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EXCEEDING ENERGY CONSUMPTION DESIGN EXPECTATIONS

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ABSTRACT

Operational building performance often fails to meet that predicted at the design stage by as much as two to three times. Many reasons for this difference have been identified and widely reported, however, the problem still continues to occur. A case study new 'energy efficient' fully air conditioned office building has been monitored since occupation in June 2010 to observe the difference between operational energy consumption and design targets. In the first full year of operation (2011) the building consumed 208.7 kWh m^{-2} yr^{-1}, 83% of the expected energy consumption (250 kWh m^{-2} yr^{-1}). This dropped further to 176.1 kWh m^{-2} yr^{-1} in 2012 (70% below expected). Factors affecting building energy consumption have been discussed and appraised in respect to the case study building. Recommendations have been made for successfully meeting future building energy design targets.

A number of energy saving technologies have been installed during the monitoring period such as LED lighting, voltage optimisation and thin client. An appraisal of these is also given, along with the performance of the photovoltaic panels and rainwater harvesting in place from the outset.

INTRODUCTION

The building energy 'performance gap', where the actual building energy consumption exceeds that predicted at design stage, regularly occurs in new and refurbished buildings. In fact buildings are often reported to consume two or more times the original expected energy (Bordass et al., 2001). In one case study, four out of five new low carbon schools were found to perform below the national average for their building type (Pegg et al., 2007). This is not the side of the national average where new building design performance should be falling. With environmental considerations and increasing fuel costs coming to the forefront of building owner and operator priority, it is important to understand how, if at all, 'low carbon' building targets are attainable. Furthermore, the 2008 UK Government budget report laid down targets for: zero carbon new homes by 2016; zero carbon new public buildings by 2018; and zero carbon new non-domestic buildings by 2019 (HM Government, 2008). Significant improvement in meeting design predictions in-use will need to be made to satisfy these targets.

Energy Predictions

In order for our new buildings to meet design predictions it is essential that the predictions themselves are realistic. Final annual energy consumption predictions for new buildings are typically made using either benchmark data or full building dynamic thermal simulation. With benchmark data, the prediction figure is based on the historical performance of similar building types, collated to give 'typical' performance values. Commonly however, due to technology development and working pattern changes, historical benchmark data becomes outdated, and new benchmarks are slow to emerge. With UK energy benchmarks, such as ECON19 for office buildings (Energy Efficiency Best Practice Programme, 2000), it is also difficult to establish the source of the information used to collate the benchmarks in the first place (Liddiard et al., 2008).

Dynamic thermal simulation can account for building fabric, specific systems and equipment, occupant numbers, hours of operation, amongst other variables. It is an expensive process (time required and license fee), so more appropriate for larger scale, higher fee earning projects. At the design stage many assumptions are made based on client information or previous project knowledge, which may not be representative of what will happen once the building is in use. Time and care should be taken to generate realistic energy predictions, based on experience and previous project knowledge. Although the ability to do this is dependent on resources available.

In-use Performance

Poor in-use performance has been recognised for many years and reasons have been identified in previous case study investigations (Bordass and Leaman, 2010b). Once occupied, many factors govern how much energy is used, the main ones of which are included in Figure 1. Most of these are discussed throughout this paper.

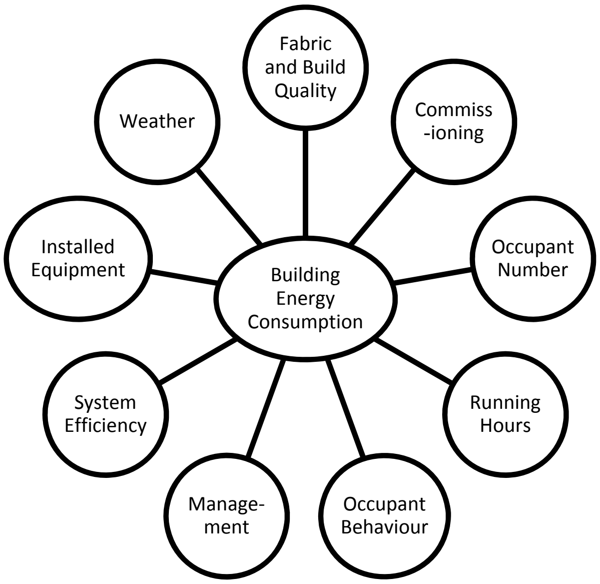

Figure 1 Main Factors Affecting Building Energy Consumption

Low Carbon Technology

The most sustainable method for decarbonising buildings is demand reduction, as outlined in the Institute of Mechanical Engineer's (IMechE) sustainability hierarchy, Figure 2. This means simply using less energy; identifying areas where energy is being wasted is often a simple and cost effective process.

Alongside demand reduction 'low carbon' buildings commonly include renewable technology to offset a proportion of the energy consumption. These systems are often included in building design on the basis of manufacturer performance data generated from laboratory based testing, resulting in optimistic savings estimates and short payback periods.

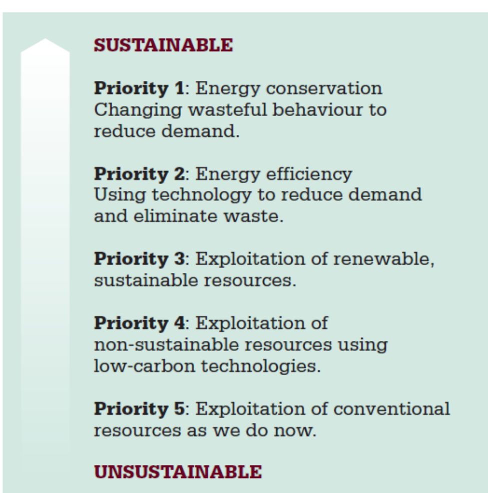

Figure 2 The IMechE's Sustainability Hierarchy. Credit – The Institute of Mechanical Engineers, UK.

Aims

This research uses a case study approach to investigate whether 'low carbon' building targets may be achieved in practice. A UK Government office building was selected in light of the Greening Government targets in the UK (see below). By working alongside the building operator and original building services designer, building access was obtained along with design stage information and energy calculations.

The case study building has included a number of low carbon technologies from the outset, and some have been implemented during the study period. This research also seeks to understand how effectively these are operating in practice.

CASE STUDY BUILDING

On 14 May 2010 the UK Prime Minister pledged that as part of leading the 'greenest government ever', central government would reduce its carbon emissions by 10% within 12 months from a 2009/10 baseline (UK Government, 2011). The government achieved this target (covering 3,000 buildings), saving a total of 13.8% with an estimated cost saving of £13 million on energy bills, and more than 100,000 tonnes of CO_2 (HM Government, 6th July 2011). Following the realisation of the initial 10% target; on 6 June 2011 a target to further cut emissions by 25% by 2015 was announced (HM Government, 6th July 2011) (an additional 11.2% on top of what has already been achieved). This case study is an example of a new government building occupied in 2010. It is a seven storey, 10,500 m^2 (GIA) rectangular shaped, largely glazed, fully air conditioned office building. A basement contains a car park, plant rooms, a regional data centre and operational offices. Floors 1-6 are predominantly open plan office space, with meeting and other small rooms surrounding the core, itself which comprises stair cases, lifts and toilets. Half of one floor contains video conferencing and seminar rooms/facilities and a hot snack bar with vending area is located on the top floor. The building was awarded a BREEAM excellent award for sustainability under the 2008 version prior to completion, and was first occupied in June 2010. It was recently awarded an International Building Award for best building operation.

The building is connected to a city-wide district heating system and receives heat via a 700 kW heat exchanger. The carbon intensity of the system has been defined as 0.137 kg CO_2 kWh^{-1} (2011) and 0.128 kg CO_2 kWh^{-1} (2012) (Veolia, 2013) compared to 0.184 kg CO_2 kWh^{-1} (Carbon Trust, 2011) for natural gas. To avoid misrepresentation of building efficiency due to lower carbon intensity heat of the heating system, results are presented in terms of kWh m^{-2}, not kg CO_2 m^{-2}. Electricity is supplied via the national grid with total incoming electricity to the building metered. Approximately 50 further sub-meters allow individual systems to be monitored for electricity consumption. Two separate air handling units, complete with heat recovery thermal wheels, provide the fresh air requirement for the office via ceiling mounted fan coil units capable of heating and cooling. Variable speed drives were added to the main air handling units at the end of May 2012.

The building temperature set-point is 21 ± 2 °C year round, programmed in June 2011. The air conditioning is set to achieve this temperature between 7 am and 6 pm, when it switches off. The system has an optimiser that works out the best time for the air conditioning to be switched on, so that the building reaches temperature by 7 am. It has one external sensor and an internal sensor on each floor which output the average internal temperature for the building and the lowest floor temperature. The optimiser monitors the time taken to reach the set point temperature each day, continually learning the time taken to reach operating temperature based on the outside temperature. In June 2011 the optimiser was reduced from a maximum of 6 hours to 2 hours. Free night time cooling was programmed into the system around this time too.

Low Carbon Technology

Prior to occupation the building was fitted with photovoltaic panels on the roof to generate electricity for the building, and a rainwater harvesting system for flushing the toilets and urinals. Following occupation LED lighting, thin client PCs and voltage optimisation have also been installed.

METHODOLOGY

The case study building has been monitored for a core two year period from 01.01.2011 – 31.12.2012, with additional energy data collected subsequently for continued system investigation. The annual energy consumption has been monitored through the building's energy management system (BEMS), which logs half hourly energy consumption of all individual sub meters, total incoming electricity, total incoming steam energy, and total electricity used for the regional data centre and associated cooling. Thorough interrogation of the electricity metering strategy, along with half hourly data verification (comparing the meters with the BEMS output) was conducted to ensure accurate data collection. It must be noted that problems were discovered with the metering, but this was rectified and this issue is outside the scope of this paper.

The building fabric has been inspected using air pressure testing and thermal imaging. Regular day and night time building visits have provided a solid understanding of the building systems and set points, occupants, and building operational requirements. Occupancy hours and density have been monitored and the management strategy and structure appraised.

Heating degree day (HDD) data was collected for the two year period (15.5 °C typical for UK) and a weather correction factor (WCF) subsequently calculated as per the UK Greening Government target methodology (equation (1)).

$$WCF = HDD\ (reference\ period) / HDD\ (reporting\ period) \quad (1)$$

This was applied to the recorded heat energy consumption to correct for weather variation from the 20 year average reference period (1987 - 2006).

The low carbon technology installed has been monitored with the current sub meter strategy to determine how they are performing in practice.

RESULTS AND DISCUSSION

Predicted vs. Actual

An annual energy prediction was made for the building at the design stage using a simplified dynamic thermal model created using DesignBuilder (EnergyPlus). The predicted energy demand generated from this model is given in Figure 3, alongside the monitored values. Details of the model set up are outside the scope of this paper, however it is worth noting that the model was created pre-construction by the design team. Figure 3 shows total electricity and heat consumption for 2011 was below that expected from the predicted design value. The energy used has been reduced further in 2012. As the building was only occupied in June 2010, the first part of 2011 was still considered a settling in period. Continued adjustments and building optimisation by the building operator are reflected by the further decreasing energy consumption in 2012.

The 'separable' in Figure 3 represents the regional data centre (including cooling of the centre). This was not considered in the original energy prediction, and as it serves several regional buildings, is only included here for additional information. It is interesting to note that the 180 m^2 data centre uses almost as much electricity as the building itself; approximately one third of this is for data centre cooling.

The overarching reasons behind the successful building performance of the case study presented are summarised as follows:

1. Sensible predictions were made for building energy consumption.

2. The building services engineer was available post-occupation to pin point and correct any operational issues during the settling in period.
3. The building operator and FM team have a good understanding of how the building systems should operate, when and where energy is being used in the building, and actively seek to lower building energy consumption.
4. The sub metering strategy, and energy management system allow energy consumption of individual floors and groups of systems to be monitored.

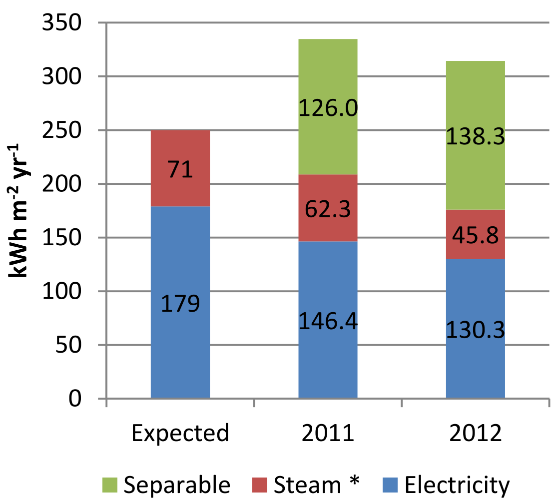

Figure 3 Case study building energy performance compared to that expected at design. * weather corrected.

Display Energy Certificates (DECs), are required in all public buildings over 500 m^2 in England, Wales and Northern Ireland (Department for Communities and Local Government, 2012). The Case Study building achieved an Energy Performance Operational Rating of 89 in 2012, where 100 would be typical for the building type (including both naturally and air conditioned offices). This corresponds to a DEC "D" grading, placing it at the top of the UK Government estate for building performance for fully air conditioned offices.

Building and Energy Management

The building operator can have a large impact on the amount of energy consumed in the building, as they control when and where energy is used. In this case, a contracted FM team is responsible for the day-to-day running and maintenance of the building, to set schedules and targets, lead by a sustainability manager (building operator). The sustainability manager is also responsible for several other buildings, however, they are primarily based in the case study building.

As a government building, some set points within the building (e.g. space temperature) are set as standard, so there is a limit to what changes can be made. Clear energy targets were initially set by the Greening Government targets, but these were met easily given the departmental move into the new building since the 2009 - 10 baseline was set. The DEC provides a separate energy target, with the aim to exceed the previous year's energy rating.

The sustainability manager is responsible for uploading half hourly building energy consumption data to the Government's "building energy transparency" web platform (UK Government, 2013). This encourages familiarity with the energy data. Additionally, the sustainability manager has investigated many energy saving opportunities and assembled a business case to obtain funding to put them into practice. This has recently included Voltage Optimisation and Thin Client installations. Further work carried out includes lighting Lux level assessments at desk height to determine if perimeter lighting can be switched off in bright light.

A separate energy management system (BEMS) to the main building management system (BMS) is in place, which records half hourly electricity consumption from the majority of electricity sub meters and stores the historical data, allowing system performance to be checked and monitored.

System Installation and Design vs. As-Built

The installed systems were subject to full commissioning prior to building occupation. The building was pressure tested for air filtration and the permeability was recorded as 8.99 $m^3\ hr^{-1}\ m^{-2}$ when the internal pressure was 50 Pa, satisfying the UK Building Regulation requirement of 10 $hr^{-1}\ m^{-2}$. Post occupation, further issues were identified and rectified. These included the replacement of faulty fan coil unit balancing and control valves throughout the building and the alteration of incorrect BMS set points.

A further problem with cold space temperatures on the north side of the building at levels 01 and 02 was reported by occupants. An investigation was made into the building fabric between ground level, 01 and 02, where a thermal bridging problem was identified and solved. Low morning temperatures have continued to be reported in the same areas, with an ongoing investigation using localised temperature and air speed logging, along with smoke path testing. To combat the low temperature, the heating has been set to come on an hour earlier as a temporary measure. Thermal imaging has shown that other than this space the fabric is sound.

A north/south temperature divide is evident in the building, with complaints of overheating on the south, and cooler temperatures on the north. The building is part of a larger complex, with a similar height and size building to the north. At the design stage another building was planned to be constructed to the south and hence solar control glazing was not included. However, this building has yet to be constructed and illustrates unexpected changes that can influence building energy consumption once in use.

Occupants and Operating Hours

The number of occupants designated to work on each floor remained very similar throughout 2011. Between April and September 2012, the occupant number on Level 01 and 02 was reduced by around 5%. An occupancy survey revealed that until the change in 2012, an average of 60 – 80% of full occupant capacity was seen, varying between floors. At times up to 95% occupancy was recorded on the upper floors, however the lower average is due to holidays, flexible working practices and meetings taking place in other offices. The expected occupancy hours were 8 am – 6 pm, which the original energy prediction was based on, but the office now operates between the extended hours of 7 am – 8 pm.

Low Carbon Technology

Photovoltaic (PV) Panels. 126 photovoltaic panels are installed on the roof of the case study building (Figure 4), occupying approximately half of the roof surface area with the remaining space allocated for plant. The electricity generated by the panels is in line with the simulated estimation of 17,370 kWh, which was calculated using PVsyst SA (Switzerland), taking into account site variables such as location and weather. Figure 5 shows the electricity generated alongside the direct normal sunshine for Sheffield (obtained from Weatheranalytics.com). The electricity generated in 2012 was 17,245 kWh, lower than 19,151 kWh in 2011; it can be seen that the performance is directly related to the incident solar power.

The building electricity savings from the PV panels are summarised in

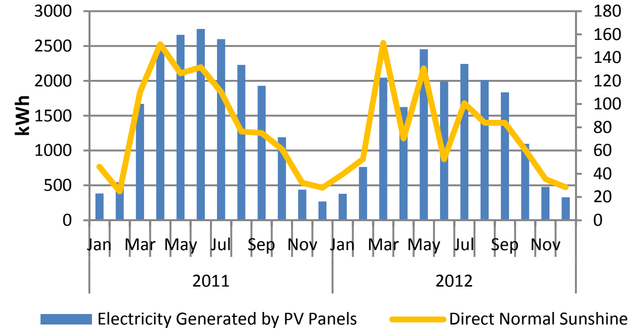

Figure 5 Monthly Electricity Production from PV Panels, Compared to Monthly Direct Normal Sunshine for the Site.

Table 1. Despite covering half of the roof surface, they still offer a very low percentage of total building electricity consumption, something to be considered when looking at future multi storey zero carbon buildings.

Figure 4 Case Study Building PV Array

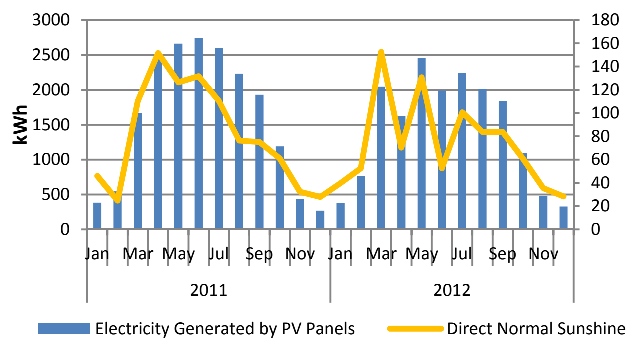

Figure 5 Monthly Electricity Production from PV Panels, Compared to Monthly Direct Normal Sunshine for the Site.

Table 1 Electricity generated by PV panels

Year	kWh	Percentage of Annual

	Generated	Building Electricity Consumption
2011	19151	1.53% (0.82% including data centre)
2012	17245	1.54% (0.75% including data centre)

Two main problems have been reported by the building operator. Several panels have been cracked during the first three years of operation, attributed to stones on the roof being blown by the wind. Additionally, during winter when the sun is low in the sky there is a large degree of panels overshadowing each other. Each row of panels obscure up to 43% of the row behind (winter solstice). Panel rows are spaced at 850 mm, but given the space available for the panels on the roof, this was the maximum spacing possible. To avoid overshadowing the minimum spacing should be 1210 mm between rows.

Rainwater Harvesting

A rain water harvesting system was installed in the building, however, the sub meter that monitors volume of recycled water gives such low readings it was considered non operational from the outset. Upon visual inspection at roof level, the system appears relatively ineffective as the rain water drain inlets to the system are on the upper part of a sloped roof, meaning water collects away from the drainage points, as illustrated by silt collection in Figure 6. The importance of regular maintenance is additionally highlighted where silt and foliage are building up around the drainage points.

Figure 6 Case Study Rain Water Harvesting Drainage

LED Lighting

All stairwell lights, car park, basement corridor and reception and entrance lobby lights were replaced with LED light fittings in August – September 2012. The sub metering strategy does not allow the resultant energy savings to be quantified, but an estimated saving of 8.49 kWh m^{-2} yr^{-1} has been calculated from equation (2).

(2) $\sum(No.\,fittings\ x\ kW\ rating\ x\ hours\ operating)_{OLD} - \sum(No.\,fittings\ x\ kW\ rating\ x\ hours\ operating)_{NEW} = LED\ energy\ savings.$

Voltage Optimisation and Thin Client

Voltage optimisation has the potential to reduce building energy consumption as well as lengthen equipment lifespan (Lawrence, 2006). The average incoming voltage for the case study building was recorded at 242.5 V, with all recorded variation in voltage also above the UK nominal voltage of 230 V. A voltage optimisation system was therefore installed in September 2012 to reduce the incoming voltage. After working for most of September, fuses became easily blown and the system was not fully operational again until mid December 2012.

Thin Client PCs were introduced throughout the building in September 2012.

Energy Savings

Figure 7 shows monthly total electricity consumption (building only, excluding data centre) for the first four fully operational months, January to April 2013, in comparison to the previous two years. The consumption reduction from 2011 to 2012 is due to operational improvements within the building. There have been no operational changes in the building in 2013, yet further significant reductions in energy consumption seen. A proportion of this can be attributed to changes, such as LED lighting (est. 0.7 kWh m^{-2} yr^{-1} reduction each month, from earlier annual saving estimate) and Thin Client (est. 0.2 kWh m^{-2} yr^{-1} reduction each month based on Figure 9), which were not introduced until later in 2012. April 2012 saw several holiday days (Easter and Royal Wedding), resulting in a lower than normal energy consumption that month. Taking into account the estimated 0.9 kWh m^{-2} yr^{-1} potential reduction seen due to efficiency changes, it is likely the effect of voltage optimisation is being realised, particularly shown in February and March 2013.

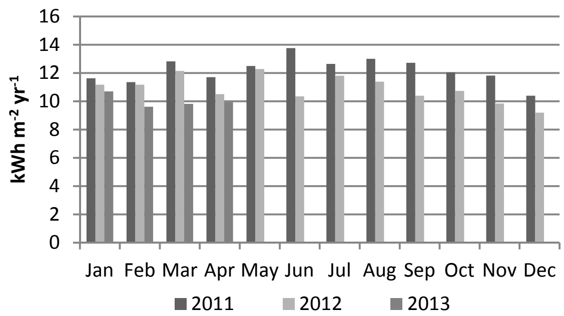

Figure 7 Case Study Monthly Electricity Consumption (exc. data centre), 2011 – Date

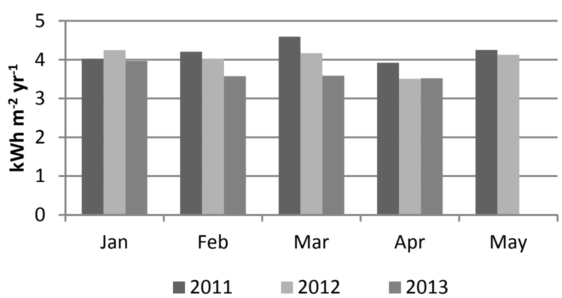

Figure 8 Case Study Floor Electricity Consumption (excluding level 03 and 07 due to video conferencing facilities and cafe)

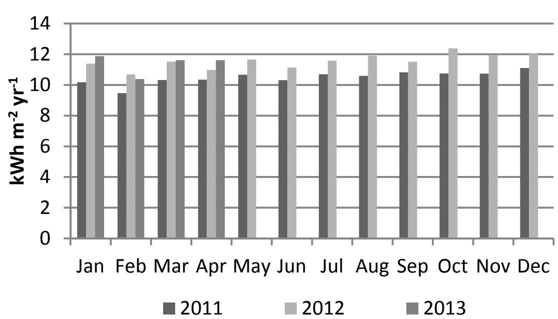

Figure 9 Case Study Data Centre Electricity Consumption, Jan 2011 – April 2013

Thin client PCs require the data centre servers to process more information, which is no longer being processed by the PC itself. This is reflected in the plot of data centre consumption (Figure 9) and floor electricity consumption (Figure 8) where data centre electricity consumption increases, as floor consumption decreases.

CONCLUSIONS AND RECOMMENDATIONS

The case study building has not only met, but continues to improve the margin by which it exceeds original design energy expectations. Observational and attentive building and energy management has had an overarching effect on the energy consumption pattern of the building. Post occupancy monitoring and adjustments have ensured that the building fabric is sound and the building systems and equipment are operating as expected, to optimised time points, which wasn't always found to be the case. Of the identified issues, many have been easy, quick and cost effective to solve.

Longer building opening hours are seen than expected at design, but with an average lower occupancy density. The set hours of the building are enforced at 7 am – 8 pm, meaning no additional energy is wasted through overtime working practice.

Heat consumption is much lower than expected. Thermal imaging has shown the building fabric is sound and additional solar gain where the south adjacent building has yet to be constructed are both contributing factors. Since the implementation of Thin Client PCs, occupants have commented on feeling cold beneath the desk, attributed to the lower heat generation of the less active PC units. Heat consumption may therefore slightly increase for 2013.

A summary of key points for building designers and building operators are given as follows:

Designers

- Re-visit completed buildings to inform future designs
- Advise of the importance and potential cost savings of employing an energy manager / energy conscious building operator.

Building Operators

- Monitor energy consumption and set targets
- Seek to reduce waste demand and increase efficiency
- Consult with the designer post occupancy where possible.

ACKNOWLEDGEMENTS

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