Total energy and environmental performance of low carbon buildings: a cross sectoral study

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Abstract
This paper reports on the key findings of performance evaluations of eight new-build and newly refurbished buildings in four sectors: Offices, Schools, Hospitals, and Apartment blocks. Energy performances of these buildings are compared against the available design estimations and good practice benchmarks. Thermal comfort and indoor air quality in these buildings have also been analysed to provide a holistic view of *total* energy and environmental performance. The performance of the building with the least energy use suggests that a performance contract can be effective if it addresses both energy and Indoor Environmental Quality (IEQ). Other improvement opportunities identified include optimisation of ventilation control, performance measurement and verification of low carbon systems, and provisions for inspection and maintenance of advanced mechanical ventilation systems in low-energy dwellings.

Keywords Total performance, energy performance, Indoor Environmental Quality (IEQ), Indoor Air Quality (IAQ), UK

1.0 Introduction
The energy performance gap has been the focus of most recent building performance evaluations. This reflects key objectives of energy policy in the context of climate change and energy security. However, the recent and emerging evidence relating to ambient air quality [1] has important implications for the health and well-being of building occupants and adds to calls for a more holistic approach to the ‘total’ performance of buildings that encompasses both energy and Indoor Environmental Quality (IEQ) [2]. This paper reports on the interim findings of an on-going investigation of the total performance of eight new buildings in four key sectors that comprise a large cross section of the UK building stock: offices, schools, hospitals, and apartment blocks.

This is part of a wider body of collaborative research between UCL and Tsinghua University in China that addresses the Total Performance of Low-carbon Buildings in China and the UK (TOP). The aim of this paper is to report how the UK case study buildings are performing against the design baselines and industry standards. A key objective is to link energy to IEQ performance and identify root causes of underperformance in new buildings. Process improvements that may help narrow the performance gap are also identified.

2.0 Background
Several research programmes in the UK such as PROBE [3], the Low Carbon Buildings Performance (LCBP) research conducted by the Carbon Trust [4], and more recently the Building Performance Evaluation Programme [5] have uncovered

significant underperformance in the actual operation of new buildings designed with high aspirations. Similar studies have been conducted in Europe [6], North America [7], [8], Australia [9] and other regions to evaluate the operational performance of new and refurbished buildings and identify the effectiveness of the existing policies and regulations to deliver buildings that are fit for purpose. Broadly speaking, the term ‘performance gap’ refers to shortfalls in operational performance of a building against its design intents. Various metrics could be used to assess whether there is any performance gap in the actual operation of a building. Whilst most studies in this field are predominantly focused on energy, the gap between actual and expected performance may also be identified for the IEQ. For example, the PROBE occupant surveys pointed to downward trends in thermal comfort, acoustic performance, perceived control, and the misfit between building performance and user expectations in buildings that were deemed to be exemplar [10]. Dissatisfaction with IEQ may have various causes. Potential conflicts between energy efficiency requirements and IEQ performance are of great interest in the context of new Building Regulations [2]. An example of these conflicts is the overheating issues uncovered in highly insulated and airtight new buildings [11], [12], [13]. Air quality may also be compromised in new airtight buildings. Several studies have shown the risk of higher concentration levels of certain Volatile Organic Compounds (VOCs) such as benzene, formaldehyde and trichloroethylene in new buildings constructed to higher energy standards [14], [15]. Outdoor sources of pollution such as traffic that can lead to high levels of exposure to NO_2 and micro particles (PM levels) are also of great interest in urban areas. Outdoor pollution may have significant implications especially where energy-efficient strategies such as advanced natural ventilation are adopted and air exchange between the indoor and outdoor environment occurs without any filtration. Using CO_2 as proxy for Indoor Air Quality (IAQ) in these circumstances may not be adequate to determine the quality of air [16]. The implication of using other proxies for air quality on the existing control strategies should be explored. An integrated approach to total energy and IEQ is therefore required to provide a better understanding of the intricate relation between these performance metrics and how performance gaps in these areas could be addressed.

3.0 Method

The focus of the TOP programme is large scale building projects where even modest improvements in building procurement and management can bring significant environmental benefits. Four key sectors were selected for a cross-sectoral examination of the performance gap and its root causes: offices, schools, hospitals and apartment blocks. Considered together, offices, educational buildings and hospitals account for around 65% of the UK non-domestic building stock and 32% of its carbon emissions. Apartment blocks also account for 12% of the UK residential floor area [17]. These building categories also cover various types of functional requirements with different building standards that pose challenges for operational performance. Therefore, a comparative analysis can provide useful insights into the problem of the performance gap and its remedies in a large cross-section of the building stock.

Eight buildings were selected in the UK, two from each sector, for an initial one-year investigation (Phase 1) with a view to carry out more in-depth investigations on four of the buildings in the second year of research (Phase 2). This paper provides an overview of the key findings of Phase 1 and the approach taken for Phase 2 along with some preliminary results.

Table 1 lists the key characteristics of the case studies.

Table 1 – Key building characteristics of the case studies

Building	Location	Useful Floor Area (m²)	Date building completed	Ventilation strategy	Heating/ cooling strategies
Office 1 (public sector)	Somerset (Keynsham)	6,363	2014	Nat. Vent.	Heat pumps & boilers/ chilled beams in meeting rooms
Office 2	Central London	5,665	2014 (renovated)	Mixed mode	VRF[1] system for heating & cooling
School 1	London (Wandsworth)	21,405	2014	Mech. Vent.	Biomass & gas boilers, VRF system in ICT rooms
School 2	London (Croydon)	11,620	2013	Nat. Vent.	Gas boilers, VRF system in ICT rooms
Hospital 1	Bristol	16,122	2015	Mech. Vent.	Steam-based heating network, mechanical cooling
Hospital 2	Greater Manchester (Altrincham)	6,755	2015	Mech. Vent.	Gas boilers, mechanical cooling (chillers)
Apartment block 1 (student accommodation)	Central London	12,669	2013	MVHR[2]	Gas-fired CHP-led community heating
Apartment block 2 (97 flats and maisonettes)	London (Tower Hamlets)	7,940	2015	MVHR	Gas-fired community heating (CHP to be installed in next phases)

All buildings have been subject to monitoring as of 2016. The monitoring programme entails the activities listed under the following subsections.

3.1 Energy performance

Following a review of the available design and construction documents, energy calculations carried out on completion of the buildings or after detailed design were taken as baselines for energy performance. These baselines are inclusive of all loads including an allowance for energy end-uses not regulated by the Building Regulations, notably, small power and other equipment loads.

[1] Variable Refrigerant Flow
[2] Mechanical Ventilation with Heat Recovery

Actual energy use of all case studies is recorded in monthly intervals. Half-hourly electricity data is also available for all non-domestic buildings which helps to identify the trends of electrical demand and buildings' operation.

To evaluate the potential gaps in energy performance, the followings are reported in this paper:

- Annual fossil thermal and electricity use of the non-domestic case studies are compared against the available baseline energy calculations and good practice benchmarks in the industry.
  Good practice benchmarks in the UK are often defined based on the 25th percentile of the performance of the existing building stock. Therefore, it is reasonable to expect new buildings perform better than these benchmarks [18]. Table 2 defines the benchmarks used in this study.
  Energy data reported for all case studies reflect the steady mode of operation and cover a measurement period beyond the first 12 months of operation when building performance may not have been stabilised yet.

- As for the domestic apartment block, the actual heating demand of all units were sourced from the heat meters in the Heat Interface Unit (HIU) installed in the apartments. Data cleaning led to exclusion of erroneous data or data points that were not reflective of whole-year operation (e.g. vacant flats). Consequently, the actual heating demand of 40 units were compared against the estimated heating demand reported on the respective Energy Performance Certificates (EPCs) available for the units. The Energy Service Company (ESCO) responsible for managing the heating network in this apartment block have not carried out an assessment of the actual efficiency of the network's energy efficiency yet. The heating demand figures reported on domestic EPCs also do not account for the heating efficiency and therefore can be used as baselines for *delivered energy* for typical households. Comparison between the metered and estimated heating demand of apartments in this paper is therefore indicative of building fabric performance and occupants' control over heating system & MVHR and does not address the supply side.

- The best performing building in this study has been subject to energy performance contracting. It is useful to review the changes in longitudinal energy use of this building post-occupancy to evaluate the effectiveness of the performance contracting process. Monthly and annual energy breakdowns for two years are presented and compared against the energy budgets set out for this building in the contract. Half-hourly electrical demand data are also reviewed to have a better understanding of the performance especially the effect of the sizable PV installation on the roof of this building (with nominal capacity of 210 kW_p).

Table 2 – Good Practice benchmarks used in the study

Building category		Fossil-thermal benchmark (kWh/m²/annum)	Electricity benchmark (kWh/m²/annum)	Source
Offices		80	68	25th percentile of Display Energy Certificate (DEC) data for offices [19]
Schools		96	54	25th percentile of DEC data for secondary schools/academies [20]
Hospitals	Hospital 1	423	74.5	ECG72 Good Practice benchmarks for Acute hospitals [21]
	Hospital 2	339	86.3	ECG72 Good Practice benchmarks for Teaching hospitals [21]
Apartment block (student accommodation)		138	49	25th percentile of DEC data for higher education ‘residential’ buildings [22]

3.2 Indoor Environmental Quality (IEQ)

Temperature, Relative Humidity (RH), and CO_2 concentration (as proxy for indoor air quality) were monitored in representative zones, covering 5-10% of each building’s floor area with a frequency of at least 5 minutes for one year in accordance with BS EN 15251 [23].[3]

Customary threshold operative temperatures defined for thermal comfort in heating season and summer in CIBSE Guide A [24], RH range of 40-70% which is deemed to be the acceptable range for thermal comfort [18], and CO_2 levels reflecting the ventilation class of the building systems in accordance with BS EN 13779 [25] were used to evaluate thermal comfort and indoor air quality.

Ventilation requirements in hospitals are generally more stringent than other buildings. The case study hospitals utilise full fresh air mechanical ventilation with heat recovery to provide 10 air change rates per hour to most medical spaces and 6 air change rates per hour to examination and measurement rooms. Consequently, the CO_2 concentration level of 750 ppm representing IDA class 1 ventilation was used for hospitals, while 1500 ppm was used for other building types equivalent to IDA class 4 ventilation in BS EN 13779.

There is no control strategy for RH in the case studies except for the operating theatres in Hospital 1. Therefore, RH levels outside the comfort range are not necessarily indicative of a performance gap against design strategies, but nonetheless are reported to provide an understanding of thermal comfort conditions in the buildings.

Radar charts showing the cumulative frequency (%) of measurements lower than the minimum recommended operative temperatures in heating season, higher than the

[3] Measurement accuracies: T: ± 0.4 °C, RH: ± 4.5 %, CO_2: ±75 ppm

maximum recommended operative temperatures in summer, measurements outside the acceptable range of RH, and CO_2 concentration levels above the thresholds defined for the respective ventilation class of the buildings are presented in this paper.

It should be noted that this is not a fully comprehensive assessment of thermal comfort and indoor air quality conditions which requires more attention to the building context, the trends and peaks, and the adaptive nature of thermal comfort in summer in naturally ventilated buildings [26]. However, this method is useful to provide a consistent way of comparing conditions in different buildings and relating energy consumption as the input to the environmental system of a building to thermal comfort and indoor air quality (IAQ) as key outputs of this system. While people may be more tolerant of high ambient temperatures in free running buildings and this will have to be considered in an assessment of the overheating risk, it is generally accepted that most people start feeling uncomfortable when operative temperatures exceed 25 °C [24].

3.3 Advanced monitoring of Indoor Air Quality (IAQ)

CO_2 concentration levels can be used to infer the ventilation rates where the number of occupants and occupancy pattern of a zone is known. However, to evaluate the quality of air in a building, and its implications for health and well-being of occupants, it is also necessary to know the concentration levels of other pollutants in indoor air.

An advanced monitoring device for IAQ has been developed for Phase 2 of this research project to measure concentration levels of various pollutants such as NO_2 (proxy for traffic), particulate matter (PM_1, $PM_{2.5}$, PM_{10}), TVOC, and CO in addition to CO_2 and thermal comfort parameters (temperature, RH, and air velocity). This equipment will be used to evaluate IAQ in four case studies (one in each sector) for a full year. In this paper, trends of indoor and outdoor CO_2, NO_2 and TVOC in Office 1 during typical days in heating season are compared to review the existing control strategy and improvement opportunities.[4]

In addition to continuous monitoring, performance evaluation of the case studies entailed detailed review of the building documentation and the Building Management Systems (BMS), observational studies during site visits, and discussion with building managers and building users. Meetings were also arranged to review the existing operation against design intents with designers and contractors in all buildings and discuss the potential root causes for any performance gap in energy and IEQ.

4.0 Results

4.1 Energy performance

Comparison against design estimates: Figure 1 compares the energy performance of the case studies with available design estimations.

4 Measurement accuracies: CO_2: ± 50 ppm, NO_2: ± 0.5 ppm, TVOC: ± 3% of measurement

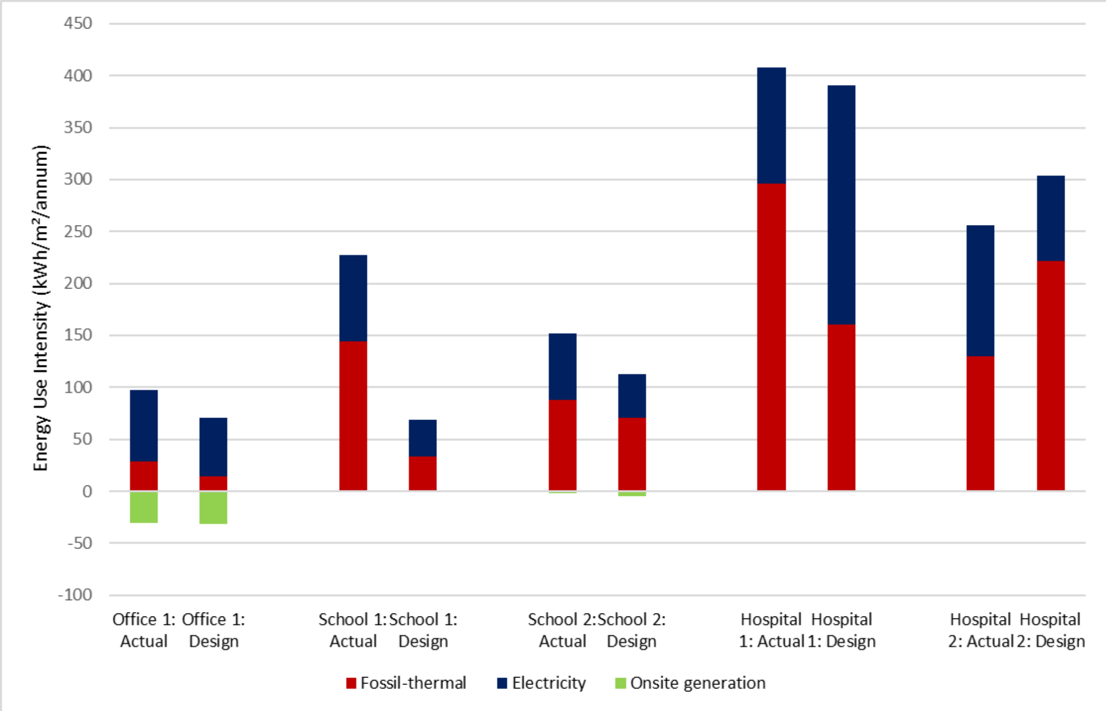

Figure 1– Energy performance of the case studies against design estimations

Fossil-thermal and electricity use of Office 1 and both schools are higher than design estimations with a significant discrepancy in school 1. School 1 comprises several buildings with different functionalities and operational schedules which makes meeting design targets susceptible to a high degree of uncertainty and the actual operation susceptible to operational inefficiencies higher than expected in a single building. It should also be noted that the biomass boiler installed in School 1 has not been operational since building handover. A biomass system was the preferred low-carbon technology for the council (the client) at design stage, whereas the school management was not content with this option from the outset and switched to natural gas in operation. Consequently, CO_2 emissions associated with energy use are significantly high.[5]

Fossil-thermal energy use of Hospital 1 is around 85% more than the design estimation. This is due to the relatively low efficiency of the old steam-based central heating network that servers the building (average measured annual efficiency: 74%). The design and Building Regulations compliance calculations allowed for operation of a new combined heat and power (CHP) plant for the building. This did not happen in practice as it was decided it would be more appropriate to integrate the CHP system into the site heating network following a major renovation to maximise the efficiency savings rather than as a separate system for the new building only. Installation of this system was put as a condition for confirming the building's compliance with the Building Regulations. However, two years after building handover it is still not clear when the central heating network will be subject to renovation and the thermal performance of the new building is consequently much worse than expected from a new building.

[5] The school currently has a DEC rating of G.

Comparison against benchmarks: Figure 2 compares energy performance of the non-domestic case studies to the good practice benchmarks.

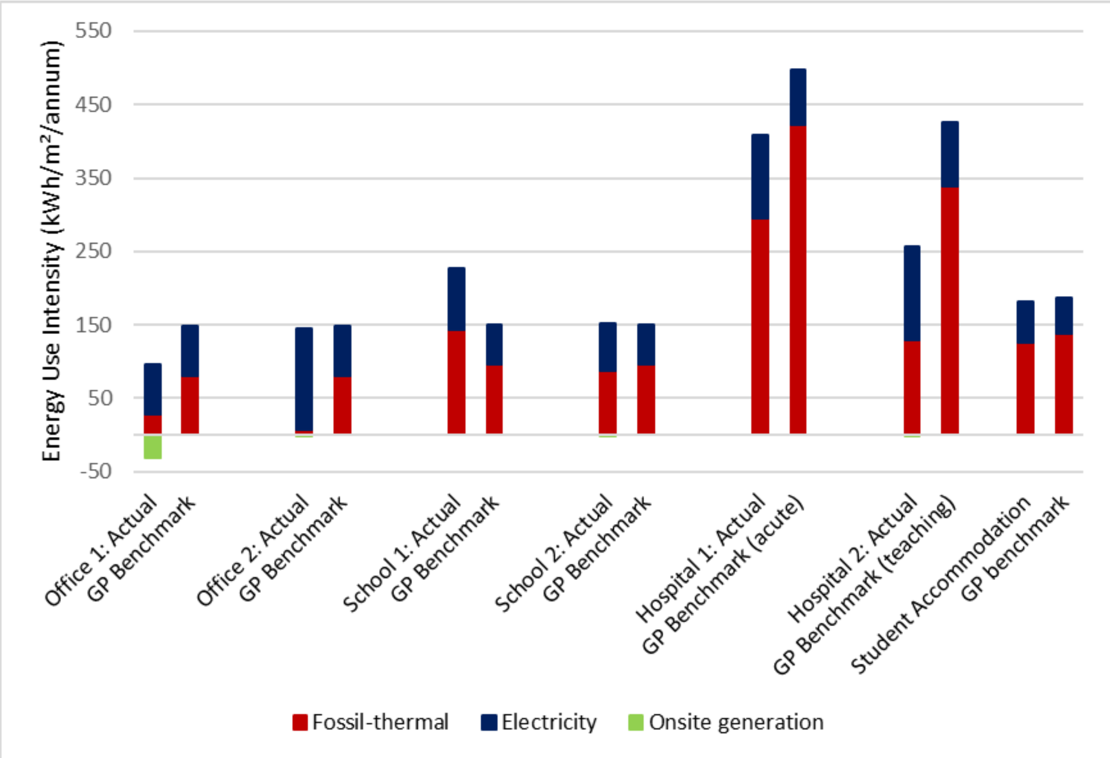

Figure 2 – Energy performance of the non-domestic case studies against Good Practice (GP) benchmarks

All case studies have fossil-thermal energy use lower than the 25th percentile of their respective building category except School 1 where the central heating system is fully operational during half-term breaks and extracurricular activities without isolating the unoccupied buildings and zones. Office 2 was subject to deep renovation that led to replacement of the gas-fired heating system with VRF. Therefore, the fossil-thermal energy use in this building is negligible and limited to wet radiators in stair cores and few circulation spaces that are served by a small gas-fired boiler. Electricity use in this building is significantly higher than the benchmark value which is reflective of a large equipment and server room load (baseline electrical demand of 11 W/m² compared to 5 W/m² in Office 1) in addition to the shift to VRF system.

The heating demand in apartments: Figure 3 compares the actual heating demand of 40 apartments against design estimations. The graph shows a large degree of scatter and relatively poor correlation. On average, actual heating demand is around 50% higher than design estimation. This could be indicative of issues with fabric performance although occupant control over the heating and MVHR system (e.g. heating set points and operational hours) should also be considered.

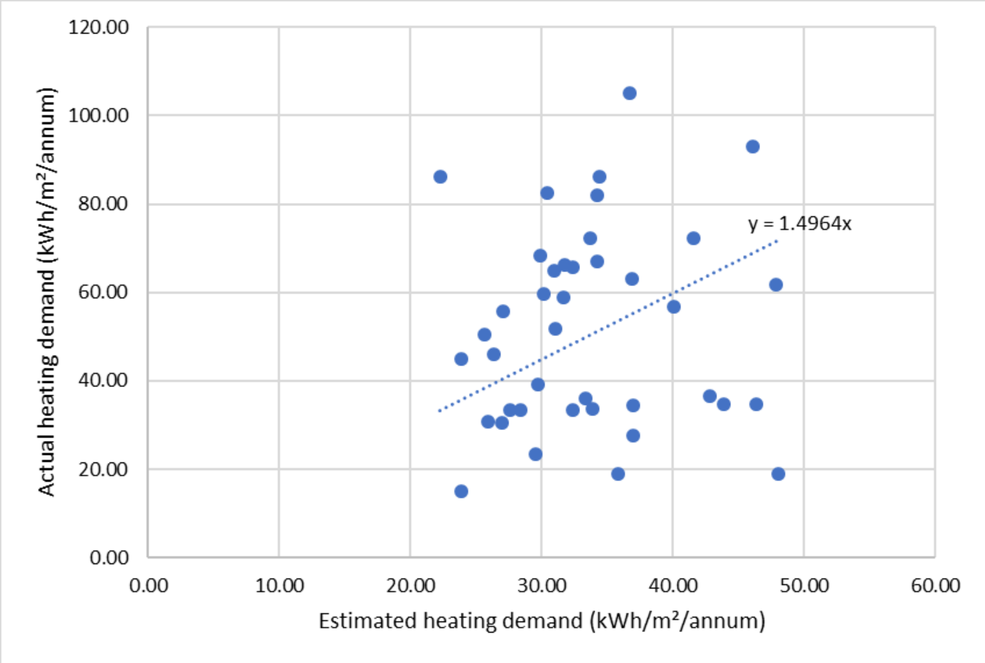

Figure 3 – Actual vs. estimated heating demand in apartments (Apartment block 2)

Narrowing the gap via performance contracting: The only building subjected to performance contracting and Soft Landings [27] to meet its energy targets in practice is Office 1. This building had a set of energy budgets calculated at design stages to meet in addition to a DEC A target to be achieved after the second year of operation. Figure 4 shows the annual disaggregated energy budgets and the actual performance of this building for two years after completion. The building achieved DEC B following the second year of operation. Although the building fell short of meeting its design targets, its fossil-thermal energy use is lower than the 10th percentile of public office buildings. Its gross electricity demand puts it on the 25th percentile of public office buildings while the net electricity use is also lower than the 10th percentile of these buildings [19].

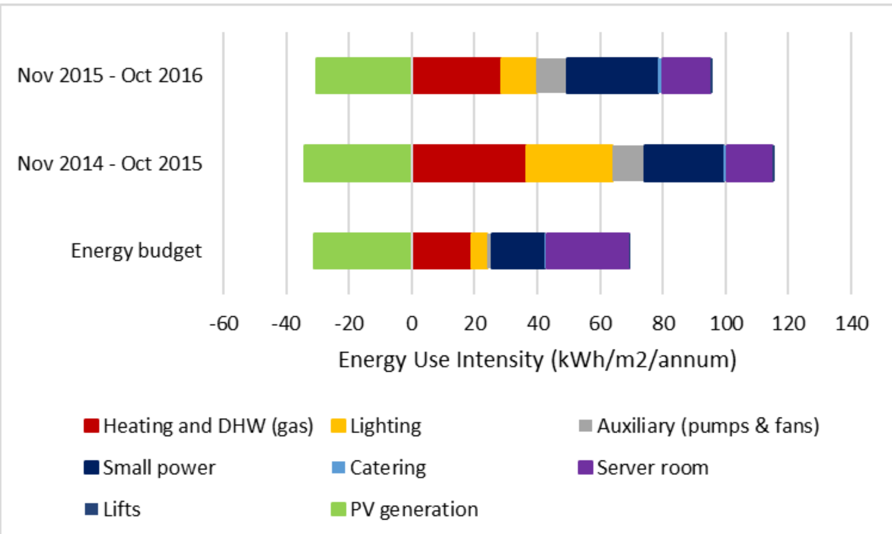

Figure 4 – Annual energy performance against energy budgets: Office 1

Figure 5 shows the monthly energy use for two years and the improvements achieved in building performance as a result of active engagement of designers and contractors in building fine-tuning.

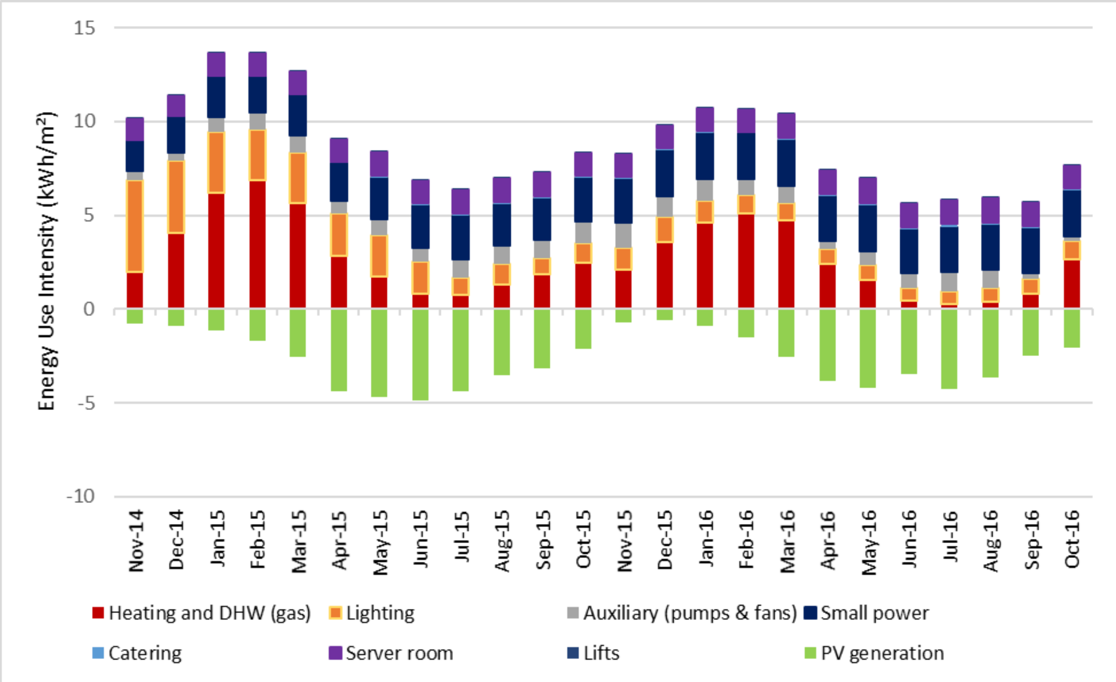

Figure 5 – Breakdowns of monthly energy performance: Office 1

The most notable reductions were achieved in heating and lighting, although the stringent design targets have not been met for these end-uses. Designers and contractors are still involved in optimising the performance of this building following the Soft Landings framework.

Figure 6 shows the net electrical demand of this building in 2016. The almost flat average daytime electrical demand for weekdays and the dip in electrical demand over the weekends when the building is not occupied shows the effect of the PV installation that has brought the net electrical demand during working days to the baseline level. It is therefore critical to reduce the baseline demand to achieve further savings in electricity use (power down management of IT equipment, virtualisation of server room load, revisiting the server room cooling set point, etc.).

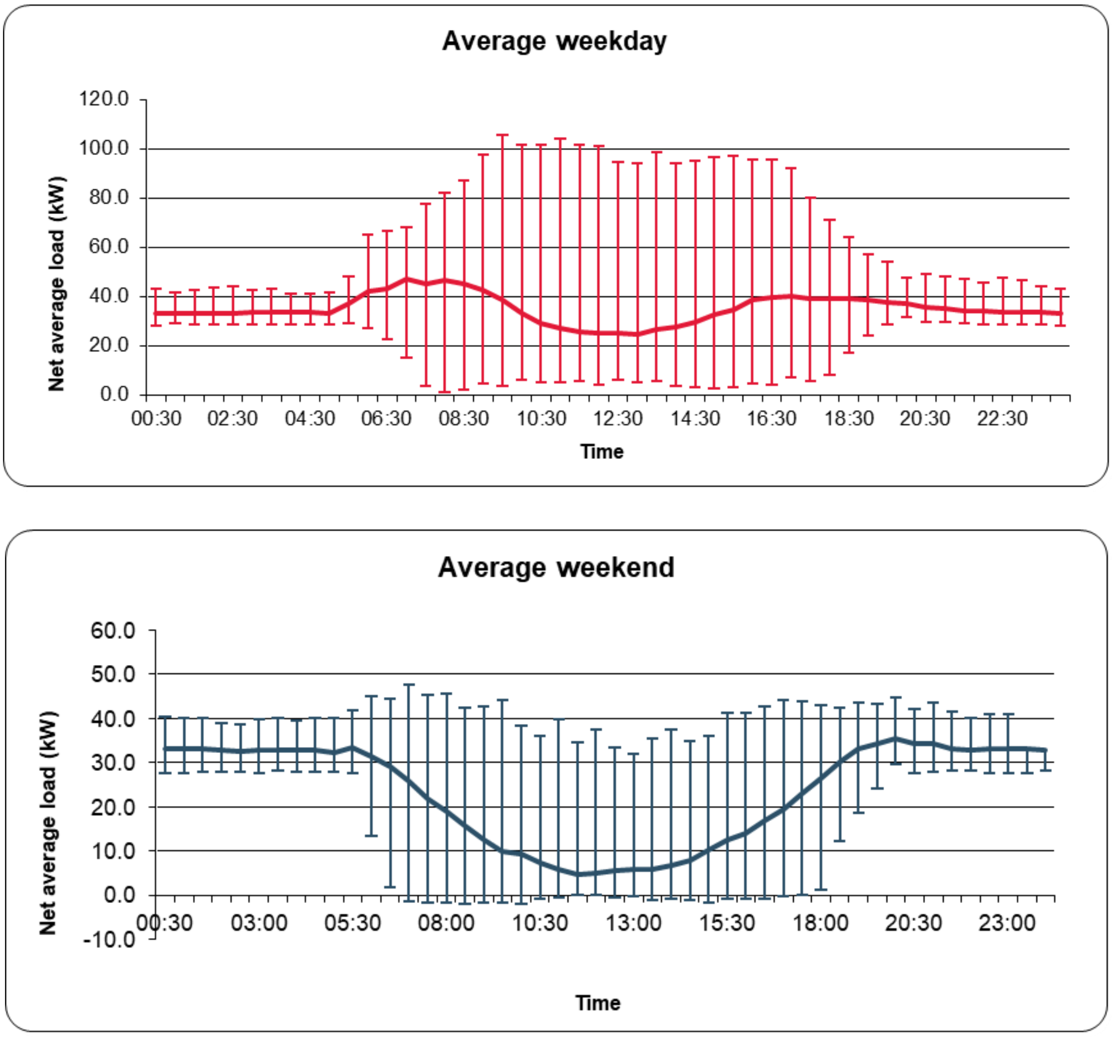

Figure 6 – Net half-hourly electrical demand curves and variations: Office 1

4.2 Indoor Environmental Quality (IEQ)

Figure 7 shows the percentage of time the occupied zones within the case study buildings did not meet the recommended thermal comfort conditions and CO_2 concentration levels in heating season and summer.

The IEQ performance gap in the hospitals, which constitute the most energy intensive buildings in this study, is significantly lower than other buildings thanks to close control over temperature and CO_2. Whilst there were episodes of operative temperatures below 22 °C in the hospitals, in both buildings CO_2 concentration levels in all monitored zones remained below 750 ppm due to effective mechanical ventilation and high air change rates.

Office 1 offers an example where energy performance objectives are not aligned with IEQ. CO_2 concentration levels on the top floor on this building were frequently higher than 1500 ppm due to a malfunctioning sensor. Subsequently, complaints about draught along with concerns over excessive heating energy use (compared against the energy budgets) led to disabling of the CO_2 trigger for motorised natural vents and thereby high CO_2 concentration levels. While the designers and contractors were proactively trying to optimise the energy performance, the IEQ performance, not specifically covered by the contract, was not a top priority and CO_2 levels in large open plan zones of this building were consistently above 1500 ppm.

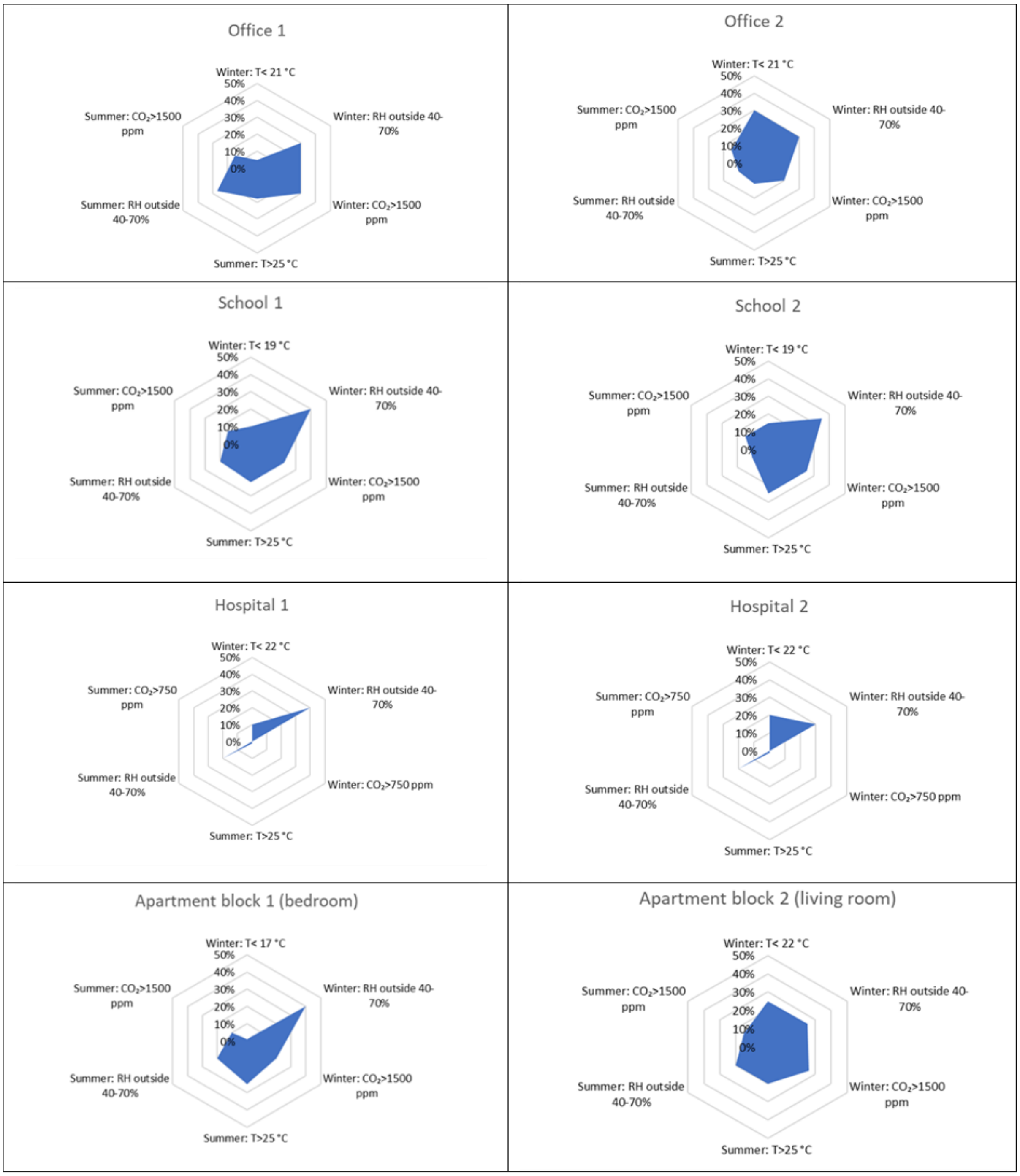

Figure 7 – The performance gap in thermal comfort and IAQ

Figure 7 offers a method for systematic evaluation of the performance gap in thermal comfort and IAQ which in principle could be extended to other proxies for air quality and other aspects of IEQ performance.

4.3 Advanced monitoring of Indoor Air Quality (IAQ)

Figure 8 illustrates time series for indoor against outdoor concentration of CO_2, NO_2, and TVOC in Office 1, a naturally ventilated building with both manual and automated control, on typical days during November 2017.

The peaks close to 2500 ppm for CO_2 represent an open plan zone with no automatic control for IAQ (third floor). It is notable that this zone has the lowest NO_2 concentrations. The balance between CO_2 and NO_2 levels on different floors suggests an effective control strategy to optimise both energy and IAQ would be to introduce additional triggers for operation of automated vents based on outdoor air quality for a building located in a critical zone (Office 1 is located close to a congested road).

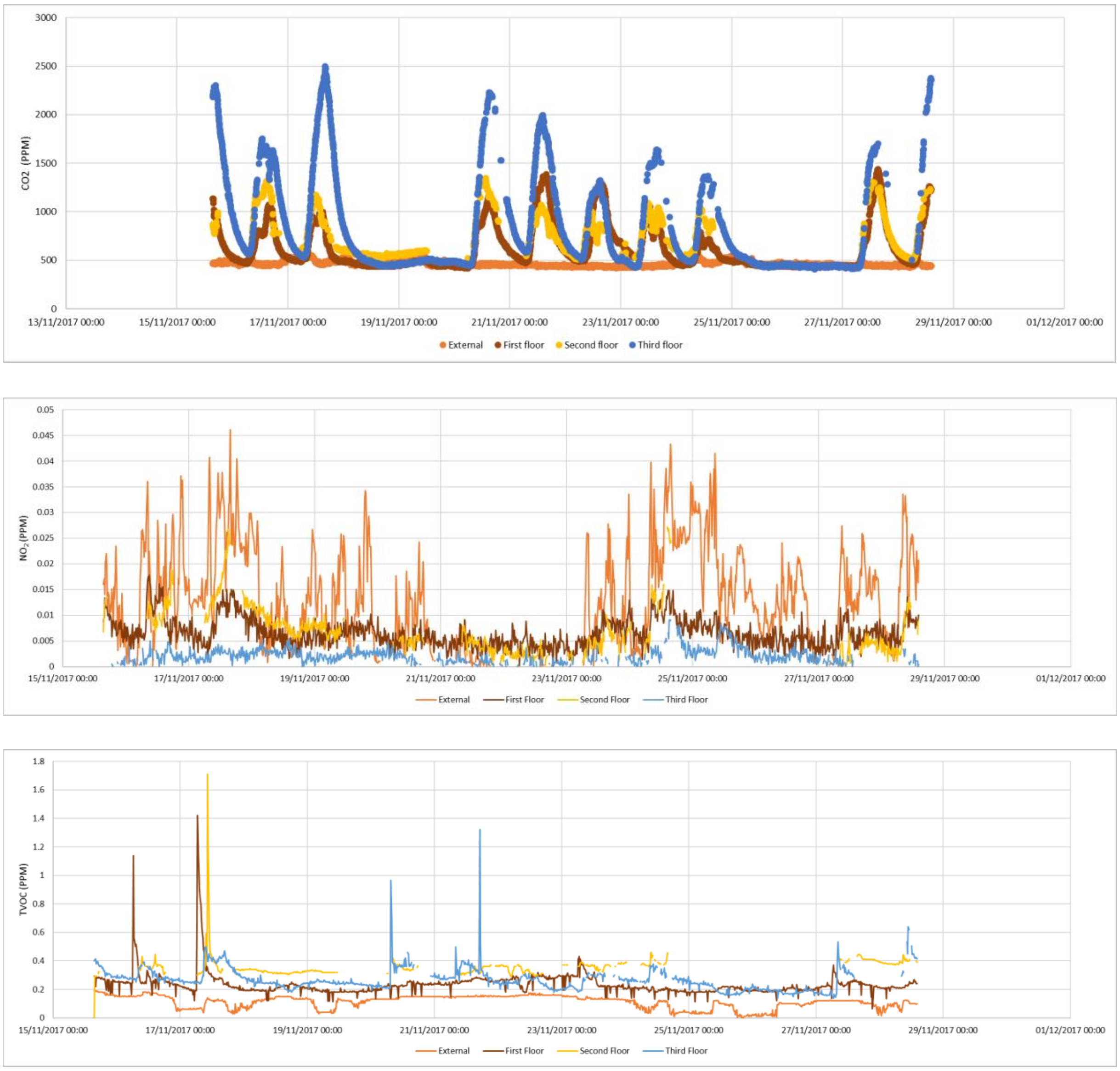

Figure 8 – Concentration levels of CO_2, NO_2, and TVOC: Office 1

Peaks in TVOC concentrations indicate the ‘events’ that may inform the ventilation strategy (e.g. cleaning). However, a more refined approach to VOC measurement would be necessary to separate compounds with health impact from non-critical compounds. Designing a control strategy based on TVOC might be an attractive option as these sensors become cheaper [28]. This may however compromise energy performance by increasing air change rates in response to non-critical events.

5.0 Discussion

The evidence emerging from Building Performance Evaluation of the case studies point to several improvement opportunities that could inform future projects and on a broader level future policy and regulations.

Performance contracting: the case study subjected to energy performance contract is by far the best performing building not only in terms of absolute energy performance but also compared to the design targets and industry benchmarks.

Whilst performance contracting of new buildings is currently a rather niche trend, it can be a favourable option where the project client has a vested interest in operational performance as is often the case for public sector offices, schools, hospitals and housing association projects. The extra capital cost incurred for post-occupancy work can often be recouped through energy savings achieved with a relatively short payback. It is however important to clearly specify the IEQ requirements in the contract to ensure the pursuit of energy efficiency will not compromise the indoor environment.

Demand-controlled strategies: optimum space-time utilisation of buildings with transient occupancy and/or seasonal operation is a very cost-effective way of saving energy. Schools are strong candidates for this strategy with partial occupancy during half-term breaks and extracurricular activities. However, strategies such as demand-controlled ventilation are also recommended for hospitals [29], but are often not effectively used in practice. Figure 9 shows the electrical demand curve for Hospital 2 with an almost constant average electrical demand during weekdays despite variations in building occupancy and operation. All main supply and extract fans in this building are equipped with inverters to enable variable speed control. However, the inverters were only used at the commissioning stage to balance the system and there is no effective demand-controlled ventilation triggered by occupancy or gas sensors.

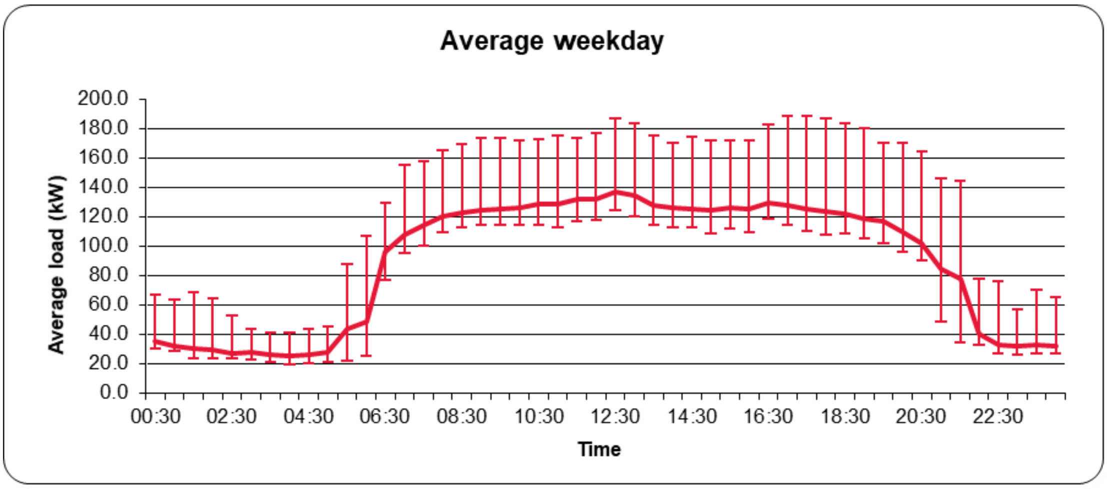

Figure 9 – Half-hourly electrical demand curve and variation: Hospital 2

Demand-controlled ventilation, hydraulic isolation of heating/cooling zones that are not occupied, and central and building level power-down management techniques can be used to optimise building performance.

Energy demand: achieving the ambitious building fabric specification set out for new buildings could be a major challenge in practice. Apartment block 2 with designed fabric U values significantly better than the Building Regulations (Wall U value: 0.19, window U value: 0.9 W/m²°K) and air permeability of 1-2 m³/m²/hour is a good example to illustrate this point. Figure 10 shows the rather large temperature gradient (approx. 5 °C) around the glazed door which is indicative of cold bridging and draught (confirmed by measurement of air speed). This is not reflected in heat demand calculations. This Figure also shows reasonable continuity in insulation across the external wall, although there are signs of thermal bridging around balconies.

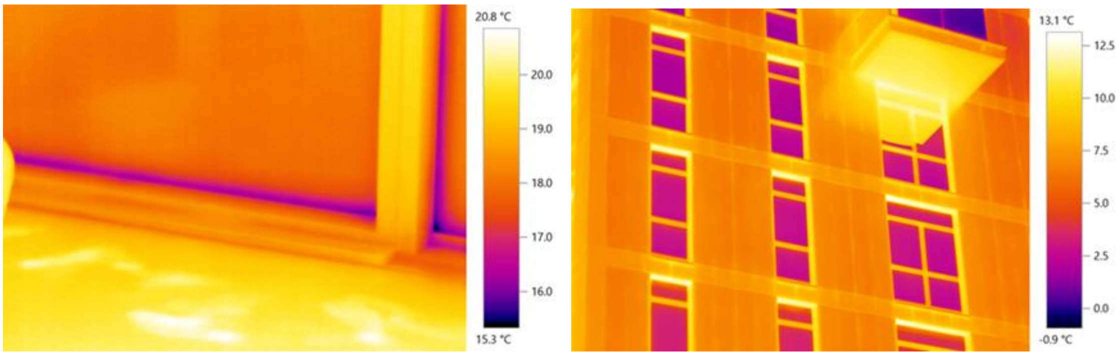

Figure 10 – Cold bridging and draught from the double-glazed door (left), and signs of thermal bridging around balcony: Apartment block 2

Figure 11 shows the rebound effect [30], [31] experienced in some of these apartments where indoor temperatures are significantly higher than the comfort ranges recommended for heating season (17-19 °C in bedroom and kitchen, 22-23 °C in living room as per CIBSE Guide A). This further increases the heating demand.

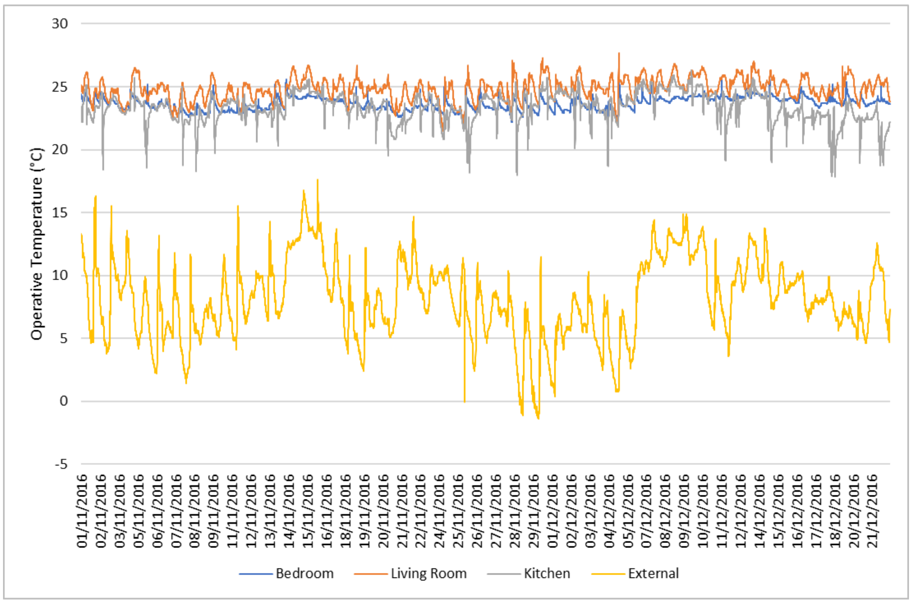

Figure 11 – Operative temperatures in a sample apartment: Apartment block 2

Routine post-occupancy evaluations at the early stages of building operation would help create a feedback loop to inform the construction teams about potential shortcomings and improvement opportunities. This would also provide an opportunity to engage occupants and develop appropriate behavioural strategies to strike the right balance between comfort and energy efficiency.

Energy supply: several case studies covered by this study utilise community or campus-wide heating networks. The existing heating network serving Hospital 1 provides the continuity and robustness expected from a steam-based plant albeit at a low efficiency. As for the new heating networks, none of them have been assessed for operational efficiency yet. Previous studies have shown that despite clear advantages of a well-managed community heating network, actual efficiency of these systems could be significantly lower than design specification [32].

Regular assessments of operational efficiency of these systems is vitally important and should be well defined in an ESCO contract.

Decarbonisation: low or zero carbon systems are increasingly important to achieve compliance with the CO_2 emissions criterion of the Building Regulations (Part L 2A). Yet these systems are not always operational post-handover as in the case of the biomass boiler in School 1. Hospital 1 is also an interesting case where installation of a low carbon system has been postponed until a decision is made to renovate/replace the existing heating network which is highly uncertain given the budgetary constraints of the NHS. The CO_2 emissions of this building will be significantly higher than what was assumed on the completion of the building for foreseeable future.

Robust safeguards and time-bound operational targets are required to ensure new buildings will be operating reasonably close to what is assumed at design stage. Design targets also need to be realistic and representative of the expected operating conditions.

Effective ventilation: The industry's main metric for assessment of IAQ is currently CO_2 concentrations. Most existing control strategies for ventilation systems also use this metric. In mechanically ventilated buildings filtration can provide a level of protection against outdoor sources of pollution such as micro particles. Maintenance of these systems and filter cleaning/replacement are critical to maintain effectiveness of filtration and energy efficiency.

New air-tight dwellings with de-centralised MVHR systems represent a special case of mechanically ventilated buildings (e.g. Apartment block 2). The responsibility of cleaning and replacing air filters in these dwellings currently lies with the occupants. Developers and housing associations at best provide the manufacturer's recommendation about the frequency of filter cleaning/replacement in building manuals. This did not happen in Apartment block 2 where building users had not been informed about the recommended frequency of filter replacement (Figure 12). The evidence from Apartment block 2 reinforces the findings of another study that pointed to the shortcomings in provision of training and information to residents in dwellings with MVHR systems across Europe [33].


Figure 12 – Sample MVHR unit in Apartment block 2 (left) along with the supply air filter after cleaning

Making landlords and housing associations responsible for regular inspection and maintenance of these systems in rented accommodation, similar to the current requirement for annual inspection of heating systems, might be a good solution. This could in turn raise awareness among other users of these systems.

Finally, advanced control strategies that consider the balance between requirement for fresh air and protection from outdoor sources of pollution could provide a healthier environment and at the same time save energy in both mechanically ventilated buildings and naturally ventilated buildings that rely on automated ventilation.

6.0 Conclusions

The cross-sectoral study of eight new non-domestic and large residential buildings found that thermal performances of these buildings are better than the 25^{th} percentile of the existing building stock (Good Practice benchmarks) except for one school. Electricity use of one office building was identical to the good practice benchmark while other non-domestic buildings and the student accommodation consumed 13-100% higher electricity than the Good Practice benchmarks. Most buildings had also higher fossil-thermal and electricity use than the available design estimates.

The best performing building was subject to energy performance contracting. The evidence suggests this type of contracts can help narrow the performance gap and would be financially viable for landlord occupiers or where the project client has long-term vested interest in a building. However, there is some evidence of conflicts between energy efficiency objectives and indoor air quality in this case study which points to the significance of defining specific requirements for the performance of the indoor environment in the contract (Environment & Energy Performance Contracting).

Key improvement opportunities identified at building level for future projects are advanced and effective demand-controlled strategies especially in seasonal buildings such as schools, and opportunities to improve ventilation control strategies by monitoring outdoor pollutants such as NO_2 and micro particles.

At policy and regulatory level, it is suggested to have robust safeguards in place to ensure the installed low or zero carbon technologies will be used in practice at a reasonably close level to the design specification. This could for example be done by measurement and verification of building and system performance within the first few years of operation.

It is also recommended to improve the existing arrangement for provision of information and maintenance for de-centralised MVHR systems installed in extremely air-tight low-energy dwellings as this can have significant implications for the health and well-being of building users.

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