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In-use energy and carbon performance of a true zero carbon housing development in England

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This paper systematically examines the in-use energy and carbon performance of a large case study housing development in England, designed to be net true zero carbon. Remote monitoring during a one-year period was used to gather high-frequency data on dwelling heat use, grid electricity use, solar PV electricity generation and export and community heating system performance. Based on data from 74 dwellings, mean energy use of 76 kWh/m^2/year and electricity use of 27.4 kWh/m^2/year per dwelling placed the case study among the lowest energy housing developments in the UK. Nonetheless, heat usage and designed fabric efficiency fell short compared to other true zero carbon housing. The mean self-consumption rate of generated energy of 23% calls for the provision of home batteries. Heat usage variance was more prominent compared to findings in other studies. Based on the 2018/19 carbon factors, dwellings emitted 20.2 kgCO2e/m^2/year on average, missing the zero carbon target. As found in other studies, this was attributed to the underperforming community heating system. This study comes timely in the context of the widespread calls for net zero carbon dwellings. The findings confirm the argument that the anticipated mainstreaming of zero carbon dwellings demands shifting toward an outcome-focused design approach.

Introduction

Policy context

The residential sector accounts for 21% of national carbon emissions in the UK (BEIS 2021). Lowering the housing sector's energy and carbon intensity plays an important role in the country's national Clean Growth Strategy (BEIS 2017), carbon budgets (HM Government 2011) and the aim to achieve a net zero economy by 2050 (DBEIS and DEFRA) 2019a). Increasingly stringent building standards have been introduced by the UK Government in order to ensure the necessary reductions in energy use and carbon emissions. The initiative for a zero carbon homes standard was announced for 2016 (DCLG 2007), convergent with the European near zero energy buildings directive for 2020 (E. U. 2010). Net zero carbon is one of the most advanced building performance targets, along with the German Passivhaus standard, net zero energy (Torcellini et al. 2006) and autonomous dwellings (Vale and Vale 1999). The initial zero carbon definition was adopted from the former Code for Sustainable Homes standard (CLG 2010). By taking into account the unregulated energy (appliances and cooking) and by allowing only the directly connected energy installations, it was often called *true* zero carbon (DCLG 2006; DCLG 2007). Achieving the performance *net*, meant that over the course of a year, any carbon emissions from the fossil fuel use need to be balanced with an equivalent export of zero carbon energy. In the response to concerns about the technical and financial viability of the proposed definition (UKGBC 2008; DCLG 2008), in the following years the zero carbon definition was weakened. Off-site measures were allowed, the minimal carbon reduction target was downgraded and the unregulated energy excluded (McLeod, Hopfe, and Rezgui 2012). Prioritizing a faster delivery of new homes (HM Treasury 2015), the Government slowed down the envisioned steep advancement of the building requirements, and eventually withdrew the plans for the zero carbon standard (DCLG 2017).

Given the climate emergency, there is an increasing agreement among the industry and academia that major changes in current Government policies and the housing delivery are urgently needed in order to meet the climate

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objectives. The Future Homes Standard announced by the Government for 2025 (MHCLG 2019) aimed to address some of the key challenges. New dwellings were envisioned as climate resilient, using low carbon heating and emitting 75-80% less carbon compared to the 2013 UK Building Regulations. Industry reports (CCC 2019; LETI 2020) and briefing papers (CIBSE 2019; UKGBC 2020) regarded the proposed reduction of carbon emissions as inadequate, calling for a net zero carbon standard (including all energy users) for 2025. The industry bodies also criticized the weakening of the proposed fabric efficiency requirements. As the decarbonizing electricity grid is on its own slowly reducing carbon emissions of buildings, minimizing building energy demand is gaining more importance. In this context, tightening of fabric efficiency levels, limiting space heating demand and introducing the energy use intensity (EUI) metric was also suggested. The application of only primary energy use and carbon emissions metrics could potentially hide the poor energy performance of forthcoming buildings (Bordass 2020).

In-use performance evaluations

Apart from uplifting the design standard, it was is also widely advocated that current regulatory compliance based on the design intent shifts toward ensuring ongoing compliance. The evidence revealing the gap between designed and actual performance in new buildings is widespread (Zero Carbon Hub 2014). It can be expected that the actual dwelling energy use is higher, as the current method for proving regulatory compliance only considers the regulated energy. However, large BPE evaluation studies have shown that all stages of the house building process can contribute to the loss of performance, identifying the building fabric, energy systems and occupant behavior as the key determining factors (Zero Carbon Hub 2014; NEF 2015). The gap greatly hinders meeting the carbon reduction targets set for the building sector. Meta-studies of new low carbon buildings in the UK revealed that compared to the design projections, the actual energy use increased 1.6 times on average (Gupta and Gregg 2020), and carbon emissions 2.6 times (Innovate UK 2016). Evaluations of UK dwellings aiming for the weakened zero carbon standard (Gupta and Kapsali 2014; Sodagar and Starkey 2016) and true zero carbon (Ridley et al. 2014), showed that the carbon target was not achieved due to an increase in energy use above predictions. Aspired net zero energy target was also not achieved in housing developments in the UK (Young 2015), Australia (Berry et al. 2014) and in two-thirds of US case study dwellings (Thomas and Duffy 2013). The Passivhaus standard seems to be more reliable in meeting the space heating target (Mitchell and Natarajan 2020) and in delivering low energy homes (Ridley et al. 2013; Mahdavi and Doppelbauer 2010; Mutani et al. 2017).

Measurement of the in-use performance is essential in the aims to narrow the performance gap. In-use (post-occupancy) assessment is a sub-process of more extensive Building Performance Evaluation (BPE) and Post Occupancy Evaluation (POE) practices (Preiser and Vischer 2005). In practice, however, monitoring and reporting the in-use performance is rarely conducted. It is not mandatory under current regulations, while its many benefits for building stakeholders can be outweighed by concerns such as high costs and possible exposure of poor performance (Leaman, Stevenson, and Bordass 2010). POE and BPE studies tend to be based on the case study approach. Although it can be seen as inferior to other scientific methods capturing large samples, case study approach is considered beneficial when studying such complex contextualized phenomena in a greater depth (Yin 2012; Flyvbjerg 2006). Evaluating advanced buildings can yield new findings and contribute to the wider knowledge base (Leaman, Stevenson, and Bordass 2010).

Dwelling performance evaluations are typically extensive, thus limited to studying only a small number of case study dwellings ((Tse and Colmer 2014). Evaluating larger housing developments forming clusters of dwellings and small neighborhoods can show a variance in achieved performance across the housing sample, usually built with similar specifications. In relation to different lifestyles, studies have showed that electricity use differed from 1.9 (Sodagar and Starkey 2016) to five times (Lee, Whaley, and Saman 2014). Heating use differed about three times in dwellings with equivalent occupancy (Gill et al. 2011) and in identical dwellings (Gram-Hanssen 2010). Evaluating larger housing developments can be also beneficial for demonstrating whether the performance target is achieved at the development level rather than at the individual dwelling level. However, a larger dwelling sample makes collecting the household profile and other contextual data more challenging. This can limit gaining a deeper understanding of performance results.

Larger zero carbon housing developments are being delivered internationally, using different design approaches adapted to local contexts (Williams 2012; NHBC Foundation 2009). However, reports on their actual performance were found for only a small number of UK projects, briefly presented in Table 1. As the Lancaster Cohousing project seems to lack a more detailed energy performance report, a single Passivhaus dwelling aiming for true zero carbon was added to showcase this design approach. The analysis of designs indicated that reaching true zero carbon in housing developments demanded highly efficient low zero carbon (LZC) measures; fabric efficiency close to or at Passivhaus levels, a mechanical ventilation heat recovery (MVHR), large photovoltaic (PV) systems and community heating. Despite concerns regarding its reliability (UKGBC 2008), biomass as community heating fuel seems to be more favored than a gas-fueled combined heat and power (CHP) system (UCL Energy Institute and Crest Nicholson 2014).

Although some of the developments presented in Table 1 achieved their energy use targets, the zero carbon performance ambition was recurrently not achieved at the development level. At four of seven selected developments,

Table 1. Basic project information and key performance findings of zero carbon/energy housing developments in the UK.

Study	Project name	Year of completion and size	Design target and key specifications	Actual performance findings
SCI (SCI 2013)	Birchway Eco Community	2009 24 flats	Zero carbon Biomass community heating PV 0.9 kWp/unit, MVHR 6 m^3/hr/m^2@50Pa	Procurement, operation and maintenance issues with the heating system. Use of backup oil boilers and electric heaters during the initial two years. MVHR issues.
BSRIA (BSRIA 2015)	Hanham Hall	2015 185 flats and houses	Zero carbon Gas boiler PV 1.5 kWp/unit, MVHR 1.5 m^3/hr/m^2@50Pa	Project design switched from true zero to zero carbon and provision of individual gas boilers. Brief interim report informs that energy use is in line with design projections.
Lowe and Altamirano (Lowe and Altamirano 2014)	One Brighton	2010 172 flats	Zero carbon Biomass community heating PV 0.1 kWp/unit, MVHR 5 m^3/hr/m^2@50Pa	High distribution loss of the heating system resulted with 10 times higher carbon intensity of heat, and reduced usage of received heat. High MVHR electricity use due to issues.
Young (Young 2015)	BedZED	2002 100 flats	Zero energy Biomass CHP 1.9 kWp/unit, Natural v. 3 m^3/hr/m^2@50Pa	Passive design approach. Ongoing issues with biomass CHP led to replacing the system with a community gas boiler and increased carbon intensity of heat. High heat usage.
NEF (NEF 2014)	Sinclair Meadows	2012 21 flats and houses	Carbon negative Biomass community heating PV 4 kWp/unit, MVHR 2.5 m^3/hr/m^2@50Pa	Very low overall efficiency of the heating system (~20%) due to boiler failure causing seven times higher carbon intensity of heat. Fabric first approach resulted in low space heating use.
Wrigley (Wrigley, XXXX) Ecoarc (Ecoarc 2013)	Lancaster Cohousing	2012 41 houses	True zero carbon Passivhaus Biomass community heating PV 2.2 kWp/unit, 160 kW hydro, 0.6 ach	Credible performance report lacking. Community heating and hydro turbine performance not disclosed. Low electricity usage likely due to cohousing lifestyle.
Ridley et al. (Ridley et al. 2014)	Welsh Passivhaus	2010 1 house	True zero carbon Passivhaus, Gas boiler PV 4.7 kWp 0.6 ach	Lack of energy efficient appliances and lights and occupant factors resulted in high electricity usage. True zero carbon target missed.

operational issues of the community heating system resulted in a significantly higher carbon intensity of heat. These findings are concerning, considering the key role of district heating in the national plan for decarbonizing heating (BEIS 2017).

A wider application of the zero carbon performance standard has been anticipated for over a decade. Design guidelines can make reaching the standard seem achievable (LETI 2020). However, the existing evidence suggests that achieving even less ambitious standards was challenging for the industry. Prior to mainstreaming zero carbon dwellings, it is essential to acquire more understanding about how to deliver such advanced performance in larger housing developments and effectively utilize the needed LCZ technologies. In response to these challenges, this study aims to present an empirical assessment of the actual energy and carbon performance of a large case study housing development in England, designed to achieve the ambitious net true zero carbon performance.

Case study

The assessed case study makes the initial two phases of a 4-phase urban extension of a town in England. The design aimed to achieve a high environmental performance, including net true zero carbon at the development level. When the study commenced, 86 dwellings (Phase 1) had been occupied for two years and 71 dwellings (Phase 2) for one year, or less. In terms of dwelling typology, the assortment of 129 two-story houses consists of 2- and 3-bed mostly terraced houses and 4- and 5-bed mostly detached houses. 28 Flats (1- and 2-bed) are situated in three-story apartment blocks. Across the development, dwellings with same number of beds vary in orientation and in total floor area (TFA) (see Table 2). Dwellings were built using a light-weight structural insulated panel (SIPs) system. An example of plans of terraced houses can be seen in Figure 1.

Table 2. Difference between the sample with available energy use (n = 74) and all Phase 1 and 2 dwellings (n = 157).

	Sample (n = 74)		Difference to all (n = 157)
1-Bed (53-56m^2)	4	5%	+0.3%
2-Bed (61-86m^2)	36	49%	+3.4%
3-Bed (92-96m^2)	23	31%	−5.2%
4-Bed (119m^2)	1	1%	+0.1%
5-Bed (165m^2)	10	14%	+1.4%
Private owned	50	68%	+5.1%
Affordable rent	14	19%	−7.2%
Affordable shared ownership	10	14%	+2.0%
Flats	18	24%	+6.5%
Houses	56	76%	−6.5%
Phase 1	41	55%	+0.6%
Phase 2	33	45%	−0.6%
Mean TFA (m^2)	92.1	–	+0.7
Mean number of beds	2.7	–	0

Key design specifications of the case study development were presented in Table 3. In line with the true zero carbon definition, the 4-phase development was designed to balance the annual carbon emissions attributed to the used energy from the grid with the energy exports from the on-site solar PV's and the CHP plant. The design calculations estimated a mean net carbon emission of −0.14 kgCO$_2$/m^2/year per dwelling. This was based on SAP[1] 2009 carbon factors, projected carbon intensity of delivered heat (0.014 kgCO$_2$/kWh), solar generation (807.3 kWh/kWp), PV system size (3.7 kWp) and energy use (75.4 kWh/m^2/year) as a sum of mean electricity usage per dwelling (30.8 kWh/m^2/year) (based on the former APEE standard[2]) and the heat requirement[3] (44.6 kWh/m^2/year). Energy efficient inbuilt lights and white goods were provided in all non-rented dwellings (74% of all case study dwellings). The community heating system was designed to supply heat to all four phases, and achieve an overall efficiency of 67%. The plant consists of a CHP engine, thermal storage and supporting gas boilers. The gas-powered CHP engine and thermal storage were expected to deliver 90% of heat, while the remaining 10% would be provided by the gas boilers. With the designed supply temperature of 85 °C, the system can be regarded as a 3rd generation district heating (Werner 2017). In the application for low energy dwellings, new 4th generation systems with lower supply temperatures seem to offer higher energy efficiency (Nord et al. 2018).

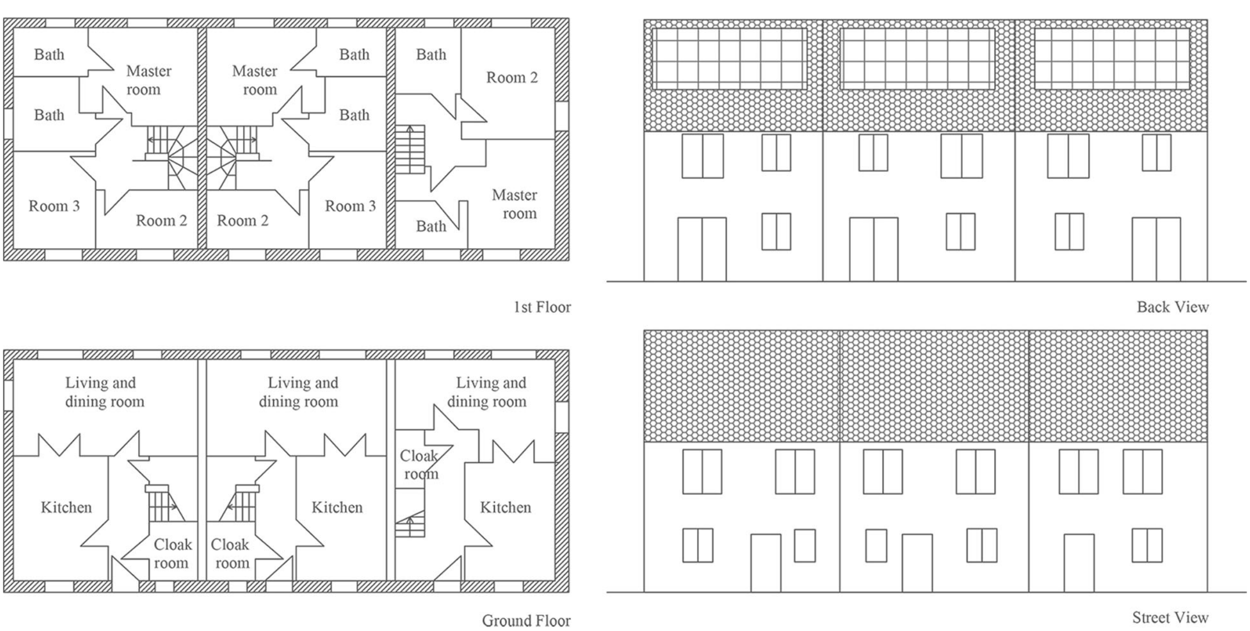

Fig. 1. Architectural drawings of a terraced houses sample.

Table 3. Design specifications of the case study development.

Designed performance per dwelling			Fabric thermal properties	
Carbon emissions	-0.14 kgCO$_2$/m^2/year	W/m^2.K	Walls	0.15
Solar generation	807.3 kWh/kWp		Floor	0.15
Solar PV system	3.7 kWp		Roof	0.13
Energy use	75.4 kWh/m^2/year		Windows	0.8
Electricity use	30.8 kWh/ m^2/year		Air permeability (m^3/hr/m^2@50Pa)	3
Heat demand	44.6 kWh/ m^2/year		Thermal bridging (y-value)	0.04
Energy efficient appliances	In private and shared ownership (74%)		Ventilation system	MEV (74%) MVHR (26%)
Heating system	Community heating for 4 phases; Plant; gas fueled CHP engine, thermal storage and gas boilers			

Table 4. Sensor specifications used for monitoring of the case study.

Meter Type	Connection Method	Granularity	Accuracy
Import & Export Electricity	Pulse	0.001 kWh / pulse	Class 2
PV Generation	Pulse	0.001 kWh/ pulse	Class 1 & MID
Water	Pulse	10 L / pulse	Not known
Heat	Pulse	1 kWh / pulse	MID certified

Compared to other presented housing aiming for true zero carbon, case study dwellings were designed with slightly weaker fabric efficiency levels. The designed fabric specifications (as U-values in W/m^2) were 0.15 for walls, 0.15 for floor, 0.13 for roof and 0.8 for windows, with a targeted air permeability of 3 m^3/h.m^2 @50Pa. MVHR systems were provided in rented dwellings (26%), and all other dwellings were provided with a continuous mechanical extract ventilation (MEV) system located in wet rooms.

Methods

The data analysis of the case study housing development was based on energy data sourced from the pre-installed energy monitoring system. The high frequency (1 minute) data from meters was sent to the Meter Concentration Unit (MCU) and uploaded to the online database. Specifications of provided meters can be seen in Table 4. In each house, five data channels were collecting grid electricity use, PV generation and export, water use and heat use. Each flat was associated with only three data channels (electricity, heat and water) as PV panels installed on the building's roof were not wired to the flats. The energy analysis was based on 1-year energy data collected in the period from 1 June 2018 to 31 May 2019. Occupancy-related data were obtained from a conducted development-wide questionnaire survey.

A comparison of monitoring data to the manual meter readings obtained from a sample of nine to ten dwellings indicated that the monitoring data used for analysis could be considered reliable. From a total of 729 meters, a detailed analysis of the dataset identified only 56% valid data channels, containing >95% of daily data collected during the monitoring period.

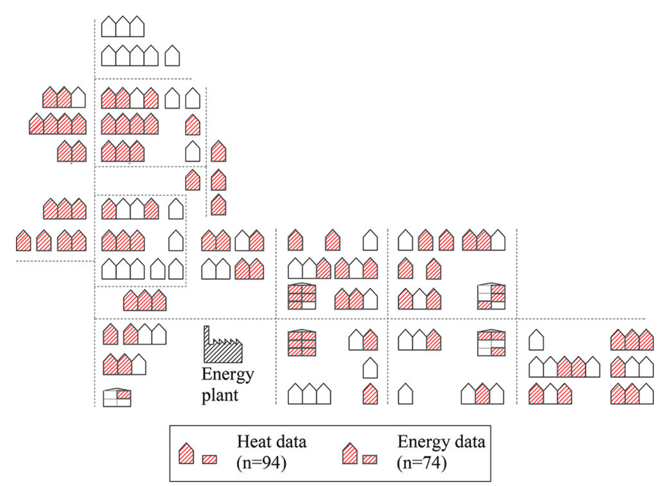

Fig. 2. Schematic of the development site with the captured dwelling sample.

The data analysis was performed on three levels. From all 157 dwellings in Phase 1 and 2, heat use data were available for 94 dwellings (60%) and total energy usage data (aggregating use of heat, grid electricity and self-consumed solar PV electricity[4]) was available for a sub-set of 74 dwellings (47%). Captured sample with available heat and energy data can be seen on the development site schematic in Figure 2. Occupancy-related data (occupant number and occupancy pattern) were obtained via questionnaires in 35 sub-set dwellings. The dwelling sample with the available energy data (n = 74) can be considered relatively

Table 5. Descriptive statistics of annual energy use per dwelling, by number of rooms.

Annual energy use (kWh/m^2)	1-Bed	2-Bed	3-Bed	4-Bed	5-Bed	All
Minimum	25.8	42.9	55.5	74.5	31.2	25.8
Maximum	114.0	115.8	139.0	74.5	93.6	139.0
Median	60.1	71.6	85.6	74.5	69.6	76.3
Mean	65.0	72.4	85.4	74.5	65.7	76.0
Sample size	4	36	23	1	10	74

representative when compared to all Phase 1 and 2 dwellings (n = 157). The difference between the mean values of the same dwelling groups in terms of size, typology and other characteristics was relatively small (Table 2).

Results

Total energy use

Based on the 74-dwelling sample, the mean net energy use (annual grid energy use) was 70.5 kWh/m^2/year. By adding the mean self-consumed PV electricity of 5.5 kWh/m^2/year, the resulting mean energy of 76 kWh/m^2/year per dwelling can be considered to have achieved the design target (75.4 kWh/m^2/year) (Table 5, Figure 3). Achieved mean energy use was low; equal to the mean use reported for a Passivhaus dwelling sample (Gupta and Gregg 2020), but it was still outperformed by the two other zero carbon housing developments, as seen in Figure 4.

Dwelling annual heat and electricity use data per total floor area were analyzed among dwelling groups that share the same building characteristics. The difference between the minimum and maximum energy use per floor area between dwellings within the same groups ranged from 2.1 to 8.1 for heat use and from 2.4 to 4.2 for electricity use (Table 6). The difference in electricity use across the dwellings with the same occupancy was slightly higher; up to 6.7 times when including a strong data outlier[5], and up to 5.1 times when it was excluded (Table 7). The resulting difference in heat use per floor area among low energy dwellings with same building characteristics is more pronounced compared to what was reported elsewhere (Gill et al. 2011). The variance in heat use (M = 4,830, SD = 3,014, CV[6] = 0.62) of the dwelling sample with the heat data (n = 94) seems also more prominent compared to the findings in Dutch and Danish households (Van den Brom et al. 2019; Guerra Santin, Itard, and Visscher 2009).

The data analysis also showed that the 3-bed houses in Phase 1 (n = 12) used almost a third less heat as a group mean compared to the same group type in Phase 2 (n = 19), while 5-beds in Phase 1 (n = 6) used nearly 90% less heat compared to the same group in Phase 2 (n = 6). Based on the dwelling sample with occupancy data (n = 35), the energy use per floor area was not significantly ($p > .05$) associated with the household profile (dwelling use pattern, tenure and occupancy), dwelling orientation or typology. In contrast to the results, the smaller household size in Phase 2 (M = 2.2) compared to Phase 1 (M = 2.8) is indicative of lower heating needs; due to more childless households (Do Carmo and Christensen 2016) and likely reduced heating in the additional bedrooms (Guerra Santin, Itard, and Visscher 2009). It should be also noted that the two Phases were built by different contractors, which might lead to differences in as-built fabric performance. A more detailed BPE study would be needed to explain the exact causes of the noted difference in heat use.

Heat use

Based on the dwelling sample with available heat data (n = 94), the achieved mean heat usage was 49.7 kWh/m^2/year per dwelling. Similarly, 48.5 kWh/m^2/year of heat was used in dwellings with available total energy use data (n = 74) (Figure 5). This is 11% and 9% higher heat use, respectively, compared to the design projections, and higher than the mean usage reported in other true zero carbon housing developments (~28 – 41 kWh/m^2/year). With a similar mean total floor area compared to UK averages (MHCLG 2018), the mean heat usage of case study dwellings was 4,830 kWh/year. This is less than half compared to 11,400 kWh (51 – 100 m^2 TFA group) gas use from the NEED database (DBEIS and DEFRA) 2018) and 12,000 kWh of gas usage for a medium UK user (OFGEM 2017).

The strong correlation (R^2=0.96) (Figure 6) between the monthly heat usage of the dwelling sample and the degree day data (Monthly Degree Day Data 2018) from a nearby weather station, indicated the hot water usage over the summer months. The lowest monthly heat usage of the sample occurred in July was regarded as an equivalent to the mean monthly hot water usage. On this basis, the hot water and space heating usage ratio was estimated as 23% and 77%, respectively, which was similar to UK averages (DECC 2014). Consequently, the estimated mean space heating use would be 38.3 kWh/m^2/year per dwelling, more than double compared to what was achieved in Passivhaus dwellings.

Third-party in-situ fabric testing conducted on a small sample of case study dwellings, indicated poorer as-built fabric performance compared to the design intent. Compared to the mean result of a large sample of tested low carbon dwellings (Gupta and Gregg 2020), a 1.2 times mean increase in Heat Loss Coefficient was similar, while a mean

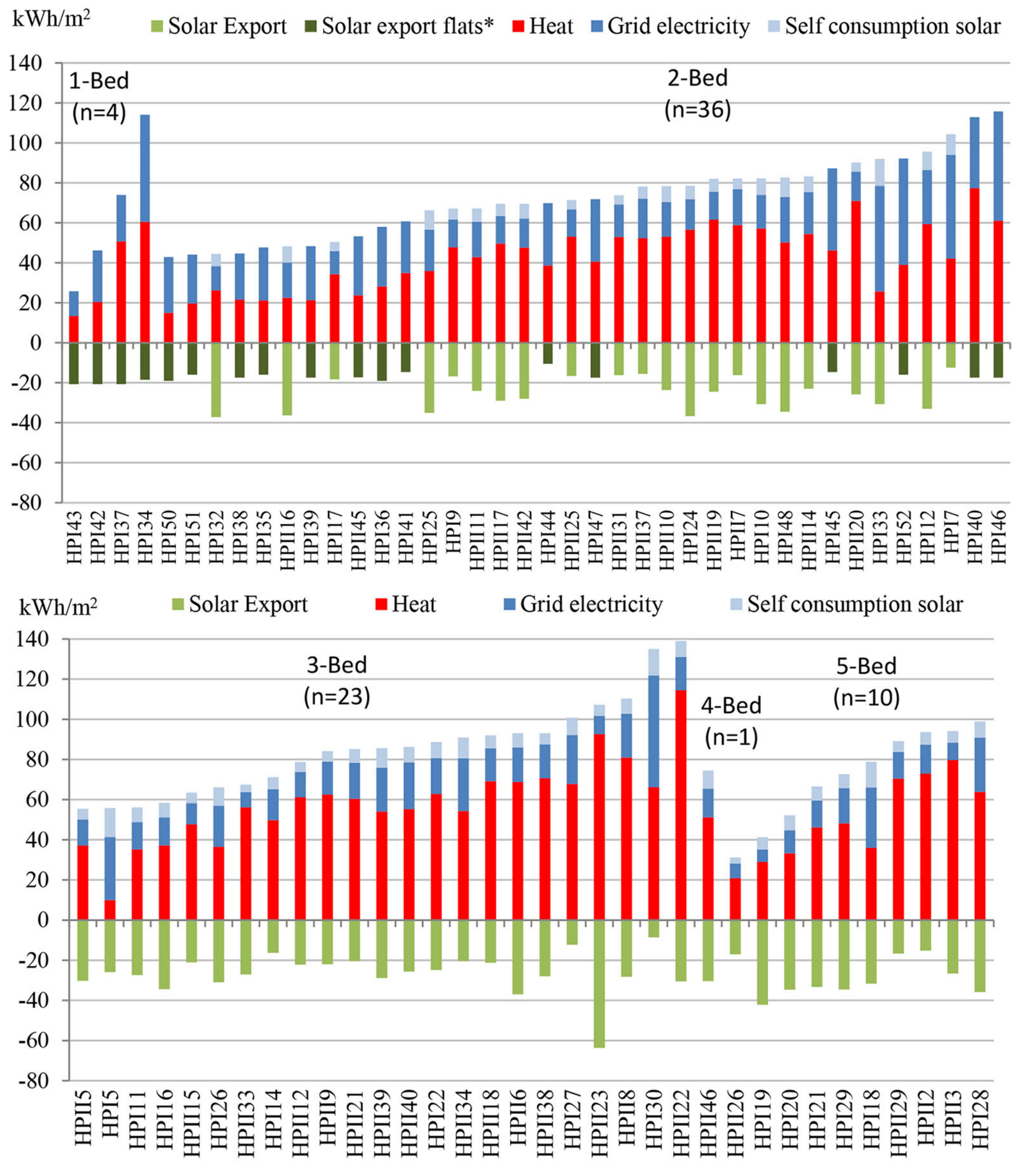

Fig. 3. Annual dwelling grid electricity, heat and self-consumed solar energy usage, and solar energy export, by number of bedrooms (n = 74). Abbreviations HPI and HPII in the names of captured dwellings stand for House Phase 1 and House Phase 2, respectively.

increase in as-built U-values of tested external walls (2 times) and ceilings (2.2 times) was more pronounced. The mean airtightness of 3.3 m^3/m^2h@50Pa was close to achieving the design target.

From the dwelling sample with available heat usage data (n = 94), four archetype groups (presented in Figure 7) were selected, in order to inspect the potential difference between the predicted annual heat usage from SAP sheets and the metered heat usage. The groups represented the most common dwellings among the sample, in terms of the dwelling typology and total floor area. The results suggested that actual heat usage was higher in three of four dwelling groups compared to design predictions. The estimated space heating usage fraction was 1.3 to 2.2 times higher compared to the predictions. Conversely, the design overestimated hot water usage between factors of 1.3 and 1.9. It seems that poorer as-built fabric efficiency overcame the effect of warmer and sunnier weather, which is expected to reduce the heat use. The analysis showed that during the monitoring period there were 13% fewer degree days recorded compared to long-term means (DBEIS and and DEFRA) 2019b), 14% higher monthly temperatures (Met Office 2019) compared to SAP 2009 figures (BRE 2010) and 8% more sun hours during the heating period (DBEIS and DEFRA) 2019c) compared to 10-year mean. Hot water use below design predictions likely occurred due to the reduced mean actual water usage of 96.2 liters/person/year. This is 34% lower compared to UK averages (AC 2018) and lower than the hot water requirement in SAP worksheets.

Electricity use

The achieved mean electricity use per dwelling was 27.4 kWh/m^2/year based on the 74-dwelling sample (Figure 8). The resulting usage is one of the lowest reported in housing developments. It is lower compared to the mean usage of selected zero carbon housing examples (~33 – 46 kWh/m^2/year[7]), low carbon (~55 kWh/m^2/year) and Passivhaus dwelling samples (~47 kWh/m^2/year) (Gupta and Gregg 2020). The mean usage of 2,527 kWh/year per dwelling is also lower by 18% compared to the mid user's electricity usage of 3,100 kWh/year and by 26% compared to 3,400 kWh/year usage from the NEED database (52 – 100 m^2 TFA).

PV energy generation, export and self-consumption

Mean energy output per dwelling solar PV systems reached the design projections. This was achieved as a balance of slightly smaller system size (2.9 kWp) and 1.2 times higher mean solar generation (991.7 kWh/kWp) than predicted. Due to the lack of monitoring data, the solar generation of systems located on blocks of flats was estimated using the mean output from houses. As seen in Table 8, the mean self-consumed solar energy accounted for 23% of total solar generation in houses (n = 56), ranging from 8% to 61%. The mean self-sufficiency rate (self-consumption of solar energy in relation to total electricity use) achieved was 30%.

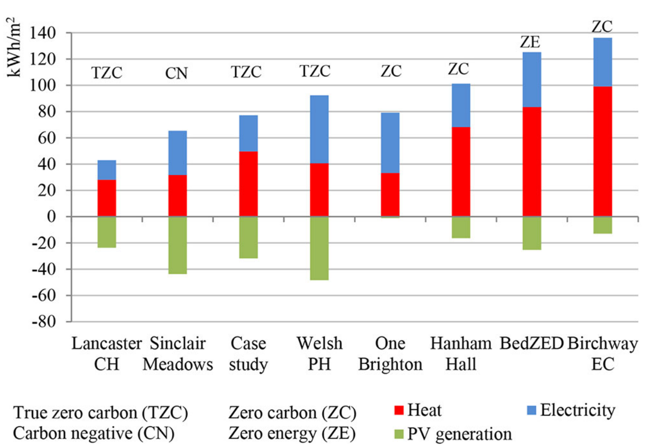

Fig. 4. Achieved mean annual electricity and heat usage and solar PV generation per dwelling compared to similar housing developments. Performance was sourced from the available reported data, using some estimations[8].

Community heating performance

The energy performance assessment of the community heating system was based on the two-year data between 1 April 2017 to 31 March 2019. The gas and grid electricity factors for 2017/2018 and 2018/2019 period were calculated (see the Appendix) by averaging the reported annual factors

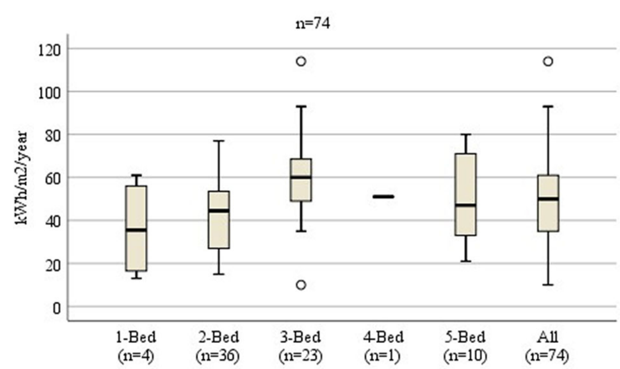

Fig. 5. Box plots of annual dwelling heat usage, by number of rooms.

Table 7. Descriptive statistics of the difference in electricity use per number of occupants.

Annual electricity use per dwelling kWh	Number of occupants per dwelling				
	1	2	3	4	5
Minimum	1,689	1,053	2,273	2,028	3,379
Maximum	5,153	7,077	4,048	6,356	3,392
Factor of difference	3.1	6.7	1.8	3.1	1.0
Sample size	2	24	5	3	2

Table 6. Descriptive statistics of the difference in energy use in four dwelling archetype groups.

	Annual energy use per dwelling kWh/m^2	2-Bed flats	2-Bed Mid-terrace	3-Bed End-terrace	5 Bed
Heat use	Minimum	21.3	34.4	10.0	20.8
	Maximum	77.3	71.0	81.0	96.2
	Factor of difference	3.6	2.1	8.1	4.6
	Sample size	9	17	23	12
Electricity use	Minimum	23.1	16.1	11.3	10.3
	Maximum	54.7	62.2	45.8	42.9
	Factor of difference	2.4	3.9	4.0	4.2
	Sample size	9	15	19	10

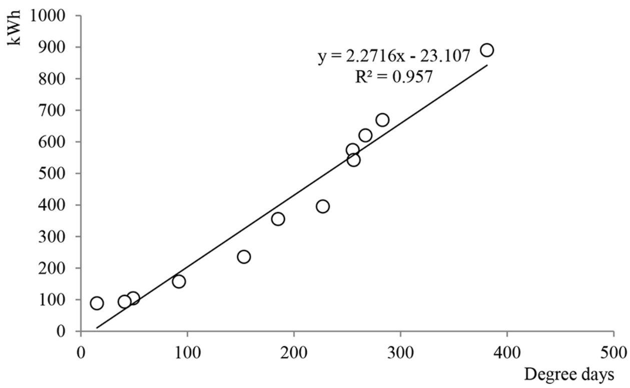

Fig. 6. Scatter plot of the mean heat usage of the sample per month and the degree days from the local weather station.

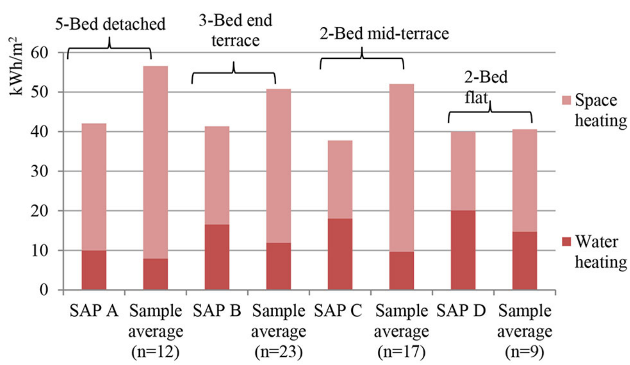

Fig. 7. Comparing heat usage fractions in dwelling archetype groups to predictions in corresponding SAP sheets.

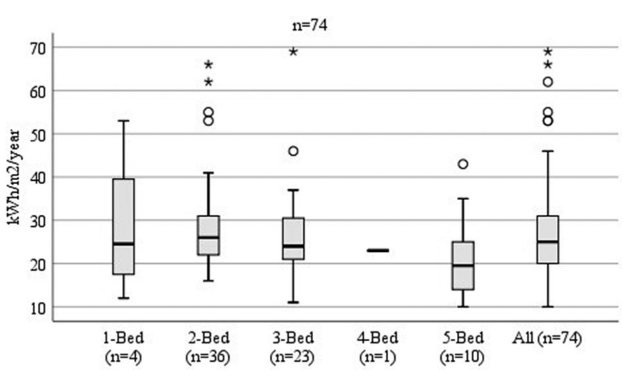

Fig. 8. Box plots of annual dwelling electricity usage, by number of rooms. Strong data outliers are marked with a symbol *.

(DBEIS and DEFRA 2017; DBEIS and DEFRA 2018; DBEIS and DEFRA 2019).

Comparison of the actual to the designed performance presented in Table 9 shows the underperformance of the community heating system. The actual carbon factor of the received heat during the 2018-2019 monitoring period was estimated as 0.432 $kgCO_2/kWh$, similar to the previous year. Although the plant's energy efficiency was at the level of the design projections, the contribution of the CHP engine in heat production was only 46% in the 2018/2019 period, about half of what was projected. Consequently, this resulted in reduced production of electricity, greatly increasing the carbon factor of produced heat.

Actual distribution loss data was not available. Therefore, a scatter plot based on empirical data from six housing developments (BRE 2016) was used for its estimation. Appling the mean heat use per case study dwelling (4,830 kWh/year, n = 94) to the formula, the resulting factor was 2 (50%) (Figure 9). This estimation also seemed sensible for district heating systems not complying with *"Heat Networks: Code of Practice for the UK"* (CIBSE and CHPA 2015) as suggested in forthcoming SAP 10 (BRE 2019). Taking this into account, the resulting overall efficiency of the community heating system was 51% for the 2018/2019 period.

Findings of a theoretical exercise presented in Figure 10 suggested that, operating efficiently as designed, the case study's plant is estimated to produce more carbon intensive heat compared to individual gas boilers, already by the first quarter of the engine's life-cycle.

Dwelling carbon emissions

The estimated carbon performance of dwellings was based on the actual dwelling energy usage data, community heating's performance data for the period between 1 April 2018 to 31 March 2019 and the 2018/2019 fuel carbon factors. The results (Figure 11) showed the mean emission of 20.2 $kgCO_2e/m^2/year$ per dwelling (n = 74), ranging from 2.8 to 45.7 $kgCO_2e/m^2/year$. This demonstrated that the net zero carbon target was neither achieved individually, nor at the development level. The achieved emissions were still significantly lower compared to projected emissions of 38.1 $kgCO_2e/m^2/year$ for an average UK dwelling in 2017 (ESC 2019).

Table 8. Descriptive statistics of annual grid electricity use, solar generation, export and self-consumed electricity fraction per dwelling. House sample (n = 56).

	Grid use (kWh)	Self-consumption solar (kWh)	Solar export (kWh)	Solar generation (kWh)	Self-consumption / generation	Self-consumption / electricity use
Minimum	717.3	335.5	792.6	1725.5	8%	16%
Maximum	5137.5	2099.0	6955.7	7959.9	61%	50%
Median	1526.0	670.1	2487.5	3173.6	21%	29%
Mean	1834.3	736.1	2727.7	3463.7	23%	30%

Table 9. Comparison of community heating performance between design projections and actual data based on empirical measurements and estimated distribution loss factor (marked with symbol*).

CHP system annual performance		Design SAP 2009	Design strategy (2013)	Actual (2017 -2018)	Actual (2018 -2019)
Fraction of heat supplied by CHP engine		90%	90%	26%	46%
Heat distribution loss factor		1.05	1.39	2.00*	2.00*
Energy efficiency	CHP engine	78%	78%	66%	75%
	Boiler	87%	87%	88%	87%
	Plant	84%	78%	77%	79%
	Overall	82%	67%	46%	51%
Energy ratio	Heat to gas	0.45	0.42	0.62	0.56
	Electricity to gas	0.39	0.37	0.15	0.23
CO2 factors (kg/kWh)	Mains gas	0.198	0.198	0.184	0.184
	Grid electricity	0.529	0.529	0.317	0.269
	Produced heat	−0.019	0.014	0.436	0.432

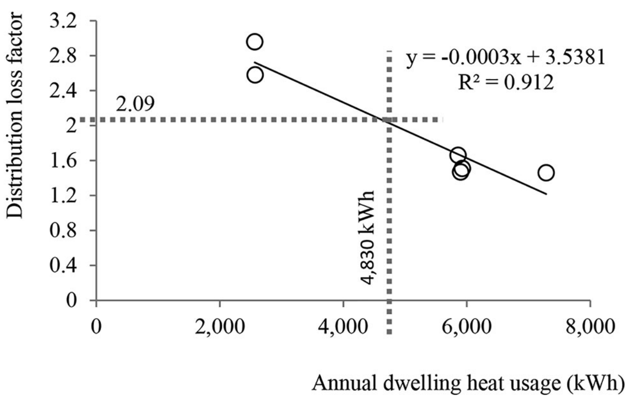

Fig. 9. Estimating the distribution loss factor with the scatter plot using the empirical data from six housing developments from the district heating report by BRE (BRE 2016).

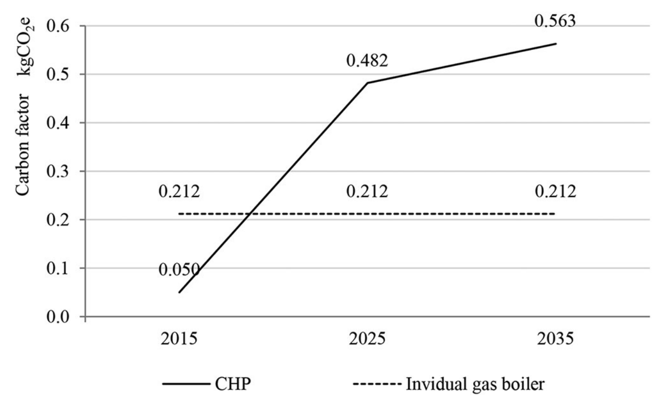

Fig. 10. Comparing the carbon coefficient of heat between the community heating CHP plant and the individual gas boilers, a 20-year projection. Using 87% efficient gas boilers, static gas factor (DBEIS and DEFRA 2015), electricity carbon factor projections (DBEIS 2019d) and expected plant's life-cycle (IEA 2013).

Discussion

Achieving the designed energy use can be considered as a success, in the context of the widespread performance gap (Gupta and Gregg 2020; Zero Carbon Hub 2014; Innovate UK 2016). The result ranked the case study among the housing developments with the lowest energy usage. It also suggested that low energy use in the level of Passivhaus dwellings could be achieved in less airtight and insulated homes, if the electricity use is significantly reduced. A closer inspection revealed, however, that lower than projected hot water usage and electricity usage masked an increase in the projected space heating use. When compared to other true zero carbon housing (NEF 2014; Ridley et al. 2014; Ecoarc 2013), it is apparent that case study dwellings were designed with a less energy efficient fabric. As a result, the estimated space heating energy use was twice as high compared to the Passivhaus standard. The rationale behind such design decision is likely related to the selection of a community heating system, promising to deliver very low carbon coefficient of heat. In this context, higher heat demand increases the cost-effectiveness of the community heating system with no significant repercussions on resulting carbon emissions. The case study therefore demonstrates a possible negative consequence of a design approach focused on the single carbon metric. Among similar dwellings, the difference in electricity use was in line with the findings of similar studies. However, the difference between the minimum and the maximum heat use among similar 3-bed (8.1 times, n = 23) and 5-bed dwellings (4.6 times, n = 12) was more prominent. As this difference occurred among the dwellings with the same building characteristics, it was attributed to the occupant factors (Gill et al. 2010). The results indicate that the impact of occupant factors in low energy dwellings might be even higher than previously thought. The early integration of the energy monitoring system is commendable. Ongoing monitoring needs to become a standard practice in the forthcoming housing, enabling remote access to data and a continuous performance evaluation.

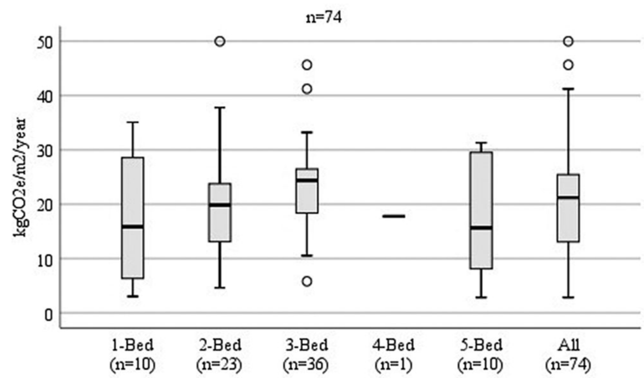

Fig. 11. Box plots of annual dwelling carbon emissions, by number of rooms.

Once all four phases are completed, the aggregated PV system size of 1.4 MWp will make the development one of the largest residential solar PV sites. The provision of roof PV's is a welcomed measure, offering multiple benefits and supporting the transition toward a smarter energy system (HMG and OFGEM 2017; Moroni, Antoniucci, and Bisello 2019). Substantial PV systems are essential in zero carbon housing for offsetting the emissions attributed to the used grid energy. However, combined with the low electricity demand, this resulted in a significantly higher solar energy surplus in comparison to the typical residential systems (McKenna, Pless, and Darby 2018). Connecting increasing numbers of PV-equipped, low-energy housing to the energy network is susceptible to causing technical issues in the energy grid (Infield and Thomson 2006). Increasing the self-consumption rate of PV electricity is therefore more and more recognized as an important design aspect in forthcoming dwellings. The case study dwellings self-consumed only 23% of generated solar electricity, about half of the rate deemed by the Government. The results indicate the need for a battery storage in the future. Home batteries are expected to become more cost-effective due to continuous reductions in cost and the introduction of time-of-use (TOU) tariffs, using dynamic energy pricing for the energy import and export.

Although the energy use target was met, the development, however, did not achieve the carbon target during operation. As in many other zero carbon housing developments, the poor operation of the community heating system was regarded as the key factor of underperformance. In the present case study, favoring gas as the cogeneration engine fuel perhaps avoided possible issues attributed to biomass. However, the selection of this fuel alternative also greatly hindered reaching the expected system performance. The design calculations based on 2009 SAP carbon factor projected achieving attractively low carbon factor of heat. This was, however, a short-sighted approach. A rapid decarbonization of the UK electricity grid has continuously driven the carbon intensity of heat above the projected value, diminishing the carbon reduction potential in gas fueled CHP systems (CIBSE 2018). Considering such technological limitations of the vital LZC strategies and other hindrances in delivering net zero housing during the past two decades, the decarbonization of the national energy grid appears to be essential for an effective decarbonization of new dwellings. Another temporary hindrance in reaching the aspired carbon performance in the present case study was likely the insufficient heat load. At the time of this study, only two project phases were occupied, while the plant was designed to cater for all four phases. For larger housing delivered in phases and supported by the community heating, the reduced plant efficiency during the initial years could be compensated by designing to surpass the targeted performance in the following years. It appears that in the current policy context, narrowing the performance gap would require the design teams to look beyond the regulatory requirements, consider the trends in the energy networks and use system efficiencies proved by empirical studies.

Conclusion

An assessment of actual energy and carbon performance was conducted on a large case study housing development in England, designed to achieve the ambitious net true zero carbon target. During the 1-year monitoring period, the mean energy use was 76 kWh/m^2/year per dwelling (n = 74), achieving the design target. The achieved heat use (48.5 kWh/m^2/year) and the designed fabric efficiency fell short compared to other true zero carbon housing. Despite the warmer weather conditions, a performance gap in terms of the space heating usage was noted. This was partly attributed to the reduced as-built fabric efficiency. Dwellings used 11% less electricity than expected, achieving one of the lowest reported usage in housing developments (27.4 kWh/m^2/year). Annual heat usage variance seemed more prominent than what was reported in other studies. Roof PV systems (2.9 kWp on average) achieved the projected solar generation levels. However, due to substantial system size and low electricity use, only 23% of generated energy was self-consumed, calling for the usage of home batteries. It is estimated that 20.2 kgCO_2e/m^2/year was emitted on average per dwelling, missing the aspired zero carbon performance. The resulting carbon intensity of heat (0.432 kgCO_2/kWh) based on 2018/2019 carbon factors, was significantly higher compared to the design projections. The underperformance of the community heating system was attributed to the changes in the electricity grid and reduced system efficiency likely caused by the insufficient heat load.

Single case study research is limited in the wider application of its findings. Nonetheless, given the widespread calls for net zero buildings and the scarcity of performance evaluations, the presented empirical evidence about the actual performance of a large true zero carbon housing development is valuable and timey. The study findings strengthen the argument that a widespread delivery of well-performing net zero dwellings demands a prompt change in the culture of building delivery. Building Regulations play an essential role in driving this change; from designing for compliance toward designing for ongoing performance, using multiple performance metrics and monitoring and reporting of actual performance. In order to deliver zero carbon in larger housing developments, it is vital that the delivery of district and community heating systems in the UK speedily matures.

Notes

1. Standard Assessment Procedure is the approved method of proving building design compliance in the UK
2. UK Energy Saving Trust's Advanced Practice Energy Efficiency (APEE) standard
3. This is calculated as a sum of the space heating requirement and water heating requirement found in SAP spreadsheets, where the latter is defined as *0.85 x Energy content of hot water + 15% distribution loss* (occurring within the home) but excluding the primary circuit, tank and combi losses occurring within the plant.
4. Self-consumed electricity was calculated by deducting available PV energy export data from solar generation data.
5. Data value more than three times above the interquartile range
6. Coefficient of variance (CV) was calculated as the ratio of the standard deviation (SD) to the mean heat use (M).
7. Excluding the result from the non-conventional cohousing project
8. PV yields are estimated for BedZED, Lancaster Cohousing and Hanham Hall developments using 850 kWh/kWp generation standard and reported PV system sizes. Due to lack of data, 85% boiler efficiency and 1.5 kWp/dwelling PV system is assumed for the Hanham Hall development

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Appendix

In order to calculate the annual energy performance of the community system the following abbreviations and formulas were applied:

Description	Abbreviation
Heat production by the CHP engine (kWh)	Q_{CHP}
Heat production by boilers (kWh)	Q_b
Electricity production by the CHP engine (kWh)	E_{CHP}
Gas use by the CHP engine (kWh)	G_{CHP}
Gas use by boilers (kWh)	G_b
Total gas use (kWh)	Gt
Distribution loss factor	DLF
Carbon factor of the mains gas	C_g
Carbon factor of the electricity grid	C_e

Description	Calculation formula
Fraction of heat produced by the CHP engine (%)	Q_{CHP} / (Q_{CHP} + Q_b)
Energy efficiency of the CHP engine (%)	(E_{CHP} + Q_{CHP}) / G_{CHP}
Energy efficiency of boilers (%)	Q_b / G_b
Total gas use (kWh)	$G_{CHP} + G_b = G_t$
Energy efficiency of the plant (%)	(E_{CHP} + Q_{CHP} + Q_b) / Gt
Overall energy efficiency of the system (%)	((Q_{CHP} + Q_b) / DLF) + E_{CHP} / Gt
Heat production to gas use ratio	(Q_{CHP} + Q_b) / G_t
Electricity production to gas use ratio	E_{CHP} / G_t
Carbon factor of received heat (kg/kWh)	(G_t * C_g - E_{CHP} * C_e) / (Q_{CHP} + Q_b) / DLF

In order to calculate the annual dwelling carbon performance, the 2017/2018 and 2018/2019 carbon factors were estimated by averaging reported factors:

Year	Grid carbon factor (kg/kWh)
2017	0.352 (DBEIS and DEFRA 2017)
2018	0.283 (DBEIS and DEFRA 2018)
2019	0.256 (DBEIS and DEFRA 2019)
Period 2017/2018 (mean of 2017 and 2018)	0.317
Period 2018/2019 (mean of 2018 and 2019)	0.269