Energy use and indoor environment in a sample of monitored domestic buildings in the UK

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Abstract

This paper is based on the low-cost approaches and transferable techniques that were applied in a PhD reserch project on energy-related occupancy activities. The strengths of qualitative and quantitative research strategies were combined for the study of this socio-technical research topic. Long-term field measurement was conducted for data acquisition using self-configured monitoring schemes. Case study was selected as the research approach. Building characteristics and household features in each case study group were purposefully selected to deploy same-standard monitoring schemes. Comparable monitoring results were pre-processed following identical procedures to implement the selected data analysis methods. The inspection results provided the researcher and the associated project partners with a novel perspective to interpret the difference in actual energy consumption and indoor environment within and between the case study groups. The research methodology and moitoring approach are covered in this paper that also presents the macro-scale monitoring results of energy use and indoor environment in two case study groups. The micro-scale presentation and algorithm-based examination will be covered in other academic papers. This paper demonstrates the huge potential for some commonly applied building assessment methods to be improved by objectively considering currently overlooked aspects, such as the low-tech design and construction of heavy-weight thermal mass houses and the largely varied occupancy activities. Future work reating to the comparision of actural monitoring data with simulation results is pointed out at the end of the paper.

Key Words: *energy use, indoor environment, occupancy activities, building characteristics, mixed methods research.*

1. INTRODUCTION

Global issues related to energy use are on the rise, ranging from climate change and energy security to fuel poverty. Targets to reduce the future atmospheric concentration of greenhouse gases, especially carbon dioxide (CO_2) emissions from fossil fuel, have been set and discussed worldwide in the Kyoto Protocol and the Stern Review (United Nations, 1998; Stern, 2007). The Climate Change Act (2008, c.27) is aiming for a reduction of the net UK carbon emissions by 80 per cent from the 1990 baseline by the year 2050. However, the costs of mitigation, especially against the backdrop of an economic downturn, make these targets difficult to achieve (House, et al., 2008). Energy saving in buildings is one of the most cost-effective sectors where CO_2 reductions can be achieved, due to the technologically simple measures that can improve energy efficiency of buildings (Ürge-Vorsatz and Metz, 2009). The effectiveness in improving efficiency gains and reducing environmental impact can be achieved on a larger scale beyond an individual study of domestic builidngs. This is mainly due to the large proportion of domestic energy use in the UK, where energy consumption in the domestic sector accounts for approximately 30 per cent of overall energy use according to the annually published energy consumption statistics of the Department of Energy & Climate Change (DECC) (2014b).

Buildings are usually graded using assessment systems such as Standard Assessment Procedure (SAP), Energy Performance Certificates (EPCs), Building Research Establishment Environmental Assessment Methodology (BREEAM), and Leadership in Energy and Environmental Design (LEED). Under the expectations of these assessment systems, houses that are graded as energy-efficient should outperform lower-graded and older ones. However, this is not the case when comparing the actual energy performance of respective buildings (Sommerville and Sorrell, 2007). One main reason for the discrepancy can be connected to the evidence that predicted performance of identically built homes does not match actual energy use (Emery and Kippenhan, 2006; Ingle, et al., 2014). Domestic energy use and indoor environment are determined by multiple non-technological factors, such as the occupants' lifestyle and activities, which can even offset the effect from energy-efficiency technologies (Sunikka-Blank and Galvin, 2012). To assess the impact of occupancy activities on actual efficiency gains can potentially provide the industry and academia with a 'twin-track approach', which involves both technology and occupancy behaviours in efficiency improvement (Gram-Hanssen, 2014). However, acquiring the actual occupancy data associated with energy use, indoor environments, building characteristics, and occupancy statuses in a uniform format to generate comparable and representative information is challenging (Energy Saving Trust, 2009; 2011). The low-cost approaches and transferable techniques that were applied in a PhD reserch project on energy-related occupancy activities are introduced in this paper.

2. METHODOLOGY

It is important to select appropriate methods, the methodological features of which can suit the socio-technical characteristics of the research subject and data profiles. Three interactive factors, including energy-related occupancy activities, fabric and service performance, and external environment, were considered in the selection of case studies.

- geographically vicinal building sites with similar external temperatures enables the comparison of performance difference from the perspective of the other two factors;
- The identical fabric and service performance of houses within the same case study group highlights the impact of different energy-related occupancy activities on actual energy use and indoor environment;
- The distinctive fabric and service features between the two case study groups enables a holistic assessment of energy-related occupancy activities based on different building characteristics.

The mixed methods research approach advocated by Bryman (2012), which combines quantitative and qualitative strengths, was applied in the process of data acquisition and analysis.

- The monitoring approach: for the purpose of acquiring physical measurements by applying the properly configured monitoring scheme in the selected case study homes;
- The sociological approach: for the purpose of enhancing the monitoring approach by using occupancy diaries with the assistance of formal and informal interviews;
- The mathematical approach: for the purpose of performing effective data pre-processing, presentation, and analysis by applying statistics and artificial intelligence methods.

3. TWO CASE STUDY GROUPS

3.1 Hockerton Housing Project (HHP) case study

The HHP case study consisted of three unconventionally built houses from the Hockerton Housing Project Trading Ltd. (HHP). The Hockerton Housing Project is among the first multi-dwelling, earth-sheltered, and self-sufficient ecological housing developments in the UK (HHP, 2011). Consisting of a terrace of five earth-sheltered and single-storey dwellings and an office annex, the self-built HHP community has been planned, designed, constructed and operated to be as 'autonomous[3]' as possible. Designed in the year 1994 by Prof. Brenda Vale and Dr. Robert Vale, the five dwellings were constructed in 1996 on a 25-hectare agricultural site outside the village of Hockerton in the northeast of rural Nottinghamshire. With no mains gas and central heating system on site, the buildings mainly rely on passive solar radiation, residents' body heat and incidental gains from electrical appliances for space heating from November to February. The thermally heavy design, which features high levels of thermal mass (2.3 tonnes of concrete and blocks per square metres) and insulation, keeps the indoor environment within a stable comfort zone.

However, the Energy Performance Certificate (EPC) produced in 2008 for one HHP house using the Reduced Standard Assessment Procedure (RdSAP) 2005 gave an energy efficiency rating at F. The assessment result mainly derived from shortcomings in the assessment approach that fails to acknowledge heavy-weight thermal mass and passive solar gain. Homes adopting similar design approaches to the HHP autonomous houses will be barred from 2016 and existing dwellings such as the low-cost and free-floating HHP houses cannot be let from 2018 or join in the feed-in tariff for solar PV microgeneration without installing unnecessary heating systems.

3.2 Nottingham City Homes (NCH) case study

In partnership with Nottingham City Homes (NCH), this case study was conducted as one part of an overarching Decent Homes programme, known in Nottingham as the Secure, Warm, Modern (SWM) programme. Since their construction around 1977, the two selected houses of NCHA and NCHB have been the homes of two retired couples. Both NCH houses were developed by Walter Llewellyn and Sons Ltd. in Eastbourne and retrofitted to same standard in the SWM programme. The Llewellyn system, also called Quikbild, was one of the 34 major types of system-built timber frame dwellings that were widely used in the public sector from 1965 to 1980 (Harrison, et al., 2004). Although having no sufficient thermal mass to store heat as is the case in the autonomous houses in the HHP case study, the energy efficiency of the NCH house was rated C in the EPC, which prioritises the retrofitted features in terms of insulation and boiler efficiency.

4. DATA ACQUİSİTİON

Mixed-method approaches were applied for the required data profiles. The physical measurements included energy use, real-time power draws, hygrothermal conditions, and occupancy statuses. Informal interviews and occupancy diaries were used in different monitoring stages to validate and explain the acquired physical data. Three adjacent HHP houses were selected as the monitoring subjects of this case study, including the seven-bay central house HHP3, the six-bay mid-terrace house HHP4, and the six-bay end-terrace house HHP5. The three households had different family profiles, including single occupant in HHP3, adult couple in HHP4, and young couple with two children in HHP5. From December 2010,

[3] Houses built to the autonomous standard are designed to be self-sufficient without the need for mains connection apart from grid-linked electricity (Vale and Vale, 2000).

the monitoring equipment was deployed in phases. The equipment, at an average cost around £1,350 per house, was officially moved out of the HHP houses in June 2013. The NCH case study started one month later than the HHP monitoring project, in January 2011, and officially ended in August 2012. The less numbers of occupancy status loggers used in the NCH homes lowered the monitoring system cost to around £900 per house.

The major criteria for the device selection and system configuration are:

- The selected devices should be non-intrusive or less-intrusive in terms of installation and maintenance;
- The selected devices should facilitate the improvised technological solutions that are required by the actual conditions in monitored homes;
- The configured system should feature low costs in terms of equipment procurement and post-installation maintenance;
- The configured system should feature transferable techniques that enable the straightforward application of the system in other similar monitoring environments.

A direct advantage of a non-intrusive or less-intrusive monitoring system is that the equipment has no or limited visible aesthetic impact on the monitored households. An indirect but crucial benefit is that the residents are expected to behave naturally under the monitoring circumstances. The actual behaviours revealed by the measuring results are thus insusceptible to the impact of psychological attention paid by the monitored house residents.

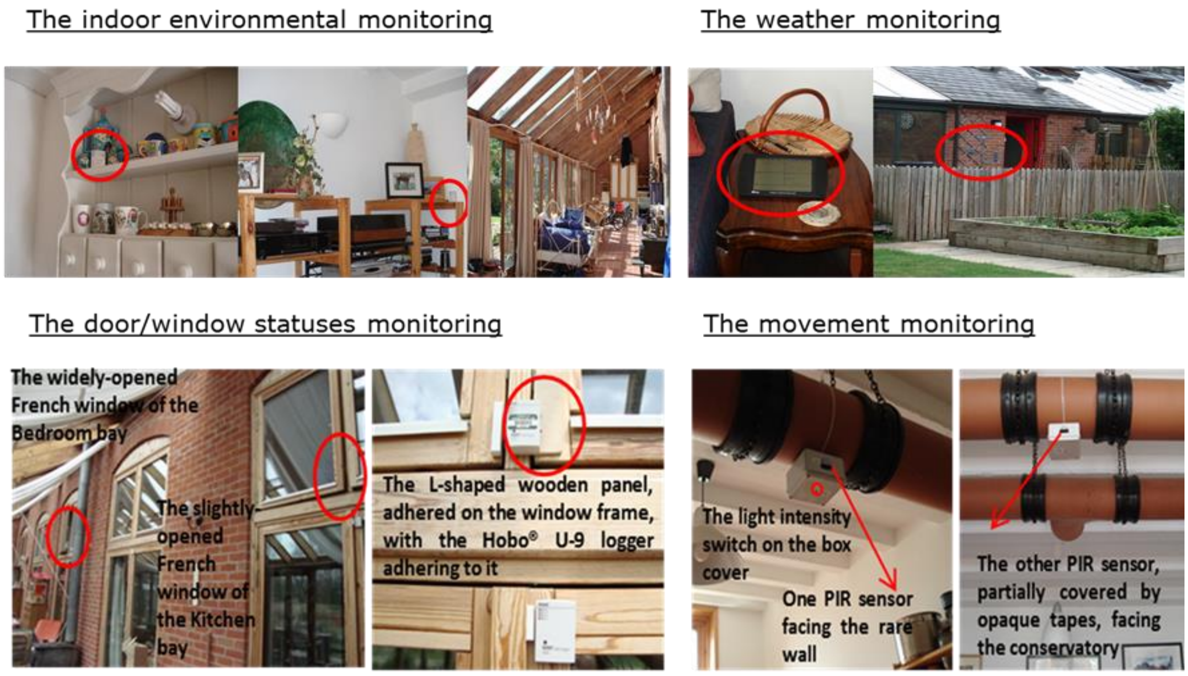

Figure 1 Monitoring devices for hygrothermal conditions and occupancy statuses in the HHP homes

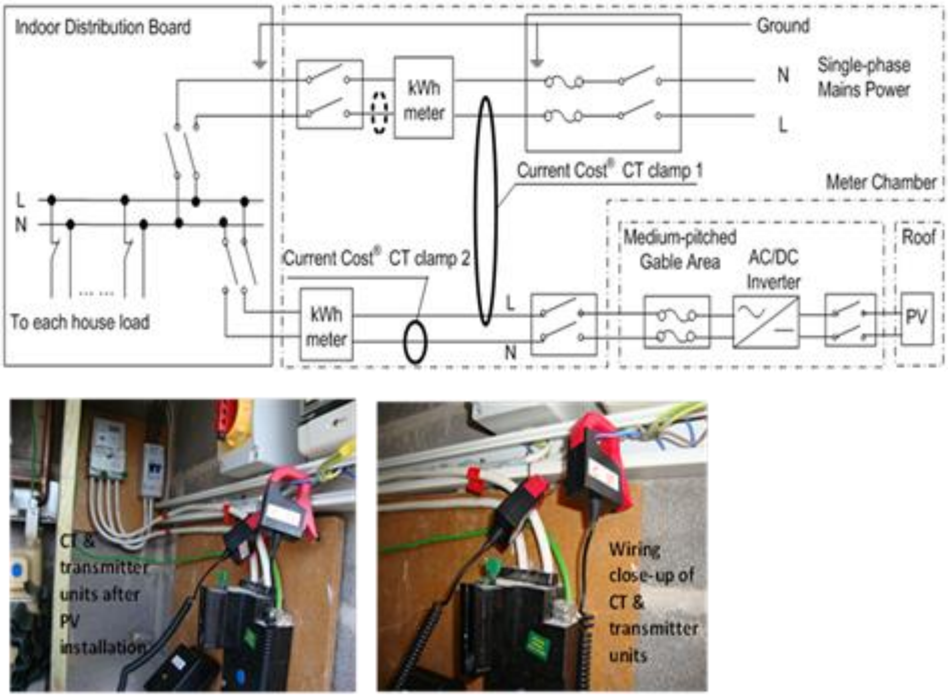

Figure 2 Improvised solution to remove the impact of PV retrofit on the power profile monitoring in one NCH house

Unable to detect current directions, the Current Cost® CT & transmitter unit in the original position as shown by the dash-line elliptical circle in Figure 2 could not correctly measure house use after PV installation in one NCH home. When more energy was used than being generated, what the CT unit monitored was the import power from the grid. When more energy was generated, what the CT unit detected was the export power to the grid. Depending on the actual conditions of house use and microgeneration, the real-time import and export power that could not be differentiated was found to distort power profiles of house use. The clamping of mains power cables and PV feed-in within one CT unit as shown in Figure 2 is an improvised solution that applies Ampère's circuital law of electromagnetic induction. The result from the overlapping induction is a magnetic field that removes the net export from total microgeneration. The current inducted by the CT unit is the separated portion that flows into the distribution board for house use. Therefore, the house use power profile at five-minute interval can be correctly measured without the influence of PV microgeneration.

5. DATA USE

The major difference in energy use within the HHP community was expected to arise from the respective household compositions, since every home adopted an energy-conscious lifestyle. In contrast, the NCH case study featured two similar family profiles of retired couples, who differed largely in their energy use habits. Homes having identical household profiles were expected to feature comparable ownership of domestic appliances and similar categories of energy-related activities. The difference in actual energy use was thus potentially due to the different intensity levels of energy-related occupancy activities in each NCH home. The acquired data profiles were pre-processed to facilitate appropriate approaches to data presentations and analyses by comprehensively examining the multi-category measurements of each case study. The visualisation-based examinations of measurements in each case study were conducted on different scales to reveal the impact of energy-related occupancy activities. The major data categories were separately examined prior to the comprehensive and micro-scale inspections conducted on measurements of exemplary days that featured special weather conditions and relatively complete data profiles for each case study. More systematic analyses based on visualisation-based examinations were conducted using two types of algorithm-based inspection methods of statistics and artificial intelligence. The box plots and mean comparison graphs generated by the ANOVA process were effective analysis approaches to enhance the visualisation-based examinations. The pre-processed power measurements were used to extract targeted end-use events from the measurements of total house use and major energy-intensive appliances and to examine interrelations between energy use occupancy activities in the monitored household. The Adaptive Neuro-Fuzzy Inference System (ANFIS) was selected as a methodological trial to extract targeted appliance use. These presentation and analysis examples will be covered in other academic papers. This workshop proceeding paper only presents the manual meter-readings of all case study homes over the period shown in Figure 3 and the long-term temperature measurements shown in Figure 4.

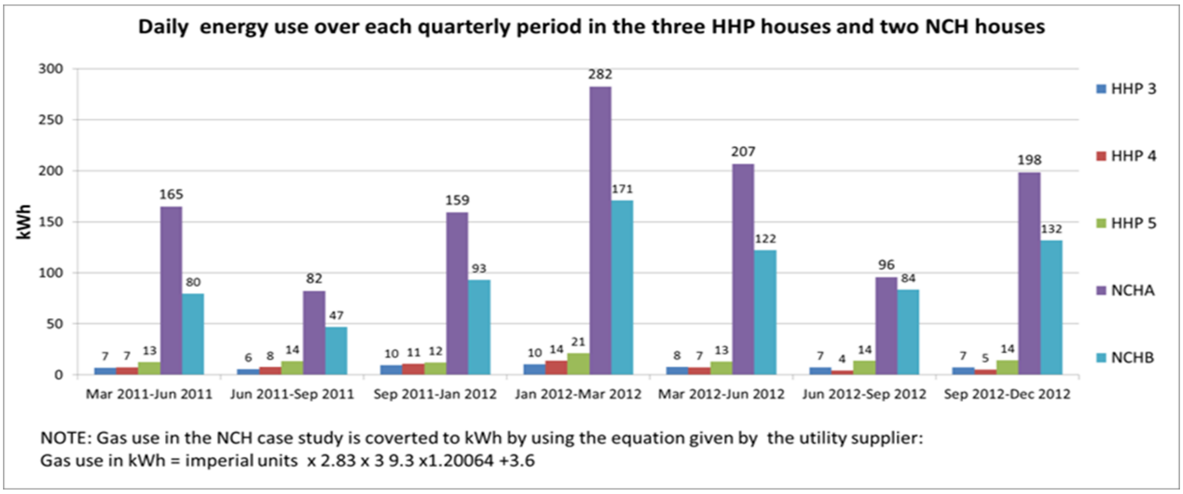

Figure 3 Daily energy use over the period of seven quarterly periods from March 2011 to December 2012 in the five houses of the two case studies

The distinctive difference in actual energy use within the NCH case study group was consistent with the temperature monitoring results shown in Figure 4. Although gas use was not directly measurable, the HDD regressions presented a difference in the baseline outdoor temperatures of the two NCH homes, 20 ºC for NCHA and 18 ºC for NCHB. The two degree difference in baseline temperatures reflected the longer period of space heating use and larger amount of gas use in NCHA. The different baseline temperatures in HHD regressions coincide with the one to four degrees of difference in the long-term indoor average temperatures of the two homes. With the assistance of the window status measurements, a micro-scale inspection and an algorithm-based examination of the data profiles of the two NCH homes were conducted. The application of these monitoring and analysis approaches was thus attested to be effective in investigating the actual difference in energy use and indoor environment from the perspective of energy-related occupancy activities. Regarding electricity use, the representative daily power profiles revealed the more frequent use of energy-intensive appliances, including tumble dryer, dishwasher, and washing machine with high temperature settings, in NCHA. This household used around twice the electricity consumed by NCHB. The information acquired from the formal and informal interviews during NCH site visits revealed that the NCHA residents preferred to heat the entire house continuously with the windows being frequently opened.

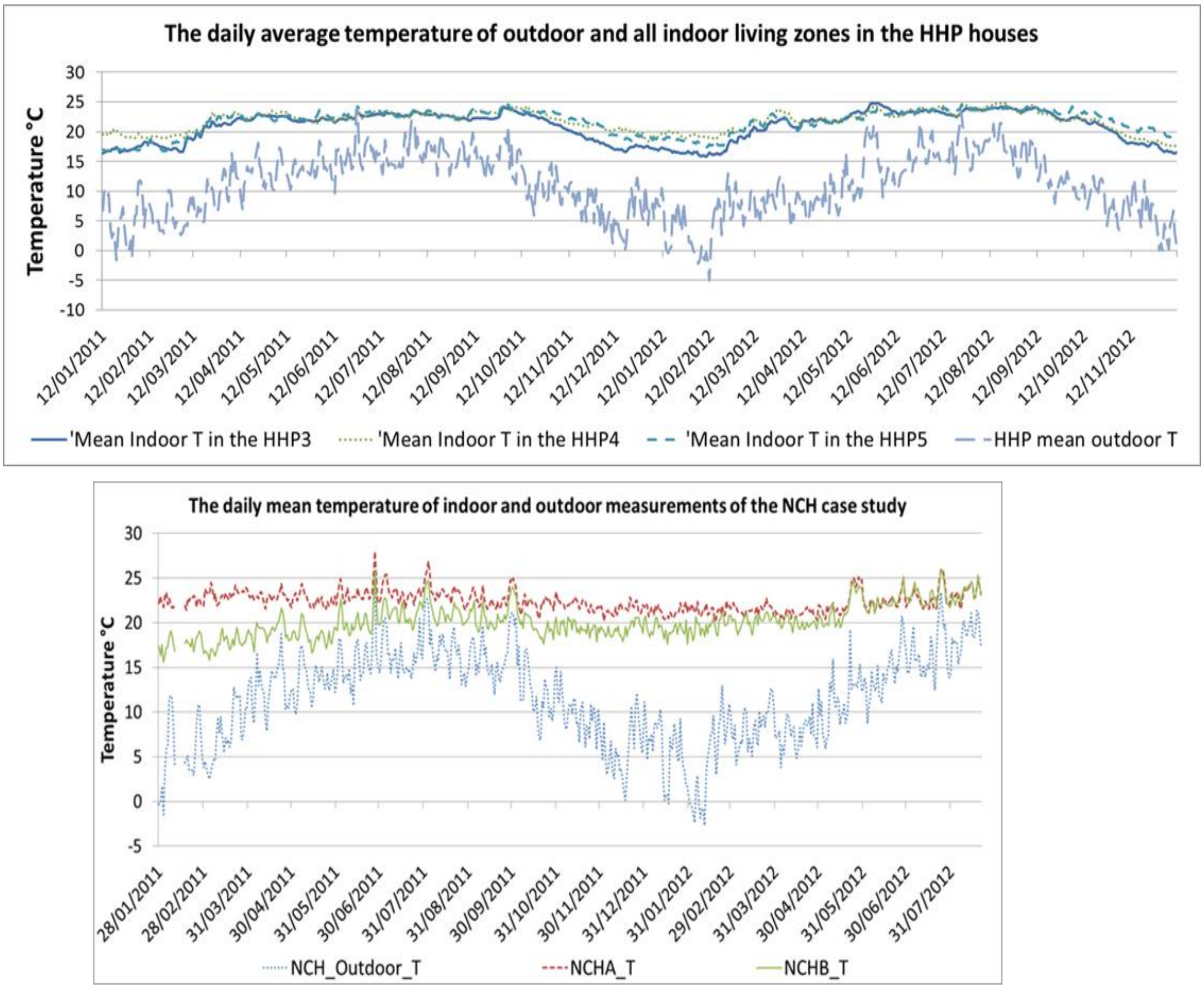

Figure 4 Monitored indoor / outdoor temperatures for the two case studies

In contrast, by removing the need for a space heating system in the autonomous HHP houses, electricity was the only energy resource in the HHP case study. The use of immersion water heaters accounted for 2.0 kWh to 8.0 kWh in the daily energy use of monitored houses, depending on the operational mode of the heater that was either timer-controlled or thermostat-operated. The supplementary heating using mobile heaters under cold weather conditions increased electricity use over winter time by about 4.0 to 16.0 kW in HHP3 and HHP4. The multi-occupancy of the household and frequent use of washing machine and dish washer made HHP5 use the highest amount of electricity among the three monitored HHP houses. The daily average of total energy use in HHP5 shown in Figure 9 was only nine per cent of that in the more energy-conscious NCHA and 17 per cent of that in NCHB.

The heavy-weight thermal mass construction in the autonomous houses functions as a ‘rechargeable battery’ that allows heat to be stored and released not only diurnally but inter-seasonally (HHP, 2012). The cross-comparison of the hygrothermal condition of all case study houses assisted in assessing the energy performance of the two distinctive built forms. The energy performance of the heavy-weight thermal mass construction in the HHP case study has been proven to outperform that of the retrofitted timber-frame house in the NCH case study against similar outdoor conditions. However, the energy-saving features of the autonomous house are not credited by the Energy Performance Certificate (EPC) that is produced on the basis of the Standard Assessment Procedure (SAP) and Reduced Standard Assessment Procedure (RdSAP). The ratings clearly do not truthfully reflect the de-facto energy use and environmental impact based on the empirical results obtained in this study. Active appeals for more objective assessment principles were raised by the Hockerton Housing Project, Ltd. (HHP, 2012). The evidential results from this research are expected to assist in their future appeal process.

6. CONCLUSION AND FUTURE WORK

Energy-saving effectiveness in the domestic sector cannot purely depend on the installation of new technologies and renewable energy microgeneration. In addition to building characteristics that play an important role in energy savings and carbon mitigations, energy-related occupancy activities also make a large difference to the actual energy performance of identically built or retrofitted houses. The long-term monitoring and selected analysis techniques introduced in this paper made knowledge contributions from practical and methodological perspectives. There is huge potential for some commonly applied building assessment methods to be improved by objectively considering currently overlooked aspects, such as the low-tech design and construction of free-running autonomous houses and the largely varied occupancy activities.

The socio-technical characteristics of the research subject require a mixed methods research approach in the processes of data acquisition and analysis, including physical monitoring techniques, supplementary sociological instruments, and multidisciplinary analytical methods. To rationally utilise the limited research resources, the selection of case study groups should consider the between-group and within-group differences and similarities in terms of building characteristics and household profiles. Within each case study group, the variations in indoor environment and energy use directly resulted from different activity patterns of each household. For example, the intensive energy use recorded in the NCHA case study house was approximately twice that of NCHB. Between the two case study groups, the variations also derived from the different building characteristics of house designs, such as the heavy-weight thermal mass featured by the autonomous HHP houses and the light-weight thermal mass represented by the retrofitted timber-frame NCH houses. The geometry build and dynamic building energy simulation for case study houses have been extended to the research stage after the PhD research to compare the simulation results and field monitoring data in the following academic papers.

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