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In-Use Energy Performance Study of Automated Smart Homes

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Abstract

Domestic energy demand has been high on the carbon reduction agenda for some time. Today new homes are being designed following the "fabric first" principle which is reducing heat demand, but it is shifting the design challenge to ventilation.

Further energy reductions and comfort improvements are needed. It is frequently proposed that automated control systems can achieve this. However, the technologies involved are currently considered expensive and complicated. There is little published evidence of how these types of systems perform in use, which leads to scepticism.

This research study aims to test the hypothesis that automated demand-controlled heating and ventilation can provide a good indoor environment while reducing energy consumption in "real-life" homes. A year-long case study was conducted using six occupied, neighbouring dwellings installed with a low-cost automated building control system. The energy consumption figures recorded were compared to the values predicted by the Standard Assessment Procedure and by a Dynamic Simulation Model, and compared to Passivhaus standard. Significant savings have been identified.

The results of this study show that an automated control system can lead to very low energy, and hence low carbon homes at a price-point that would incentivise widespread role out. This means that such systems have the potential to make a considerable contribution to reducing the carbon footprint of housing stock, and hence to meeting carbon reduction targets.

Keywords

Smart homes, smart ventilation, domestic energy management, automated building control, energy efficiency, low carbon homes, low energy homes, building performance.

1. Introduction

It is widely accepted that in order to meet the UK's legally-binding carbon reduction targets, significant changes must be made to the nation's energy system. Large reductions can be achieved via supply-side technology shifts to low and zero carbon generators, but this requires substantial infrastructural changes that are, and will continue to take, considerable investment of time and money. The importance of energy demand reduction is rightly being recognised by engineers and strategists.

Figure 1 compares the energy use per final user for the UK in 1990 and 2017. It can be seen that the domestic sector consistently represents approximately 30% of the total energy use. It is therefore a justifiable focus for demand-reduction solutions.

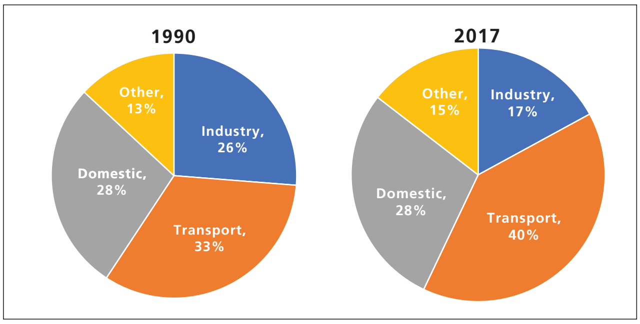

Figure 1. UK Energy Consumption by End User *(Department for Business, Energy & Industrial Strategy).*

The challenge that domestic energy reduction presents is quite different to other sectors. Energy reductions in the travel and industrial sectors are by no means trivial but they can generally be addressed via centralised decision-making "at the top", i.e. by government or business management. This should lead to wide-reaching actions and consequences.

In the domestic sector actions are required of individuals in their own homes. Solutions are needed that enable autonomous induviduals to make changes that are large-scale within their lives, but small-scale in terms of the national requirement. These solutions must also yield repeatable results across the large and diverse set of users that is the UK population.

For some time engineers played down this problem, proposing that the role out of "smart meters", and hence the provision of energy-charging information, would provide the solution. This hypothesis seemed largely based on the assumption that induviduals make rational decisions and can therefore be easily influenced when provided with rational motivation. This hypothesis has long been debunked by social scientists and more recently with specific respect to smart meters (Hargreaves, *et al.*, 2013).

It is becoming clear that active behaviour change can not be relied upon to achieve the large-scale energy demand reductions required, and certainly not within the time left to achieve them. Smart meters will not make a smart home.

Building regulations can and have gone a considerable way to improving the energy performance of modern dwellings without any burden of behaviour change on the occupants – no intended burden at least. High levels of thermal insulation and air tightness are no longer purely the aspiration of the "green" builder but are now expected of all new homes (Ministry of Housing, Communities & Local Government). This so-called "fabric first" approach presents new building services challenges that are only just beginning to be recognised. Keeping homes warm has long been the main battle for engineers, but with modern-day fabric design, minimal heat input is required and overheating is now a greater threat than under heating. Superior air tightness combats energy losses but managing air quality now must become a priority (Sassi, 2017).

Finding a way to balance the new requirements for space heating and ventilation in modern homes, within the ever-present constraints of energy efficiency and in the acknowledgement that that needs to be achieved with minimal active participation from the occupant, is the problem. This research study aims to test the hypothesis that automated demand-controlled, fast-response heating and decentralised ventilation can provide a solution.

1.1 The Automated Home

Automated building services aim to maintain a comfortable indoor environment without any need for active input from the occupant. Systems typically consist of:

- a series of sensors to monitor the indoor conditions, e.g. room temperature, relative humidity levels, CO_2 levels;
- control hardware to operate devices, e.g. heaters, extractor fans;
- and the software to enable the latter to react to the former.

Many automated systems will also sense occupancy to ensure that energy-hungry devices only operate when actually required. The concept of sensor activated-lights is well established and it's now time to bring them into our homes. The next step is occupancy-activated heating which is now possible by the characteristically low heat demand of "fabric first" buildings (Bionda, *et al.*, 2017).

Importantly, systems should also operate without actively restricting the occupant. It is well documented that occupants' perceptions of their own comfort can be impacted if their perceived control is limited. A common example is the situation where the temperature and air quality is perfectly maintained, but if the occupants can't open a window when they want to, they will feel uncomfortable. A successful building control system should react to, and maintain, conditions despite occupant behaviour.

Expectation of the automated home as a method of reducing domestic energy demand, and as one incarnation of the "smart-home", is fairly widespread. In qualitative studies of early adopters, energy reduction is often stated as one of their main motivators, e.g. (Mennicken, *et al.*, 2012) (Wilson, *et al.*, 2017), and research studies which push the concept forward often assume energy reductions as a forgone consequence of "smart home automation", e.g. (Mehdi, *et al.*, 2015) (Louis, *et al.*, 2015). Numerous simulation studies have been published estimating the energy savings that could be made available, e.g. (Bionda, *et al.*, 2017) and (Masoodian, *et al.*, 2014).

However, published analysis of the savings actually achieved under real-life conditions are relatively thin on the ground. It has been proposed that this lack of evidence indicates that current products have little, or even a detrimental effect on energy efficiency (Darby, 2018). The NHBC Foundation recently published a report that attempted to look into the future. It suggests that current control systems are too complex to achieve the energy reduction potential made available by the concept. However, the Foundation prophesises that "by 2050 a single [technology] will emerge, tackling the existing issues …" (NHBC Foundation, 2018).

1.2 The case study

This case study provides an in-use evaluation of one of the simplest and inexpensive control systems currently available on the market. Data was collected over one year from six neighbouring, modern-built flats in Cardiff. Every flat benefits from modern fabric construction and all have the same control system fitted. The system was in control of most of the building services of the homes but this analysis focuses on the heating and ventilation. It was felt that these were the most important, in terms of energy use and comfort maintenance, but also as the most interesting given the shifting needs of modern homes.

All flats were rented and occupied during the study, the ground and first floor flats in both buildings by undergraduate students, and the smaller, top-floor flats by young professionals.

With respect to heating and ventilation only, the data collected has been analysed to observe the system operation and assess whether the target conditions for occupant comfort were realised. Total heat energy consumption figures are used to evaluate the energy performance of the system. In order to quantify the energy savings achieved, the actual energy consumption of the dwellings is compared to the estimates or thresholds generated by the three environmental design/compliance methods suggested in CIBSE's recent technical memorandum for homes (Lelyveld, *et al*., 2018), that of:

- *Standard Assessment Procedure (SAP)*
  As the dwellings are real, it was obligatory that a SAP was carried out and that an Energy Performance Certificate (EPC) was issued. The estimates made via this method form the primary basis for comparison and therefore, for quantifying energy savings made;
- *Dynamic Simulation Modelling (DSM)*
  Virtual representations of the case study properties were built using the thermal modelling package IES. This was done to better understand the thermal performance of the buildings overall, and to provide some reference estimates of heating demand. Simulations were run to generate annual space heating demands for more conventional ventilation strategies to which the case study consumption figures were compared;
- *Passivhaus standard*
  The houses were not designed via the highly-prescriptive Passivhaus standard, so therefore the full Passivhaus Planning Package was not used. However, mechanical ventilation with heat recovery (MVHR) is stipulated by the Passivhaus standard and this was simulated via the DSM. For an overall direct comparison, the totals per unit floor area are compared to the requirements set down by Passivhaus in order to show the level of environmental design achieved via the control system.

Considerable energy efficiencies were identified when compared to the values generated by the SAP. It is shown that the energy performance of the properties are comparable to Passivhaus standard, but importantly without any of the restrictive design and additional expenditure typically associated with that method. The construction costs of the case study properties were, in fact, less than typical new-builds and less time was required on site for installation.

The results of this study show that the combination of good, but not extraordinary, fabric design and an automated control system can lead to very low energy, and hence low carbon homes at a price point that would incentivise widespread role out. This means that the system has the potential to make a considerable contribution to reducing the carbon footprint of new and retrofitted housing stock, and to meeting the UK carbon reduction targets.

2. Case study details

The flats are built on the site of two demolished Victorian terraces on Cogan Terrace in the Welsh city of Cardiff. Cardiff has a characteristically mild, maritime climate. Winters are typically wet and windy but frosts are rare, with an average minimum winter temperature reported at 2°C (Met Office UK). The buildings face approximately north-west.

The buildings have retained the addresses of No.14 and No.16 Cogan Terrace and are mirror images of each other with each consisting of three flats. In both buildings there is a 3-bed flat "A" on the ground floor, a 3-bed flat "B" on the 1st floor, and a 1-bed flat "C on the top floor.

Table 1 provides the total floor areas of each of the case study properties.

Flat	Flat Size (m^2)
No.14A	67
No.14B	58
No.14C	34
No.16A	67
No.16B	58
No.16C	34

Table 1. Floor areas of all flats in No.14 and No.16 Cogan Terrace.

The key fabric components used, their main material type and their representative U-values are provided in Table 2. It can be seen that the thermal properties of the fabrics used are good, but not in excess of what is typically expected of a new-build dwelling. Importantly, the total building expenditure was similar to a typical new build.

2.3 Automated control system

Both buildings were fitted with building services under the control of the Atamate building control system. The system connects to and controls all the building services in the properties. Those that are relevant to the heating and ventilation analysis conducted here are as follows:

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Envelope component	Main Material	Overall component U-value, (W/m²k)
External Walls	Insulated Concrete Form (ICF) Block	0.16
Windows	Aluminium and Timber Composite Windows	0.92
Roof	Wood Fibre Insulation	0.15
Floors	Concrete Slab	0.11

Table 2. Characteristics of key building fabric components of No.14 and No.16 Cogan Terrace.

- a ceiling-mounted sensor unit in each room measuring temperature (both ambient and wall temperature using a thermopile infrared sensor), humidity, passive infrared (PIR) and CO_2;
- a central Linux computer known as the "hub" that receives sensor input, processes it using original software and then activates output commands;
- Standard and inexpensive cabling between sensors and the hub, and the hub and devices – either CAT5 for low voltage or conventional mains cables, e.g. twin and earth.

2.4 Ventilation

The control system constantly monitors the air quality in the rooms using CO_2, humidity and temperature sensors. With this information it can control both the incoming air and air extraction to ensure the best air quality throughout the building with the minimum amount of ventilation and associated heat loss.

2.4.1 Fresh air supply

No.14 Cogan Terrace was fitted with "Demand Controlled Ventilation Inlets" (DCVi) comprising 100mm vent pipes drilled through the wall of all "dry rooms" (bedrooms and living rooms). The DCVi has an electrically-operated damper valve which can be controlled by the control system to vent the room when the air quality is poor. This means that background ventilation is only provided to bedrooms and reception rooms when the CO_2 or humidity levels are high enough to require it. When the air quality was judged to be poor, the DCVi was opened and the MEV was activated. As soon as the air quality of the room was good, then the DCVi was closed to minimise the ventilation heat losses.

No.16 Cogan Terrace was not fitted with DCVi but all rooms were finished with a 100mm diameter trickle vent.

2.4.2 Stale air extraction

Both properties used MEV for extracting the stale air from the "wet rooms" (bathrooms and kitchens). The MEV system chosen had a micro heat pump which extracts the heat from the exhaust air and feeds it into the domestic hot water storage. In these properties the extracts to individual bathrooms and kitchens could be controlled with "Demand Controlled Ventilation outlets" (DCVos). This allows better control of the MEV to extract air from only rooms that need it, not across the whole building.

Flat	Bedroom	Living Room
No. 14A	400W medium response electric panel heaters	No heater
No. 14B	400W medium response electric panel heaters	400W medium response electric panel heaters
No. 14C	400W medium response electric panel heaters	400W medium response electric panel heaters
No. 16A	400W medium response electric panel heaters	No heater
No. 16B	400W medium response electric panel heaters	400W medium response electric panel heaters
No. 16C	Fast response infra-red heater	Fast response infra-red heater

Table 3. Devices used in heated rooms across No.14 and No.16 Cogan Terrace.

2.5 Heating

Table 3 provides a schedule of the heating devices installed in the heated rooms across the case study properties.

Occupancy was one of the key triggers for heating, along with temperature, and was monitored via PIR and CO_2 sensors. The control system restricted the devices so that the heating would only turn on when the room was occupied and the temperature was below the set point of 21°C. Consequently, there was no heating when the rooms were unoccupied. The heat loss of the rooms was quite low at around a maximum of 300W at a temperature differential of 22°C. In a typical year, outside temperatures in Cardiff would not be expected to drop below freezing (Met Office UK), so the panel heaters were thought sufficient to raise the temperature of the room rapidly to comfort thresholds when required.

The fast response of the heating devices should also quickly cease heat input when set point temperatures were achieved, and hence help to avoid overheating. An added benefit of direct electrical heating devices are that they are much quicker, and hence cheaper, to install then wet heating systems.

None of bathrooms in the flats had any external walls and the heat losses in these rooms were predicted to be negligible, so only the bathroom in No.16C was heated by an infra-red heater. Kitchens were not heated as it was predicted that the additional internal gains of cooking would be sufficient to heat these rooms when occupied. Hallways were also not heated.

2.6 Comments on the test period

The data was recorded from the 15 September 2017 to 14 September 2018. This was a period of uncharacteristic extreme temperatures with the winter having the "Beast from the East" and the summer having a sustained heat wave.

During the year there were only two short periods where data was not collected due to change of system database. The first was two days in November. It was decided to leave these days blank as if the flat was unoccupied for a weekend, rather than fill the gap with an estimate. The second was two days in April, when the temperature trends recorded in days before and after were above the heating set point anyway.

3. System operation

Data gathered from the case study properties during the test period is examined to observe the system operation and assess whether the resulting indoor environment met the design requirements.

3.1 Heating

Figure 2 shows the resulting operation profile across most of the winter heating period in No.14B in Bedroom 2 only. When the room is occupied the room temperature is kept above 21°C. If the temperature sensor registers that it has dropped below set point, the heaters turn on; if they register that set point has been achieved, the heaters switch off, although the room temperature may continue to rise due the presence and activities of the occupant. When the room is vacated, the heaters stay off and the temperature drops.

A sustained drop in temperature can be seen when the room is left vacant for the Christmas break. However, it can also be seen that the room warms up quickly when it is reoccupied. It can also be seen that, at the end of January and beginning of February, the room temperature is kept at set point by internal gains only when occupied, so the heater does not turn on. Bedroom 2 in No.14B is selected to show this, but the behaviour is the same across both buildings.

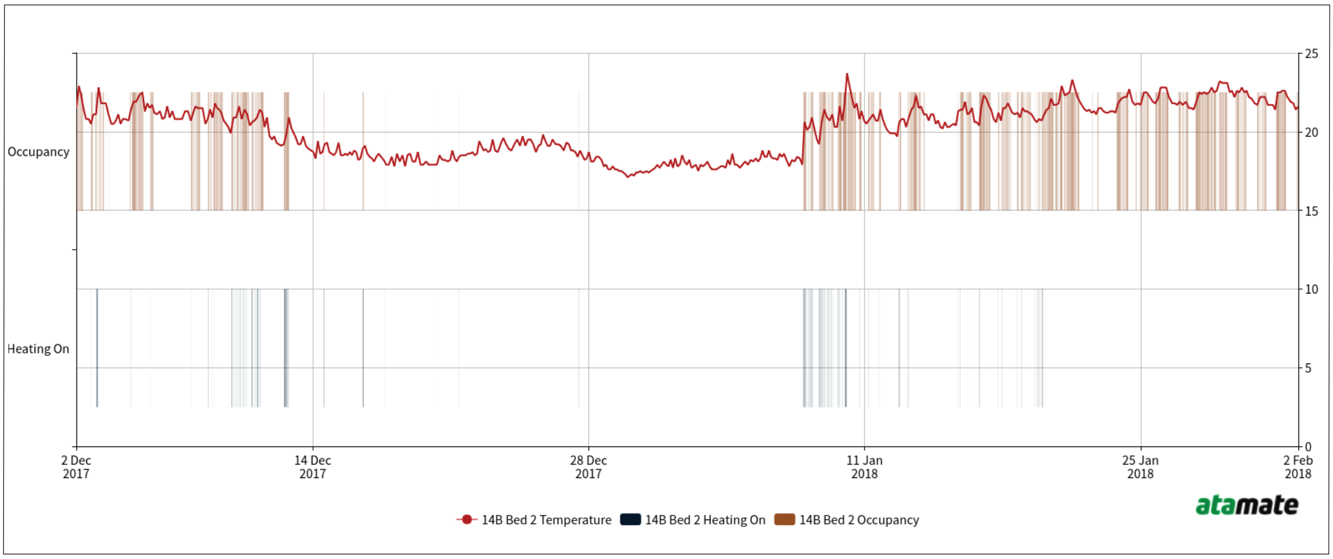

Figure 2. Heating operation against occupancy and ambient air temperature of No.14B, bedroom 2 during winter, Dec-Feb. *(Atamate Ltd, 2018).*

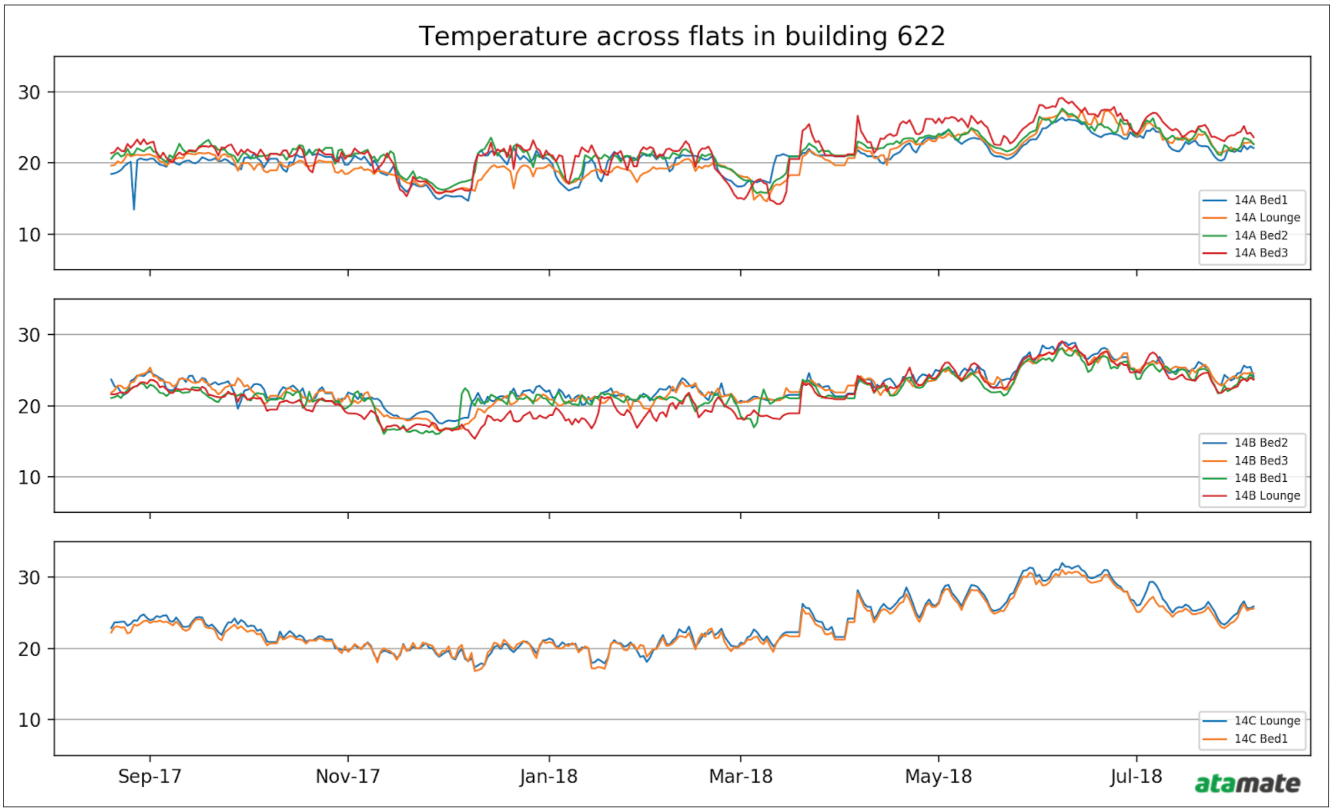

Figure 3. Air temperatures across all flats in No.14 Cogan Terrace (DCVis fitted). *(Atamate Ltd, 2018).*

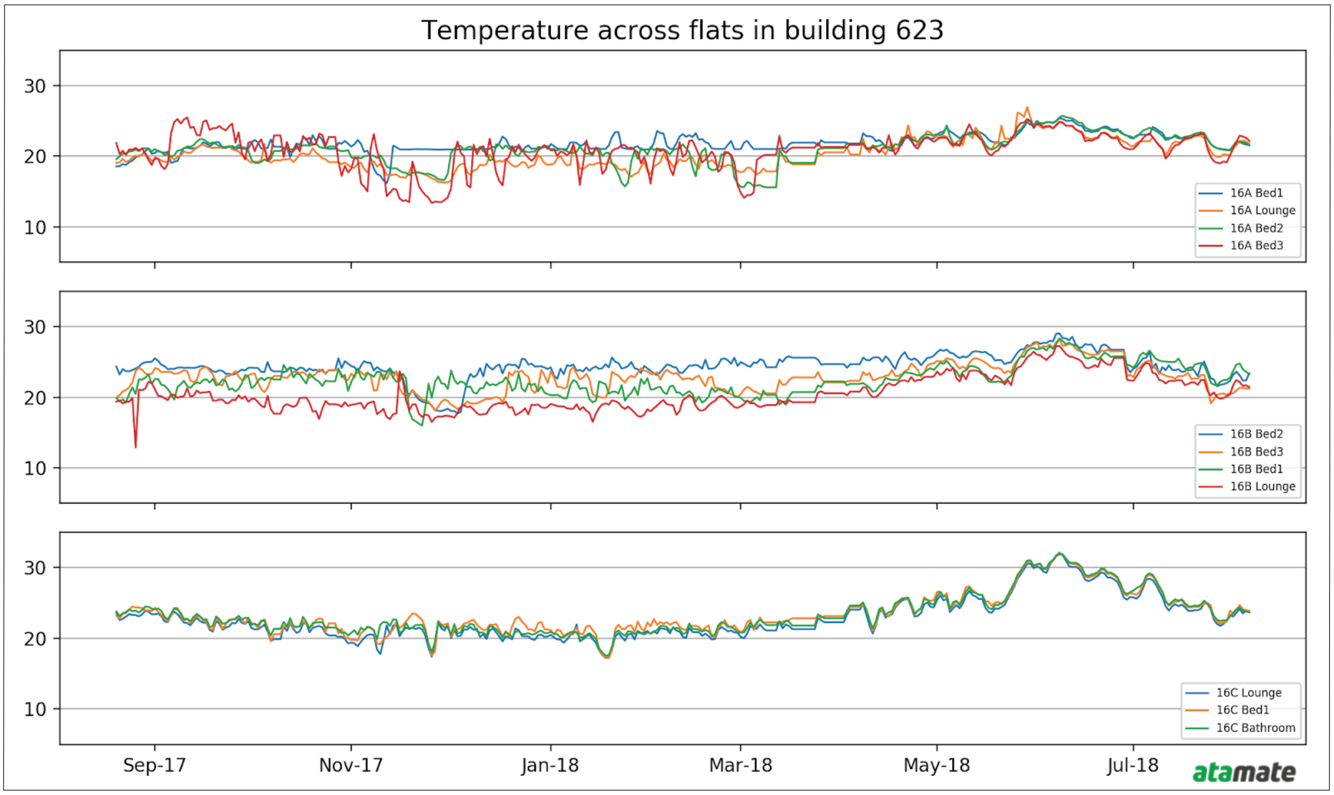

Figure 4. Heating operation against occupancy and ambient air temperature of No.14B, bedroom 2 during winter, Dec-Feb. *(Atamate Ltd, 2018).*

Figures 3 and 4 show the temperature profiles in all the bedrooms and common lounges over the whole year studied. They show that the automated control system not only worked, but maintained the desired levels of temperature at all times. The temperature in the lounges in both ground floor flats, No.14A and No.16A, track the other room temperatures well and are comfortably warm despite not having a heater installed.

The temperatures dropped significantly over the two holidays periods of Christmas and Easter, when the flats were unoccupied. Due to a sensor error in No.16A, the control system thought that Bedroom 1 was consistently occupied over the winter and a flat line at 21°C can be seen over the Christmas break. Although this is obviously not how the system was designed to operate, it does demonstrate how much temperature variation occurs when the properties are occupied and hence how responsive the system is.

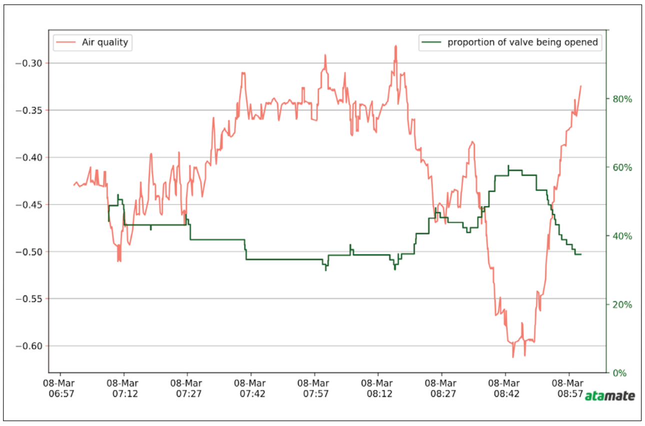

Figure 5. DCVi operation against air quality over a 2 hour period in No.14 Cogan Terrace. *(Atamate Ltd, 2018).*

3.2 Ventilation

Only 14 Cogan was fitted with automated control DCVis, while 16 Cogan was fitted with trickle vents. Figure 5 shows how the control system reacts to air quality data to operate the DCV in order to quickly improve the indoor conditions.

- the scale on the left is devised from a combination of air quality threshold ranges such that a score of "0" means the air is OK, i.e. at acceptable levels for all air quality indicators, and "-1" means the air is bad, i.e. at unacceptable levels for all air quality indicators;
- the scale on the right shows the proportion that the valve is open, i.e. 0% is closed and 100% is fully open.

The valve operation profile is shown in green and it can be seen how the valve opening profile is inverse to the air quality, which is shown in orange. When the air quality is judged to be poor, the valve begins to open. As the air quality continues to deteriorate, the valve opening widens. As the bad air clears, the air quality improves and the valve closes again.

4. Heat energy consumption and comparisons

In order to quantify the energy savings achieved, the actual recorded energy consumption of the dwellings is compared to the estimates or thresholds generated by the three environmental design/compliance methods suggested in CIBSE's recent technical memorandum for homes (Lelyveld, *et al.*, 2018), that of:

- Standard Assessment Procedure (SAP);
- Dynamic Simulation Modelling (DSM);
- Passivhaus Standard.

Flat	SAP Estimate for heat energy demand (kWh/yr)	Actual Consumption (kWh/yr)	Reduction (%)
No. 16A	1141.81	1447.08	27%
No. 16B	905.87	674.98	-25%
No. 16C	738.59	339.66	-54%
Totals	**2786.27**	**2461.72**	**-12%**

Table 4. Comparison of actual energy demand for space heating with SAP estimates for No.16 Cogan Terrace (trickle vents).

4.1 SAP

As with all new buildings a Full SAP was obligatory and an Energy Performance Certificate (EPC) was issued. The estimates made via this method form the primary basis for comparison and therefore, for quantifying energy savings made.

Table 4 and Table 5 compare the actual energy consumption with the "As Built" SAP estimates for each flat in each building. It can be seen that the energy consumption for heat in the flats decreases as the floor height increases. This is obviously because the floor area of the flats decreases as floor height increases, but also because upper floor flats will benefit from heat rising from lower floor flats. It can also be seen that where automated DCVis were used, i.e. in No.14 Cogan Terrace, consumption figures are noticeably lower than in the flats where trickle vent were used, i.e. in No.16 Cogan Terrace.

Overall it can be seen that the actual consumption figures are considerably below the SAP estimates. The whole building consumptions are 34% and 12% less for No.14 and No.16 Cogan Terrace respectively. The performance improvements are identified on the first and top floor flats, which range from 25% up to 72% better than the SAP estimates. This is a significant result and goes a long way to demonstrate the potential of an automated control system as a tool for reducing domestic energy demand. However, it can also be seen that the ground floor flats do not perform as well and actually show an energy increase on the SAP estimates.

Flat	*Base Case Infiltration and fresh air supply only*		*Intermittent Extractor fans (in wet rooms)*		*Additional MVHR*	
	Heat Energy (kWh/yr)	Reduction Achieved (%)	Heat Energy (kWh/yr)	Reduction Achieved (%)	Heat Energy (kWh/yr)	Reduction Achieved (%)
No. 14A	859.97	-59%	1664.29	18%	1209.36	-13%
No. 14B	212.80	-44%	918.59	67%	463.65	34%
No.14C	146.80	-42%	907.99	77%	427.58	51%
No.16A	892.65	-62%	1701.70	15%	1247.40	-16%
No.16B	228.65	-195%	936.47	28%	482.62	-40%
No.16C	147.63	-130%	907.32	63%	427.22	20%

Table 5. Comparison of actual energy demand for space heating with SAP estimates for No.16 Cogan Terrace (trickle vents).

Figure 6 shows a breakdown of these figures, room by room. In both ground floor flats, No.14A and No.16A, the larger overall energy consumption is obvious and it can be seen that most of the demand, almost half in both cases, comes from Bedrooms 1, which are situated at the front of the building. The exact cause of the heat loss in these front bedrooms warrants further investigation, but is outside the scope of this study. Possible explanations are that both front bedrooms have characteristics common to one another that are not found in any other rooms in the building. Both rooms:

- feature bay windows;
- are built over the old coal cellars, which on the structural engineer's advice were not infilled;

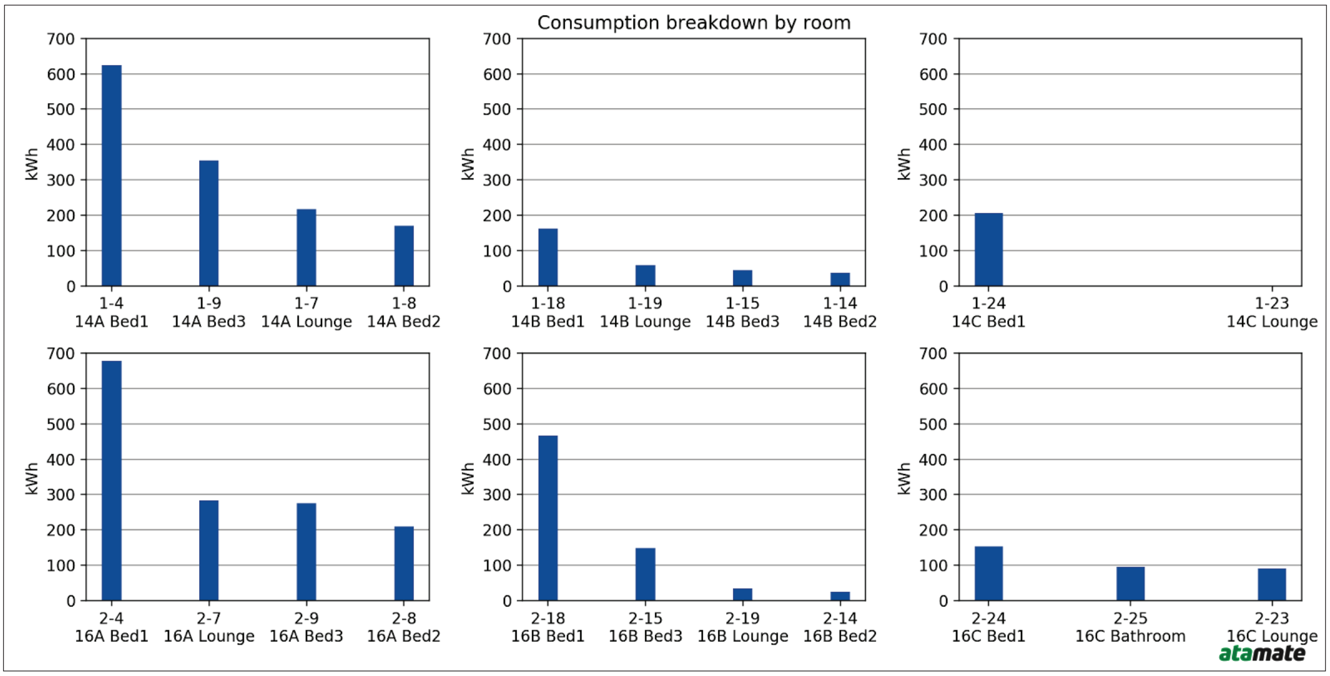

Figure 6. Room by room break down of heat energy consumption. *(Atamate Ltd, 2018).*

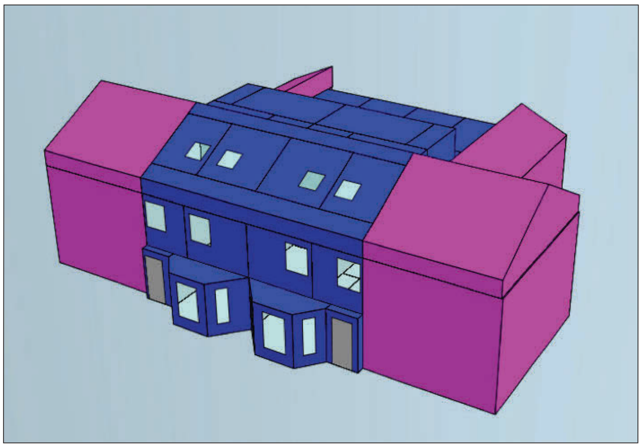

Figure 7. Virtual representation of No.12-18 Cogan Terrace, looking from the west.

- have significant rebar reinforcing in the external concrete-form walls due to the lack of support on the party walls;
- may suffer from exposure to a communal corridor next to the front door of the building.

The thermal dynamic simulation model offers some insights into why the ground floor flats performed more poorly than estimated by the SAP, see Section 4.2. However, further investigation is necessary. The next step would be an investigation with a thermal imaging camera.

It is also worth saying here that it is very common for buildings to perform worse post-occupancy when compared to the SAP estimates. This is often referred to as the "performance gap". This also makes the reductions in the upper floor flats all the more significant.

4.2 Dynamic simulation modelling

Virtual representations of the case study properties were built using the thermal modelling package IES. This was done to better understand the thermal performance of the buildings overall, and to provide some reference estimates of heating demand. Figure 7 provides an image of the virtual representation of the properties constructed for DSM.

A dynamic thermal model is typically regarded as more refined than a static model, as used by the SAP. It is generally expected that energy demand estimates would be more "realistic" and this usually means greater than that estimated by the SAP.

All simulated scenarios assume the following:

- the heating set point for heated rooms is 21°C during the day (7:00-22:00) and 16°C at night (22:00-7:00);
- internal gains in all rooms can be represented by the default values for lighting, occupants and other miscellaneous sources;
- the infiltration rate is the default value of 0.25ach;
- the fresh air supply is 8l/s/person, where the number of people per room is derived from the floor area.

Three simulation scenarios were run to generate annual heating loads for more conventional ventilation strategies to which the case study loads were compared.

- The "Base Case" simulation assumes no additional ventilation system;
- The "Intermittent Extractor Fans" simulation includes MEV in the kitchens and bathrooms at a flow rate of 8ach, operating for one hour in the morning (7:00-8:00) and for two hours in the evening (20:00-22:00);
- The "Additional MVHR" simulation has the same MEV as above but with a heat recovery system operating at a seasonal efficiency ratio of 0.65. As no specific research was done into what MVHR system would be appropriate for the properties, it was thought most transparent to select a default value from the modelling package at 0.65 was the highest available.

Table 6 lists the annual energy consumption for heat in each flat as estimated by each of the simulation scenarios. As might be expected, the "Base Case" that has no active ventilation system yields the lowest consumption figures and these are lower than the actual consumption in all cases. The "Intermittent Extractor Fans" simulation yields the highest figures and these are higher than the actual consumption in all cases.

The flats in No.16 Cogan Terrace had no automated inlet ventilation, only trickle vents, so comparing the actual consumption figures for the flats in this building with the results from the "Intermittent Extractor Fans" simulation gives the best indication of the energy savings that can be achieved by occupancy-based automated heating.

It is interesting to observe that the DSM results show that the flats in No.16 Cogan Terrace fairly consistently consume more heat energy

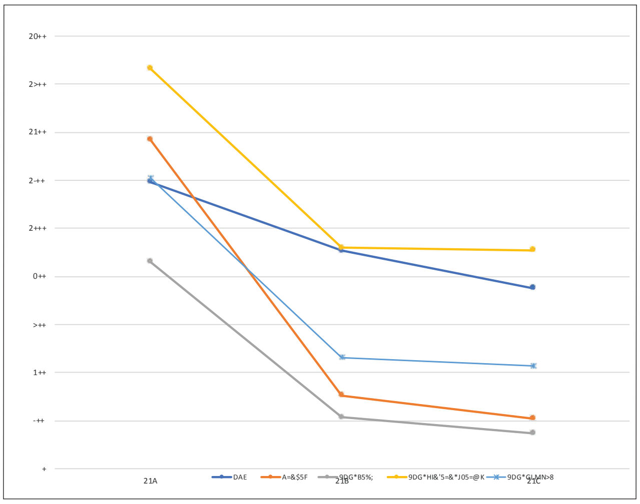

Figure 8. Heat energy profiles for 14 Cogan Terrace (DCVis).

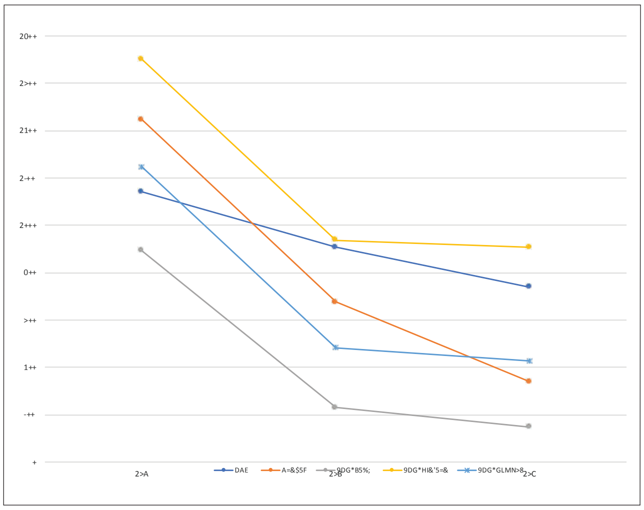

Figure 9. Heat energy profiles for 16 Cogan Terrace (trickle vents).

than their opposite flats in No.14 Cogan Terrace. This implies that the actual recorded differences in the properties may not be due only to the differences in the ventilation schemes, and there is some extra demand due to other characteristics, e.g. orientation.

Perhaps most significant is how close the actual consumption figures are to the results from the "Additional MVHR" simulation; three out of six of the case study flats have higher actual consumption figures than those generated by the "Additional MVHR" simulation but, importantly, three out of six have lower actual consumption figures, and by margins of 20%-51%. High insulation levels with an MVHR system is generally considered the highest energy efficiency option for building design. To have achieved such comparable results with a control technology, that can be considered cheaper and easier to install, suggests it is a realistic and appealing alternative.

Furthermore, in the real-life Cogan Terrace properties heat is actually recovered from the stale air but via a micro heat pump that feeds the domestic hot water (DHW). If an MVHR system had been used an additional energy source would have been required to heat the DHW. An analysis of the energy performance inclusive of the DHW would be required to prove it, but it seems likely that the case study properties would outperform the alternatives overall. This is outside the scope of this study but will be important in future studies.

Figure 8 and Figure 9 plot all of the heat energy consumption estimates generated by both models and the actual consumption figures recorded. The profile of the consumption figures generated by the DSM follows that of the actual consumptions much more closely than the estimates generated by the SAP. Specifically, in the DSM the ground floor flats have a proportionally much higher energy demand than that of the upper floor flats, in line with the recorded demand. The SAP estimates appear fairly linear. This further confirms the theory that the apparently poor performance of the ground floor flats against the SAP estimates can, at least in part, be explained by dimensional features that were not well represented in the SAP, such as the bay windows in the front bedrooms.

The figures also show how close the actual consumption figures are to the "Additional MVHR" DSM estimates in absolute terms. Previous studies have shown that the use of MVHR can be omitted in mild climates, such as the UK, without compromising energy savings (Sassi, 2013), and the results of this study suggest that greater energy savings could be available via automated control technology.

Further refinement and calibration of the DSM is clearly required to generate better heating profiles before a rigorous assessment of the performance differences could be considered. Equally, further data gathering is required at the case study properties over a number of years to generate a more representative average annual consumption figure.

4.3 Passivhaus

MVHR is stipulated in Passivhaus design and the DSM results above have already demonstrated that the energy consumption recorded at the case study properties is likely to be comparable had an MVHR system been adopted. This is an interesting result given the high energy efficiency status that MVHR systems are accredited, particularly by the Passivhaus standard. However, as already stated, the DSM model requires more work before it could be used for a full comparative performance assessment.

Flat	Flat Size (m^2)	Actual Heat Requirement ($kWh/m^2/yr$)
No. 14A (DCVi)	67	20.32
No. 14B (DCVi)	58	5.26
No. 14C (DCVi)	34	6.11
No. 16A (trickle vent)	67	21.6
No. 16B (trickle vent)	58	11.6
No. 16C (trickle vent)	34	10.0

Table 7. Actual heat energy demand per unit floor area, per flat.

For an overall direct comparison with Passivhaus the totals per unit floor area are calculated. The Passivhuas standard sets a threshold heat energy requirement of 15kWh/m^2/yr (Passivhaus Institut). Table 7 provides the total floor area and the heat demand over the year per unit floor area for each of the flats. It is clear that mid and top floor flats in both buildings (No.14B, No.14C, No.16B and No.16C) easily outperformed the standard. Although both ground floor flats (No.14A and No.16A) fall short of the Passivhaus standard, it is impressively close for a building that was not designed according to Passivhaus recommendations.

It is important to note here that a Passivhaus generally costs more to build than a traditional building, typically 20%-25% in the UK (Barnes, 2015). Using the automated control system actually gave considerable savings on the building services cost compared to traditional energy efficiency systems such as MVHR and gas boilers.

5. Conclusions

Domestic energy represents approximately 30% of energy demand in the UK (Department for Business, Energy & Industrial Strategy). The need to reduce this demand is rightly being recognised by engineers and strategists. In the domestic sector actions are required of individuals in their own homes. Design solutions are needed that enable autonomous individuals to make changes that are large-scale within their lives but small-scale in terms of the national requirement. Hence these solutions must also yield repeatable results across the large and diverse set of users that is the UK population.

Modern homes are (and should be) designed following the "fabric first" principle in order to minimise energy demand while maximising comfort. This means the need for space heating is being driven down but the need for controlled ventilation is being driven up (Sassi, 2017). Thoughtful design is required to balance the two and there is an expectation that automated building control systems can achieve this. However, so far the technologies involved are often considered too expensive or too complicated for widespread uptake (NHBC Foundation, 2018). Additionally, the lack of published analysis of the savings actually achieved under real-life conditions leads to some scepticism that the technology can really deliver (Darby, 2018).

This case study provides an "in-use" evaluation of one of the simplest and more inexpensive control systems that are currently on the market. Data was collected over one year from six neighbouring, modern-build flats in Cardiff. Every flat benefits from good, but relatively inexpensive, fabric construction and all are fitted with the Atamate building control system.

The energy performance of the case study properties was analysed with respect to heating and ventilation only. The data collected was used to assess whether the target conditions for occupant comfort were obtained and to evaluate the demand reductions made available by the system. In order to quantify the energy savings achieved, the actual recorded energy consumption of the dwellings is compared to the estimates or thresholds generated by the three environmental design/compliance methods suggested in CIBSE's recent technical memorandum for homes (Lelyveld, *et al.*, 2018):

- Standard Assessment Procedure (SAP)
- Dynamic Simulation Modelling (DSM)
- Passivhaus Standard

Considerable energy efficiencies were identified when compared to the values generated by the SAP in all but the ground floor flats. A number of suggestions were proposed to explain why the ground floor flats performed worse than expected and these warrant further investigation. It is noted however that post-occupancy buildings often perform worse than predicted by the design model, and this is termed the "performance gap". It is a substantial result that four out of six properties performed better and by a considerable margin.

The DSM provided reference consumption estimates for alternative ventilation systems, given continuous daytime and night time temperature set points. The results of the DSM also show that savings were achieved by the automated heating system at the case study properties. The recorded heat energy consumption figures proved to be comparable to that estimated by simulating an MVHR system. However, it is acknowledged that the DSM requires further refinement before rigorous comparisons can be made.

It was also hypothesised that if the energy demand for DHW were included in a future analysis, then the case study properties could comprehensively outperform the ventilation alternatives considered. This is because the properties use a micro heat pump to recover heat from extracted air for DHW; the alternative ventilation options would require an additional energy source for DHW. The DSM also provided evidence that the poorer performance of the ground floor flats when compared with SAP was due to dimensional features that could be represented in the DSM but not in the SAP, such as bay windows.

It was shown that the energy performance of the properties are comparable to Passivhaus standard, but importantly without any of the restrictive design and additional expenditure typically associated with that method. The construction costs of the case study properties were, in fact, less than typical new buildings with more conventional building service systems and less time was required on site for installation. The low capital expenditure and the reduced lead time, has the potential to appeal to volume house builders, even if the improved energy performance does not.

The results of this study show that the combination of good, but not extraordinary, fabric design and an automated control system can lead to very low energy, and hence low carbon, homes at a price point that would incentivise widespread role out. This means that the system has the potential to make a considerable contribution to reducing the carbon footprint of new and retrofitted housing stock, and, hence, to meeting the UK carbon reduction targets.

6. Further work

Further investigation of the thermal performance of the buildings needs to be carried out in order to better understand the heat energy consumption figures gathered. As already mentioned, the next step is to use a thermal imaging camera. The results of that investigation will help refine the DSM. This will provide further context for the energy efficiencies achieved but should help improve the design for further installations.

The DSM should be used to investigate a number of other areas more thoroughly. For instance, the impact of using better-performing MVHR systems and the effect of orientation on the energy performance.

Data from the study year was collected for energy use for domestic hot water and lighting. This data is yet to be assessed as rigorously as heating and ventilation have been here. An overall energy performance assessment is required.

The flats became reoccupied in September 2018 and a new study began. During this study year a series of structured occupant interviews will be carried out in order to assess the comfort provided from the tenant perspective. This will be in addition to a full set of sensor data that will be collected again.

Data gathering at the Cogan Terrace properties will be ongoing. As the flats are mostly student rentals, it is likely that the tenants will change most academic years. This provides the opportunity to assess the system with a large pool of users. The intention is that end-of-year results will be compiled regularly. With this data more representative average annual consumption figures can be generated for comparison with modelled estimates and a greater depth of understanding will accumulate.

Exploring the opportunities and challengers presented by buildings with different occupancy patterns will be particularly significant. This study shows that high-response, occupancy-controlled electrical heating can provide occupant comfort with very low overall energy demand in intermittently-occupied buildings such as student accommodation or most family homes. However, it is unlikely to do so in continuously-occupied buildings, such as elderly care accommodation. Identifying the tipping point where an alternative set up is required and what that set-up would be will be an important consideration.

An investigation into how automated systems of this kind could, and are being, retrofitted into existing housing stock, and how they are performing in this sector, is desirable. Working out the ways in which automated systems could reduce the cost and increase the speed of retrofit projects could make a very powerful contribution towards meeting the UK's low carbon aspirations.

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