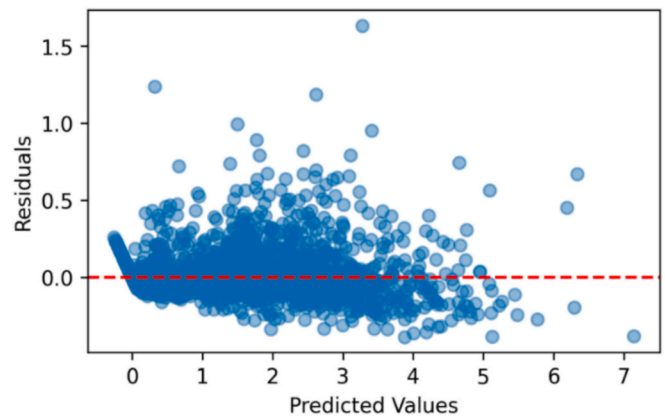


Fig. 3. Residual analysis.

Table 2

Coefficients of the MLR model with statistical significance.

Variable	Coefficient	Std. Err	t-value	p-value	[0.025	0.975]
Constance	0.2031	0.043	4.706	0.000	0.118	0.288
Heat Pump (kW)	0.9894	0.002	415.969	0.000	0.985	0.994
Cooker (kW)	1.0568	0.005	220.748	0.000	1.047	1.066
Sockets (kW)	0.7366	0.004	184.268	0.000	0.729	0.744
Lights (kW)	1.7099	0.052	32.856	0.000	1.608	1.812
PV (kW)	-0.8637	0.02	-44.085	0.000	-0.902	-0.825
Temperature_Indoor(degC)	-0.0063	0.002	-3.383	0.001	-0.01	-0.003
Temperature_Outdoor(degC)	0.0026	0.001	5.126	0.000	0.002	0.004
Month	0.0091	0.004	2.571	0.010	0.002	0.016

Notes – Std.Err: Standard deviation; [0.025 0.975] represents the lower and upper bounds of the 95% confidence interval for the estimated coefficient. t-value: Measures how far the coefficient is from zero in standard errors; p-value: Probability that the coefficient is zero; small values mean significant effect.

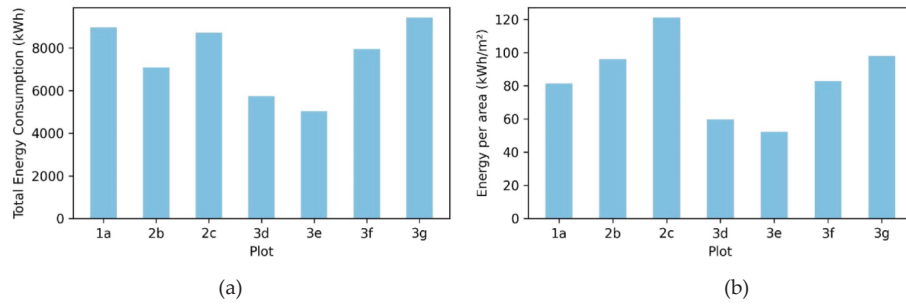


Fig. 4. (a) Annual total electricity consumption and (b) per m2 (kWh/m²) for each plot.

expected due to the lower efficiency of heating system in Plot 2c, which is discussed in more detail in Section 3.3. Plot 3e, has the lowest value at 52.09 kWh/m², which is likely due to the building form factor. Plot 3e is a mid-terrace dwelling, with fewer external wall surfaces than the end-terrace and semi-detached dwellings, which could account for the reduction in overall power consumption. Average per typology is: Type 1 (1a) is 81.4 kWh/m², Type 2 (2b and 2c) is 108.5 kWh/m², and Type 3 (3d, 3e, 3f and 3g) is 72.5 kWh/m² considering floor area. Fig. 5 can be used to understand the difference. This shows the breakdown of energy consumption for each plot. Generally, heating and hot water accounted for the largest energy consumption, with energy metering in heat pump, electrical furnace radiator and immersion heater. The heat pump energy usage varies significantly. In Type 1 and 3, the heat pump energy is 43.8 and 30.5 kWh/m².year while the heat requirement for Type 2 is 50.5 kWh/m².year, with 22 and 28.5 kWh/m².year in heat pump and furnace radiators which represent hot water and heating.

The estimated energy consumption is given in Table 3, which has been extracted from the appropriate Energy Performance Certificate. The energy performance certificate (EPC) is produced from a standardised methodology by a third party; it was not calculated as part of this study but will be used to compare the expected consumption with the realised energy consumption. For a number of dwellings, the in-use energy consumption is lower than the design expected (Plot 1a, 2c, 3f). There are a number of factors which impact this difference. First, the real weather patterns compared with the design temperature used to calculate the EPC. As these do not match, there will be a difference in energy consumption which may be more favourable to the in-life dwelling if there are fewer heating degree days than in design. Second, is the occupant usage. Within the EPC calculation, standardised occupancy profiles are used to drive the calculation, while in practice the usage will vary significantly.

Table 4 summarises the imported power consumption across various plots, highlighting key statistics such as mean, median, standard deviation, minimum, maximum, count, 90th percentile, and 95th percentile. Among the examined plots, Plot 1a and Plot 3g consistently display the highest power usage, with Plot 1a reaching a peak of 9.19 kW and Plot 3g not far behind with a maximum of 8.47 kW. These figures suggest that these plots may have higher operational demands compared to others.

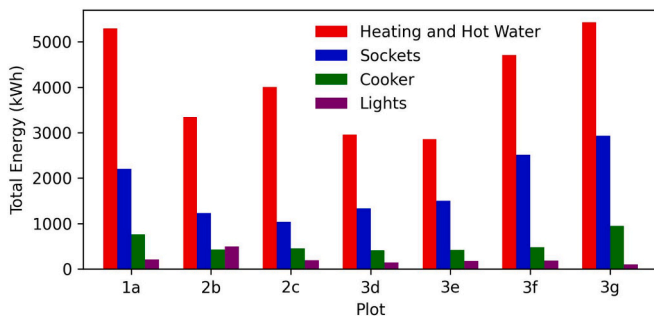


Fig. 5. Breakdown of energy consumption per plot.

Table 3

Space heating and hot water energy consumption, compared with estimated energy consumption for heating and hot water, based on Energy Performance Certificates (EPC).

Plot	Space Heating (kWh)	Hot Water (kWh)	Space Heating and Hot Water (kWh)	Space Heating and Hot Water (kWh/m ²)	Estimated Heat Demand from EPC (kWh/m ²)
1a	2358	2935	5293	48.1	48.1
2b	2741	604	3345	45.4	43.9
2c	1435	2572	4007	55.7	54.2
3d	891	2064	2955	30.7	30.8
3e	1754	1106	2860	29.7	29.8
3f	2523	2181	4704	48.9	49.0
3g	1979	3448	5427	56.4	41.1

Table 4

Statistical summary of imported power per 15 min.

Plot	Mean	Median	Std Dev	Min	Max	90 %	95 %
1a	0.91	0.43	1.06	0.00	9.19	2.34	2.92
2b	0.64	0.43	0.68	0.00	6.67	1.61	1.98
2c	0.85	0.59	0.89	0.00	6.18	2.11	2.59
3d	0.54	0.19	0.91	0.00	8.10	1.81	2.64
3e	0.48	0.10	0.76	0.00	7.12	1.52	2.17
3f	0.80	0.29	0.93	0.00	8.06	2.07	2.66
3g	0.97	0.44	1.20	0.00	8.47	2.66	3.51

Additionally, the table shows notable disparities in imported energy consumption patterns and reveals the inherent fluctuations within different operational contexts. For instance, Plot 1a and 3g have higher standard deviations of 1.06 and 1.2, indicating more significant variability in power consumption, possibly due to varying operational demands or inefficiencies. Conversely, Plot 2b exhibits a more consistent energy profile, with lower variability and peak usage, indicating a potentially more stable power demand. These contrasts are further elucidated through statistical metrics such as maximum and percentile values, which provide deeper insights into the upper thresholds of consumption. Through such analyses on detailed energy monitoring, it helps to understand the efficiency and sustainability in power consumption across various residential settings.

In great Britain, residential energy consumption is separated into regulated and unregulated energy consumption. Regulated energy is energy for heating/cooling, lighting, and ventilation. Unregulated is everything else. Generally, heat is the largest overall consumption. Fig. 5 shows that heating and hot water account for the highest energy consumption, around 56 % of annual energy consumption among the plots. Cooking is the second highest energy consumer not only from cooker but also a large part of energy from kitchen sockets. The kitchen sockets energy is part of sockets energy which also includes ground-floor and other-floor sockets energy.

Fig. 6 shows the breakdown of non-heat related electricity

consumption, compared with 2022 benchmark. The results indicate that the sample dwellings follow the order of the benchmark data: sockets consume the largest point of consumption, followed by cooker and lights, then everything else. In the benchmark data, lighting is slightly higher (15 %) than cooking (14 %) [30]. The benchmark data was from 2022. It is acknowledged that the survey may not be indicative of modern usage, particularly in light of behavioural changes brought on by the COVID-19 pandemic. The benchmark building has energy consumption of sockets at around 51 %, while in 2023 the study dwellings mostly exceeded 60 % of total non-heat power consumption in the use of sockets. The study may support the argument for changing user behaviours against the benchmark energy patterns in 2022.

3.3. Heat consumption

The heat consumption was analysed based on the electricity usage for space heating and hot water. It is used to estimate the energy efficiency for those low-carbon homes.

Fig. 7 presents a comprehensive overview of total heat consumption, including both space heating and domestic hot water (hot water and water heater immersion), normalized to the floor area for each property. This normalization allows for a fair comparison across properties of different sizes. Type 2 dwellings (Plot 2b and 2c) use direct electric panels for heating and an individual heat pump for domestic hot water, but the energy patterns are totally different. Plot 2b consumes the highest amount of energy for space heating across all plots while Plot 2c consumes more energy in hot water than space heating. This is reflected in the highest consumption per area in Plot 2c due to its high hot water usage. The immersion heater is used the least, as this is only used when the heat pump cannot meet the demand.

However, in Type 1 (1a) and 3 (3d-3g) dwellings, where they use a heat pump for both space heat and hot water, a large amount of energy has been used by hot water immersion heater. Especially in Plot 3g, where immersion heater energy consumption is the highest among all plots. Such high demand from the immersion heater is unexpected as they should use the immersion heater only when it cannot meet the demand for hot water. A survey was carried out in these properties to reset heat pump and hot water tank in the middle of the year 2023. During that visit, it was explained to occupants that the immersion heater should only be used very occasionally if the heat pump was not meeting demand. Apparently, occupants believed that the switch outside the cylinder cupboard had to switch it on to supply hot water, thus putting the immersion heater on unnecessarily and increasing the energy consumption. After that visit, immersion heater energy was dramatically reduced to the same level as Type 2 dwellings.

Fig. 8 shows the average heat power demand (including space heating and hot water) in hour of day for all plots across the year. Plot 1a shows a large spike at 6am, with higher demand through the night when

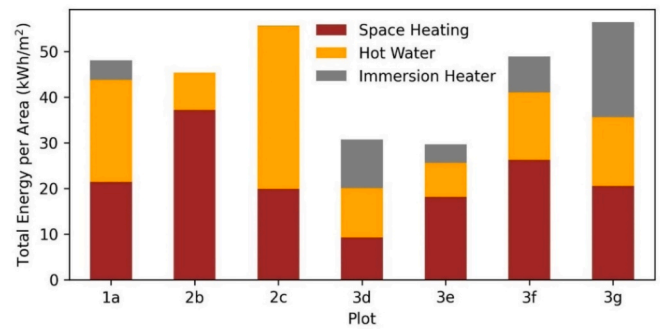


Fig. 7. Breakdown of heat demand per plot per area.

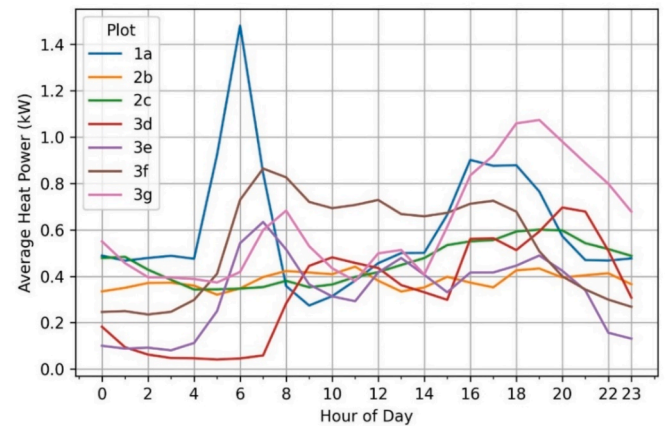


Fig. 8. Average hourly heating load profile. Average heat power demand by hour of day was calculated using whole year data. Heat power refers to both space heating and hot water energy usage in the unit of kW.

compared to the other plots. Plot 1a is around 0.5kWh between midnight and 4am, while other plots are mostly below 0.3kWh. It is clear from the graphs that several of the demands have similar shapes. Peak power demand periods are around 5-9am and 4-8 pm, showing two peak periods in the morning and evening. However, the peak points/hours are rarely aligned as peaks are found in different hours even during these peak periods. Although the adoption of heat pumps increases the peak demand at individual dwelling level, this study provides evidence that the diversity of heat pump operation is greater than previously expected. As a result, the coincident peak demand at the local grid level is lower than it would be if all heat pumps peaked simultaneously, because peak demands vary over time across different plots.

Fig. 9 illustrates a load duration curve for heat demand across the plots. This curve is crucial for understanding the distribution of heat demand over time. It shows the percentage of the time in a year that the demand is at or above a certain level. The shape of the load duration curve provides a visual representation of the distribution and variability of heat demand over the year. The highest points on the curve represent the peak heat demand, which typically occurs during the coldest days of the year. These peaks are critical for designing heating systems that can handle maximum loads without failure. The flatter or lower part of the curve indicates the base load, which is the minimum heat demand that occurs consistently throughout the year. This base load is essential for maintaining basic heating requirements. Heat related power demand is up to 6 kW. Among all the plots, Plot 2b and 2c demand heat energy in longer periods, with 60 % of time in a year; while Plot 3d only uses energy for heat in 25 % of a year (as shown in Table 3, Plot 3d uses far less heat for space heating than other dwellings). The zero consumption for the rest of time represents the warmer summer period when no heat energy was consumed. This emphasises the importance of

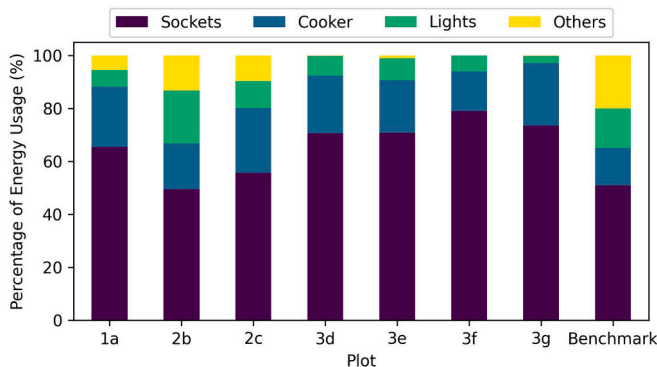


Fig. 6. Energy consumption as a percentage of the total consumption, excluding heat and hot water related electricity, compared with 2022 benchmark.

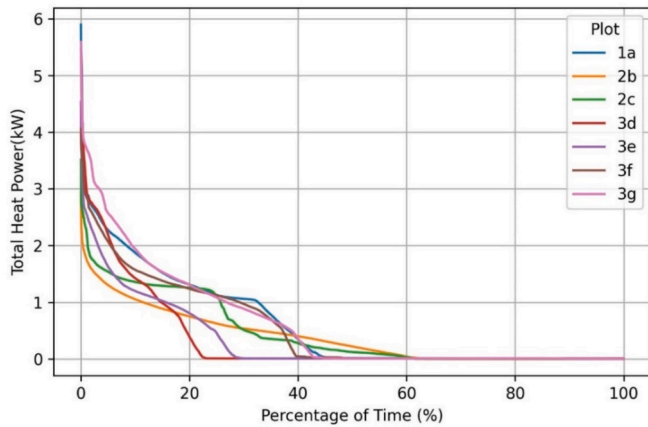


Fig. 9. Load duration curve for total heat power demand (Space Heating, Hot Water, Water Heater Immersion) across the plots.

understanding the impact of occupant behaviour on power networks.

The steepness of the curve's decline can indicate how quickly the demand decreases from peak to base load. A steep curve suggests a high degree of variability, with short periods of high demand and long periods of lower demand. A more gradual curve indicates more stable and predictable demand patterns. The load duration curve can inform decisions about energy supply strategies, heating system capacity, and energy efficiency measures. The curves sharply decline from their peak values in less than 1 % of the time, indicating a short-term heat demand. Especially in Plot 1a with a steep descent from 6 kW to 3 kW, this indicates that such high demand is not sustained for long periods. Plot 3f and 3g exhibit more gradual declines compared to other plots, suggesting a more consistent demand for heat over a larger percentage of time. This could imply a different usage pattern, possibly due to varying occupancy behaviors.

3.4. Peak electricity consumption

The analysis of peak electricity consumption provides crucial insights into how spikes in power usage affect local power networks, particularly within the context of the typical power supply capacity of homes in the UK. Given that traditional homes in the UK are generally equipped with a 230 V single-phase connection, supporting between 60–100 A, this translates to a potential maximum power supply ranging from 14 to 23 kW, as outlined in the British Standards Institute's 2018 guidelines [31]. Understanding these peak consumption levels is vital, as it directly informs whether the existing infrastructure can handle moments of highest demand without overloading the system.

Table 5 presents the peak power consumption for each household in the study. The peak power demands for the low-carbon dwellings were found to be between 6.2 kW and 9.2 kW, averaging 7.7 kW per household. This peak demand constitutes about 33.5 %, or roughly one-third, of the maximum power capacity of 23 kW that each dwelling can handle, according to standard domestic electrical service limits. This lower

Table 5

Peak electricity demand from each dwelling.

Description	Peak Power (kW)
Plot 1a	8.4
Plot 2b	8.1
Plot 2c	9.2
Plot 3d	8.3
Plot 3e	6.2
Plot 3f	7.1
Plot 3g	6.6
Sum of Dwelling Peak Power	53.9
Measured Combined Peak Power	23.5

utilization of the available power capacity is encouraging, indicating that homes built with Future Homes Standard could accommodate heat pumps without necessitating upgrades to current main electrical supply. Furthermore, in managing the power network, a diversity factor is employed to represent the non-coincidental occurrence of individual peaks. Notably, the aggregate peak power recorded was only 23.5 kW, significantly less than the total potential peak if each home were to reach its peak simultaneously.

The combined individual peak demand of the seven dwellings totalled 53.9 kW, which is one-third of the theoretical total design capacity of 161 kW based on 23 kW per home. However, these peaks did not occur simultaneously. The measured diversified maximum demand across all homes was 23.5 kW, representing just 14.6 % of the total design capacity. This highlights the substantial effect of demand diversity. In practice, power infrastructure is sized using After Diversity Maximum Demand (ADMD) rather than the full design capacity of each dwelling. This finding underscores that relying solely on theoretical or installed capacity could significantly overestimate actual network requirements and reinforces the importance of diversity-based planning and the role of occupancy patterns in shaping peak demand.

The composition of the peak energy demand is important in understanding the drivers of peak electricity consumption in dwellings. Fig. 10 shows the breakdown of peak electricity consumption for each dwelling's respective peak period. On average across the samples, space heating and hot water contributed to 43 % of the peak electricity power, and cooking-related appliances, including cooktops and kitchen sockets, contributed about 41 %.

The highest peak demands across the sampled homes occurred at various times throughout the year, predominantly during the cold months of December through March. It is expected that the heating will draw the most power, as it is likely to be the largest appliance. Heat consumption is usually considered to provide indoor thermal comfort, resulting in high power demand in the cold season. This is also significant as the peak electrical demand from the mass roll-out of heat pumps could be based on the maximum installed capacity of the heat pump. However, the combined or diversified peak power from all samples was significantly lower than the total designed power capacity. In addition to heating, substantial power consumption is from cooking in power peaks. The occasional use of high-power electric appliances can also significantly influence the maximum power demand, with peak power reaching up to three times the heat pump's maximum power in the same house. These findings suggest that relying solely on the installed capacity of heat pumps may lead to significant overestimations, and a more comprehensive understanding of occupant behaviour is necessary to accurately assess the impact of heat electrification on local power networks.

This point is further shown by the heat map of pearson coefficients in Fig. 11. The pearson co-efficient shows the linear correlation between two variables, in this case pairs of total consumption for each dwelling.

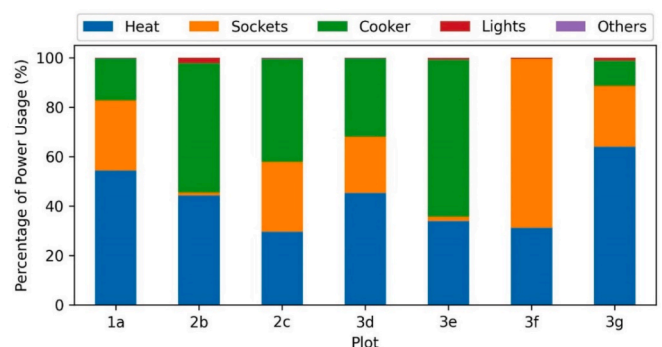


Fig. 10. Breakdown of the maximum electricity peak power for each plot. Peak hour is based on each individual plot i.e. each plot has a different peak time.

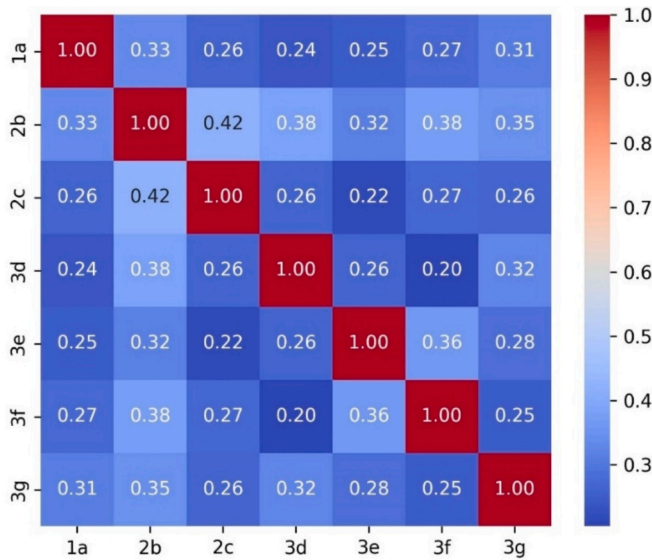


Fig. 11. Pearson coefficient for time-series total electricity consumption between plots.

The coefficients are all very small, which supports the previous data showing a low level of coincidence between power consumption in different dwellings.

Table 6 shows the Pearson coefficients for energy consumption within each dwelling. Generally, there is a stronger correlation between the heat related load and the overall demand, which is to be expected given the large power draw for space heating and hot water, with the highest correlation coefficient of 0.9 in Plot 3f. The high correlation between heat and total energy suggests that increases in heat energy significantly impact the total energy usage. Cooker and Sockets generally exhibit moderate correlations, with values fluctuating around the 0.4 mark, suggesting a varying impact depending on the plot. Interestingly, the Lights tend to have the weakest correlation in almost all plots, averagely at 0.3, highlighting their lesser relative impact on the overall energy usage.

3.5. Electricity generation

The electricity generation has been analysed to understand the importance of demand side generation and how it can be used to minimise the impact of electrification of heat on peak power demand.

Due to the dwelling orientation, the solar panels have varying orientation, resulting in different energy production. Fig. 12 illustrates the monthly energy generation from solar PV across various plots over a year. The patterns of monthly solar energy are similar among the plots, with high production in summer and low in spring and summer. The peak generation during the summer period, particularly from May to August, coincides with higher levels of solar irradiance, characteristic of these months. Variability between the plots can be observed, indicative of potential disparities in aspects such as orientation, shading conditions

Table 6

Pearson coefficient for various energy sources vs total energy consumption in each plot.

Plot	Heat vs Total	Cooker vs Total	Sockets vs Total	Lights vs Total
1a	0.86	0.47	0.46	0.22
2b	0.71	0.37	0.31	0.26
2c	0.82	0.33	0.19	0.29
3d	0.88	0.40	0.46	0.39
3e	0.83	0.46	0.50	0.42
3f	0.90	0.40	0.43	0.21
3g	0.85	0.41	0.57	0.34

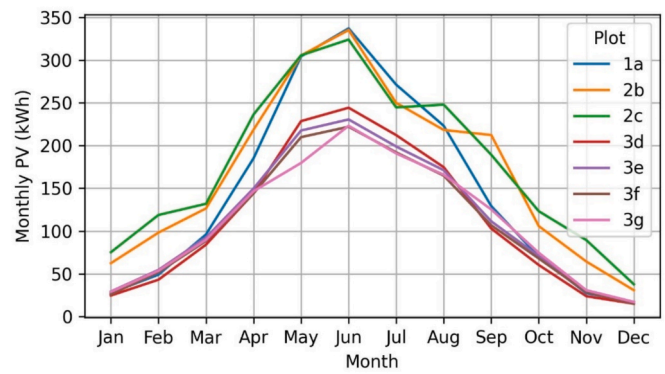


Fig. 12. Monthly energy generation from solar PV.

or installation methods. PV panels were installed on the same side of roofs Plot 1a, 2b and 2c, but installed on both sides of roofs in the other plots. This may be the reason why these three plots have higher production than other plots. Plots 1a, 2b and 2c have peak PV generation at about 330 kWh in June, almost 100 kWh more than the other plots.

Table 7 presents a summary of solar energy generation, export, and usage patterns across various dwelling plots. Plots 2b and 2c show the highest generation of more than 2000 kWh in total over a year, benefiting from all PV panels facing south or south west. Although both plots generated similar amount of solar energy, Plot 2b used more and exported less renewable energy into the grid, showing higher solar penetration. Similar patterns are observed in other plots, with export percentages ranging from as low as 26 % in plot 3d to as high as 44 % in plot 3e. The data illustrates substantial differences in the efficiency of PV generation, utilisation and export behaviors among the plots, which may be attributed to occupants behaviour or disparate household energy needs. The PV export is overall high, up to 44 %, emphasizing the diverse potential for solar energy distribution and local consumption. The PV used within the home varies from 56 to 71 %, resulting in an average of 65 %.

Fig. 13 provides a comparative analysis of seasonal variations in hourly average photovoltaic (PV) generation and total energy consumption across multiple plots. The hourly averages for all sites are aggregated to compute the mean and standard deviation across sites for each hour, representing average PV generation and average total energy consumption throughout a typical day for selected low carbon dwellings, from 0 to 24 h. The shaded areas around each mean line represent the variability or standard deviation, indicating the range within which the actual PV and total energy fluctuate.

In spring and autumn, there is a noticeable overlap in the PV generation and total energy consumption curves, with PV generation peaking around midday and then tapering off, closely mirroring the decline in total energy usage. The summer graph shows the highest PV generation, with the peak extending over a broader part of the day, reflective of longer daylight hours and higher solar irradiance. Conversely, the winter graph exhibits the lowest PV generation with reduced daylight hours, yet there is a significant energy demand throughout the day. These visualizations underscore the impact of

Table 7

Summary of solar PV utilisation within dwellings.

Plot	PV Generated (kWh)	PV Export (kWh)	PV Export (%)	PV Used (%)
1a	1738	730	42	58
2b	2029	583	29	71
2c	2125	890	42	58
3d	1358	350	26	74
3e	1373	598	44	56
3f	1317	399	30	70
3g	1326	426	32	68

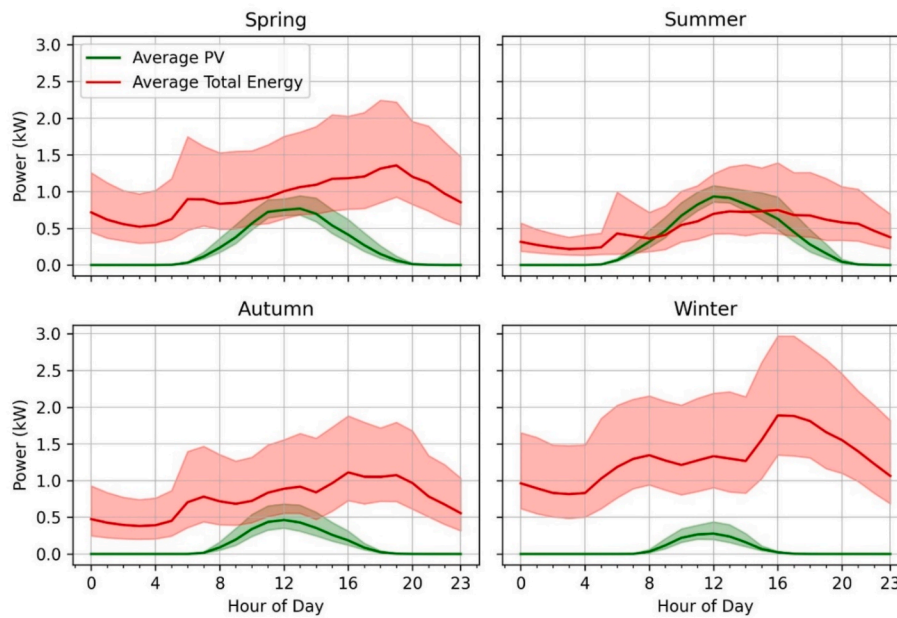


Fig. 13. Seasonal variation in hourly average PV generation and total energy for all plots, illustrated with shaded areas denoting variability around the mean. The shades represent for the variation of PV and total energy across the season.

seasonal changes on energy dynamics and the potential mismatches between energy supply from PV and consumption patterns, which could inform energy management strategies and optimization of PV system designs.

4. Discussion

In discussing energy consumption within UK dwellings, heat related energy accounts for the highest energy consumption in UK dwellings. The monitoring data reveal considerable variations in energy consumption across different dwelling types, suggesting that a significant portion of actual energy usage remains unaccounted for by the standard Energy Performance Certificate (EPC) methodology. This discrepancy indicates that the EPC might not fully or accurately represent real-world energy consumption. Furthermore, even among dwellings of the same type, energy demand varies significantly, which can be attributed to different occupant behaviours and usage patterns. These findings highlight the need for a more nuanced approach in energy assessment methods to better capture the diversity of energy usage and efficiency in residential settings.

It is important to discuss the non-heat or unregulated energy consumption as it represents real energy usage related to occupants activities such as cooking and lighting. Electrical consumption from sockets, particularly in the absence of heating, emerges as the predominant energy draw across the sampled dwellings. A substantial proportion of sockets energy is detected from kitchen sockets, accounting for the use of kitchen appliances including microwave, oven, air fryer, fridge and washing machine. These high-power electrical cooking appliances, such as oven, consume a significant amount of energy. Such unregulated energy consumption is generally not included in initial energy estimates during the design phase, as these estimates often fail to consider the variability introduced by occupant behaviour. Estimating unregulated energy consumption at design stages may offer very little practical benefit as the designer has no control over what will be plugged in, though may increase consumer awareness of realistic energy consumption and therefore costs.

The energy regulator, Ofgem, estimates the typical household in Great Britain uses 2,700 kWh of electricity and 11,500 kWh of gas per annum; this is a total energy consumption of 14,200 kWh/year [32].

Fig. 5 shows each of the dwellings in this study were far below this average by 40–67 %. This is a huge saving over the typical household which demonstrates real energy and carbon savings. While it is impossible to completely mimic the design assumptions (e.g. occupancy, small power usage, outdoor temperature etc.), the findings indicate that even with the performance gap between design and practice, these dwellings achieve considerable energy and carbon savings.

Interestingly during the monitoring period, it was observed that 2 of the 7 systems (air source heat pumps) had not been properly commissioned which resulted in overuse of the immersion heater, as occupants didn't know that the immersion heater had to be switched on only when the heat pump could not cope with demand. This was subsequently rectified and occupants educated about how to properly use the system. Until then, the immersion heater was operating often at the same time as the heat pump. This increased the peak demand by the immersion heater load of 3 kW and reduced the use of the heat pump. This obviously increased some of the annual electrical consumption and cost the occupants more. If tighter supply (nearer to maximum load with a lower diversity) is being adopted then more effort needs to be placed on commissioning, a greater degree of monitoring installed and occupant education to ensure that houses are working within their expected parameters. Such monitoring will probably be necessary as further developments are made in future homes equipment to make them more efficient.

The peak electricity consumption within domestic buildings is critically important in maintaining a secure, resilient electricity network. As homes electrify with the addition of electric vehicles, heat pumps, and increasing numbers of smart gadgets, the electricity networks struggle to keep up with the demand. It is therefore of crucial importance to understand the actual peak demand required in practice. Traditional home within the UK are commonly supplied with a 230 V single phase connection at between 60–100 A [31]. These equates to a maximum power supply of around 14–23 kW. This does not mean each building uses this, but this is the approximate maximum allowance. National Grid [33] and Electricity North West [34] suggested 15 to 20 kW (kVA) in their guides to new electricity supply for individual domestic properties. The sampled dwellings demonstrated about two third less in power demand than maximum power supply, highlighting their potential to substantially lower the overall demand on electricity networks.

Households exhibit variations in energy consumption due to differing simultaneous energy use patterns, leading to diversity in energy demand across homes. This variability is accounted for by the concept of After Diversity Maximum Demand (ADMD), which represents the actual peak combined demand for a group of homes [35]. Typically, as the number of customers increases, the ADMD per household decreases, and the associated uncertainty diminishes. Historically, ADMD has been estimated based on statistically predicted small appliance loads, with an average value of 2.27 kW per UK household [36]. Similar findings were reported in the Customer-Led Network Revolution (CLNR) project at Durham University, indicating that typical planning guidance aligns with an ADMD for gas-heated properties, being approximately 2 kW per household, rising to 3 kW when using electric heating, or higher if extra bedrooms are included [37]. However, the electrification of heating and transport introduces new challenges, adding uncertainty to network planning. With the adoption of heat pumps and electric vehicles (EVs), traditional ADMD estimates are no longer applicable. To address the increased loads associated with electrification, it has been suggested the existing ADMD of 2.5 kW to be doubled to approximately 5.5 kW to support these demands in the most cost-effective manner [38]. If only considering heat pump, the ADMD per heat pump was estimated to be 1.7 kW per site [39]. Assuming 2.27 kW as the base ADMD for a typical UK home, adding the heat pump would increase the ADMD to 3.97 kW per dwelling with heat pump. However, the average ADMD for a low-carbon dwelling is calculated at 3.36 kW (23.5 kW for 7 homes), which is 15.4 % lower than the typical ADMD. This difference arises because the typical ADMD is based on all UK homes, whereas the sample represents only 7 low-carbon dwellings. If the sample size of low-carbon dwellings with heat pumps were increased, the ADMD per dwelling would likely decrease further, falling well below the typical ADMD for UK homes. This highlights the potential to reduce grid pressure by expanding the adoption of low-carbon dwellings in the future.

Increasing the size of PV array may reduce the overall energy consumption from the local power network and it is likely to reduce the overall peak energy consumption. This can be explained by looking at Fig. 13. These figures show the average hourly PV generation for each hour of the day for the full year, but in four seasons. PV generates far less electricity in winter than in summer months because the solar radiation level is considerably low in winter. Increasing the size of PV could increase a small amount of solar energy, but may still not be enough due to the limitation of roof area and low solar radiation. PV generation is highest in summer, resulting in excess energy exported to the grid in some hours during the day. But it still has its limitation in covering early morning and evening energy consumption. The figure shows that there is generally a larger spike in demand in the early evening which is not coincident with PV generation. If storage were to be used to save excess energy during the day and released at night, it will allow better utilisation of PV energy. Other than storage, the control algorithm within the properties could also be optimised to improve the utilisation of PV generation on site by charging the domestic hot water storage during periods of excess PV generation.

The dwellings sampled in this study exhibit a high degree of variability in energy usage across different plots and plot types, particularly in heating and cooking demands (as shown in Fig. 6 and Fig. 7), which account for a large share of total energy use. This underscores the importance of occupant behaviour on overall energy consumption. This is an important finding as it demonstrates the limitations of current modelling approaches. In current modelling approaches, similar plot types would show similar energy demand patterns, but results indicate that even identically designed dwellings within the same geographic location can show significant deviations, which is likely driven by occupant behaviour. This variability introduces significant uncertainty into local power networks' ability to predict future energy needs effectively. Further work is needed to better capture the impact of occupant behaviour on power and heat consumption.

The development studied in this research is the first Future Homes

Standard demonstrator in the UK, consisting on 12 homes in a brown-field site, of which 7 participated in the study. As more houses are built under this Standard, it will allow us to increase the sample size and check that results from this study are consistent.

5. Conclusion

Carbon emissions from dwellings are increasingly being targeted in the efforts to achieve net zero carbon globally. While electricity can be decarbonised at transmission level networks, the decarbonisation of heat is much harder as it requires higher building efficiency. Heat pumps are often quoted as an issue for local power networks as they add additional demand on local infrastructure. However, this study has presented strong evidence that domestic air source heat pumps, and in some cases even electric heating panels, increase power demand at individual dwelling level but this is not necessarily transmitted to local grid peak demand. This is attributed to the fact that, although individual dwellings exhibit significant peak demand, the aggregated demand across multiple households remains dispersed due to operational diversity. Other factors such as unregulated heating or kitchen electric appliances, may contribute more to grid-level power demand and can sometimes dominate during peak periods rather than heat pumps.

The conclusions and recommendations of this study can be summarised as:

- In low-carbon homes, space and hot water heating represent the predominant uses of electricity, together accounting for approximately 56 % of the annual electricity consumption. This could have been further reduced by introducing smarter controls on the heat pumps and domestic hot water tanks, as well as more education to occupants.
- Peak demand mainly occurred during the cold months, with heating and cooking accounting for more than 80 % of the peak power. High power demand can also arise from electric appliances such as portable heaters, which can consume three times the maximum heat pump power observed in this study. Occupancy behaviours such as intermittent operation of heat pumps can significantly influence the timing and magnitude of peak demand, as heat pumps require time to raise indoor temperatures while occupants may turn to faster high-power alternatives when immediate warmth is needed.
- On average across the samples, space heating and hot water contributed to 43 % of the peak electricity power, and cooking-related appliances, including cooktops and kitchen sockets, contributed about 41 %, underscoring the impact of occupant behaviour on heat and cooking demands.
- The electrical peak power demand for heat is far lower than the installed capacity of heating equipment. This is an important finding, which should be utilised within power network planning to critically analyse the resilience required for electrification of heat scenarios.
- The peak demand constituted about 33.5 % of the maximum power capacity of each dwelling. This lower utilization of the available power capacity indicates that homes built with Future Homes Standard could accommodate heat pumps without necessitating upgrades to current main electrical supply.
- The measured diversified peak demand was just 14.6 % of the total design capacity, highlighting the importance of diversity-based planning over theoretical capacity estimates. This reinforces the need for smart monitoring within homes to understand the significance of occupant behaviour on local network resilience and unlock local flexibility. Although this can be seen to suggest that the estimation of under capacity in the network is over stated, it must be noted that these are high specification new dwellings and no use was made for other electrical demands such as EV charging.
- Solar generation may reduce the overall carbon footprint and power cost for occupants, but it did not reduce the peak demand for electricity within this study. Electrical storage is unlikely to be currently

economically viable, therefore thermal storage should be explored. This has been studied at great lengths in literature, though it is unclear if the overall low energy consumption would discard the merit of short term storage.

CRediT authorship contribution statement

Michael-Allan Millar: Writing – original draft, Visualization, Formal analysis, Conceptualization. **Kui Weng:** Writing – review & editing, Visualization, Methodology, Formal analysis. **Monica Mateo-Garcia:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **David Boyd:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michael-Allan Millar reports financial support was provided by Research England. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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