A study of energy-related occupancy activities in a sample of monitored domestic buildings in the UK

NOTTINGHAM TRENT UNIVERSITY

by

Jia (Michelle) Cui

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Copyright Statement

Abstract

Domestic energy use is determined by multiple non-technological factors, such as the occupants' lifestyle and activities, which can even offset the effect from energy-efficiency technologies. Acquiring the actual occupancy data relating to energy use in a uniform format to generate comparable and representative information is challenging. Projects that seek to address this issue, such as the Retrofit for the Future and Building Performance Evaluation programmes of the Technology Strategy Board in the UK, usually require major investment. Long-term monitoring and longitudinal observation are two major features in these major investment projects. The former approach refers to the frequent measurement of indoor / outdoor environments and energy use conducted over at least two heating seasons, in line with the whole-house carbon and energy monitoring protocol of the Energy Saving Trust (2011). The latter approach, longitudinal observation, refers to observations conducted on the same group of individuals over an extended study period of years or decades to examine changes over time (Bryman, 2012). The majority of existing households and associated stakeholders that could potentially benefit from the investigation of energy-related occupancy activities cannot feasibly be involved in projects requiring major investment. The present study seeks to address the issue, identified as a research gap, of how to effectively apply low-cost approaches and transferable techniques in a small-scale study on energy-related occupancy activities.

To suit the socio-technical characteristics of the research topic, a mixed methods research approach, advocated by Bryman (2012) and combining quantitative and qualitative strengths, was applied to the processes of data acquisition and analysis. The methodology was enhanced in the course of this research. In line with Yin (2014), a case study approach was adopted in this project that was underpinned by two purposefully selected case study groups. One case study was conducted in the autonomous community of the Hockerton Housing Project Ltd. (HHP), in Southwell

Nottinghamshire. The HHP is among the first multi-dwelling, earth-sheltered, self-sufficient ecological housing developments constructed in the UK. Three monitored free-running households featured different family profiles, including a single occupant, an adult couple, and a young couple with children. The other case study was conducted, in partnership with Nottingham City Homes, in two conventionally built and identically retrofitted timber-frame social houses, which were home to two families composed of pensioners. Long-term and longitudinal monitoring schemes were configured and deployed in the case study houses using low-cost and transferable monitoring techniques. Both off-the-shelf products and self-configured equipment were adopted in the monitoring of indoor environmental conditions, power draws and electricity use, and occupancy statuses. Supplementary sociological approaches, including occupancy diaries and interviews, were adopted in accordance with the interview guidance for the occupant evaluation process of the Retrofit for the Future programme (Energy Saving Trust, 2014). Analysis of Variance (ANOVA) and Adaptive Neuro-Fuzzy Inference System (ANFIS) were applied for data analyses as a methodological trial based on different scales of data presentation. The major findings of this empirical study proved the feasibility of conducting a cost-effective study on energy-related occupancy activities by applying long-term and longitudinal monitoring approaches. Within each case study group, the variations in indoor environment and energy use directly resulted from the different activity patterns of each household. Between the two case study groups, the variations also derived from the different building characteristics of house designs, such as the difference made by heavy-weight and light-weight thermal mass. The cross-comparison between the two case studies revealed an aspect that has been overlooked by the building assessment system, regarding low-tech house design featuring heavy-weight thermal mass. The research findings in the retrofitted social house case study are of importance since they enable the participants of retrofitting programmes to access actual information derived from empirical case studies in order to secure both efficiency gains and financial gains.

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List of abbreviations and notations

AC	Alternating Current
ADC	Analog-to-Digital Converter
AI	Artificial Intelligence
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANOVA	Analysis of Variance
BPE	Building Performance Evaluation
CIBSE	Chartered Institute of Building Services Engineers
CO_2	Carbon Dioxide
CT	Current Transformer
DECC	Department of Energy & Climate Change
EST	Energy Saving Trust
FIS	Fuzzy Inference System
HHP	Hockerton Housing Project
HMI	Human Machine Interface
IALM	Intrusive Appliance Load Monitoring
IAM	Individual Appliance Monitor
KDD	Knowledge Discovery in Databases
MF	Membership Function
MVHR	Mechanical Ventilation with Heat Recovery
NaN	Not a Number
NCH	Nottingham City Homes
NIALM	Non-Intrusive Appliance Load Monitoring
PIR	Passive Infrared
POE	Post-occupancy Evaluation
REMODECE	Residential Monitoring to Decrease Energy Use and Carbon Emissions
RF	Radio Frequency
RFF	Retrofit for the Future
RMS	Root Mean Square
SRD	Short Range Device
T and RH	Temperature and Relative Humidity
TRVs	Thermostatic Radiator Valves
TSB	Technology Strategy Board
UN	United Nations
^{o}C	Degrees Celsius
A	Ampere
tCO_2/\$m	tonnes of carbon dioxide per million dollars of GDP
V	Volt
W	watt
Wh	watt-hour

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Chapter 1: Introduction

1.1 Background and rationale

Global issues related to energy use are on the rise, ranging from climate change and energy security to fuel poverty. Natural resources, such as fossil fuels, are no longer considered as infinitely available for exploitation. The relationship between global warming and human activities relating to energy use has been widely researched, especially since the publishing of the 2007 report of the Intergovernmental Panel on Climate Change (IPCC) (2007). 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). Traditionally, the consideration of energy saving and carbon reduction in the building sector has been concentrated on the aspects of renewable energy microgeneration and thermally related standards for new buildings. However, due to the slow turnover rate of new house construction, at least 87 per cent of the existing housing stock in the UK is expected to still be standing in 2050 (Boardman, 2007; Crilly, et al., 2012). The improved energy efficiency, if it is only applied to more recent buildings, will therefore not have as great an effect as expected.

Chapter 1: Introduction

Domestic energy use is 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). Theoretical gains in energy efficiency through retrofitting measures or installations of renewable energy microgeneration have a technical plateau when the technological improvements and associated upgrades reach their maximum effectiveness. At the top of this technical plateau, the occupants' presence and energy-related occupancy activities in both new and existing houses can significantly influence the actual energy use and the delivered effect of low-carbon and energy-efficiency technologies (Ingle, et al., 2014). To assess the impact of occupancy activities on actual energy use and 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). The potential impact of conducting research to reveal actual energy use activities includes:

- Revealing the actual effectiveness of tighter regulations relating to building fabric in reducing the requirement of spacing heating (Bell and Lowe, 2000; Hong, Oreszczyn and Ridley, 2006);
- Justifying the wider acceptance of energy-efficiency measures undertaken voluntarily by householders and landlords to reduce energy bills in the light of soaring energy prices (Berry, et al., 2014; Fawcett and Killip, 2014; Galvin, 2014);
- Providing the policy makers and associated parties with evidential results regarding the actual effects of energy-efficiency measures from the perspective of the impact of post-occupancy behaviours (Bartiaux, et al., 2014; Gupta, Barnfield and Hipwood, 2014);
- Presenting actual energy use scenarios for the consideration of the parties involved in certain retrofit schemes regarding the improvements in energy

effectiveness of existing domestic buildings, such as Green Deal participants (Booth and Choudhary, 2013);

- Influencing the building design criteria and policies regarding building performance from multiple perspectives, including the proper credit assigned to heavy-weight thermal mass and the appropriate consideration given to post-occupancy behaviours in any building simulation process (Tuohy , et al., 2005; Christensen, et al., 2014).

If the aforementioned research impacts are potentially realisable, the effectiveness in improving efficiency gains and reducing environmental impact can be achieved on a larger scale beyond an individual study. 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). Major energy consumption in buildings derives from the basic demands of human society and its associated anthropogenic activities, such as those associated with the need for appropriate temperature, humidity, air quality and illumination. For example, energy use for space and water heating approximately accounts for 80 per cent of the total energy consumption in residential buildings; and the rest of energy use, including lighting and appliances, for 20 per cent (DECC, 2014b). The increasing trends in multiple ownership of consumer electronics per household and multi-source lighting from walls, table lamps and multi-ceiling lights have contributed largely to the energy use proportions from lighting and appliances (DECC, 2011).

Featuring no cost, requiring minimal hi-tech equipment, and widely applicable in both new and existing buildings, the changes in energy-related occupancy activities of building residents have a large potential to achieve energy savings. However, the sociological diversity of human behaviours presents great challenges to the forecasting or simulation of energy-related occupancy activities in laboratory conditions. 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, buildings that are graded as energy-efficient should outperform lower-graded and older buildings. However, this is not the case when comparing the actual energy performance of respective buildings (Sommerville and Sorrell, 2007). Both domestic and non-domestic buildings that have the same building characteristics and geographical features can feature varying levels of energy consumption (Summerfield, 2007; Gram-Hanssen, 2014). 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). The accuracy level in building assessment has the potential to be improved if sufficient field measurements relating to actual energy use activities are incorporated into the assessment process and simulation procedures (Wei, et al., 2014). However, the behavioural aspects in a post-occupancy environment tend to be overlooked or simplified in building design and assessment, especially in the advanced building simulation that focuses on facility performance (Malkawi and Augenbroe, 2003).

In addition to the lack of appropriate approaches to effectively integrate the actual occupancy data into building assessment and simulation processes, a major reason for the overlooked post-occupancy aspects resides in the fact that acquiring the actual occupancy data relating to energy use in a uniform format to generate comparable and representative information is challenging (Energy Saving Trust, 2009; 2011). Long-term studies of real households are required to reflect the seasonal variations in occupancy-related aspects. By combining the strengths of industry and academia, the Technology Strategy Board (TSB) launched the Retrofit for the Future (RFF) programme in March

2009 (TSB, 2009) and the Building Performance Evaluation (BPE) programme in May 2010 (TSB, 2010). The £17 million RFF programme of the TSB covered 119 occupied social homes across the UK to drive innovations and cut carbon emissions using multiple and systematical approaches (TSB, 2013a; Sweett, 2014). The retrofitted houses were subsequently monitored over two years for the investigation of energy savings and carbon mitigations. The £8 million ongoing BPE programme of the TSB aims to investigate the key factors in the in-use performance of domestic and non-domestic buildings that were newly built or recently retrofitted (TSB, 2010). However, the majority of existing households and associated stakeholders that can potentially benefit from the investigation of energy-related occupancy activities cannot feasibly be involved in projects requiring major investment such as the TSB programmes. How to effectively apply low-cost approaches and transferable techniques in a small-scale study on energy-related occupancy activities has been identified as a research gap.

1.2 Research Aim and objectives

This research set out to investigate the energy-related occupancy activities in actual domestic environments of the selected case study homes by conducting longitudinal and long-term field measurements.

To achieve the research aim, the following objectives were determined:

- **Objective 1:** To investigate the associated research fields involving energy-related occupancy aspects for the identification of appropriate field-monitoring approaches and data-analysis methods;
- **Objective 2:** To select case study groups that have distinctive building characteristics between groups but feature identical built form and similar household profiles within each group;

- **Objective 3:** To deploy the configured monitoring scheme, once tested in pilot studies, in the selected case study groups; and to ensure the monitoring within each group and between different groups can produce comparable results;
- **Objective 4:** To establish the datasets of effectively pre-processed raw data for each case study home;
- **Objective 5:** To perform appropriate data presentation and analysis by applying the selected methods to the established datasets.

1.3 Research approaches

The socio-technical characteristics of energy-related occupancy activities demand multi-disciplinary research approaches for a variety of purposes.

- **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.

The three approaches are interwoven with each other in the literature review, methodology selection, and data analysis.

1.4 Originality and contribution

The work is considered as original in the following aspects:

- The comprehensive monitoring scheme, involving both off-the-shelf products and self-configured equipment;
- The use of purpose-built programmes to pre-process data;
- The establishment of a well-indexed dataset from which daily data of different categories over the monitoring period can be conveniently recalled by date;
- The methodological trials using statistics and Artificial Intelligence (AI) methods to assist in the algorithm-based inspections of monitoring results.

The major knowledge contributions made by the research include:

- The application of a longitudinal and long-term approach in the purposefully selected case studies using interdisciplinary approaches;
- The low-cost, less-intrusive, and transferable monitoring techniques to facilitate cost-effective investigations into energy-related occupancy activities in the majority of existing homes; for example, the monitoring contents and costs in Table 5-2 and Table 5-3 (see Chapter Five);
- The application of interdisciplinary techniques that are sourced from other study fields to cost-effectively solve the technical issues in low-cost monitoring processes; for example, the wiring solution to solve the PV and house use measurements in Figure 5-8 (see Chapter Five);
- The visualisation-based data presentation using multi-category measurements to reveal the impact of energy-related occupancy activities and building characteristics on actual energy use and indoor environment; for example, the micro-scale inspection in Figure 7-9 and Figure 7-16 (see Chapter Seven);
- The algorithm-based data inspections using adjusted methods that are sourced from the fields of statistics and AI; for example, the results presentation in Figure 8-1 to Figure 8-7 (see Chapter Eight);

- The jointly compiled project report with one case study partner, regarding the retrofit of social houses; for example, the Nottingham City Home (NCH) reports (2011; 2012);
- The evidence provision to the other case study partner in the appeal process for fair assessments regarding the featured heavy-weight thermal mass and free running in the design of autonomous houses.

The above-listed originality and contribution aspects are based on the assessment of some associated studies, which are listed in Table 1-1, from some key experts or organisations in the related research fields of energy use in the built environment.

Table 1-1 Key experts and organisations in some related fields

Research fields	Key experts or organisations	Research features
Building Performance Evaluation Energy Auditing Carbon counting	Technology Strategy Board (TSB, 2009; 2010; 2013a; 2013b); Energy Saving Trust (EST, 2008; 2010; 2014)	Monitoring techniques and assessment processes featuring major investment
	Gupta, Barnfield and Hipwood, (2014)	Focus on carbon auditing on the scale of communities or cities
Building regulation and sustainable housing	Bell and Lowe (2000)	Focus on energy-efficiency modernisation of houses and the associated implementing standard
construction performance and user behaviour	Hancock and Stevenson (2009)	Emphasis on indoor environment assessment in the post-construction and post-occupancy stages
Electricity end-use	Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe (REMODECE) (2008a; 2008b)	pan-European scale of study using equipment with a higher accuracy level than the most of off-the-shelf products
Non-Intrusive Appliance Load Monitoring (NIALM)	Hart (1992); Zeifman and Roth (2009); Kolter and Johnson (2011);	Emphasis on the monitoring and algorithms development to break down the household electricity consumption at mains power

Table 1-1 covers a small sample of work conducted by key researchers and organisations. It was not compiled to enumerate research areas of any specific expert involved, but to assist in identifying research gaps in knowledge and practice. For example, the major investment required by the TSB programmes and the large-scale coverage in the REMODECE programme make the associated monitoring techniques less conveniently repeatable in the majority of existing houses. The NIALM-based research, although it features computational strength in electricity load disaggregation, is based on accurate and sensitive electricity monitoring that is infeasible for a long-term study in actual homes. The construction performance and building regulation studies, though they provide the backdrop to this study, are not directly related to the research topic of this project. The originality and contribution aspects that are summarised in this subsection aim to fill the research gap based on the difference between this research and the studies of some key experts and organisations. More literature is reviewed in Chapter Two to assist in selecting the appropriate methodology in Chapter Three.

1.5 Thesis structure

Following the general introduction in this chapter, the thesis is organised as described below:

Chapter Two conducts a comprehensive literature review that ranges from research background and relevant concepts to commonly applied approaches in associated research fields.

Chapter Three justifies the selection of mixed methods research and case study approaches in data acquisition and analysis in this research project with a reference to the whole-house carbon and energy monitoring protocol of the Energy Saving Trust (2011). The selected algorithm-based Analysis Of Variance (ANOVA) and Adaptive Neuro-Fuzzy Inference System (ANFIS) methods are introduced following the outline of data acquisition approaches.

Chapter Four introduces the selected off-the-shelf equipment and the configured monitoring devices.

Chapter Five describes the pilot and case studies of this research, with the focus placed on two case study groups. For each case study group, the project background, the house and site conditions, and the monitoring scheme are separately introduced.

Chapter Six focuses on the pre-processing of raw data collected from the filed monitoring.

Chapter Seven performs visualisation-based inspections on the macro-scale and micro-scale using the pre-processed monitoring results of each case study.

Chapter Eight performs the algorithm-based analyses by applying the ANOVA and ANFIS methods to the pre-processed monitoring results of each case study.

Chapter Nine presents a general summary and reiterates the knowledge contributions. Future work is outlined at the end.

Chapter Ten concludes the entire research project by reiterating the research originality and contribution aspects.

Chapter 2: Literature Review

2.1 Introduction

The previous chapter narrowed down the research perspective to energy-related occupancy activities and associated impacts on indoor environment and energy use from generic aspects, such as post occupancy and occupant behaviours. To investigate this multidisciplinary and socio-technical research topic, this chapter surveys a wide range of related studies and research fields from the technological, environmental, economic, political and psychological perspectives. Starting from the research background and rationales of energy savings and carbon mitigations, the chapter reviews the underlying principles and associated concepts that are applied in the relevant disciplines, prior to moving on to the research approaches used in associated studies to assist in the selection of research methodology for this research.

2.2 Background of energy use and carbon emissions

Ever since the *naissance* of the built environment from the natural environment, the primary function of buildings has been to provide residents with shelter and security for their daily activities (Shove, 2003). Advances in science and technology have increasingly introduced human-made infrastructure and facilities, such as energy and water supplies and a wide range of domestic electrical appliances, into the modern built environment. Energy is thus increasingly consumed to maintain appropriate indoor temperature, humidity and air quality and to facilitate cooking, lighting, entertainment and other modern activities. Along with the largely improved living standard is the increasing consumption of many finite natural resources with a negative impact on climate change.

Depending on the resources, energy can be categorised as either primary or secondary. Electricity, as a form of secondary energy, is either obtained from the burning of primary fossil fuels, such as coal, oil, and natural gas, or harnessed from other natural resources (British Petroleum, 2014). Although being frequently applied as a unit of electricity use, watt-hour (Wh) can be converted to and from the units of other forms of energy consumption by using calorific equivalents as the medium, since in essence heat is harnessed and consumed in the process of energy conversion. For example, tonnes of oil equivalent (toe) are commonly used as a standard unit for the generation and consumption of primary or secondary energy. The toe is also adopted for the calculation of primary energy equivalents by using the calorific equivalents between one tonne of oil and other forms of fuels or energy by international energy stakeholders, such as British Petroleum (BP). The calorific value within one toe equals to that within 12 MWh of electricity (BP, 2014). The average thermal efficiency of a modern thermal power station is lower than 100 per cent, because only proportional heat energy in fuel or fuel mix can be converted into electricity and / or useful heat output. For example, electricity generated by one million tonnes of oil or oil equivalent (Mtoe) is around 4.4 TWh, instead of 12 TWh, in a modern thermal power station (BP, 2014). In addition to heat loss in the conversion and transmission of electricity, the major side-effect from burning finite fossil fuels is atmospheric carbon emissions and the consequent environmental impacts. Therefore, the consumption of secondary energy, such as electricity, is more carbon intensive compared with the direct use of primary fuels.

According to the reserves-to-production (R/P) ratio in the BP Statistical Review of World Energy in June 2014, the finite reserves of oil, natural gas and coal are only sufficient to meet global production for another 53.3, 55.1 and 113 years respectively (BP, 2014). Even before the depletion of proven reserves, the energy-related carbon emissions have brought serious environmental impacts. At the 15th Conference of the Parties (COP-15) of the 2009 United Nations Climate Change Conference in

Copenhagen, the two Degrees Celsius (ºC) target was officially agreed (United Nations, 2009). This means the atmospheric carbon dioxide (CO_2) concentration has to be stabilised at 450 part per million (ppm) in order to achieve a 50 per cent opportunity to curb global warming to two ºC above pre-industrial levels (United Nations, 2009). However, according to the PricewaterhouseCoopers's (PwC) Low carbon economy index (LCEI) 2012, the two °C target appears highly unrealistic (PwC, 2012). Due to the slow start of the annual rate of global decarbonisation at 0.7 to 0.8 per cent since the year 2000, it is estimated that an average of six per cent annual decarbonisation has to be achieved from the present to 2050 (PwC, 2013). This means the carbon intensity in tCO_2/\$m, or tonnes of carbon dioxide per million dollars of GDP, has to decrease by six per cent globally (PwC, 2013). In no single year since World War II has the world witnessed such a decarbonisation rate (PwC, 2012). Therefore, the International Energy Agency (IEA) has put forward the four ºC and six ºC scenarios that project the average global temperature increase corresponding to the various levels of changes in policy, technologies and energy consumption (IEA, 2012).

The difference in carbon emission levels between regions or countries arises from the different components of fuel mix, the respective stages of economic development, and the extent of activity in carbon-intensive sectors such as industry and forestry. As pointed out by PwC (2012), the emission levels of many developed countries would be adjusted upwards if exports from other regions where their manufacturing needs have been outsourced were fully accounted for. Without counting in outsourced energy use and carbon emissions, the carbon-intensive sectors in developed countries, such as the UK, are domestic and transport sectors as shown in Figure 2-1, based on the data from the Department of Energy & Climate Change (DECC).

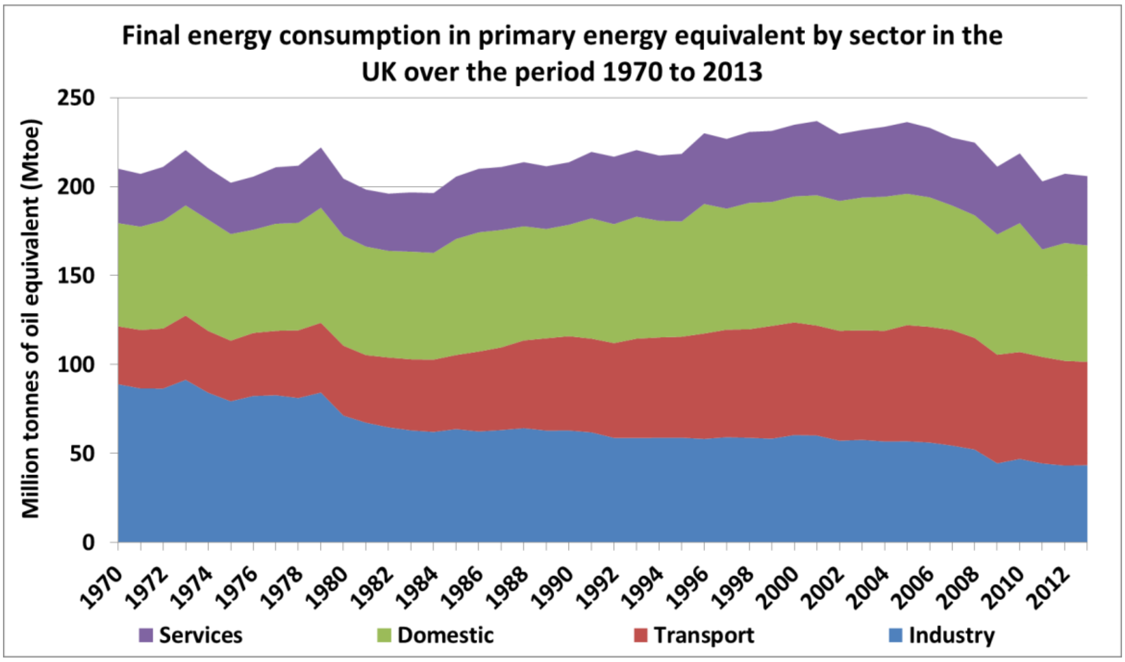


Figure 2-1 Final energy consumption in primary energy equivalent by sector in the UK over the period 1970 to 2013 (Data source: DECC (2014a), Table 1.02)

The long-term trends of final energy use shown in Figure 2-1 demonstrate the social, economic and climatic changes in the UK, such as the impact of two oil crises in the 1970s and the economic slowdown since 2007. The recent fluctuations of energy use resulted from the cold winter in 2009 to 2010 and the milder winter in 2010 to 2011. In general, the decrease of energy use in the industrial sector has been counteracted by an increase in the transport sector since the late 1970s, with energy consumption in the domestic sector oscillating around 30 per cent of the final energy use over the entire period. A long-term increasing trend of energy consumption was witnessed until 2004 in the UK's domestic sector. The downward trend since 2004 benefits from the improvement in energy efficiency in the domestic sector, such as more efficient domestic appliances and heating systems, the active application of renewable microgeneration, and large-scale improvements on building insulations (DECC, 2011). The reduction in energy use and the consequent carbon emissions from the UK's domestic sector plays a crucial role in cost-effectively meeting the national carbon target.

The fuel mix for domestic energy use in the UK has changed significantly since 1970. The coal consumption dropped significantly and was replaced largely by natural gas and electricity. The average ratio between the consumption of gas and electricity in domestic sector has been 3:1 since 1990 (DECC, 2014b). As shown in Figure 2-2, space heating remains primary in energy use for the domestic sector. The temperatures presented in Figure 2-2 are the averaged external temperatures, during January to March and October to December, that are provided by the UK Meteorological Office (DECC, 2014b). The long-term trend in gas use for space heating inversely correlates with the average external temperatures and positively correlates to the increasingly higher average internal temperatures over the period 1970 to 2012.

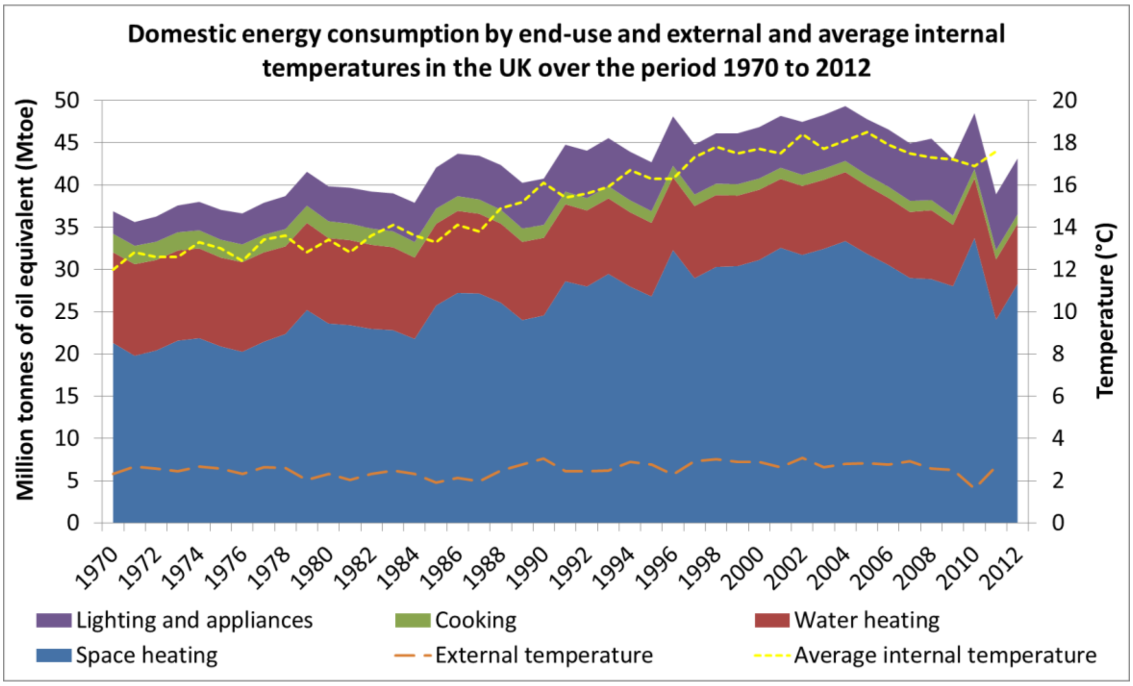


Figure 2-2 Domestic energy consumption by end-use and averaged external and internal temperatures in the UK over the period 1970 to 2012 (Data source: DECC (2014b), Table 3.04 and Table 3.06)

As a type of secondary energy, electricity has a higher CO_2 intensity ($KgCO_2/KWh$) although its net consumption is not as high as natural gas. Electricity use for lighting and appliances presents a continued rise until the year 2006, as shown in Figure 2-3. One explanation is the increasing numbers of consumer electronics appliances per household, which was 11 times higher in 2009 than in 1970 and 3.5 times higher than in 1990 (DECC, 2011). The technologically improved energy efficiency of lighting products and domestic appliances partially explains the downward trend of electricity use after the year 2009. Consumer purchase behaviour and multiple-ownership of electrical and electronic appliances fall in the scope of sustainable consumption, which is subsequently reviewed in this chapter.

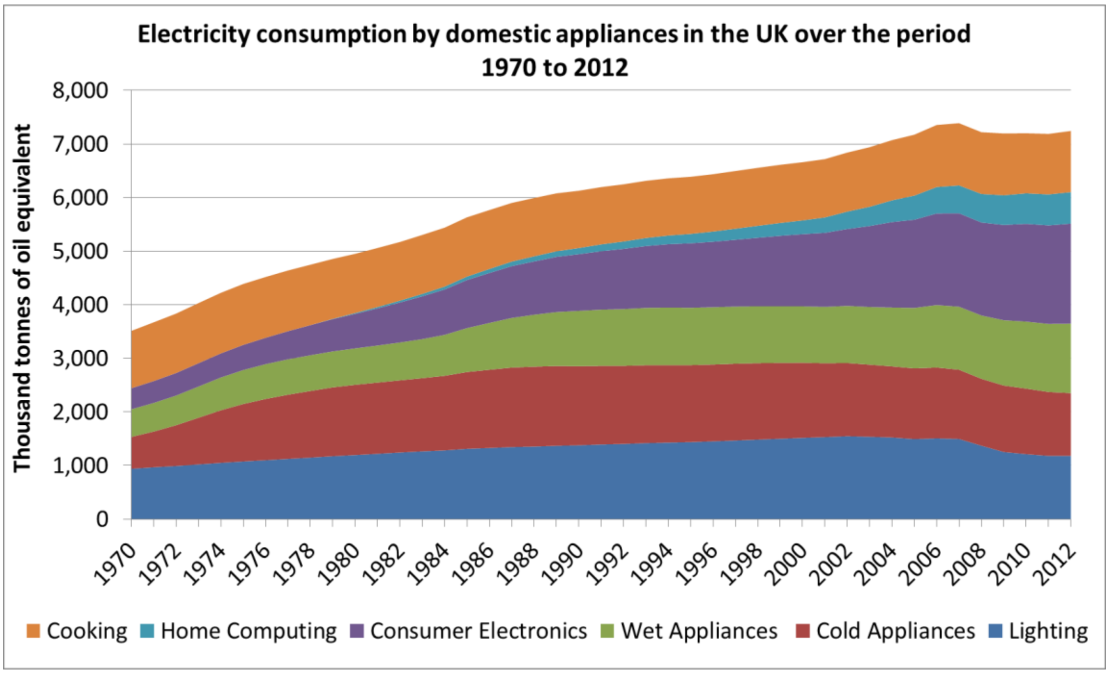


Figure 2-3 Electricity consumption by domestic appliances in the UK over the period 1970 to 2012 (Data source: DECC (2014b), Table 3.10)

The historical trend of energy use and environmental impacts provide the background context within which this research project sits in. To assess actual energy use activities and the associated indoor / outdoor environment of a specific household, it is of importance to quantify the use of natural gas and electricity by using appropriate approaches.

2.3 Quantification of domestic gas and electricity use

2.3.1 Quantification of gas use

According to the whole-house carbon and energy monitoring protocol of the Energy Saving Trust (2011), there are three major quantification approaches for the total domestic use of natural gas, depending on the actual type of utility gas meter in a specific household.

- Automatic meter reading if the pulse output is supported by the digital modern utility meter;
- Automatic meter reading if a secondary digital modern meter can be retrofitted to the mains gas that is originally metered by a mechanical utility meter;
- Weekly or monthly manually conducted meter reading if the automatic meter reading is infeasible.

Manual recording at weekly intervals was the highest feasible frequency in previous Energy Saving Trust (EST) projects (EST, 2009; 2011). Accurately separating the gas use for space heating and water heating is difficult, unless a sub-metering approach is used. If the direct measurement of heat consumption or fuel use for space heating is infeasible, the Heating Degree Days (HDD) method can be used to estimate the heating energy consumption or to justify the energy use through the process of weather normalisation. By integrating temperatures (in degrees) and time period (in days), the HDD provides a simple quantifying method for the space heating demand of buildings in a particular location. The temperature is defined as the difference between a baseline and the outdoor average temperature of the daily maximum and the daily minimum. The HDD baseline is a selected outdoor temperature above which buildings need no artificial heating in a particular location. Various figures and units of baseline temperatures are adopted in different countries. Based on the assumption that buildings are heated to a temperature around 19 ºC, including the internal heat gains from occupants and occupancy activities, the Department of Energy & Climate Change (DECC) has selected 15.5 ºC as the national base temperature, and the mean value of daily average temperatures from 17 weather stations across the UK as the national average daily temperature (DECC, 2011). Climatic and geographical variations are thus considered in the HDD regression to enable effective data comparisons.

The HDD is mathematically the integration of temperature differences over the time domain. It can be visualised as the area between the outdoor temperature curve and the baseline temperature. The HDD is positively correlated with the energy use for space heating in buildings. The correlation coefficient is proportional to the product of heat transfer co-efficient (U-value) and envelope area of the specific building. A more statistically significant correlation can be achieved if the temperatures are measured continuously instead of using the daily average. However, the statistical significance does not equate to the reliability of prediction power of the obtained linear relationship between HDD and space heating energy use. The sources of inaccuracy that can lead to misleading results when using the HDD approach to approximate heating energy use include the selection of baseline temperature, the intermittent heating patterns, the baseload components of heating fuels, the temperature measurement, and the meter-reading mechanism of energy use (BiZEE, 2013). For example, the baseline temperatures of buildings vary largely; so do the internal heat gains. A rigid number such as 15.5 ºC cannot represent the specific heating requirement in all buildings. The selection of baseline temperatures largely influences the numbers of calculated HDD and the proportional distribution of HDD over the same time period. Even if an appropriate base temperature can be identified, the real operation of heating systems in buildings does not necessarily follow the theoretical heating mode, which assumes space heating is applied only and continuously when the outside temperature drops below the baseline. Intermittent heating patterns in actual heating practices, especially heating use within ambiguous areas where the outdoor temperature approaches the baseline, can make the calculated HDD either underestimate or overestimate the actual use of space heating. A linear correlation should be established between HDD numbers and the energy use only for space heating. Unless purpose-installed sub-metering is used, it is challenging to accurately isolate the proportion of space heating energy from the baseload that is used for activities other than space heating. In addition, the statistical strength of linear regression relies on the accurate measurement of historical outdoor temperatures and heating energy usage (BiZEE, 2013). Ideally, the outdoor temperature should reflect the microclimate environment adjacent to a specific building under study. For most cases, when the best-equipped weather station of the region is not adjacent to the studied building, an alternative is to install a personal weather station. However, due to the inherent device constraints or improper installation and maintenance, personal stations can potentially produce problematic readings or fail to provide continuous long-term records for the HDD calculation.

In addition to the prediction of energy use for space heating by extrapolating the obtained linear regression, HDD is widely used for the weather standardisation of heating energy use. Standardised consumption in KWh/HDD is calculated using the average HDD of the regions over the past 10 years to remove the climatic influence on heating energy use (DECC, 2011). Heating use correlates to the climatic conditions as shown previously in Figure 2-2. The direct comparison of absolute numbers of annual energy usage can result in misleading interpretations. For example, one possible reason for a higher post-retrofit gas use for space heating might be a thermally focused rebound effect. To identify whether it is the relatively cold and prolonged heating season that results in the larger energy use figures compared with previous years, a simple approach is to calculate the heating energy use per averaged HDD. The ratio-based weather normalisation of energy consumption enables the identification of unusual use without the influence of weather conditions (DECC, 2014).

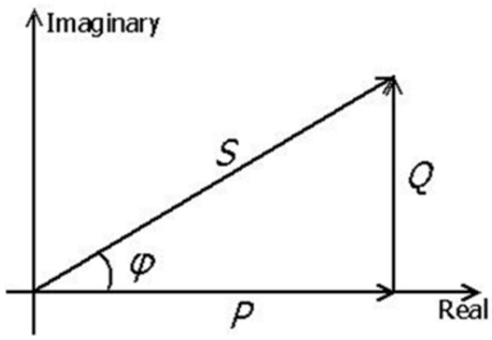
Theoretically, the ideal HDD figures can also indicate heating behaviours. Rahman (2011) pointed out that HDD can better represent the space heating behaviour of domestic users due to its unidirectional character, which means HDD only accepts positive accounts when the outdoor temperature is below the baseline. This corresponds to the probable use of heating in order to compensate for the temperature difference. The HDD remains unchanged when the outdoor temperature reaches or exceeds the baseline. This corresponds to behaviours such as switching off the heating or opening windows during the warm and hot days. Using the temperature data at higher resolutions, HDD can also reflect the impact of cold snaps when residents might need to set their thermostat higher or utilise forceful gas heating. Together with the average U-value and envelope area of a specific building, HDD can facilitate the estimation of heating energy use of the building, and thus enable the cross comparison of buildings in the same or different geological locations. These theoretical benefits when using the HDD method are based on the assumption of appropriate selection and measurement of relevant parameters.

2.3.2 Quantification of electricity use

The three major quantification approaches for natural gas consumption in the whole-house carbon and energy monitoring protocol of the Energy Saving Trust (2011) are also applicable for the quantification of domestic electricity use. In the public monitoring domain, where technologically intensive resources are potentially not sufficient to install secondary meters or to acquire the pulse output from existing utility meters, the use of off-the-shelf products is an extra approach to measure electricity use and power demand, to various accuracy standards. In the laboratory environment, where features of power and electricity are acquired for the purpose of load investigations, professional devices are used to perform scientific experiments beyond the level of utility meter readings. However, off-the-shelf products and professional lab equipment are not designed to replace the electricity utility meters that are used by energy suppliers to bill households.

The amount of energy use of a household not only depends on the ownership levels of domestic appliances but also relates to the use patterns of appliances, such as operational frequency and duration. The power demand distributed over various lengths of time forms a series of unique power curves / profiles for the appliances or entire household. Knowledge of these power profiles is required to disaggregate household electrical loads by breaking down the house use profile into end-uses. Utility suppliers can utilise disaggregated load information to optimise their energy supply tariff schemes and make full use of the shrinking generation capacity (Darby, 2010). Provided with more informative utility bills involving end-use feedback, householders can be enlightened about the energy use profiles of different daily activities. It is thus potentially feasible to encourage householders to achieve domestic energy savings through behavioural changes, such as adjusting the usage patterns of appliances and switching off identified unnecessary stand-by loads (Matthews, et al., 2008). In general, the knowledge of end-use demand can benefit both stakeholders and common consumers of power systems, although this research focuses on the common consumers, especially the case study householders. Meyers, et al. (2010) pointed out that the similar portfolios of domestic appliances and relative consistency of energy end-uses facilitated energy reduction strategies in the domestic sector as compared with the commercial and industrial sectors. The importance of more informative utility bills that can provide householders with disaggregated feedback has been discussed by Darby (2006), who also highlighted the feasibility challenges of daily load disaggregation. Major challenges reside in the cost-effectiveness of end-use classifications using one-point readings from mains power. With the advancement in digital technologies and the prevalence of ‘smart-meter’ products in the domestic environment, the load disaggregation challenges gradually move from acquiring data to developing algorithms that suit the data acquired in the context of relatively low sampling rates and accuracy levels.

The investigation into different power elements is beyond the scope of this research. However, it is important to clarify which power element the measuring equipment is recording to quantify electricity use. Figure 2-4 includes a sketch drawn by the researcher in March 2012 and the formulae extracted from Gibilisco (2006).



Complex Power: S = P + *j**Q, *j* is the imaginary unit
Apparent Power: $|S| = \sqrt{P^2 + Q^2}$
Real power: P = $|S| * |\cos(\varphi)|$
Reactive power: Q = $|S| * |\sin(\varphi)|$
In a simple AC system, $|S| = V_{RMS} * I_{RMS}$, where RMS is the Root Mean Square of the instant value

$$V_{RMS} = \sqrt{\frac{1}{T2-T1}\int_{T1}^{T2}[V(t)]^2\,dt}$$

$$I_{RMS} = \sqrt{\frac{1}{T2-T1}\int_{T1}^{T2}[I(t)]^2\,dt}$$

Figure 2-4 The real and reactive elements of the complex power in AC systems

Although the ‘watt’ is used as the unit of rated power on the energy rating label of most domestic appliances, it is actually the unit of real power element, which is the real component in the complex power of the Alternating Current (AC) system as shown in Figure 2-4. Complex power is denoted by *S* with volt-ampere (VA) as its unit. Real power, denoted by *P*, is the power demand for the intended purpose of energy use in kilowatt-hour (KWh). The imaginary component of complex power *S* is the reactive power that is denoted by *Q* with volt-ampere reactive (var) as its unit. The φ is the phase angle between complex power *S* and real power *P*. Therefore, the power factor $cos(\varphi)$, as the ratio between real power *P* and apparent power |S|, is the percentage of real power in complex power. Higher ratios denote that more real power is integrated into the expected energy use in KWh. Domestic electricity loads consist of the collective real power profiles of various household appliances that are connected to the mains power circuit. According to the use patterns, Firth, et al. (2008) classified the commonly used domestic appliances into continuous, standby, cold, and active categories.

As regards practical measurements of electric power, except for the professional monitoring aimed at capturing detailed AC features, 240 Volt (V) is taken as the default Root Mean Square (RMS) value of end-use AC voltage when the national end-use is supplied at 240 V ± 10%. Unlike AC voltage, AC current varies over the operational cycles of an appliance. To calculate the power demand and integrated energy use, the current is measured in real time. Depending on the sophistication levels of monitoring devices, the phase angle φ is not always monitored, especially when AC voltage is not measured. Instead, the values of φ and the power factor $cos(\varphi)$ take zero and one respectively by assuming the appliance load is purely *resistive*. Some appliances, such as the electric immersion water heater and electric kettle, have negligible reactive power draws and are thus denoted as *resistive* appliances. The measurements of *resistive* appliances are relatively robust, even if the selected measuring equipment is not capable of distinguishing different power elements.

In order to accurately bill the customers, meters fitted by utility suppliers apply different mechanisms to indirectly count the pulse output of digital utility meters or the *disc revs* of mechanical utility meters that are proportional to real power consumption. Therefore, the whole-house carbon and energy monitoring protocol of the Energy Saving Trust (2011) suggests the pulse output approach. However, many off-the-shelf digital monitoring devices in the public monitoring domain only measure real-time AC current and use the default values of AC voltage and power factor. The calculated power values in watts tend to be larger than the actual value of real power *P* recorded by utility meters (Liikkane and Niemimen, 2009).

Modern digital monitoring devices use Analog-to-Digital Converter (ADC) to convert a continuous analog input into a digital series of zeroes and ones that can be read and stored by a device microprocessor or peripheral PC equipment (James, 2000). The width of a digital value is measured in the unit of ‘bit’, which stands for the power index of base two (the two digits of zero and one). The ‘bit’ number is a critical factor for the *resolution* of an ADC. The *resolution* is decided by the maximum measurable range and *sensitivity*, or minimum detectable analogue values. For example, in order to measure the power demand changes as low as one watt within a 240 V ± 10% system, minimum AC current changes at 1/240 Ampere (A) need to be detectable (Liikkane and Niemimen, 2009). Considering 32 A as the maximum trip capacity of a typical domestic circuit fuse or micro circuit breaker, at least 7,680 digital series are required to be detectable by the ADC, where 7,680 results from the division of 32 by 1/240. If the entire house has 80 A as the maximum capacity, 19,200 digital series are required. A 16-bit ADC can theoretically distinguish 65,536 (2^{16}) digital series. Since not all numbers can be represented as noise-free ones, the effective bit of a 16-bit converter is usually less than 16, although it can suffice for the measurement of the household capacity of 80 A, with one watt as the minimum measurable unit or *sensitivity* (Liikkane and Niemimen, 2009; James, 2000).

Sampling *frequency* is another key factor in power measurement. Depending on the monitoring purpose and requirement, sampling frequency can vary from levels of MHz, KHz or Hz (once every second) to once every minute, every five minutes or every two hours. Each point on the power curves represents the average rate of energy consumption over the associated sampling intervals. Over the same time period, the integrated energy use at various sampling frequencies remains the same, although the instantaneous power demand varies at each sampling point. Power curves obtained at a relatively high frequency can capture more features of the power profiles. Different frequencies are adopted for various research purposes, usually as a trade-off between the targeted features and the storage feasibility of larger volumes of data as the result of high-frequency monitoring. For example, sampling at the rate of MHz is rarely used except for the purpose of load detection by acquiring harmonics features within AC waveforms (Gupta, et al., 2010 cited in Kolter and Johnson, 2011, p.2). The recommended sampling frequency of electricity use at mains power in the whole-house carbon and energy monitoring protocol of Energy Saving Trust (2011) is once every five minutes.

Knowledge about the AC power elements and the monitoring *sensitivity*, *resolution* and *frequency* is essential to distinguish professional equipment and advanced off-the-shelf monitoring devices. Liikkane and Niemimen (2009) selected 11 types of advanced off-the-shelf products to investigate the measuring accuracy levels of these relatively inexpensive devices against the monitoring results of a lab-based professional power metering set in their electrical laboratory of Helsinki Institute for Information Technology. These tested meters were widely available in the European market for domestic electricity measurement at prices ranging from €13 to €180. The average test errors were found to be ranging from two to 19 per cent. The lowest-priced device had a test error of 12 per cent. The researchers stated that the technical standard of the tested meters varied to a large extent, and the interpretation of measurements acquired using advanced off-the-shelf metering devices in the public monitoring domain therefore could require extra consideration.

2.4 Commonly used concepts in relevant studies

Energy use in buildings is a dynamic system that consists of transient trade-off statuses, such as energy savings and indoor comfort that are seemingly conflicting requirements. The previous subsection is about the quantitative aspects of energy use in a domestic environment, including the measurement and analysis of natural gas use and electricity consumption. This subsection focuses on the qualitative properties of energy use and indoor comfort, from the perspectives of sociology and econometrics.

2.4.1 Energy efficiency and efficient energy use

Energy savings can be achieved through energy efficiency improvement and efficient energy use. The former approach refers to technological methods applied to the energy services of a system in order to increase the ratio of ‘useful’ outputs to energy inputs of the system. The latter approach falls in the scope of behavioural changes that aim to reduce the energy consumption of a system with the status quo efficiency (Sorrell, 2007). For example, insulating a house and replacing low-efficiency heating systems are commonly encountered retrofitting measures of the first category for energy savings in domestic environments. The reduced use of space heating during heating seasons by lowering indoor temperature settings and by controlling window opening frequency and durations are widely encouraged energy use behaviours of the second category for household energy savings (Sorrell, 2007). Similarly, the replacement of any aged household white goods, such as washing machines and tumble dryers, with the energy-efficient appliances belongs to the first category. Limiting the usage frequency and managing washing and drying loads fall in the scope of the second category of energy savings (Sorrell, 2007). Both approaches are of importance to reduce energy use and the subsequent carbon emissions, although behaviour-related energy savings in the domestic environment are the focus of this research project.

2.4.2 Rebound effect

If the difference between engineering estimates and the actual energy savings is associated with the price decrease as the result of system efficiency improvements, the phenomenon is defined as the rebound effect (Sommerville and Sorrell, 2007). The phenomenon was first investigated by Stanley Jevons in 1865, in the book: *The coal question: can Britain survive, to* observe the paradox of the ever-increasing consumption of coal after the introduction of efficient steam engines in Britain (Gottron, 2011). The paradox has been commonly referred to as the ‘Jevons paradox’ and developed further into different categories of rebound effect by later researchers when similar phenomena in the supply and demand of electricity and gasoline were investigated. The Jevons paradox, also referred to as ‘back-fire’, describes the scenario when the rebound effect exceeds 100 per cent (Sorrell, 2007). This means the efficiency improvement of energy services results in no energy savings but more consumption when new technologies suddenly make the previously expensive resources widely affordable in an unsaturated market. The rebound effect usually stays between zero and 100 per cent under the circumstances of cost-effective energy efficiency improvements being applied in a less unsaturated market (Sorrell, 2007).

Sorrell (2007) conducted a theoretical taxonomy of the rebound effect:

- If the avoided expenditure from efficiency improvement is re-spent on the same energy service and fails to deliver the expected energy savings, it is termed a *direct effect*.
- If the avoided expenditure is re-spent on a different energy service and leads to unexpected energy use, it is named an *indirect effect*.

An example of the *direct effect* is a more efficient dishwasher that makes it cheaper to use per wash. The household may use it more frequently without fully loading it, thus use more electricity. An example of the in*direct effect* is overseas holidays using the money saved from a space heating improvement. Since travelling by air is a more energy and carbon intensive activity compared to space heating, such an *indirect* rebound effect can cause a ‘back-fire’ that results in more consumption and emissions, partially due to the heating system improvement (Druckman, 2011).

The *direct effect* was further classified by Sorrel (2007) as follows:

- If the consumption is maintained at a constant level of satisfaction or ‘utility’, then it is a *substitution effect*.
- Or else, it is an *income effect* if the money saved allows a higher level of ‘utility’.

Most empirical studies only evaluate the *income effect* since quantifying the *substitution effect* is challenging (Chitnis, 2013). A relatively controversial development in theoretical research on the rebound effect is the ‘Khazzoom-Brookes (K-B) postulate’ (Sorrell, 2007). The postulate claims that, if the energy price remains unchanged, cost-effective energy efficiency improvements will inevitably cause an economy-wide ‘back-fire’ effect. If confirmed, the postulate will cast negative implications on the policies and regulations that advocate low-energy and low-emission lifestyles. Although the postulate has been criticised and refuted for the incompleteness of empirical evidence and the weakness in theoretical rigor, many researchers attempted to point out that its implications are not negligible (Chitnis, 2013; Druckman, 2011). Druckman (2011) also discussed the theoretical possibility of negative rebound effect if the saved expenditure is reinvested in ultra-low carbon technologies with the support of governmental policies.

Energy use for space heating in retrofitted houses has been widely used as an empirical subject to investigate the rebound effect. The evidence given in the evaluation report of Sommerville and Sorrell (2007) showed that a gap between expected and observed energy savings from space heating improvements existed in all evaluated studies to different extent, although the existence and extent of price-related rebound effects might be debatable. Sorrell (2007) differentiated the concepts that have been widely misused to describe rebound effects in the context of household space heating. Rather than the price-related concept of rebound effect, the *shortfalls* in energy savings were more commonly used for the discrepancy between observed and expected savings following retrofit measures. *Temperature takeback* or *actual energy consumption,* which refers to the increased temperature or energy use within retrofitted houses, was utilised as a metric proxy for efficiency shortfalls in most research projects reviewed by Sommerville and Sorrell (2007). Energy used to obtain the increase of indoor temperatures in a typical domestic building depends on multiple factors, such as the installation quality of retrofit measures, the building age and form, the household size, the previous indoor temperature preferred by the household, the accuracy level of energy simulation models, and the behavioural changes of the household with respect to the adjustments of heating and ventilation controls (Sorrell, et al., 2009). Behavioural changes can only partially explain the *temperature takeback* and *efficiency shortfalls*. It is inappropriate to equate the behavioural changes and associated aspect of rebound effect with the *takeback* and *shortfalls* or even the entire rebound effect. Therefore, this research project directly utilised temperatures and actual energy consumption values, rather than incorporating the concept of rebound effect, in the circumstances of retrofitted case study homes.

2.4.3 Sustainable consumption

The aforementioned rebound effect closely relates to the consumption habits and daily routines that play an important role in the sustainability context of energy and resource consumption in the built environment, such as the comfort conditions via an artificially altered indoor climate and cleanliness acquirement through showering, bathing and laundering. From a socio-technical perspective, Shove (2003) investigated the coexistence and co-evolution of the entwined technological standards, lifestyle alterations and economic stimuli. Shove (2003) identified the dynamic interaction process of comfort demands and technological innovation, especially the societal standardisation of private practices brought by the advancement in science and engineering. Two examples given in the study were the gradually outdated siesta lifestyle in some southern European countries and the increasingly accepted anti-seasonal dress codes during winters in some northern European countries, due to the air-conditioning prevalence in artificial indoor environments that permeated cultural and geographical boundaries around the world. Despite certain levels of sociologically biased perspectives towards technology innovations in studies, such as the one conducted by Shove (2003), the improvements brought to individual lives and society by technological innovations are impossible to completely negate.

Rennings, et al. (2005) investigated consumption behaviours in German residential buildings from the economic, sociological and psychological perspectives. The study attempted to define the relationship between sustainable consumption and consumer behaviours regarding individual decisions. One econometrical approach reviewed in the study was the discrete choice model of Allenby and Rossi (2003 cited in Rennings, et al., 2005, p.81), who developed a hierarchical Bayes model using lower-level multinomial logit models to calculate the decision-making probabilities of investigated individuals. The calculated probability depended on a list of driving factors that might influence the decision-making process. Following the methodological models, the empirical research on consumption behaviours regarding household appliances, heating systems, and green electricity was quoted by Rennings, et al. (2005) to verify the conclusion that sustainable consumption have been characterised by the socio-political atmosphere and the individual actions of consumers and suppliers.

Most research on sustainable consumption in the built environment adopted either narrative or statistical approaches, as exemplified by the aforementioned two studies by Shove (2003) and Rennings, et al. (2005). This was mainly because of the macro-scale characteristics of the overarching subject of consumption behaviours. The data applied in the statistical modelling process, as in the research of Rennings, et al. (2005), were usually acquired using large-scale surveys. The data acquisition and analysis in this research category provided a holistic methodological map relating to the study on energy savings and indoor comfort, although the associated methods were not selected for this research project.

2.4.4 Indoor environment and thermal comfort

The indoor environment of buildings is closely related to a perception-based physiological concept, indoor comfort. In various national or industrial standards, indoor comfort has been used to quantify building residents' requirements for, and feelings of satisfaction towards, thermal comfort, visual comfort, acoustic comfort, and indoor air quality (Kolokotsa, 2005). Among the four major indices, thermal comfort closely relates to both physical variables, such as temperature, humidity, and air movement, and personal variables, such as clothing and activity (Smith, et al., 1982). Debates over thermal comfort mainly focus on the standards and the two approaches to define these standards, which are the heat-balance approach and the adaptive approach (Darby and White, 2005). The former approach concentrates on the engineered physical thermal environment that provides a narrow range of tolerable temperatures. This laboratory-based approach has been critically reviewed by researchers, such as Shove (2003) and Humphreys, Rijal, and Nicol (2010), for its perceived lack of consideration of the varieties in culture, history, demography, geography and specific built forms beyond the laboratory climate chamber; and for its commercially driven standardisation for the market prevalence of air-conditioning systems. The adaptive approach, on the other hand, is based on a field survey approach that examines the occupants' behavioural thermoregulation and the associated impacts on occupants' perception of thermal comfort (Nicol and Humphreys, 2009). For example, activities and clothing can change the metabolic heat production and heat loss respectively; the adjustment of blinds, windows, doors and fans can create a wide range of satisfactory comfort levels (Darby and White, 2005).

Most studies on thermal comfort aimed to understand the highly dynamic and complex interaction between human beings and indoor environments (Mishra and Ramgopal, 2013). A great deal of research attempted to discover what combinations of physical variables can best describe the subjective comfort responses of residents by performing multiple regression analyses (Taleghani, et al., 2013). The obtained comfort indices were important for setting localised comfort standards of design temperatures in both air-conditioned and free-running buildings. Although the personal variables of activities, clothing, and metabolic rate were measured or assumed at various levels in different studies, which either conducted field surveys or adopted climate chambers, the measurement of physical environmental parameters were inevitable in all studies.

The basic physical measures to describe thermal environment include air temperature (T_a), radiant temperature (T_r), air velocity (V_a), water vapour pressure (P), and Mean Radiant Temperature (MRT), which removes the directional issues of T_r and is usually approximated by the globe temperature in most thermal comfort studies (Nichol, 1993; Chartered Institution of Building Services Engineers (CIBSE), 2006). This research project made no attempt to conduct detailed investigations into the aspects of physiology and psychophysics in thermal conform concepts, which were adequately described and referenced in Nichol (1993) and the CIBSE Guide A (2006). Instead, the investigation approach regarding physical indoor environment parameters in this study was similar to the methods that were recommended in the whole-house carbon and energy monitoring protocol of the Energy Saving Trust (2009). Being designed for the Retrofit for the Future (RFF) and Building Performance Evaluation (BPE) programmes of the Technology Strategy Board (TSB), the Energy Saving Trust (EST) protocol (2009) focused on the measurement of ambient and fabric temperatures. Given the research topic of energy-related occupancy activities, the temperature variables selected for the field measurements in this study focused on the indoor and outdoor environments. The selection of monitoring variables and associated data acquisition approaches are further discussed in Chapter Three, with reference to the EST protocol (2009; 2011) and the TSB programmes.

2.5 Research approaches in associated studies

Three commonly applied approaches in associated studies on energy use and indoor environment are reviewed in this subsection, including the monitoring, sociological, and mathematical methods. In field studies that are undertaken to assess selected variables, monitoring and / or sociological approaches can serve the task of data acquisition, either in actual living environments or under laboratory circumstances. The sociological approach in this research refers to data collection using questionnaire surveys or interviews that differ from the physical measurement used in the monitoring approach. The sociological approach is either independently applied or jointly conducted to enhance the monitoring approach. The mathematical approach, in the context of this research, refers to various types of numerical and analytical methods that are resorted to in the process of data analyses. The mathematical approach was used as an overarching concept in this study, since some multidisciplinary methods in the fields of computational intelligence or statistics can be considered as separate research methods beyond the conventional mathematics field.

2.5.1 Monitoring approaches

Depending on the research field, various variables can be selected as monitoring subjects. Among the reviewed research projects in this subsection, some studies boasted multi-category measuring parameters for comprehensive assessments of the respective research topics, whilst others concentrated on a certain type of variable to conduct in-depth investigations. The scales, durations, and professional levels of different monitoring projects varied to a large extent depending on the purpose and project management of the specific studies. Three types of variables, including hygrothermal variables, energy and power, and occupancy statuses, are separately surveyed in the following subsections.

2.5.1.1 Hygrothermal parameters

Hygrothermal variables, including temperature and relative humidity, are usually monitored outdoors as part of weather variables, in addition to being measured in indoor living zones. The monitoring purpose varies from the assessments of building fabric to the examinations of indoor comfort as in the Retrofit for the Future (RFF) and Building Performance Evaluation (BPE) programmes of the Technology Strategy Board (TSB, 2013a). As introduced in the previous subsections on HDD methods and indoor comfort, the ambient temperature can act as a proxy to investigate space heating activities. If weather conditions are not directly monitored, third-party data, such as measurements from public or private weather stations, are another source of data acquisition. The EST monitoring protocol (2009; 2011) gave no specific suggestions on the monitoring frequency of indoor and outdoor ambient temperatures, but stated that weekly measurements can suffice for the purpose of fabric temperature monitoring for non-dynamic analyses. Although the five-minute interval was preferred by the EST-stipulated data acquisition system (EST, 2011), it was the utility meter readings of natural gas and electricity, instead of temperatures, that were recorded in the RFF programme of the TSB (2013b). The monitoring duration suggested by the EST protocol (2009; 2011) was at least two heating seasons for the long-term assessment of building performance. The TSB programmes and the EST protocol are further discussed in Chapter Three. The following reviewed studies are academic research projects involving temperature monitoring over various monitoring durations.

Over a period of 15 years from 1987 to 2002, Emery and Kippenhan (2006) conducted a series of paired experiments (occupied / unoccupied) with two pairs of purpose-built houses near the campus of the University of Washington, Seattle, USA. One pair of houses was built to conform to the codes in existence at that time and the other pair to the proposed codes with improved thermal standards of building envelopes. Comprehensive instrumentations, including heat flux meters, air and surface temperature sensors, weather station, air and water flow meters, and power meters for 24 electrical circuits, were deployed to the same standard in each house. Emery and Kippenhan (2006) used the measurements of temperatures and space heating use in two typical heating seasons of 1987 to 1988 and 2000 to 2001 to examine building performance from the perspectives of building characteristics and occupancy behaviours. The sensitivity performance of the established statistics regression, which utilised HDD, indoor and outdoor temperature difference, and average daily weather variables to predict the heating energy use in four houses, revealed the impact of occupancy behaviours on space heating use. Emery and Kippenhan (2006) thus proved that this statistical regression analysis approach can suffice to predict heating energy use, serving as a cost-effective method between standard HDD regressions and more complex energy simulations.

However, the long-term and comprehensive ambient monitoring conducted by Emery and Kippenhan (2006) was rarely witnessed to the same extent in other research projects, mainly due to its expense and time-consuming nature. A two-year hygrothermal monitoring was conducted in Oxford Brookes University, UK by Hancock and Stevenson (2009), who reported their first-year data of post-occupancy study on a newly built and semidetached house. As part of post-construction testing, the measurement conducted by Hancock and Stevenson (2009) aimed to identify a minimum level of monitoring to reliably indicate building performance when considering post-occupancy factors. Energy-related activities were thus not the major investigation subject, although Hancock and Stevenson (2009) also conducted interviews with the occupants who helped to keep a weekly logbook of occupational activities. Based on certain limitations from the short-term monitoring, such as data loss due to equipment malfunctions, Hancock and Stevenson (2009) pointed out that monitoring results collected over the course of one year were possibly not able to represent typical post-occupancy conditions.

Long-term monitoring over 15 years such as that carried out in the aforementioned project by Emery and Kippenhan (2006) was rarely seen; so were re-visit studies in the associated research on energy use and hygrothermal conditions. Summerfield (2007) reported a follow-up study of 15 low-energy houses in Milton Keynes, UK. After the monitoring period of 1989 to 1991, the measurement was resumed in 2005 and 2006 to produce comparable results for the indoor temperatures and energy use of three groups of households that were classified as low-level, middle-level, and high-level energy users. Summerfield (2007) found that the high-level energy users remained the highest-level energy users and consumed an amount of energy equating to the sum of energy used by the other two groups, although the building size and income level of the high-level energy users were not the highest. Studies revisiting the case study site are not always feasible since the household profiles might have changed over the time period, although it was not the case in this Milton Keynes study (Summerfield, 2007).

Yohanis and Mondol (2010) conducted indoor temperature monitoring in 25 houses in Northern Ireland by using four Tinytag® hygrothermal loggers in the bedroom, living room, hall and kitchen areas of each house from January 2004 to December 2005. The measurements over a one-year monitoring period were used to analyse seasonal, monthly and daily average temperatures. No other monitoring parameters or information on built forms and household profiles of the 25 houses were given by Yohanis and Mondol (2010), who focused on examining the proportion of homes that were respectively under-heated, over-heated, or maintained comfortable by using 21 ºC as a point of reference.

The four studies reviewed in this subsection featured various extents of monitoring intensity and durations for different research purposes. It was infeasible to replicate the monitoring involving hygrothermal variables in this research to a similar extent as the 15-year project of Emery and Kippenhan (2006). Lessons were learnt from the experience of short-term monitoring conducted by Stevenson (2009), regarding the equipment maintenance and appropriate monitoring durations. The re-visit approach in the research of Summerfield (2007) was neither feasible for this doctoral research, although the research methods provided the field monitoring with another methodological perspective. In addition, the large sample size used in the studies of Yohanis and Mondol (2010) and Summerfield (2007) was beyond the scope of available research resources in this study, which has not attempted to conduct statistical analysis using only one type of measurement in a large number of houses.

2.5.1.2 Energy use and power profiles

Some of the studies reviewed in the last subsection, such as that of Emery and Kippenhan (2006) and Summerfield (2007), already involved the monitoring of energy use. As is the case with hygrothermal monitoring, the measurement of energy use in different studies also relates to the project scale, equipment standards, house numbers involved, and investigation focus.

A series of monitoring and survey campaigns, known as the Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe (REMODECE), were conducted in households of the ‘EU-25+2’ countries at the level of domestic appliance end-use classified into 24 categories (REMODECE, 2008b). In the 12 participating countries (the UK not being included), 500 copies of detailed surveys out of 6,000 questionnaires and 100 successfully monitored households per country out of 1,300 measured homes were selected to enter the final REMODECE database (REMODECE, 2008a). The overarching objective of the project was to understand energy use in the ‘EU-25+2’ families. The monitoring interval of power draws at the end-use point was set at 10 minutes. The data were collected over a two-week period before the equipment was moved to another household (REMODECE, 2008a). The electricity use was monitored by professional metering devices, the Standby Energy Monitor (SEM) SEM-10 and NZR23 of SparoMeter® products. Although the accuracy level of these meters is much higher than that of most off-the-shelf products, the monitoring results were not used by the REMODECE to investigate power draw features but to conduct the comparable and statistical analyses of energy use.

Compared to a pan-European project such as the REMODECE, energy monitoring conducted by universities and research institutes usually targets at the breakthroughs in analysing power draw features. One example is the Reference Energy Disaggregation Dataset (REDD) project of the Massachusetts Institute of Technology (MIT) (Kolter and Johnson, 2011). The REDD dataset consisted of several weeks of power data from six different homes, including high-frequency data from the mains power once every second and from individual circuits and plugs once every three seconds. In two of the six homes, the super high-frequency sampling was conducted at millisecond intervals to enable feature extraction within a single cycle of AC current and AC voltage waveforms. For a 50 Hz (cycle per second) power system, the period of one cycle of AC current and AC voltage waveforms is 1/50 second or 20 milliseconds (Gibilisco, 2006). To extract the features from a single cycle waveform, the sampling interval has to be less than 20 milliseconds. In fact, according to the Nyquist–Shannon sampling theorem (Sveum, 2000), in order to reconstruct the target function of a signal cycle, sampling frequency is required to be higher than twice the original signal frequency. For 50 Hz AC signals, the sampling frequency is thus required be higher than 100 Hz in order to reconstruct the waveform from the samples that are acquired at least once every 10 milliseconds.

The REDD project of MIT was designed for the investigation of Non-Intrusive Appliance Load Monitoring (NIALM) algorithms, which are multidisciplinary approaches to disaggregate electric power loads. Aiming to break down the household electricity consumption from the one-point measurement at mains power into the end-use of individual appliances, NIALM was originally proposed by a MIT research team led by Hart (1992). The pre-condition to perform effective NIALM resides in the quality of load measurements. The focus of NIALM is the disaggregation algorithms that suit the respective sampling rates of available AC elements (Berges, et al., 2010; Zeifman and Roth, 2009). Most disaggregation approaches require the power draw features of individual appliances to be acquired from the Intrusive Appliance Load Monitoring (IALM) process (Kolter and Johnson, 2011). Therefore, the measurement of power profiles in the REDD project was conducted at the levels of both house use and individual circuits. The NIALM and IALM thus differ in the presence of individual circuit and appliance monitoring that is considered to be intrusive for the monitored household. Some non-plug loads, such as cooking and shower circuits, need to be monitored from the distribution box adjacent to the mains power inlet if the associated end-use is required (Kolter and Johnson, 2011). It is not always feasible to conduct such comprehensive power load monitoring, especially for the measurement at super-high frequencies, in an actual domestic environment. Therefore, most NIALM-associated research focused on the algorithm development, ranging from finite state machine learning to artificial intelligence, rather than the monitoring implementation in actual domestic environments (Liang, et al., 2010).

The research that investigates energy use in the built environment is different from the NIALM-related studies, which lie in the research field of electricity and electronics. However, a proper sampling frequency and an appropriate monitoring accuracy level are still major aspects to be considered. Wright and Firth (2007) investigated to what extent the monitoring intervals of power draw and supply, when renewable microgeneration is on site, would suit research objectives in the built environment. By using one-minute power profiles from seven houses and performing a time-averaging process to convert the data to five-minute, 15-munite, and 30-minute data prior to superimposing them for comparisons, Wright and Firth (2007) concluded that the five-minute interval can suffice for the monitoring purpose of renewal power supply but not for that of house use, since the averaged power draws of house use were found to be skewed in some instances. In the field of Building Performance Evaluation (BPE), the recommended measuring interval of electricity use by the EST protocol (2009; 2011) is five minutes, which has been implied in the RFF and BPE programmes of the TSB (2013b). How to select the appropriate monitoring interval and accuracy levels to suit the research topic of energy-related occupancy activities was a key aspect in the design and deployment of experimental work in this study. The associated methods and applications are further discussed in Chapters Three to Five.

2.5.1.3 Occupancy statuses

The presence and motions of occupants are two major occupancy statuses that are commonly captured by direct or indirect monitoring approaches. The measurements are either used to enhance the multi-category monitoring scheme or applied independently in a specific research field. Direct methods include the use of a vision-based system, such as the cameras that were used in an office environment by Benezeth, et al. (2011). The potential interference with privacy and the demand for a large capacity of data storage for long-term monitoring make the vision-based system rarely witnessed in a domestic environment, where indirect monitoring is usually adopted as an alternative. One of the indirect monitoring approaches is to use Passive Infrared (PIR) sensors for the monitoring of occupants' motions. However, the potentially sedentary statuses of residents tend to be missed out by PIR and are thus recorded as absence statuses. Therefore, the use of PIR is often accompanied by other types of environmental parameter measurements. Dong (2009; 2010) applied an event-based pattern detection algorithm to extract the office workers' presence and motions by using a data acquisition toolkit that, in addition to PIR measurements, measured hygrothermal conditions, CO_2 contents, acoustics levels, and light intensity. Puteh, et al. (2013) and Mahmoud, et al. (2013) applied the purpose-built toolkits, which included door contact detectors, temperature sensors, light intensity sensors, and electrical current sensors, in both office and home environments to extract energy-related events by using stochastic process and Artificial Intelligence algorithms. The application of wearable intelligence products onto monitored occupants is an approach that lies between the direct and indirect monitoring of occupancy statuses. Spataru and Gillott, (2011) used the ultra-wideband radio frequency (RF) location system in a 1930s replica of a three-bedroom semi-detached house located on the University of Nottingham campus to track the space use of occupants. Based on the assessment of the research topic and monitoring environment in this project, the indirect monitoring of occupancy statuses accompanied by other monitoring parameters was selected to acquire occupancy statuses.

2.5.2 Sociological approaches

Sociological approaches are either applied independently in a research project that has no physical measurements, or jointly conducted in a multidisciplinary project to enhance the physical monitoring. The Energy Saving Trust (2014) compiled a topic guide for occupant evaluation in the RFF and BPE programmes of the TSB. The guide aimed to acquire feedback from post-retrofit households rather than to investigate actual energy end-use. In contrast, the questionnaires were used in the aforementioned REMODECE project (2008a; 2008b), which aimed to understand domestic electricity end-use. To obtain statistical strength, a large and representative sample size is required for the questionnaire-based approach. The valid 500 surveys obtained from the 1,300 households in the REMODECE (2008a; 2008b) project can be considered as having a relatively high response rate. Andersen, et al (2009) in Denmark posted 5,000 invitations for a questionnaire-based survey. With a completion rate of 19 per cent, 933 valid samples were obtained for repeated surveys in two seasons. After the two-round surveys, only 636 fully responding household samples were acquired by Andersen, et al (2009), who aimed to explore the possibilities in defining a regional or national standard of behavioural patterns for a future usage in energy simulation. Compared to the study by Andersen, et al (2009), the strength of the

REMODECE project arose not only from the large and representative sample size but from the presence of on-site monitoring. Without field measurements, survey data cannot fully reveal the features of socio-technical phenomena (Yohanis, 2012).

Sociological approaches also include the sourcing of data from a third party. Santin, et al. (2009) attempted to compare the holistic impact of occupancy and building characteristics on actual energy consumption. Rather than conducting a purpose-designed survey, Santin, et al. (2009) used the Kwalitatieve Woning Registratie (KWR) database of the Housing Ministry in the Netherlands and bills over three years from energy providers. The interview-based KWR national database included 15,000 households that were registered in a survey that included information on housing quality, household characteristics, and occupancy behavioural patterns.

In the field of indoor environment, surveys are commonly used to investigate determinants, such as gender, age, income, and education levels, in an adaptive thermal comfort model (Karjalainen, 2011). For example, the ventilation behaviours of window opening and thermostat setting are directly related to actual energy use. Most of the identified occupancy-associated determinants have the potential to be considered in the development of building simulations (Wei, 2014). Sociological approaches come in multiple forms in addition to questionnaire-based surveys and interviews. Yun, et al. (2009) conducted a sub-hourly observation to gather window use data from several modern UK offices. The observations were used to develop a Monte Carlo Markov Chain (MCMC) algorithm for naturally ventilated offices.

2.5.3 Mathematical and computational approaches

Statistics regression, stochastic process, and Artificial Intelligence (AI) algorithms were applied in most of the previously reviewed studies. For example, an improved HHD regression was established between heating energy use and indoor-outdoor temperature difference by Emery and Kippenhan (2006); a stochastic algorithm was designed by Dong (2009; 2010) to extract sequential occupancy events; an AI algorithm was built by Mahmoud, et al. (2013) to identify and predict occupancy patterns in intelligent environments. It is beyond the scope of this research to investigate each of these approaches in detail. One aspect that is missing from the mathematical and computational approaches applied in relevant research is the numerical analysis methods of electric power that are focused on in this subsection.

By examining half-hourly electricity use from 27 houses in Northern Ireland over the period December 2003 to September 2005, Yohanis, et al. (2008) performed a macro-scale analysis. The electricity data was grouped according to different building characteristics, such as bedroom numbers, built forms, and daytime occupancy. Except for the regression that was established between floor areas and total electricity consumption, only visualisation-based presentations were conducted by Yohanis, et al. (2008). Kilpatrick (2011) discussed a separation filter that was designed and applied to a real-time domestic power dataset. The standby and cold loads were filtered first, followed by other relatively complex power loads. The algorithm was based on rigid Boolean Logic using direct value comparisons.

While relatively straightforward methods for data presentation or filtering were used by Yohanis, et al. (2008) and Kilpatrick (2011), diversified mathematical and computational methods in load disaggregation were applied in the NIALM research. Zeifman and Roth (2009) critically reviewed the techniques applied in NIALM studies over the past 25 years. Most of these techniques are in the *supervised* learning format that requires the stage of IALM to collect targeted end-use features, except for the work of Kim, et al. (2011). The latter described how Factorial Hidden Markov Models (FHMMs) can be used for *unsupervised* NIALM, requiring only a one-point measurement at mains power. Artificial Intelligence (AI) approaches were also applied in NIALM research, such as the Fuzzy rule-based Inference System (FIS) modelling used by Baranski and Voss (2003).

Regarding the extraction of occupancy activities from energy use profiles, there are two seemingly opposite research directions in the discipline of electricity and computational science and the field of built environment. The former direction has been endeavouring to push the sampling frequency of AC parameters to the technological limit. By doing so, advanced algorithms are applied in order to utilise acquired features for the extraction of targeted occupancy events. In contrast, the latter direction strives to construct the simulated household electricity use through surveyed time-of-use and associated modelling algorithms. Widén, et al. (2009) built a model to generate load profiles for household electricity and hot water usage from time-of-use data. The TU-SCB-1996 dataset that was drawn on by Widén, et al. (2009) contained the survey results, which included information on time-of-use of the activities relating to energy use of a large number of Swedish households in the year 1996. In 179 households, 464 residents who were no younger than 10 years old were asked to write an occupancy diary on one weekday and one weekend. The timing of activities, geographical location and transportation use were all required to be entered in the diary every five minutes or every one minute in the diary-keeping day. Finally, 431 residents from 169 households produced valid diary recordings to be included in the TU-SCB-1996 dataset, which was used as the input of a purpose-built algorithm to infer the power amplitude by Widén, et al. (2009). The house use profiles were thus constructed by classified occupancy activities. Richardson (2010) and Ellegård (2011) conducted similar research on the construction of daily energy usage using associated time-of-use datasets, although different algorithms were developed in each model.

The two seemingly opposite research directions supplement each other. Not all the houses can be measured to the standard of NIALM that utilise super-high measuring frequency as in the reviewed REDD project undertaken by MIT. If it is feasible to accurately construct scenarios of daily energy consumption using information in the survey results on time-of-use, the survey approach undertaken by Widén, et al. (2009)

can be used as a substitute for occupancy activity monitoring for a wide range of applications. No matter which approach is used, either to disaggregate measured house use profiles or to aggregate surveyed time-of-use, the extraction results enable a better understanding of energy use related occupancy activities. A proper feedback process whereby the extraction results are presented to house residents can potentially initiate changes in energy use behaviours (Wood, 2007; Ueno, et al., 2006).

2.6 Chapter summary

A wide range of literature, ranging from the background of energy use and indoor environment to the research approaches used in associated studies, has been comprehensively surveyed in this chapter to identify and justify appropriate methods in this research. The cost-effective monitoring that suits the research aim and objectives and appropriate sociological approaches that enhance physical measurements underpin the data acquisition methodology in Chapter Three. The Energy Saving Trust's monitoring protocol (2009; 2011) provides a methodological guidance for this research in the selection of appropriate measuring variables, sampling frequencies, and sociological methods. In addition to visualisation-based inspections of field measurements with the assistance of information acquired using sociological approaches, algorithm-based examinations using multidisciplinary numerical methods are explored in the methodology section of data presentation and analysis in Chapter Three.

Chapter 3: Research Methodology

3.1 Introduction

Energy-related occupancy activities are directly associated with energy use, indoor environments, building characteristics, and occupancy statuses. Multiple research approaches, including the monitoring, sociological, and mathematical methods applied in associated studies, have been reviewed in Chapter Two. It is important to select appropriate methods, the methodological features of which can suit the socio-technical characteristics of the research topic and data profiles involved in this study. 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. In line with Yin (2014), the research unit was defined as a case study. This project was thus underpinned by two purposefully selected case study groups. The selected research approach and associated analysis techniques, including the longitudinal, long-term, and mixed-method monitoring in case studies and the Analysis of Variance (ANOVA) and Adaptive Neuro-Fuzzy Inference System (ANFIS) analytical approaches are justified in this chapter.

3.2 Mixed methods research

The term ‘mixed methods’ or ‘mixed approach’ originated from the discussion engaged in by Campell and Fiske (1959 cited in Osborne, 2008, p.125) on various perspectives, traits, and methods from which a multidisciplinary phenomenon can best be investigated. The development and acceptance of mixed methods in academia has undergone five stages, according to Creswell and Plano Clark (2007 cited in Bryman, 2012, p.630). A formative period during the 1950s to 1980s preluded a paradigm debate period in the 1970s and 1980s, during which time a number of prestigious researchers including Alan Bryman contributed to the academic acceptance of mixed methods from the epistemological and paradigmatic perspectives (Bryman, 2012). Following the procedural deployment period from the late 1980s when the design of mixed methods studies were fully investigated, an advocacy period began in the twenty-first century along with increasingly emerging research projects boasting multidisciplinary features (Bryman, 2012). The reflective stage started around 2005, when researchers launched a thorough assessment of the state and direction of mixed methods research (Bryman, 2012). The epistemological and paradigmatic debates are beyond the scope of this research, which directly applied mixed methods through the integration of quantitative and qualitative research strategies in the process of data acquisition and analyses.

One major reason mixed methods were applied in this research was to holistically investigate the socio-technical research topic of energy-related occupancy activities. Bryman (2012) pointed out four aspects underpinning the quantitative and qualitative contrast: behaviour versus meaning, theory testing versus concept exacting, numbers versus words, and artificial versus natural. As regards the first aspect, quantitative approaches in this research were applied to explore the targeted energy use activity patterns emerging from data profiles. Qualitative tactics were adopted to interpret the impact of energy use activities on actual energy use and indoor environment. Where the second aspect is concerned, qualitative and quantitative approaches in this research were not clearly divided since both were used to extract targeted occupancy activities. No theoretical hypothesis was set for testing regarding the existence of discrepancy in actual energy use, except for examining the actual extent of the discrepancy due to variations in built forms and occupancy activities. The third aspect describing the contrast between both approaches was directly embodied in the data formats of this research, such as the physical measurements in numerical figures and the informal interviews in narrative form. The final aspect of the contrast was interpreted by Bryman (2012) in terms of the difference between artificial aspects of questionnaires and interviews and natural features of ethnographic participant-observations. In this research, the participant-observations were conducted by digital devices over most of the monitoring period and enhanced by the researcher herself in monthly site visits. The informal interviews conducted and occupancy diaries collected in certain site visits were used to corroborate findings from physical measurements.

Bryman (2012) conducted a mixed method investigation into mixed methods research, by searching the Social Sciences Citation Index (SSCI) for journal article samples that applied mixed methods and conducting semi-structured interviews with 20 selected authors. The classification outcome was a list of 16 approaches to perform mixed methods research by combining quantitative and qualitative research strategies. Eight of the 16 tactics were relevant to the context of this research and some have been mentioned above in justifying the application of mixed methods. For example, occupancy diaries and informal interviews were used to *corroborate* physical measurements. The quantitative results were used to *explain* the qualitative findings. The two approaches were used for *instrument development*, the outcome of which can potentially contribute to other similar research projects in the future. The *credibility* of employing both approaches was to enhance the integrity of findings. The use of quantitative findings enriched the qualitative information via *illustration*. The qualitative information was used to improve the *utility* of useful quantitative findings since quantitative approaches were more prominently used in this research. The *diversity of views* of research participants were revealed by combining the researcher's and participants' perspectives. The *enhancement* of research findings were thus realised in the investigations of energy use related activities.

Bryman (2012) also pointed out that mixed methods research should not be considered as a universally applicable method. To produce integrated and interpretable results, the selected approaches that suit the research subject and area should be competently designed and professionally conducted. In addition, the application of mixed methods should thoroughly consider the resource limits of a research project to prevent the diluting of research focus and effort (Bryman, 2012). These principles are embodied in the following subsections, which focus on the design and implementation of mixed methods for data acquisition and analysis.

3.3 Methodology of data acquisition

3.3.1 Longitudinal and long-term case study approach

A longitudinal study or investigation is terminology borrowed from the sociological and medical research fields, where observations are conducted on the same group of individuals over the extended study period of years or decades to examine changes over time (Karlsson, 2009). This research method is also used by building service researchers to investigate and predict the changes in the operational energy of non-domestic buildings (Brown, et al., 2010; de Wilde, Tian and Augenbroe, 2011). The energy use data of buildings and associated plants are collected using various metering devices rather than by researchers themselves as in sociological and medical studies. Consistent data profiles from and permitted accessibility to the studied buildings are the basis of effective applications of longitudinal methodology. Therefore, it is less-commonly witnessed in research on domestic buildings, especially when various building technologies and statistically sufficient building numbers are considered factors in holistic investigations on the energy use and indoor environment.

Consigned by the Retrofit for the Future (RFF) programme of the Technology Strategy Board (TSB), the Energy Saving Trust (EST) compiled the monitoring guidance and protocol as the baseline for measuring and reporting results relative to different retrofitting techniques and renewable energy technologies (EST, 2009). The short-term testing and long-term monitoring were respectively defined in the EST protocol as one-time tests for fabric and mechanical elements and frequent measurements of energy use and indoor / outdoor environments over at least two heating seasons (EST, 2009). According to the whole-house carbon and energy monitoring protocol of the Energy Saving Trust (2011), a sample size of 100 or at least 25 buildings is required to form test and control groups in order to investigate the improved energy performance under the influence of each type of newly added feature, such as enhanced insulation or air-tightness, by using on-site measurements.

The well-designed protocols for data acquisition and the large amount of investment in system installation and maintenance from the initial stage prior to data acquisition and analysis demand a powerful project platform far exceeding one doctoral research team. The associated resources were available to the RFF and Building Performance Evaluation (BPE) programmes of the TSB. However, it was infeasible even for such a powerful platform as the TSB to cover the majority of existing housing stock in the UK in the RFF and BPE or other similar major investment programmes. Post-occupancy evaluation (POE), which is one part of the BPE, should ideally not be limited to newly built homes or recently retrofitted houses, since the impact of occupancy activities on actual energy use and indoor environment is likely to be of interest to other types of occupiers and associated stakeholders. The research gap in applying the longitudinal and long-term approach and associated protocols to a wide range of housing stock led to the first research question:

- How to effectively apply the longitudinal and long-term approach in a small-scale research, especially a study on energy-related occupancy activities?

The fact that this is a ‘how’ type of question justifies the inclusion of case studies as an appropriate research method. Indeed, Yin (2014) defined the case study as a type of empirical method to answer a ‘how’ or ‘why’ research question that comprehensively investigates a contemporary phenomenon, over which a researcher has little or no control, in the real world context. Energy-related occupancy activities in actual homes fit the method definition. Yin (2014) also pointed out that a case study inquiry relies on multiple sources of evidence with acquired data converging in a triangulated fashion. Mixed method research on energy-related occupancy activities integrates qualitative and quantitative approaches to corroborate research findings, meaning that case studies can feasibly be applied within this context. Bryman (2012) stated that case study research frequently includes longitudinal elements, especially when a researcher participates in a lengthy observation period. In fact, the longitudinal case study is one of five types of case study categorised by Yin (2009 cited in Bryman, 2012, p.70). Therefore, the longitudinal and long-term features are compatible with the case study method. A frequently quoted limitation of the case study method is the difficulty in generalising research findings (Bryman, 2012). Bryman (2012) also provided counter arguments from case study researchers, who strived to meet the criteria of reliability, replicability, and validity but asserted that generalisability has never been the purpose of the case study method. Case study design involves the selection between a single-case and multi-case study and the justification of levels of adaption allowed during the data acquisition process (Yin, 2014). Resource restrictions in terms of time and cost also need to be considered in the case study design stage (Bryman, 2012; Yin, 2014). In the following subsections, the selection of appropriate case study groups and data acquisition approaches are discussed on the basis of the case study design required for this research.

3.3.2 Selection of research case studies

Although it features the merits of direct acquisition of physical measurements, longitudinal and long-term monitoring, even in the TSB's major investment projects, cannot feasibly be as widely implemented in a large number of houses as questionnaire-based data acquisition. Unlike the RFF and BPE programmes that used longitudinal and long-term monitoring approach to test the effectiveness of certain types of building technology or retrofitting technique, this research aims to investigate actual energy-related occupancy activities associated with actual energy use and indoor environment. In order to generate comparable measurements, it is important to select case studies that fit the research context and are representative or 'exemplifying' (a term preferred by Bryman (2012)), rather than purely emphasising the sample size. Considering the available research resources in terms of time and cost, the appropriate number of case study houses to be purposefully selected for this research was identified as two case study groups with two or three houses in each group.

Energy-related occupancy activities, fabric and service performance, and external environment are three interactive factors that need to be considered in the selection of case studies. Although each building group features unique microclimate characteristics to a certain extent, choosing 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 of each of the two case study groups enables a holistic assessment of energy-related occupancy activities based on different building characteristics. In addition, the cooperation with and the support from case study homes are of great importance for data quality maintenance, which is closely associated with the frequency of site access and proper equipment management. The two case study groups that are presented in Chapter Five were selected based on these aspects.

The second and third research questions, which are answered in the next subsection, derived from the identification of appropriate intensity levels of long-term monitoring in the purposefully selected case studies.

- How to select monitoring variables that suit the research topic of energy-related occupancy activities?
- What are appropriate monitoring levels and techniques that are transferable to the majority of existing domestic buildings?

3.3.3 Low-cost and less-intrusive monitoring approach

To examine energy-related occupancy activities and the associated energy use and indoor environment, occupancy statuses that were not included in the EST monitoring protocol (EST, 2009; 2011) were added in the monitoring scheme of this research. The monitoring variables relating to building fabric performance are not directly associated with the research topic and were thus excluded. Unlike the RFF and BPE programmes of the TSB, the indoor temperature (T) and relative humidity (RH) monitoring in this research covered multiple indoor living zones, including kitchen and bathroom areas that were not recommended by the EST monitoring protocol, due to concerns about potential damages to monitoring devices by the extra humidity in these areas. Loggers with appropriate dust and water resistance levels were used in such circumstances to trace the variations in T and RH variables, from which energy-related occupancy activities relating to cooking and shower events can be inferred to certain extent.

The electricity measurement in this research was extended to the level of individual appliances, since end-use is directly related to the research topic. In contrast, the EST monitoring protocol only included readings at the level of utility meters, which should have pulse output for data communication with the EST-stipulated data acquisition system (DAS). The mechanical utility meters that had no pulse output in the RFF and BPE programmes were thus replaced or supplemented with a secondary meter by the TSB project participants. To sustain the higher levels of power draws by EST-stipulated systems compared to self-powered and distributed devices, an extra power supply was required with incurring fees being compensated to the TSB project occupants (EST, 2009; 2011). Due to limitations imposed by the actual situation and available resources, this type of meter replacement or circuit alterations is infeasible in most existing houses. As stated in the EST monitoring protocol (2009), the EST-stipulated data acquisition system suits new or newly retrofitted buildings that already have the required wiring systems built in, such as wired or wireless telecommunication systems for centralised data transmission and storage and digital utility meters with pulse output.

The post-occupancy interview report on 10 households of the RFF programme was compiled by the Institute for Sustainability and researchers from University College of London. Some interviewed households expressed their dissatisfaction about the monitoring system as being oppressive and intrusive in addition to taking extra space. Others expressed their bewilderment at being spied on by housing associations (Institute for Sustainablity, 2013). Intrusiveness levels can be apprehended from various perspectives, including the presence and aesthetic appearance of monitoring equipment in houses, the psychological influence of monitoring systems on the studied occupants, and the relatively frequent access to the studied homes for data download and equipment maintenance. In the specific research field of Non-Intrusive Appliance Load Monitoring (NIALM), intrusive and non-intrusive monitoring are differentiated by the fact of whether the appliance loads are measured beyond the level of mains power. Some intensive monitoring projects reviewed in Chapter Two, such as the REDD project of the MIT (Kolter and Johnson, 2011) and the REMODECE pan-European project (REMODECE, 2008a), did not take the long-term and longitudinal approach. The intrusiveness level was thus not highlighted as strongly as it was in this research project. Other reviewed research projects used vision-based systems, such as cameras, in an office environment (Benezeth, et al., 2011). This type of intrusiveness is beyond the scope of this research project since the domestic environment has more privacy concerns. The access to monitored case studies, if controlled at an acceptable level, such as monthly site visits, can lower the intrusiveness level and assist in equipment maintenance. Therefore, distributed, less-intrusive, self-powered, and off-the-shelf equipment was selected for this research project. The power demand by monitoring equipment that requires plugging into a domestic socket was controlled at an acceptable level. An extra advantage for this type of scheme configuration is that the distributed devices are inconspicuous to the residents and thus lower the psychological impact on the occupants, who behave naturally in the monitored environment. The actual occupancy activities are thus objectively revealed by the acquired data. In addition, less-intrusive equipment is relatively easy to acquire from off-the-shelf product suppliers. The simple monitoring technique is transferable to a wide range of households that cannot be covered by the major investment programmes of the TSB.

The cost of measuring devices is another key issue relating to monitoring technique transferability. Without performing energy end-use and occupancy status measurements and with fewer monitored living zones, the approximate cost per household given by the EST monitoring protocol was £1,900 (EST, 2011). This estimate excluded the measurement of renewable energy and building fabric, costs relating to the retrofitted wiring system, and electricity used by the system in TSB programmes. In contrast, the distributed system in this research not only featured relatively low costs but flexibility of equipment reuse and redeployment to other houses after completion of the research project. The actual costs varied depending on the layout of the monitored houses. For example, the number of monitored windows and doors and living zones differed among case study houses. The costs are tabulated individually for each case study involved in this research project in Chapter Five. The experimental work, including the selection of monitoring devices and configuration of off-the-shelf equipment, is introduced in Chapter Four. One major drawback of using distributed and low-cost off-the-shelf products resides in lower control over the quality of acquired data.

Prior to using the measurements for further analysis, appropriate pre-processing procedures are required as discussed in Chapter Six.

3.3.4 Supplementary sociological methods

In addition to applying monitoring approaches to acquire physical measurements in the houses under study, sociological methods are commonly used to explore behavioural changes of occupants in the BPE and POE studies. For example, the EST was appointed by the TSB to compile interview guidance for the occupant evaluation process of the RFF programme (EST, 2014). Energy-related occupancy activities in this research can be considered as a subset of the POE study, although the research emphasis is more on the occupancy element and less on the building aspect. Appropriate applications of sociological methods, as a form of mixed methods research, can enhance low-cost monitoring in the following ways.

An occupancy diary was designed for this research to validate the information extracted from physical measurements. A blank copy of the diary can be found in Appendix One. The raw data collected by the low-cost monitoring system in this research, especially the measurements of electricity use and power draws of individual appliances, were subject to multiple equipment-inherent factors that are discussed in Chapter Four and Chapter Six. Prior to being used for further analyses, the raw data were pre-processed using purposely-compiled signal filtering programmes. The diary was used to attest the signal-filtering results in addition to acquiring information on the occupancy routines of monitored households.

Informal interviews were conducted during site visits that were mainly arranged for the purpose of data download and equipment maintenance of the distributed monitoring system. Unlike the procedures described in the formal interview guidance drawn up by the EST, the informal interviews took the approach of rapport-building with the occupants who were present during certain site visits. The walkthrough part recommended in the EST guidance was conducted not only during the informal interview but in the process of data download in each monitoring living zone. The observations on certain energy-related occupancy activities were thus conducted and key information recorded. For example, space heating and ventilation habits that were not covered by occupancy diaries were directly observed during certain site visits. Some uncertain information extracted from the physical monitoring, such as uncopied time periods, use status of certain appliances or windows / doors, and approximate starting time and durations of power breaks, can be confirmed by the feedback given by the occupants during informal interviews. The monitoring contents could therefore be adjusted according to the feedback from the residents to fully explore the flexibility advantage of the low-cost and distributed monitoring system, which was deployed in phases rather than in a fixed format of design and installation as was the case in the RFF programme of the TSB.

Formal interviews in the semi-structured format recommended in the EST guidance were applicable in certain case study houses. One case study in this research was conducted in collaboration with a social landlord. The formal interviews were thus jointly conducted with a project investigator of the social landlord to examine the health conditions and post-retrofit satisfaction levels of the social tenants, although not all information acquired in the formal interviews was directly related to the research topic of energy-related occupancy activities. Together with the other two types of sociological approaches, the jointly conducted formal interviews enhanced the physical monitoring from different perspectives.

3.4 Methodology for data presentation and analysis

The three categories of monitoring variables, which were acquired using the longitudinal and long-term monitoring approach, required different presentation and analysis methods to serve the research aim of examining energy-related activities and the associated impact on energy use and indoor environment. The pre-processing of raw data acquired by using low-cost monitoring scheme is discussed in Chapter Six. This section focuses on the visualisation-based and algorithm-based examination methods that are applicable to the pre-processed data. The actual examination results of the case studies are respectively presented in Chapter Seven and Chapter Eight.

3.4.1 Visualisation-based presentation

The visualisation-based presentation of multi-category data was manually conducted to recognise the distributions and interrelationships of data points with the assistance of appropriate scales of display. The measurements were inspected on the macro-scale and micro-scale that refer to the temporal scale of data presentations. For example, the macro-scale presentation of temperatures and electricity use measurements over the entire monitoring period can assist in revealing time-series features, such as seasonality and trend. In the case study homes that were served by mains gas, certain features of gas use for space heating can be indirectly inferred from the visualisation-based examinations on hygrothermal variables with the assistance of simultaneously measured ventilation behaviours. The HDD regression can be produced by using the averaged outdoor temperatures and the manual recordings of natural gas use. Although not directly usable for activity extraction, the HDD regression can assist in disclosing the difference in baseline temperatures between the studied homes. The macro-scale display of manually recorded electricity and gas consumption can also reveal the general ratios of energy use in different homes.

Based on the macro-scale presentations, data profiles of certain days with specific weather features or energy use characteristics can be selected to perform micro-scale inspections by comparing the simultaneous measurements of hygrothermal conditions, power draws, and occupancy statuses. The tracking trajectory between indoor and outdoor hygrothermal conditions not only results from energy-related occupancy activities but also relates to specific building characteristics. For example, the indoor hygrothermal conditions in unoccupied circumstances track the outdoor conditions under the influence of building performance. The indoor temperature and relative humidity (T and RH) vary inversely to each other in the same way as the simultaneously recorded outdoor T and RH. However, the variation amplitude is closely related to the building characteristics, such as thermal mass levels and insulation standards. In an occupied environment, some energy-intensive occupancy activities, such as space heating, are featured by localised variations in the hygrothermal conditions. The similar microclimatic conditions of two geologically vicinal case study groups facilitate the cross-comparison of micro-scale presentations of simultaneously measured data profiles in different houses.

3.4.2 Algorithm-based examinations

The macro-scale and micro-scale presentations provide insights into some basic features of indoor environment and energy use in the monitored houses and form the basis of algorithm-based analyses. The algorithm-based examinations in this research refer to the process of using relatively advanced methods to investigate data profiles and succinctly summarise hidden regularities. Two types of inspections were respectively conducted on the measurements of hygrothermal conditions and power draws in case study homes, with the analysis methods being sourced from the fields of statistics and Artificial Intelligence (AI).

- To examine the difference in indoor environmental conditions associated with energy-related occupancy activities and building characteristics;
- To explore the electricity end-use associated with the difference in actual energy use, by examining the interrelationships of power draws of house use and individual appliances.

3.4.2.1 Applying ANOVA methods to examine hygrothermal conditions

Conventionally, statistical tests are applied on limited numbers of samples to infer population characteristics. The test results are used to prove whether or not the characteristics of collected samples can represent those of the entire population within an accepted confidence interval (Osborne, 2008). Statistical tests usually assume that the data are independently and randomly sampled and follow certain types of distribution (Sproull, 1995). However, the real-time measurements in this research do not fit the conventional context of statistical tests. Although they are recorded at various intervals rather than continuously, the temperature and relative humidity (T and RH) variables are not random samples but inherent elements of the time-series recordings. From the perspective of statistical concepts, these measurements can be considered as a population rather than randomly collected samples. Therefore, the statistical analysis was conducted in this research not to infer the population characteristics but to grasp the statistical features of measurements within and between respective groups. Depending on the analysis scales, the group defining factor can be different living zones in a single house, or different houses in a case study, or different case studies in the research. The difference in building characteristics, space heating habits, and ventilation preference of the monitored homes has been embodied in the comparison process of the mean and variance in indoor hygrothermal parameters.

To perform efficient analyses beyond the manually conducted process of macro-scale and micro-scale examinations, Analysis of Variance (ANOVA) was applied to hygrothermal variables, especially the temperature measurements. As a measure of dispersion, variance relates to the extent to which the parameters vary between elements in a sample group, such as hygrothermal measurements in daily recordings of one specific zone. It is an indicator of how much the value of an individual element varies from the group mean, which is a measure of the central tendency of all elements. By assessing the variance of all sample groups, conclusions within an acceptable confidence interval can be reached as to whether or not the data from several groups have a common mean. If so, the samples of different groups are considered to be sourced from the same population. If not, the samples of each group have unique characteristics in terms of central tendency and dispersion.

ANOVA comes in many forms, including one-way ANOVA, two-way ANOVA, and n-way ANOVA, which differ in the categories of group defining factors (Sproull, 1995). N-way ANOVA is used to handle data having more than one category of defining factors. When dealing with two group categories, n-way ANOVA can be used as an alternative to two-way ANOVA. Using one group category, monitored living zones, the ANOVA results can suffice for the purposes of algorithm-based analysis in this research. Therefore, one-way ANOVA, which is described by the following linear model as quoted from (Osborne, 2008), was applied to temperature measurements in this research.

$$y_{ij} = \mu_{.j} + \varepsilon_{ij}$$

in the context of this research:

- y_{ij} is a matrix of measurements in which each column represents a different group, such as different monitored living zones;
- $\mu_{.j}$ is a matrix whose columns are the group means (the '.j' denotation means that the mean value μ applies to all rows from the first measurement to the i^{th} measurement in column j);
- ε_{ij} is a matrix of random disturbances.

ANOVA consists of two important concepts, which are within-group variance and between-group variance (Gary, 2006). Within-group variance relates to how much the values within a group vary from the mean of that specific group. Regarding the hygrothermal measurements in different zones of a home, this type of variance refers to the different levels of T or RH in each monitored zone. A small within-group variance suggests that the T or RH values of the zone have remained at a relatively stable level. A within-group variance approximating to zero suggests that the T or RH values have remained almost unchanged. In contrast, a large within-group variance means that the particular zone witnessed drastic changes in T or RH conditions. Severe changes might potentially result from energy-intensive occupancy events, such as shower in the bathroom or cooking in the kitchen. Under extreme weather conditions, the variations can also arise from the combination effect of space heating, ventilation behaviours, and specific building characteristics.

Between-group variance is associated with the extent to which groups appear to differ from one another. The variance in T or RH values that is apparently exhibited in a certain group might be an exclusive feature within that specific group or might just be down to the large variance across all groups. The way to examine which is the actual case is to look at between-group variance. Regarding the aforesaid measurements in different living zones of one home, there is a certain amount of variance across all living zones. Extremely high or low values of T and RH parameters can be witnessed in a certain living zone as explained by within-group variance. Extreme hygrothermal conditions in one living zone can potentially lead to associated fluctuations of hygrothermal conditions across the entire house, especially when different zones are interconnected with each other. It is also possible to witness variations in one living zone only if the zone in question is relatively isolated from other living zones, or if ventilation measures are adopted in the zone right after the occurrence of targeted energy-related occupancy events.

The ANOVA results can be used to assess the effect that group membership exerts on the T and RH variables. For example, when within-group variance is significantly larger than between-group variance, the associated test result can be obtained to prove that the two groups of samples have been taken from distinguishable populations. As the starting point for ANOVA, a null hypothesis states that variance is not affected by group membership. It is equivalent to saying that the samples have been taken from the same population with a common mean. Representing the ratio between within-group and between-group variance, the F statistic is calculated to identify the statistical significance (p-value) that is used by ANOVA to determine whether or not to reject the null hypothesis of common mean across all groups (Osborne, 2008). With a p-value less than 0.05, it is statistically safe to state that the null hypothesis is not true and can be rejected.

Osborne (2008) pointed out the importance of assumptions prior to performing ANOVA tests, although the F statistic is relatively robust as an alternative to ANOVA that utilises the F statistic to calculate p-value. Three key assumptions are independence of observations, normality in population distributions, and homogeneity of population variance (Sproull, 1995; Gary, 2006). The T and RH measurements in different living zones can influence each other via the functional design of houses and occupancy activities, thus the hygrothermal data as digital observations of indoor environment are not independent among different groups of living zones. Neither are normal distributions of T and RH guaranteed, especially when using short-term measurements that only derive from limited numbers of observations. The case study houses were purposely selected to feature the differences in building characteristics and energy use activities. The already-known difference defies the third assumption relating to homogeneity of population variance. Therefore, compared to the final output of p-values, the interim outputs of the two types of variance and associated F statistic, which is more robust when different groups have identical numbers of observations (Osborne, 2008), are more meaningful in the context of this research. Regarding the hygrothermal measurements, there are four combination scenarios for the two types of variance:

- **Scenario A:** If the between-group variance is large, and the within-group variance is also large, then it can probably be concluded that the hygrothermal levels vary intensively but distinctively in each living zone;
- **Scenario B:** If both types of variance are small, then the hygrothermal conditions are relatively stable across all living zones;

- **Scenario C:** If the between-group variance is large but the within-group variance is small, then each living zone has distinctive but stable hygrothermal conditions;
- **Scenario D:** If the between-group variance is small but the within-group variance is large, then the T and RH values vary intensively to a similar extent across all living zones.

Scenario A means that the monitored house features functional divisions of living zones. Each zone has distinctive and intensive occupancy activities. The relatively stable T and RH levels of the entire house in Scenario B are probably due to certain building characteristics, such as thermal mass levels, ventilation measures, and probably interconnected design of indoor space. The relatively low level of occupancy activities is another probable reason for generally stable indoor conditions, depending on the tracking trajectory between indoor and outdoor hygrothermal conditions. The distinctive variations in T or RH levels in Scenario C are probably caused by different functional divisions of living zones, within each of which the hygrothermal level is relatively stable due to specific building characteristics or occupancy activity levels. In Scenario D, the indoor T and RH in all living zones probably track the outdoor conditions in most circumstances due to the light-weight thermal mass and inter-connected design of indoor space. The variations in hygrothermal conditions in all living zones respond quickly to the influence of space heating and ventilation behaviours in a certain living zone.

The ANOVA test in this research was performed by applying the ANOVA functions in Matlab® Statistics Toolbox on the pre-processed hygrothermal measurements that have identical intervals and numbers for data from each living zone over the same time period. The T and RH recordings in different living zones were pre-processed and synchronised as exemplified in Chapter Six to construct the Matlab®-required format of matrices, with each column containing the time-series measurements of a living zone.

The ANOVA results and associated box plots and mean comparison graphs, which are presented in Chapter Eight, can be considered as an advanced type of visualisation-based examination of hygrothermal measurements. Although *p*-value, *F* statistic, Sum of Square (SS), and Mean Square (MS) are not of importance within the context of this research, these ANOVA results are still included in the demonstrations provided in Chapter Eight. Box plots and mean comparison graphs are exemplified in Figure 3-1, which takes the car mileage of manufacturers in different countries as an ANOVA test example.

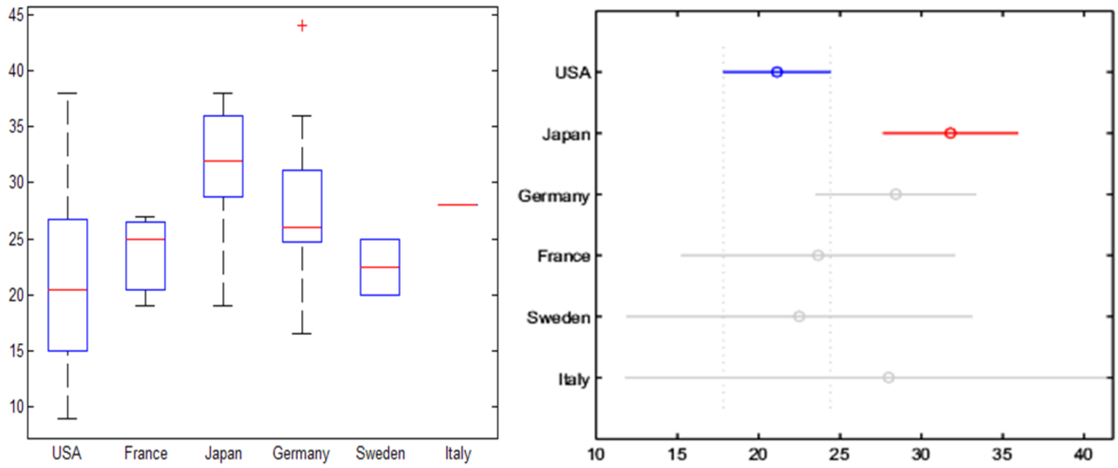


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Figure 3-1 Exemplary box plots and mean comparison graphs produced by ANOVA test using Matlab® statistics toolbox (From the Matlab® support documentation (MathWorks, 2014))

The line in the middle of each box plot in Figure 3-1 is the median mileage value of each manufacturer. The quartile divisions of 75 per cent and 25 per cent are denoted by the top and bottom bars, between which the distance is the interquartile range. Mileage values that are more than 1.5 times the interquartile range are considered as the outliers and denoted by the '+' markers by the Matlab® ANOVA function default settings. The stable mileage features correspond to a short interquartile range and fewer outliers. Unlike the medians used in box plots, the centre points in mean comparison graphs in Figure 3-1 are the respective group means. The intervals in the graphs are computed by the Matlab® ANOVA function based on the ANOVA statistics. If the intervals of two groups of data are disjointed, the two groups are significantly different from each other, such as the USA and Japan groups. If the intervals overlap, the groups are not significantly different. The box plots and mean comparison groups are two major approaches to ANOVA results presentation in this research. The features reflected in Figure 3-1, including medians, means, interquartile, outliers, and intervals in mean comparison, are of importance for the ANOVA application in Chapter Eight to reveal differences in indoor environmental conditions relating to energy use activities and building characteristics. Compared to conventional time-series presentations of hygrothermal measurements in Chapter Seven, the box plots and mean comparison graphs of temperature measurements in different houses over various time periods, either a specific day or the entire monitoring period, can express differences in acquired indoor measurements in a succinct and rigorous fashion to cross-check findings from conventional data presentations.

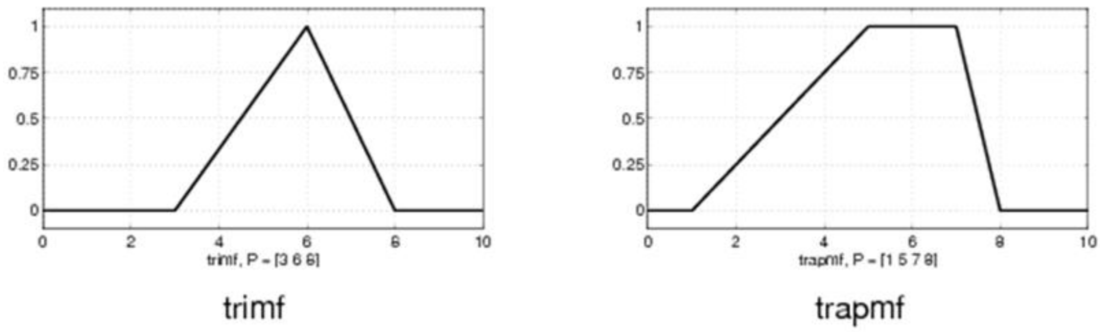
3.4.2.2 Applying ANFIS methods to inspect power draw profiles

Electricity end-use at the level of individual appliances is one of the directly monitored items in this research. In addition to the macro-scale and micro-scale presentations of power profiles and electricity use, the application of algorithm-based methods to examine the interrelationships of power demand between house use and monitored appliances is of importance to examine energy-related occupancy activities from the perspective of methodological trials. The low-cost measurements, after being pre-processed as discussed in Chapter Six, cannot meet the application standard of most methods in the field of Non-Intrusive Appliance Load Monitoring (NIALM). However, similar principles of pattern recognition and classification are applicable to examine the interrelationships of monitored power draws. As introduced in Chapter Two, NIALM is a specific research field that recognises the end-use event from the one-point measurement of house use at mains power. The basis to perform an effective NIALM analysis is to have sufficient power draw features, such as distinguishable real power and reactive power that are calculated by using relatively high sampling frequency for AC elements, of the targeted end-use events that can be *learnt* by the selected methods. Two types of *learning* processes, *supervised* and *unsupervised learning* respectively, are usually conducted in the associated data analyses. If the features are acquired, prior to the NIALM stage, in the process of Intrusive Appliance Load Monitoring (IALM) that directly and intensively measures the power draws of targeted end-use, then NIALM is a *supervised learning* process.

The long-term and low-cost monitoring of power profiles in this research was not aimed at NIALM-related investigations. The only available monitored power draw features were the amplitude and temporal sequence of power values. These values were not numerically fixed for a specific type of end use that was measured at much lower frequency compared to conventional NIALM monitoring. For example, the identical operational cycles of a monitored washing machine had slightly different power draw profiles when the starting moments of the operational cycles varied within the time window of a monitoring interval. These power profiles can be visually categorised into the same type of end-use. However, the power draw variations in duration and amplitude cannot be mathematically described for the application of pattern extraction methods that directly compare the features in the *learning* process. Therefore, an appropriate algorithm-based process that has a degree of *adaptive intelligence* is required, in order to simulate visualisation-based classification procedures conducted by human beings. The method selection process included the following three stages.

Firstly, a rule-based expert system formed the basis of pattern recognition. As described by Negnevitsky (2005), the basic and complete structure of a rule-based expert system has three major components, including knowledge base, database, and inference engine. The antecedent (the *IF* part) and consequent (the *THEN* part) in the rules are connected by logic calculators *AND*, *OR*, and *NOT,* and written in the semantic format of associated programming tools to form the knowledge base. The pre-processed database is usually split into three portions for the purposes of training, testing and checking. The features are *learnt* and stored in the training process. The training effectiveness is validated in the subsequently conducted checking process. The trained and validated system is then tested in the testing process. If the final errors or unexplained residuals fall within an acceptable scope, the testing phase is passed. The inference engine connects the *IF-THEN* knowledge base and the split database to perform the inference process. For example, the conventional Boolean Logics that deal with a classical dataset by following rigid *IF-THEN* rules produce the classification output of either *True* or *False*. An advanced inference engine that is not confined in the field of Boolean Logics was needed to process the varied power measurement features in this research.

Secondly, the Fuzzy Inference System (FIS) in the field of computational intelligence was selected to replace the conventional Boolean Logics in the inference engine of the rule-based expert system. As the basis of FIS, fuzzy logics allocate each fuzzy set with a probability-based membership function (MF). The output *True* is assigned a probability value of one and *False* a value of zero. The interim probability values between one and zero permit the fuzzy judgement to categorise the output statuses in the fuzzy set. For example, an output of 0.7 stands for being *True* to the 70 per cent and *False* to the 30 per cent. The MF is such a curve that maps each element in an input space with a membership value between one and zero. The input space is denoted as the *universe of discourse* in the context of FIS. For example, the fuzzy set of house use power draws is the probably occurred power values at the measuring point of mains power depending on the monitoring interval. The *universe of discourse* is all possible values of measurable power draws. The description of power draw levels corresponds to a MF curve that defines the degrees or probabilities to which any piece of power draw data is considered to be high or low. In a rigid boundary of classical set in Boolean Logics, two pieces of power draw data that differ by one watt can be classified into different categories of being high or being low. This classification is apparently against common sense. In contrast, the fuzzy set assigns each piece of power draw data with a value, μ, on the MF curve to define a smooth transition from being low to being high. Therefore, one piece of power draw data can be simultaneously considered to be high to the degree of μ and low to the degree of (1- μ). The MF comes in many forms with the only requirement to satisfy the output range between one and zero corresponding to each element in the *universe of discourse*. For the sake of simplicity, convenience, and computational efficiency, commonly used MFs include triangular and trapezoidal curves that are respectively defined by three and four parameters as shown in Figure 3-2. Each of the defining parameters is the inflexion point on the *universe of discourse*.



Permission to reproduce this figure has been granted by the MathWorks, Inc..

Figure 3-2 An example of triangular and trapezoidal curves for the membership function of a fuzzy set (From the Matlab® support documentation (MathWorks, 2014))

A fuzzy set accepts a vague concept, such as very high and relatively high, rather than strictly defined numerical values. For an inference model of a system that follows the *IF-THEN* format, each input element in the antecedent *IF* part can be represented by a fuzzy MF. The input elements are connected by the fuzzy logic operators, such as *AND*, *OR*, and *NOT*, to produce an output judgement that is also defined by a fuzzy MF. The fuzzy logic operators follow principles that can maintain the associated relationships while keeping the result within a range between one and zero. For example, to represent the expression of ‘A *AND* B’, where the A and B inputs correspond to the probability values, a maximum principle of *max* (A, B) is invoked to express the calculated result as the maximum probability between input A and input B. Similarly, *min* (A, B) is used for the ‘A *OR* B’. More complicated calculation principles that can be used for fuzzy operators are beyond the scope of this research. The output of the FIS is therefore a value between one and zero to stand for a probability of the output in its fuzzy MF curve. To produce an interpretable result, a *defuzzification* process is needed to translate the value to a lingual concept, such as high and relatively high. For example, if a FIS is used to infer the power draw level of the tumble dryer from the power draws of the simultaneously measured house use and certain energy-intensive appliances, the power draws of house use and appliances are *fuzzified* by the selected fuzzy MFs and connected by proper logic operators. The output between one and zero is then *defuzzified* to a lingual description, such as ‘the tumble dryer is very likely being used’. Therefore, a complete FIS is a fuzzy rule-based expert system that includes three major stages of *fuzzification, inference, and defuzzification*. The implication operator, which comes in many forms, is used for the *defuzzification* process. The simplest form adopts a constant to truncate the range between one and zero. In practice, two or more rules are entered in the input of a FIS. The output fuzzy sets of all rules are aggregated into an output fuzzy set prior to the *defuzzification*. The implication operator for this type of *defuzzification* requires a more comprehensive approach, such as the centroid value of the output fuzzy set.

In Figure 3-3, the exemplary *universe of discourse* of start time, power draws, and duration of an electricity-use event were spilt by the researcher of this project into different categories using the trapezoidal MFs, the defining parameters of which were *arbitrarily* selected on the basis of visualisation-based examinations of house use and individual appliance power profiles. The scales of input space for start time and duration were converted into a numerical format to be recognisable by software such as Microsoft® Excel and Matlab®.

By *arbitrarily* defining the MF and associated parameters, the FIS is essentially a white-box process, the operational procedures of which are straightforward but not *adaptive* in adjusting to the actual power draw scenarios of the studied houses. The trials using the MFs of the three types of input in Figure 3-3 did not produce effective results for the purposes of examining electricity end-use and the interrelationships of power draws. A black-box approach is thus more suitable, achieving the expected results that approximate to the actual power draw situations.

The introduction of *adaptive* or *learning* capability into the FIS leads to the third stage of the method selection process. The *adaptive* characteristics were added into the FIS using the Adaptive Neuro-Fuzzy Inference System (ANFIS). The power draws at the mains power and the individually measured power draws of certain energy-intensive appliances, such as the tumble dryer and dishwasher, were selected to be the input of ANFIS, which automatically captured the required features rather than the three fixed features of start time, duration, and power draws. The output was set to be the measured status of a targeted end-use in the form of a series of ones and zeroes. The numbers of MFs and associated curve shapes were pre-selected for each ANFIS. Depending on the generated results, the numbers and curve shapes of the MFs of each input can be consequently altered. Rather than being *arbitrarily* defined, the parameters of MFs were assigned by the established ANFIS to fit the relationships between input and output by incorporating the *neuro-adaptive learning* techniques.

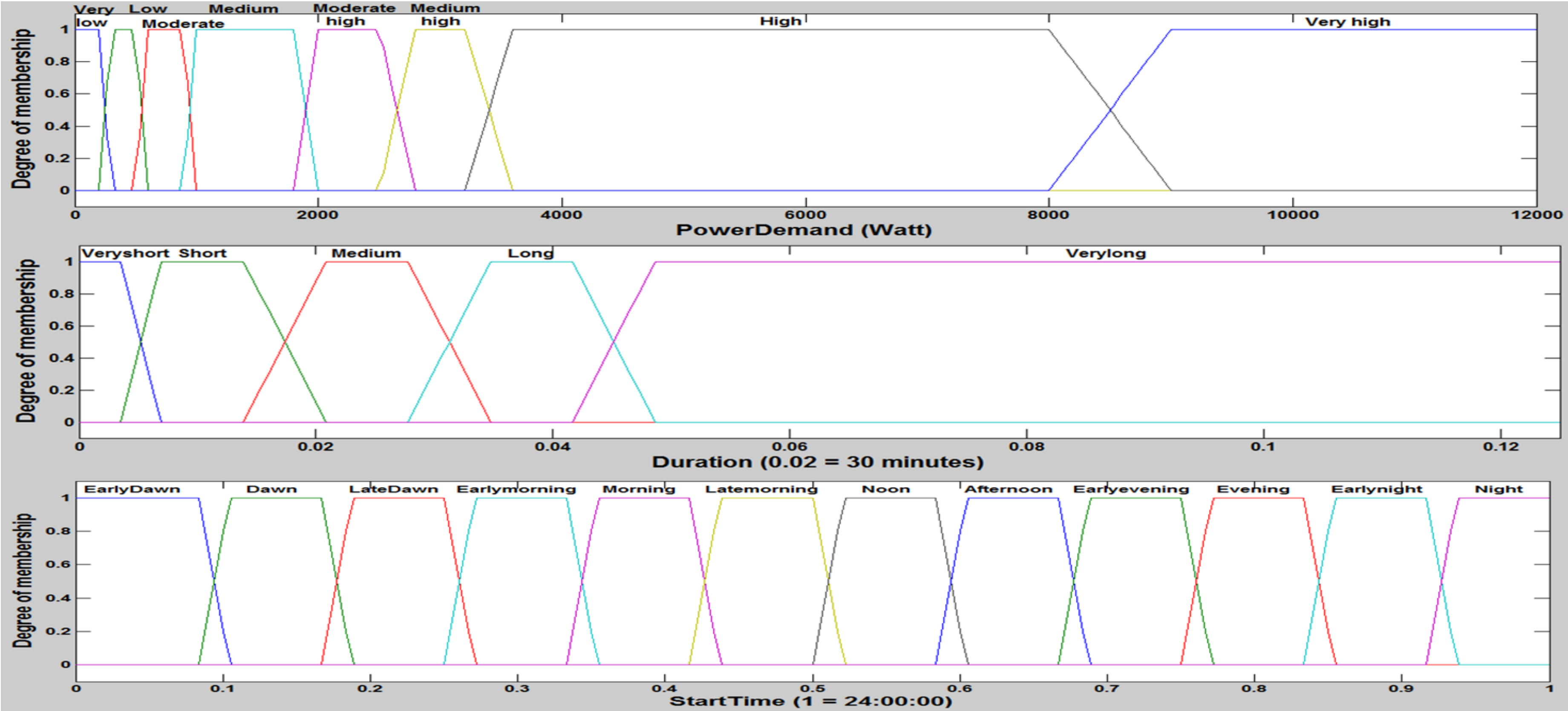


Figure 3-3 Example of FIS membership functions of the power draw values, duration, and start time of the electricity end-use

Deriving from neural networks, ANFIS provides the basic FIS with a certain level of *learning* capability, by incorporating either a backpropagation algorithm or a combination of backpropagation with a least square method. It is beyond the scope of this research to investigate the difference between these optimisation algorithms, which enable ANFIS to gradually reduce the errors between input and output into an acceptable range. A pre-requisition to achieve better modelling results using ANFIS is the quality of the training data that can represent all required features without the impact from noise or errors. Noisy and erroneous signals within the raw data were filtered by appropriate pre-processing procedures that are introduced in Chapter Six. Therefore, the pre-processed power profiles over appropriate time periods, depending on the macro-scale examinations conducted on power measurements, can be split for the purposes of training, testing, and checking. The application of ANFIS to the power measurements of one house in each case study, including the selection of appropriate input and neural network structure, is demonstrated in Chapter Eight.

Different terminologies are used in the studies that apply FIS and ANFIS processes, depending on the research fields. For example, machine learning is frequently used in the field of Artificial Intelligence (AI) and computational engineering. Knowledge Discovery in Databases (KDD) and Data Mining are cited by both AI researchers and conventional statisticians. There is no attempt in this research to distinguish the academic history and application fields of these terminologies, which are thus exchangeable within the thesis context.

3.5 Chapter summary

The methodology for data acquisition and analysis were identified and justified in this chapter. The longitudinal, long-term, and mixed-method case study approach, selected as the methodology for data acquisition in this research, was identified with reference to the RFF and BPE programmes of the TSB. Following the research question about the feasibility of applying the longitudinal and long-term approach in a small-scale research project aiming to study energy-related activities, the chapter examined the selection principles of case studies, monitoring variables, and supplementary sociological approaches. A low-cost and distributed monitoring scheme was thus identified for this research to make the monitoring technique transferable to a wide range of existing housing stocks that cannot feasibly be covered by programmes requiring major investment, such as the RFF and BPE of the TSB. Appropriate data analysis approaches were subsequently explored in this chapter to deal with measuring results obtained in the context of a low-cost monitoring scheme. Based on the characteristics of macro-scale and micro-scale examinations, which are typically visualisation-based and manually conducted, two types of algorithms-based methods, ANOVA and ANFIS, were respectively selected to assess the hygrothermal recordings and power measurements. The execution processes of the associated methodologies for data acquisition, presentation, and analysis are described in the following chapters, with the configuration of experimental work being introduced in the next chapter.

Chapter 4: Experimental Work

4.1 Introduction

Sensors and loggers function as the observer in monitored houses to detect and record the targeted occupancy activities. Considering the experimental environment in actual homes, the selected devices should be as inconspicuous as possible. In addition to bringing less inconvenience into the daily life of monitored homes, less-intrusive monitoring schemes are expected to objectively reflect the targeted occupancy activities (Marceau and Zmeureanu, 2000). Starting from general principles in system configuration for the long-term field monitoring of this research, this chapter focuses on the device selection of each monitoring category, including energy use, power draws, hygrothermal conditions, and occupancy statuses. The actual testing and deployment of configured systems in the monitored homes are described in Chapter Five.

4.2 Selection criteria for monitoring schemes

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, in addition to meeting the fundamental measuring requirements of the research;
- 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. This type of monitoring therefore fulfils one of the major stated aims of this research, which was the investigation of actual behaviours associated with energy use in a real domestic environment.

The disadvantage of distributed and less-intrusive monitoring system resides in the aspect of device management and maintenance. Battery failure can lead to data loss of battery-powered equipment. If the portable loggers are moved by the residents to other locations without the researcher being notified, the downloaded measuring results are potentially flawed. The non-repeatability features of field measurements make it infeasible to supplement the lost data and challenging to remedy the flawed data by repeating the experiment. Even if the monitoring period can be prolonged with the agreement of monitored households, the same levels of energy-related activities under the same indoor and outdoor environment conditions are very unlikely to artificially reoccur.

Further consideration needs to be given to key aspects regarding data transmission and storage. If the distributed equipment stores data locally in the internal memory or externally connected hard disks rather than transmitting the real-time measurements to a centralised database, the memory capacity for data storage between two adjacent manual downloads and the equipment accessibility for periodical maintenance are important factors to prevent unnecessary data loss. If wireless communication takes place among system components, proper installations and periodical examinations can sustain the network stability and reduce the probability of data loss. If measurements are transmitted to a web-based server via a domestic Internet service rather than a purpose-built network, appropriate data volumes are essential to access the domestic router that should not be overloaded by transmitting real-time measurements. In addition, the level of accumulative energy used by plug-in monitoring devices should be acceptable to the monitored households.

4.3 Principles of device selection for analogue parameters

Most monitoring parameters in this project, including energy use, power demand, and hygrothermal variables, have analogue values that differ from the digital values of occupancy status parameters. Hygrothermal parameters were mainly used in this research as indicators of outdoor and indoor environments relating to building energy performance. The measured power profiles were used to examine the targeted energy-related occupancy activities in monitored houses. The amplitude of power demand, which is the energy consumption rate of the monitored appliance or entire house, varies significantly in response to the occurrence states of certain occupancy activities. One example is the power demand variations at the beginning and the end of electric shower use that features large power draws. To recognise the states of targeted appliances and associated energy use activities, the measurement of real-time power demand has stricter requirements on the sensitivity, resolution, and sampling frequency, which were introduced in Section 2.3.2 (see Chapter Two) as the three important factors for measuring analogue parameters.

The standard of equipment with respect to the sophistication and advancement of measuring mechanisms varies largely among power and electricity monitoring devices. In general, three categories of measuring devices, including professional devices, smart meters, and advanced digital metering devices, are applied for various purposes in different environments. Professional devices are usually applied in lab-based environments to detect real power, reactive power and apparent power. The calculation of these AC power components relies on the real-time values of AC current, AC voltage, and power factor that are sampled at the same frequency. The measurement of multiple AC parameters at high or super high levels of sensitivity, resolution, and frequency leads to large data volumes over the same monitoring time period. Smart meters are installed by utility suppliers, usually on the scale of either communities or cities to support bilateral data exchange between households and utility suppliers. If the metering accuracy can meet the billing requirements of utility suppliers, the sampling frequency and measuring standard are not necessarily as high as lab-based professional devices. The advanced digital metering devices are normally used in individual domestic environments for the cost-effective measurement and digital display of real-time power demand and accumulative electricity use. Most off-the-shelf products belong to this category, which only measures the real-time AC current and then calculates the pseudo-real power by using the default values of AC voltage and power factor. Although it is advanced in providing digital feedback in a portable format, this type of off-the-shelf product is not designed to collate utility meter readings but only to provide the users with certain levels of awareness about various energy use events. The bilateral communication that occurs with smart metering is not required.

The long-term monitoring undertaken in this research project aimed to facilitate the investigation into the targeted energy-related activities and associated indoor environments from post-occupancy perspectives, rather than to capture AC wave details or load features by reconstructing AC waveforms at the points of mains power, each appliance, and individual circuits. In practical monitoring, basic sampling frequencies are not raised without limits, even if it is technologically feasible for the monitoring devices. A balance is struck between the high frequency and the consequent large volume of data for storage and transmission. Therefore, the deployment of professional devices was not feasible in the actual home environment studied in this research. No smart metering programs were conducted by the respective utility suppliers of the monitored homes to facilitate direct data collection prior to and during the research period. With no requirement to replace utility meters or alter mains power circuits, the convenient-to-maintain features of off-the-shelf metering devices was thus preferred in this study to generate appropriate data volumes using acceptable measuring mechanisms.

For most off-the-shelf metering devices, the sensitivity or minimum detectable load is firmware-fixed by manufacturers. The resolution level depends on the 'bit' numbers of the built-in Analog-to-Digital Converter (ADC) of digital devices and the required range of monitored variables. The basic sampling frequencies are also firmware-fixed, although the acquired data can be potentially aggregated or averaged over user-definable intervals[1] that are longer than firmware-fixed intervals. If the data are locally processed and compressed before being sent to a centralised database through the Internet or a purpose-built network, the buffering and processing capacity of the device and the reliability of real-time network transmission are usually bottleneck factors for the applications of off-the-shelf metering devices.

Appropriate sensitivity, resolution, sampling frequency, and advancement level in measuring mechanisms are not exclusive to power measurement and energy monitoring. Similar issues exist in the monitoring of other types of analogue parameters, such as temperature and relative humidity (T and RH). For the same type of energy-related occupancy activity, such as the use of electric showers, the responding speed T and RH differ from that of the associated power draws. The conflict between the sampling frequencies and the consequent data volumes is not a primary concern for the experimental design as in the case of power measurements. The relatively limited range of likely values of T and RH makes no specific demand on the large bit number of a logger's Analog-to-Digital Converter (ADC) in ordinary indoor and outdoor

[1] For example, power draw in Watts over a period of five minutes can be averaged from the five pieces of minutely data if the firmware-set interval is one minute. Energy use in kWh over the period of one hour can be aggregated by using 12 pieces of five-minute data of averaged power draws.

measurements. Therefore, specific consideration was given to the measurement of power draws within the context of this research project.

After a comprehensive assessment of the measuring requirements for this research project and the technical standards of available devices, off-the-shelf equipment and associated services were directly adopted. Both localised data storage and Internet-based data transmission are used by the selected products. The internal memories of devices adopting localised data storage become full over various periods, depending on their respective memory capacity and the settings of logging intervals. The subsequent data logging can either stop or continue by overwriting the historical records. To avoid the occurrence of missing data under such circumstances and to minimise intrusiveness to the monitored homes, a monthly site visit frequency was selected and appropriate sampling frequencies set accordingly for each device.

4.4 Monitoring devices for energy use and power draws

A metering mechanism that operates by optically detecting the pulse output of digital utility meters has been developed by some manufacturers of advanced metering products. However, the associated off-the-shelf devices became available too late to be applied in this research. In addition, the mechanical utility meters in most of the monitored homes could not facilitate this measuring technique unless they were replaced with digital ones. Therefore, electricity use was measured by products that adopt Current Transformers (CT). A few trials to automatically record the real-time gas consumption were conducted by using cameras placed in front of mechanical gas facility meters. Meter readings in most trial photos were not up to recognisable standards due to the confinements of installation conditions. In addition, night-vision photo shooting in a dim or dark meter chamber environment generates a relatively high power demand from the camera batteries. To sustain the power draw between two monthly site visits, sufficient power supply would have to be outsourced and adapted from adjacent AC power sockets. This type of alteration to the domestic utility chamber of gas and electricity meters by introducing external power supplies is not permitted by the associated safety regulations. Therefore, when mains gas served the monitored houses in this research project, the real-time gas use was not automatically measurable but had to be manually recorded during site visits. The devices used to measure, transmit, and validate power draw and electricity use in this research are listed in Table 4-1.

Table 4-1 Electricity monitoring devices used in this research (photo sources: Current Cost (2010) and NZR® SEM software interface)

Name	Picture	Specifications
Current Cost® CC128 Envi display & receiver unit		10 RF channels at 433MHz SRD band; raw power data in watts updated every six seconds from transmitter units; internally stored data in kWh integrated over bi-hourly, daily, and monthly periods for manual download; no date input; no internal battery; one RJ45 port for the connection either with PC or with NetSmart bridge; one DC port for three-VDC mains block adapter; power draw: 0.4 to 1.0 watt
Current Cost® CC128 Envi CT & transmitter unit		Seven-year battery life; five mW Effective Radiated Power (EPR) for Radio Frequency (RF) wireless communication at 433MHz SRD band; sensitivity of CT-measured AC current at 50 mA and maximum at 100 A; CT diameter at 30 mm; accuracy level at 95%
Current Cost® CC128 Envi CT & transmitter mini unit		CT diameter at 12 mm; increased accuracy level at 98%; other parameters are the same as the above 30 mm CT unit
Current Cost® Individual Appliance Monitor (IAM)		Maximum detectable current at 13 A; RF communication at 433MHz SRD band; power draw: 0.4 to 1.0 watt
Current Cost® RJ45 to USB 'active' cables		Built-in prolific (USB-Serial) chipset for historical and dynamic data download to PC from the display & receiver unit
Current Cost® NetSmart bridge connected with domestic Internet router, DC plug, and display & transmitter unit		Serial communication via RJ45 Ethernet port; 16-KB flash memory and 512-bytes EEPROM to buffer and average the raw power data from the display & receiver unit; five-minute averaged power data being sent to the Current Cost® database broker via DHCP setting-up in the domestic Internet router; five-VDC mains block adapter; power draw: 2.0 to 2.5 watts

Name	Picture	Specifications
NZR® Standby-Energy-Monitor (SEM) LOG16+		Maximum measurable current: 16 A; LCD display sensitivity: one mA, 0.1 V, 1º phase angle, 0.1 watt, 0.1 Var, 0.1 VA; downloadable data sensitivity: one mA, 0.1 V, 0.1 watt, and 0.1 Var; selectable intervals: one, two, three, four, five, six, 10, 12, 15, 30, and 60 minutes

4.4.1 Hardware configuration

The Current Cost® CC128 Envi equipment was selected to monitor the electricity use and power profiles for this research. The basic set consists of a display & receiver unit and a Current Transformer (CT) & transmitter unit as shown in Table 4-1. The former unit is a table-top set that can be located in selected places of monitored houses as a Human Machine Interface (HMI). The latter unit is placed adjacent to the domestic electricity meter by clamping the CT around the mains cable and mounting the transmitter unit on a surface near to the cable. When the primary AC current flows through the monitored mains cable, it is sensed as the secondary AC current by the CT through electromagnetic induction. When multiplied by the CT ratio, the secondary current is converted to equal to the primary current. The Analog-to-Digital Converter (ADC) in the transmitter unit then converts the analogue current values into a digital series. Prior to sending the digital series to the display & receiver unit, the microprocessor in the transmitter unit calculates the power draw using the sensed current. Without the simultaneous measurements of other power parameters, default power factor at one and default Root Mean Square (RMS) value of AC voltage at 240 V are used to calculate the pseudo-real power draw. The Individual Appliance Monitor (IAM) is a transmitter-equipped sensor to detect the end use of a given plug load by being placed between the socket and the appliance plug. The Current Cost® NetSmart Bridge (bridge hereafter) is the Internet peripheral equipment used to transmit real-time power draws via the web portal service from the retired Google PowerMeter® (Google PowerMeter, 2011) and the later Current Cost® dashboard (Current Cost, 2010). The

NZR® SEM in Table 4-1 is a professional device selected by the researcher to validate the measurements of Current Cost® IAMs.

4.4.2 Wireless network

The 10 radio frequency (RF) channels between the Current Cost® CC128 receiver and transmitter units are established using the Short Range Device (SRD)[2] frequency band at 433 MHz. The RF signals fired by transmitter units can penetrate walls and other common house obstacles to be captured by the antennae of receiver units. This short-range technology, normally with a range of less than 100 metres (Cook and Das, 2005), can cover the indoor and outdoor range of a typical residential building and support multi-node transmissions with allocated pairing IDs. Multiple transmitter-equipped sensors that are distributed indoors and outdoors can simultaneously transmit RF signals to more than one receiver node in the house. There is only one output serial port on the receiver unit for either Internet access or PC connection. The multi-node configuration can circumvent the interruption to the specific display & receiver unit that is deployed either for Internet-based data transmission or manual download via PC connection. If permitted by the coverage range, a display & receiver unit located in one house can receive the RF signals sent from the transmitter units in neighbouring households where Internet service or monthly site visit is not accessible.

The ID allocations for the 10 channels of Current Cost® CC128 Envi devices are assigned by button operations before distributing the transmitter units in the house. Under the user interface of a specific channel of one or more than one display & receiver unit, buttons on the display & receiver unit(s) and the associated transmitter units are pushed and held for the required number of seconds. Following the button

[2] The Short Range Devices (SRD) band is widely applied for communication between short-range wireless devices, such as power meters, weather stations, wireless earphones, and security alarms. The frequency band has low interference impact on other radio equipment. In the UK, the frequency band of 430-440 MHz is allocated to armature use and does not require specific approval for Wireless Transmission-Reception license. The Radio Frequency (RF) energy of the SRD band is usually very low. For example, the Effective Radiated Power (ERP) of the Current Cost® CT & transmitter unit is 5 mW (Current Cost, 2010). The FM radio signal has an ERP around 100,000 Watts

operations, a time window remains open for a given period, over which the RF channels between the receiver unit(s) and the associated transmitter units are stabilised. The main channel is used by the CT & transmitter unit for house use measurement. The remaining nine channels are reserved for other transmitter-equipped sensors. For example, a separate CT & transmitter unit takes one RF channel to monitor another AC phase if PV microgeneration or a three-phase power system exists in the house. Each Current Cost® IAM takes one RF channel to detect the associated plug load.

The RF channels are not permanently paired. After the centralised pairing process in the initial installation stage, decentralised maintenance and re-pairing of certain channels need to be periodically conducted by performing button operations in multiple locations within the limited time window. When the transmitter units are deployed in difficult-to-access places of the monitored house or in the neighbouring household, the post-installation maintenance can be problematic. For example, the power sockets for the plug load of wet appliances, such as dishwashers and washing machines, are usually located within the utility recess behind the appliances. When the RF re-pairing is needed, buttons on the IAM can only be accessible by moving the associated appliance around with extra concerns given to the associated water pipework connection and the available space between the wall socket and appliance plug. High temperatures during the measurement of appliances with intensive power draws can result in heat accumulation within a confined monitoring space. Damage to the monitored appliance and destruction of the IAM are potential risks due to the overheating or excessive warming of the surfaces. In one instance, when the dishwasher in one monitored home underwent professional repair and maintenance, the technician from the dishwasher supplier did not take note of the space required by the IAM and pushed the repaired machine too deep back into the recess. Over a month after the repair, surface fusion between the plug and the dishwasher back-panel was discovered by the residents. The reluctance of residents to re-deploy the IAM after the second instance of dishwasher maintenance led to a period of two months over which no dishwasher power profiles was able to be recorded.

4.4.3 Power demand of equipment sets

The display & receiver unit is powered by a mains block adapter of three VDC that demands a constant power supply from the domestic socket ranging 0.4 to 1.0 watt. If connected with the network peripheral devices, a block adapter of five VDC is needed to power the device set that has a higher level of power draw, ranging 2.0 to 2.5 watts. The CT & transmitter unit draws power from an included battery that has a seven-year lifespan. It needs no extra supply from a power socket, which is usually not available in the meter cabinet if mains gas exists adjacent to mains power. An IAM that is sending real-time measurement via a successfully paired RF channel has a constant power draw around 0.5 watt. If the power socket is not switched off, the successfully paired and plugged IAM constantly demands a stand-by load around 0.5 watt even if the monitored appliance is not in use. Therefore, for a house that has nine pieces of IAMs and two sets of display & transmitter units, one for manual download and the other for an Internet connection, the total power draw of the Current Cost® equipment set is 7.0 to 8.0 watts, assuming the stand-by load of IAMs constantly exists. When multi-node RF communication is used in one house within which a third display & receiver unit is used to communicate with the transmitters in a neighbouring house, the total power demand increases to 9.0 to 11.0 watts.

4.4.4 Sampling frequency and time-keeping mechanism

The sampling frequency of AC current is firmware-fixed for Current Cost® devices. At the end of every six seconds, a snapshot of power draw is received from the transmitter in the CT unit or the associated IAM by the display & receiver unit, which buffers and averages 10 pieces of live data over a one-minute period. The raw data sampled in every six seconds are accessible exclusively by the inner firmware of Current Cost® CC128 unit. Without an externally connected and software-running PC[3] that operates continuously, the minutely data are not accessible. Instead, the display & receiver unit stores the bi-hourly energy consumption in kWh based on the 1,200 pieces of six-second power draw data or the 120 pieces of one-minute data over the past two hours. Similarly, daily use is accumulated on the basis of 12 pieces of bi-hourly records by 23.00 hours each day, and monthly consumption on the basis of 30 pieces of daily records since the starting of measurements. The figure of 30 is fixed for monthly data aggregation whether there are actually 30 or 31 days in each calendar month. Energy use of the 10 channels is saved in the rolling stacks of the internal memory of receiver unit. Zero kWh is saved in the associated stack for any inactive channel that is either not in use or under radio interference. For each channel, 372 stacks are appropriated for bi-hourly use over the past 31 days (12 entries per day), 90 stacks are allocated for daily use over the past three months (30 entries per month), and 84 entries are reserved for monthly use over the past seven years (12 entries per year) (Current Cost, 2010).

Bi-hourly use is aggregated at the end of the first minute in every odd number of hours according to the clock time of the transmitter & display unit, such as 07:01 and 09:01. Similarly, Daily use is updated at 23:01. The display & receiver unit cannot track the actual calendar date since it only supports manual input of clock time in the HH:MM format. Without the date element in the clock setting, the clock time is the only reference point for the aggregations of bi-hourly, daily and monthly recordings. If the clock time is set to be one hour earlier than the actual time, the bi-hourly and daily

[3] A major reason not to adopt the continuously running PC for minutely power data logging is out of concern for energy used by the PC equipment over the long-term monitoring and the consequent acceptance level from the households. To record the minutely power draw, a trial has been conducted using the Viglen® MPC-L PC that is a low cost PC with an ultra-low energy use profile. For example, the continuous running of the Viglen® MPC-L only cost £1 a year. The compact size of W x D x H at 140x145x35 mm reduces intrusiveness compared with other ordinary PC equipment (Viglen, 2011). However, the 512 MB RAM of the MPC-L only suffices for the included Linux-based operating system but not for the Windows® platform which is required by the Techtoniq Energy Station® 2.0 version (2011) used with the Current Cost® product

energy use can be respectively aggregated at one minute past every even hour and at 00:01 of the next day to circumvent the anti-intuitive daily use integration at 23:01.

The historical data files are downloadable via a software-running PC. The timestamp of the latest bi-hourly recording stored in the rolling stacks is assigned, in the 'HH:00' format, on the basis of the clock time shown on the display unit. The hour elements in timestamps are always odd numbers, even if they should be the following even numbers when the clock is manually set to be one hour earlier than the actual time. The date element of the latest recording is assigned with date information as acquired from the connected PC. The entire timestamps, including the time and date elements, for the rest of historically aggregated energy use are assigned backwards from the latest recordings to the earliest ones stored in the rolling stacks.

The sampling interval, over which power draws are averaged and energy use is integrated, was decreased from two hours to ten minutes and then five minutes by the application of Current Cost® NetSmart Bridge and associated web portal services. Sourcing data from the display & receiver unit, the bridge buffers, integrates, and stores the six-second real power values from the CT & transmitter unit(s) and IAMs. Via the connected domestic Internet router, the bridge then posts the five-minute data to the COSM® server that serves the Current Cost® database. Two major web portals used by the Current Cost® product include the retired Google PowerMeter® and the later-improved Current Cost® dashboard. Not initially being designed for data download, the Current Cost® dashboard was mainly used to visualise five-minute power profiles that were sourced from the COSM® server. Before 16 September 2011, the Google PowerMeter®, which was an online service product among a range of other applications developed by Google®, partnered with several energy monitoring device manufacturers to provide public access and visualisation of daily electricity use at 10-minute intervals (Google PowerMeter, 2011). The Current Cost® manufacturer was one of the partners of the former Google PowerMeter® that averaged the adjacent two pieces of five-minute data in the COSM® server into one piece of 10-minute data for presentation and download. After the retirement of the Google PowerMeter® from the online energy monitoring service, manufacturers of various energy monitors started to improve their own online portals. The Current Cost® dashboard gradually developed the download functions for its users to access the five-minute data directly from the COSM® server. The main channel of house use was first accessible for download, followed by the other nine channels.

4.4.5 Sensitivity and resolution

4.4.5.1 Measurement of house use

AC current is the only measurable parameter of the basic set of Current Cost® CC128 Envi. The sensitivity of the CT & transmitter unit is 50 mA, which is the minimum detectable current. The maximum-rated current is 100 A, which is approximately the capacity upper limit for most domestic mains power. When the AC current of mains power is less than 50 mA, the non-detectable power draw is presented as zero watt on the display unit. When the current approaches the sensitivity threshold of 50 mA, unstable power draw values are presented, fluctuating between zero watt and 12 watts on the display unit. Only when the sensitivity level of 50 mA is reached, can the minimum variation in power draw of one watt be detected. Using 240 V as the default RMS value of AC voltage and one as the default power factor, the minimum detectable current variation is 1/240 A or four mA. This at least calls for the resolution of a 15-bit[4] ADC in the transmitter unit that generates 65,536 (or 2^{16}) digital series to represent the analogue current range of 50 mA to 100 A, or the equivalent power range of 12 watts to

[4] The full scale range of detectable current is the difference between the maximum current of 100A and the minimum of 50 mA. If 4 mA is the minimum detectable current variation, at least 24,988 (using 4 mA to divide 99.95 A) digital series are required to present the detectable range. A 16-bit ADC can provide 65,536, or 2^{16}, digital series to cover the required conversion. In practice, the 65,536 series is only theoretically available, since not all of the series can be used for noise-free conversion. Therefore, the effective number of bits (ENOB) of the ADC is less than the rated number of bits, as the 16-bit in this case. The actual bit number of the ADC is not provided by the Current Cost® manufacturer. The 16-bit calculation was assumed on the basis of the digital electronic theory and the actual display results when the Current Cost® products were put in use.

24 kW. To a certain extent, the relatively low levels of sensitivity and resolution restrict the feasibility in the accurate measuring of small base loads of less than 12 watts, and in the monitoring of minor variations in power draws of less than one watt. The base load, or the daily minimum power demand of the monitored houses, is usually larger than 12 watts. Therefore, the impact of the low sensitivity of Current Cost® CT unit is less obvious compared to that of the relatively low resolution and sampling frequency. For example, the minor variations in power profiles caused by some occupancy activities with low-level power draws, such as the use of artificial lighting appliances, are not individually recognisable from the recorded five-minute profiles of house use.

4.4.5.2 Measurement of individual appliances

The RF signals from each Current Cost® IAM can be received by more than one display & receiver unit within a range of around 30 metres, if multi-node installation is adopted. In practical monitoring, the sensitivity and resolution levels of IAMs are revealed to be one watt or four mA if using the default values of AC voltage at 240 V and power factor at one. Compared to the sensitivity level at 50 mA or 12 watts of Current Cost® CT & transmitter unit, IAMs are more suitable to detect small plug load and minor power variations as low as one watt. With a maximum detectable current of 13 A, rather than 100 A as in the case of the CT & transmitter unit, the IAMs have a narrower measuring range of 12 A and thus have no specific resolution requirement on the bit number of built-in ADC, although the actual ADC features of IAMs are not revealed by the manufacturer.

The IAMs are placed between the sockets and associated appliance plugs to capture the snapshots of current flow, voltage level, and phase angle at the end of every six seconds. The ADC and microprocessor in the IAM convert and calculate the real power in watts using the snapshots of each variable. With the actual power factor less than one being measured, the real power detected by the IAM is only a portion of the pseudo-real power that is recorded by the Current Cost® CT & transmitter. Even when the IAM-connected appliance is the only switched-on end use in the monitored house, the detected house use by CT & transmitter unit is theoretically larger than the IAM-measured value that bears the same timestamp.

4.4.6 Equipment-inherent limitations

4.4.6.1 Time-keeping mechanism

The time-keeping mechanism used by the Current Cost® display & receiver unit is an equipment-inherent disadvantage since no internal batteries exist to sustain the timing process when the display unit is unplugged. The HH:MM value at the unplugging point is stored in the associated stack. When power is resumed, the clock counts up from the temporarily saved power cut point rather than the actual time. The rolling stacks only hold measurements but not the timestamps. Once the associated stacks are filled with the aggregated values in kWh, the stored records are maintained until the stacks are rewritten by the new recordings. Therefore, if the clock time is not adjusted after the power break or unplugging events, data aggregation is resumed on the basis of an incorrect clock time. After being integrated into the wrong time windows, the bi-hourly, daily, and monthly aggregation recordings taken after the clock disorder point cannot match the actual time or date when the associated amount of energy was consumed. It is difficult and sometimes impossible to trace back the exact time point of disorders.

Interruptions to the power supply of a display & receiver unit can be caused by incidental unplugging of the display unit, the auto-tripping of the mains circuit breaker, or a purposefully conducted power break for electrical system maintenance. In addition, the alternations between GMT and DTS times on the last Sunday of every March and October in the UK exert a further impact on time-keeping. The clock time is only manually adjustable. Without extra support from the monitored household, the clock time can drift severely. The problematic clock time can be discovered by the researcher during monthly site visits when several days or even weeks have elapsed since the disordered time points.

Time-keeping issues are partially solved by the Current Cost® NetSmart Bridge that transmits real-time data without relying on the clock time of the display & receiver unit. The data timestamps from the web portals are synchronised with the Internet time. If power-cut or unplugging events affect the bridge, the timestamps of the last piece of data when the power was cut and the first piece of data when power was resumed are recorded by the power profiles in the web-based database. The historical recordings taken prior to the power break are thus potentially recoverable. The wrongly aggregated data, recorded after the power break, are partially replaceable if the online recordings over the associated time period are relatively complete.

4.4.6.2 Incomplete online power profiles

The applications of Current Cost® bridge and associated online services improve the measuring frequency and partially solve the time-keeping problems that affect the display & receiver unit. However, the online profiles are usually incomplete as they are dependent on the stability levels of Internet service and peripheral devices. The daily profiles that are visualised as complete and continuous lines on the web portal are often found to be missing several pieces of data once downloaded. To supplement the missing data by inserting artificially predicted values is usually infeasible since the average power draws can vary significantly over the associated periods. Therefore, despite the time-keeping issues discussed in the last subsection, the manually downloaded data remain important in keeping relatively complete recordings when the online profiles are incomplete.

The dashboard data timestamps are synchronised with the Internet time to the level of a millisecond when the data are posted online. A fractional second is taken by the bridge in the process of receiving the response from the data server for a successful online posting, before the next five-minute period is reset to buffer the next batch of data. The actual intervals between two adjacent five-minute posts are always longer than five minutes by a fractional second. When the bridge or Internet router service is initiated or rebooted after an interruption, the timestamp of the first piece of data starts from the actual start or reboot time rather than the end of an integer minute. As a result, the daily power profiles rarely include the fixed 288 entries of five-minute power data even if there appear to be no missing data. The consequent drawback resides in synchronising the power data with other monitored variables, such as T and RH. Being recorded at the end of integer minutes of pre-set intervals, such as 07:00:00 and 07:10:00, the daily profiles of such variables contain constant numbers of data entries.

4.4.6.3 Inaccurate bi-hourly and daily use measured by IAMs

The AC current input at the inlet of domestic mains power is theoretically the arithmetic sum of AC current output at every end-use point within the house. However, it is the real power draws in watts that are recorded as the product of associated AC current, AC voltage and power factor. Domestic appliances have different power factors at the point of each end use. The calculated real power draws of house use are thus not equal to the arithmetic sum of real power draws at every end-use point, even if the measuring mechanisms are the same for the Current Cost® CT & transmitter unit and IAMs. The end-use measurement was not conducted using an exclusive approach in this research. In addition to being limited by the numbers of available RF channels of display & receiver unit, the IAMs are only applicable to plug loads but not to individual circuits such as lighting, cooking hob and electric shower. Therefore, the sum of power draw and electricity use measured by IAMs should be smaller than the associated house use monitored by the CT & transmitter unit. However, opposite scenarios were frequently discovered in practical monitoring, as exemplified in Figure 4-1.

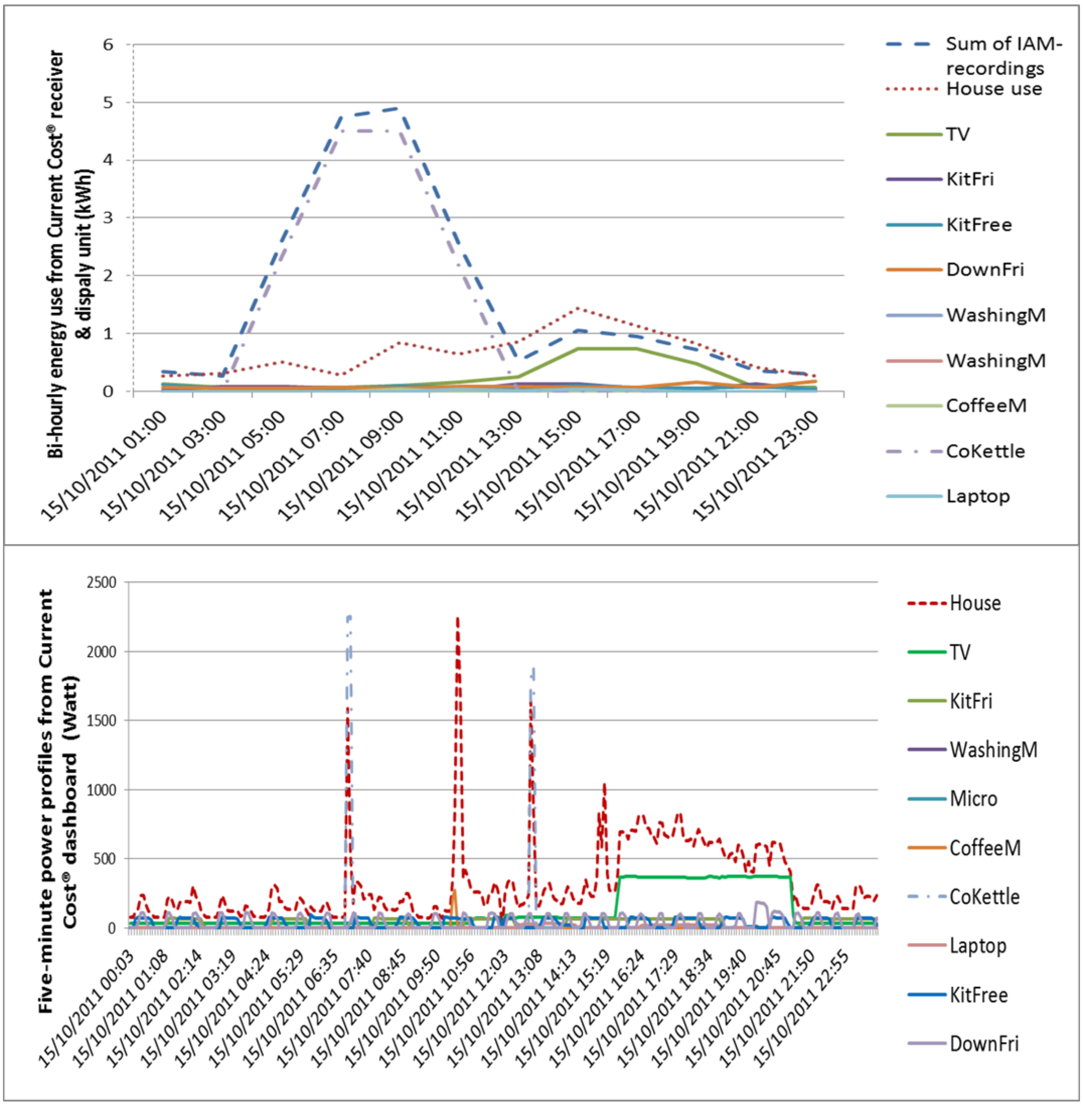


Figure 4-1 An example of flawed bi-hourly recordings of an IAM-measured kettle that retained intensive power draws over prolonged periods and led to enlarged sum of IAM-recordings

The enlarged power draws measured by IAMs result from the lack of signal-filtering function in the firmware design to remove the impact of power surges or surrounding radio interferences. Power draws from appliances that feature short-term and intensive energy use, such as electric kettles and microwaves, are more likely to experience measurement errors. The power draw amplitude of the kettle in Figure 4-1 is larger than the respective power draw of house use for the two recorded use events. When power surges or radio interferences are experienced by any IAM-connected appliances, power draw patterns similar to the use of the electric kettle randomly occur even when the appliances are not in use. It is thus more challenging to identify the actual use of appliances such as kettles than the states of appliances with relatively stable power draw patterns, such as refrigerators and washing machines. The two types of faulty detections by IAMs, either being larger than the actual demand or being faulty when no actual use exists, are hereafter named faulty spikes or faulty peaks of IAM-measured power draws. The distorted bi-hourly use shown in Figure 4-1 results from faulty spikes in kettle power draws whose values are maintained by the Current Cost® display & receiver unit for a prolonged time period. Erratic energy use in kWh is thus recorded by the display & receiver unit. Therefore, the sum of the downloaded bi-hourly and daily energy use of IAM-measurements usually exceed the associated house use. The flawed bi-hourly and daily IAM-measured data were thus discarded and not used for the analysis in this research. The five-minute power draws of IAM-connected appliances were used for the extraction of targeted activity after being pre-processed.

4.4.7 Validation of inaccurate measurements

Considering the flawed measurements due to the equipment-inherent limitations of selected devices and services, manual recordings of electricity meters were conducted during monthly site visits. Quarterly or half-yearly utility bills were also collected from the residents, although some bills were based on estimated instead of actual figures. Manual meter readings and billing recordings were used to validate the macro-scale energy use. Regarding the validation of micro-scale power draws, such as IAM-measured power spikes, two approaches were adopted, including manually recorded daily activities and professional metering devices. Manually recorded daily activities were collected in the form of occupancy diaries as demonstrated in Appendix One. In order to avoid subjecting the monitored homes to excessive intrusiveness, manually kept diaries were conducted no more than certain numbers of days.

The NZR® Standby-Energy-Monitor (SEM) LOG16+, as previously shown in Table 4-1, was adopted to validate the load profiles of certain IAM-measured appliances. The

SEM stores data in the internal memory for local display and manual download but does not support remote data transmission over networks. The SEM has relatively high sensitivity and resolution in measuring the real-time current, voltage, and power factor in every second. Raw data are buffered and averaged over the selected logging intervals, including one, two, three, four, five, six, 10, 12, 15, 30, and 60 minutes. At the highest resolution of one minute, the internal memory capacity of approximately 14,000 entries can last for over nine days for continuous monitoring. Recordings beyond the nine days are not stored in the internal memory except for being locally displayed on the LCD screen. One mA, 0.1 V, 0.1 watt, and 0.1 Var are sensitivity levels in the downloadable recordings of AC current, AC voltage, real power, and reactive power. With such high sensitivity and resolution levels, the SEM is mainly designed for the purpose of measuring stand-by load. For example, a stand-by mobile phone charger has a continuous current draw around two mA and real power draw around 0.12 watt. Around one kWh is used over a year if the charger is always plugged in the socket. Such a level of measurement cannot be facilitated by Current Cost® devices. The stand-by power draw of a successfully paired Current Cost® IAM is around 0.5 watt. This was actually tested by using the NZR® SEM.

Considering its limited internal memory capacity and the manual-download approach it requires for data access, the SEM cannot feasibly be used to test all IAM-monitored appliances. At the researcher’s request, several monitored households moved the IAMs among different appliances that have distinguishable power draw patterns. By being plugged between the IAM and the wall socket of any IAM-connected appliance, the SEM can assist in the discovery of key features of the associated power demand. Superimposed measurements can facilitate the calibration of faulty spikes in IAM-measured data and the explanation of discrepancies in CT-measured and IAM-measured power profiles. For example, the cross-comparison in Figure 4-2 was conducted on power profiles of the same freezer that was measured simultaneously by the CT & transmitter unit, IAM, and SEM over the night-time period when a lower power load relating to energy use activities occurred, except for the base load and the use of a refrigerator and a freezer.

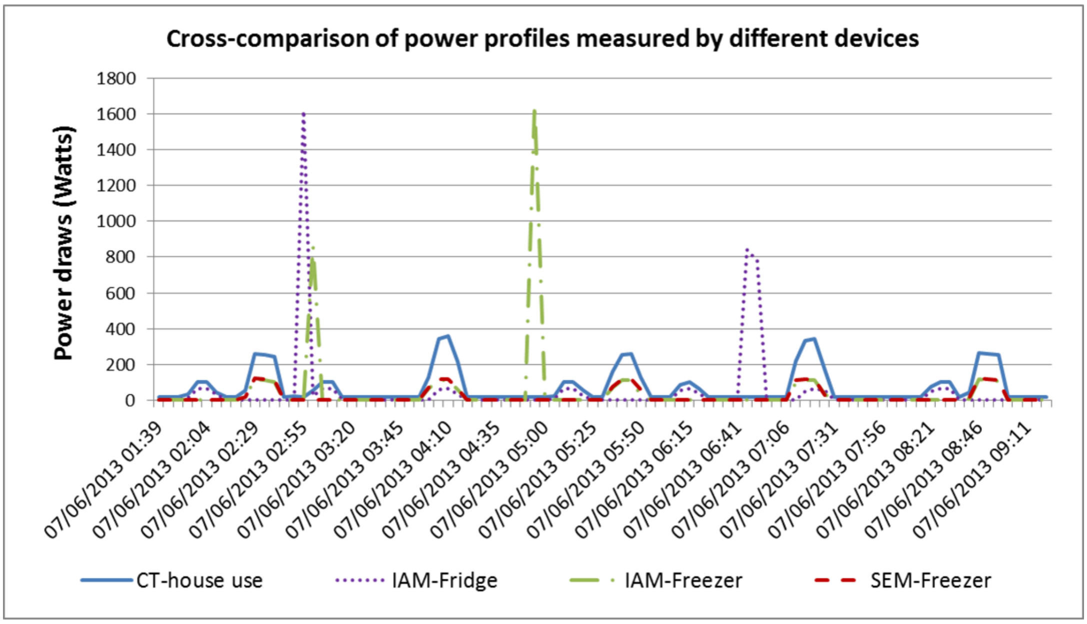


Figure 4-2 Cross-comparison of power profiles for cold appliances measured by the Current Cost® and NZR® devices

Three features are revealed from the cross-comparison process shown in Figure 4-2:

- The power spikes of IAM-measurements of fridge and freezer are faulty and should be removed by applying appropriate signal-filtering procedures;
- The IAM-measurements approximate to the actual power demand recorded by the professional NZR® SEM device;
- The pseudo-real power draws recorded by the Current Cost® CT & transmitter unit are larger than the actual power draws, since AC current is the only measured parameter.

4.5 Monitoring devices for indoor and outdoor environment

Some energy-related occupancy activities, such as showering and cooking, are not directly measurable by Current Cost® IAMs but are potentially detectable from the variations of indoor Temperature (T) and Relative Humidity (RH) in associated living zones. The influence of natural or mechanical (when existing in the house) ventilation on the indoor environment is reflected in the tracking trajectory between the outdoor and indoor variations of T and RH. Under the same microclimate and built-form conditions in each case study, fluctuations of the indoor T and RH in associated living zones are important indicators for energy-related occupancy behaviours in the paired study homes, such as heating and ventilation activities in different seasons. In addition, the building thermal performance is reflected in the comparison of indoor hygrothermal conditions of different case studies against their respective outdoor environmental conditions. Therefore, T and RH were selected as the major indoor and outdoor environmental variables in this research project, which had no intention to investigate other indoor conditions relating to comfort and health, such as air quality and pollutants. The occupancy statuses, which were directly measured by state sensors and indirectly reflected by power profiles in this research, had no specific requirement to be extracted from the variations in other indoor environmental variables, such as CO_2 concentrations.

4.5.1 Devices for indoor hygrothermal measurement

Two types of indoor hygrothermal loggers were used to measure the indoor T and RH in this research project, including Tinytag® TGU-4500 hygrothermal loggers and Hobo® U12-012 hygrothermal & Light-intensity loggers. The technical features are presented in Table 4-2.

Table 4-2 Indoor hygrothermal monitoring devices used in this research (photo sources: Tinytag (2009) and Hobo (2010))

Name	Picture	Specifications
Tinytag® TGU-4500 T/RH data logger		Bit number of the Analog-to-Digital Converter: unknown; Internal memory: 48Kb (32,000 entries), non-volatile; Temperature: -25º to 85ºC, accuracy: ±0.4º for 0º to 50ºC, resolution: 0.01ºC; Relative Humidity: 0% to 95% RH, accuracy: ±3.0% RH at 25ºC, resolution: 0.3% RH; Dust and water proof level: IP53
Hobo® U12-012 T/RH/L data logger		Bit number of the Analog-to-Digital Converter: 12-bit; Internal memory: 64Kb (43,000 entries), non-volatile; Temperature: -20º to 70ºC, accuracy: ±0.35º for 0º to 50ºC, resolution: 0.03ºC at 25ºC; Relative Humidity: 5% to 95% RH, accuracy: ±2.5% to ± 3.5% RH, resolution: 0.03% RH; Light intensity: one to 3,000 lumen/ft^2, maximum relative light level 1,500 to 4,500 lumen/ft^2

Each individual light intensity measurement of the Hobo® U12-012 logger is recorded within a narrow time window shorter than a second at the end of each logging interval. It is thus the instantaneous snapshot of environmental light-intensity levels. Cloudy conditions, glass reflections, and incidental solar radiations within the associated measurement window are potentially influential to the detected intensity levels, which are sometimes erratic. Therefore, the logging results of light intensity levels are not intended for quantitative work and numerical analysis in research on horticulture (Hobo, 2010) but can be used in this research as indicators of the indoor lighting environment. For example, relatively stable recordings over a time period indicate the dim or light conditions of associated living zones or the use of adjacent artificial lighting. Although stable recordings of light intensity potentially indicate certain behaviours that require artificial light sources, it can be problematic to infer the behaviours by using light intensity recordings alone. For example, when the artificial lights are left on by oversight, the recordings can be a faulty indicator for the statuses of associated activities. One of the advantages in having extra light-intensity parameters is to use the recording as a reference in keeping valid measurements of T and RH. If erratically high intensity levels appear regularly on most monitoring days, the logger is probably under the influence of direct solar radiation and thus requires relocation to another place in order to keep rational T and RH recordings of the indoor hygrothermal conditions.

After a few trials of different logging intervals in one pilot study, a 10-minute interval was selected for most of the monitoring periods in this research project although other intervals were used under various conditions. For example, when the researcher could not access the homes over a period exceeding one month, a 20-minute interval was selected to prevent data missing due to the limits in the loggers' internal memory capacity. Once the five-minute interval was available for power data from the Current Cost® dashboard, a trial using five-minute intervals was conducted over a period of a few months for the purpose of cross-comparison between power draw profiles and hygrothermal recordings. In typical living zones that have relatively frequent variations in T and RH values, such as the kitchen and shower room, an extra hygrothermal logger was set to record at five-minute intervals and placed next to the original logger that was set at 10-minute intervals. The comparison between the five-minute and 10-minute measurements of T and RH parameters revealed similar patterns, such as trends and variations. It proved the effectiveness of using 10-minute intervals for hygrothermal monitoring.

The completeness of five-minute power profiles was hindered by the inconsistent stability of the Internet service and time-keeping mechanism of Current Cost® devices. Taking the identical five-minute interval, power data over a one-day period rarely had complete 288 data entries that were featured by the T and RH measurements. Automatic pattern extraction by comprehensively using multi-category variables relies on synchronising the same number of entries of different variables over the same time period. Programmes that were purposefully built to process data on a larger scale than the daily records required relatively complete profiles of different variables containing identical data entry numbers. Since the synchronisation was not feasible in this study, hygrothermal recordings and power profiles needed to be analysed separately, although manual cross-comparison was still applicable to examine the measurements for certain days on a micro-scale. It further proved the sufficiency of using a 10-minute interval in the hygrothermal monitoring.

4.5.2 Devices for outdoor hygrothermal measurement

The outdoor T and RH are major variables that were selected in this research to combine with the indoor T and RH measurements in the assessment of building thermal performance and residents' interaction with the built environment. The outdoor temperature recordings facilitated the HDD calculation when mains gas existed in monitored houses. Wind- and rain-associated weather parameters are reference variables of the microclimate conditions but were not directly used in the analysis within this research. Therefore, the installation of outdoor sensors associated with wind direction, wind speed, and rain gauge had no specific requirement on the mounting height and distance from the houses as would be the case in research on accurate weather analysis.

The Easy Weather® station, which consists of an indoor touch-screen & receiver unit and an outdoor sensor & transmitter unit as shown in Table 4-3, was used for the weather condition monitoring in this project. The SRD RF band at 433 MHz, which is the same for Current Cost® devices, is used for wireless communication between indoor and outdoor units. No button operation is required for the RF channel establishment since the RF ID is automatically assigned once the station units are powered by batteries.

Table 4-3 Outdoor hygrothermal monitoring devices used in this research (photo sources: Tinytag (2009) and site-picture of one case study)

Name	Picture	Specifications
Tinytag® TGP-4500 T/RH data logger		Bit number of the Analog-to-Digital Converter: unknown; Internal memory: 48Kb (32,000 entries), non-volatile; Temperature: -25º to 85ºC, accuracy: ±0.4º for 0º to 50ºC, resolution: 0.01ºC; Relative Humidity: 0% to 100% RH, accuracy: ±3.0% RH of at 25ºC, resolution: 0.3% RH; Dust and water proof level: IP68
Easy Weather® Station: outdoor unit and indoor touch screen	 	Five RF channels at 433MHz SRD band between indoor base station (receiver) and outdoor transmitter unit: outdoor temperature, outdoor RH, wind direction, wind speed, and rain gauge; SRD transmission distance: 100 m; Temperature: -40º to 65ºC, resolution: ±0.1º, unknown accuracy; Relative Humidity: 10% to 99% RH, resolution: 1% RH, unknown accuracy; Rain volume: 0 to 9999 mm, resolution: 0.3mm (if volume ‹ 1000 mm), unknown accuracy; Wind speed: 0 to 44 m/s; Air pressure: 700-1100 hpa, resolution: 0.1hpa; Internal memory: 6kB (4,080 entries), volatile; Dust and water proof level: IPX3

The major drawback of the Easy Weather® portable weather station resides in the aspect of volatile and limited internal memory. Without sufficient battery capacity, the stability of the RF channels cannot be sustained, especially in colder seasons. Under these circumstances, no outdoor parameters can be recorded due to the interrupted wireless communication. Data loss also occurred in this research when the residents changed batteries in between two monthly site visits without alerting the researcher and thus enabling her to download the data prior to the operation. The relatively small memory capacity of the station compared to other loggers means the history data start to be overwritten over a shorter time period at the same logging interval. For example, 4,080 entries can last for around 28 days if a 10-minute interval is used. A 20-minute interval has to be adopted when site visits cannot be conducted every 28 days. Another drawback of using the Easy Weather® station to measure the outdoor T and RH is the grey colour of the all-weather shield for the hygrothermal sensors. The dark colour of the shield surface makes the inside sensors more sensitive to strong solar radiations than a reflective or light-coloured surface.

In addition to using the recordings of professional weather stations near to the monitored houses, the Tinytag® TGP-4500 loggers as pictured in Table 4-3 were used to calibrate the Easy Weather® station. Although not designed for outdoor T and RH measurement, the logger meets higher hygrothermal monitoring standards and can be used in outdoor conditions due to the IP68 dust and water proof level. Without an all-weather shield, the outdoor RH recordings were found to be erratic, although most of outdoor T measurements fell in an acceptable scope.

4.6 Monitoring devices for occupancy statuses

The occupied and unoccupied statuses of monitored homes were indirectly reflected by the measurements of energy use and hygrothermal conditions to a certain extent. By applying state loggers, such as Hobo® U9-001 and Hobo® U11-001 and the configured event recording sets as demonstrated in Table 4-4, the occupancy statuses were also directly detected in this study. The event button on the front panel of the Hobo® logger can be pressed to manually record extra events, such as the use of space heating out of programmed heating hours.

The one-state Hobo® U9-001 logger and included magnate reed-switch were directly mounted onto window or door frames for status-recording. The three-state Hobo® U11-001 logger was used with other sensors to configure event-detection equipment sets. For example, the stand-alone motion / light intensity detection box in Table 4-4 consisted of two Rapid® PIR sensors and one adjustable light switch to make full use of the three-state channels. The two PIR sensors facing opposite directions can be used simultaneously or as maintenance back-up for each other. The PIR Fresnel lens can detect a change of infrared energy radiated from a moving human body or other heat sources similar to the temperature of human bodies. To avoid faulty detections from moving pets in certain houses, opaque taps were used to deactivate parts of the vertical detectable angles of Fresnel lens. The internal memory capacity of Hobo® logger and the mAh capacity of AA batteries were bottleneck factors when the detection box was used in living areas that were frequently occupied or in seasons when frequent light-intensity variations occurred around the pre-set values of light-switch. The configured detection box, which evolved from a former prototype using wired system, was considered as the prototype of the latest-series compact loggers as demonstrated in the acknowledgement letter in Appendix Two. The newly developed Hobo® logger, although convenient and economical to use and free from the bottleneck factors, arrived on the market too late to be applied in this research.

Another type of configured equipment set is the mattress pressure detector shown in Table 4-4. By inserting the pressure mat underneath the door mattress adjacent to the main entrance, digital pulses were recorded by Hobo® U11-001 to reflect the occupational patterns of the house. This research did not seek to distinguish the entry and exit events and calculate the frequencies of presence and motions. Therefore, the use of the other entry and exit points that could not be covered by the pressure mat was not a major influential factor in meeting the monitoring requirement. One major drawback of using the portable pressure mat is that the mat can be moved by the residents for various reasons, such as house cleaning or the prevention of home pets from chewing the input cable. Missing data under such circumstances can lead to a faulty conclusion of unoccupied status being assigned to the house, if no appropriate validation is conducted.

Table 4-4 Occupancy status monitoring devices used in this research (photo sources: Hobo (2010))

Name	Picture	Specifications
Hobo® U9-001 state data logger		Internal memory: 64Kb (43,000 entries), non-volatile; One internal reed-switch to establish a magnet field with the included magnet or out-sourced strip; One state: triggered by either an external contact closure via the included input cable, or by the included magnet strip; One event: triggered by pressing the button on the logger surface for one second
Hobo® U11-001 state data logger		Internal memory: 64Kb (43,000 entries), non-volatile; Three states: triggered by either an external contact closure via the included input cables; One event: triggered by pressing the button on the logger surface for one second
Mattress pressure detector		The passive contact closure, which can be triggered by the pressure sensor in the pressure mat, is wired to the Hobo® U11-001 state data logger via one included input cable.
The motion / light intensity detection box		Two Rapid® PIR sensors are set on two opposite sides of the box. The Fresnel lens: horizontal detectable angle ±50ºC, vertical detectable angle ±30 ºC, 1.0 to 2.0 mA constant DC current draw; One light switch is set on the front cover of the box; The positive contact closure of each PIR sensor is powered by three rechargeable 1.5 V AA batteries and wired to the Hobo® U11-001 state data logger via one included input cable; The passive contact closure of the light switch, tunable using adjustable resistor, on the top cover is wired to the Hobo® U11-001 state data logger via one included input cable.

The power profiles measured by Current Cost® devices and the occupancy statuses recorded by the window / door status loggers, the motion / light intensity detection box and the mattress pressure detector were used interactively to detect the actual occupancy statuses, especially when any type of measurements was incomplete.

4.7 Chapter summary

Starting from the selection criteria for monitoring devices and configured schemes for a long-term and longitudinal monitoring project on the scale of this research, this chapter presented the technical details of each type of selected equipment, with the focus being placed on the monitoring devices for analogue parameters. The monitoring devices for the measurement of energy use and power demand were succinctly introduced, including the flawed measurements that were caused by equipment-inherent limitations. Therefore, appropriate pre-processing procedures need to be effectively conducted prior to using the raw data for further analyses. The monitoring interval of electricity use at mains power was reduced from two hours to five minutes by utilising peripheral Internet equipment. The five-minute interval meets the requirements for measurements at mains power set out in the monitoring protocol of the Energy Saving Trust (2009; 2011). The actual values of acquired house use were larger than the utility meter readings, since the measuring mechanism of the CT-based off-the-shelf meters is different from the pulse output data acquisition in the EST protocol. Validating acquired data by using collected utility bills and manually recorded utility meter readings is thus important. Although the electricity and power measurements have been extended to the end-use level, the acquired plug loads require pre-processing prior to the visualisation-based and algorithm-based examinations. The pre-processing of raw data is conducted in Chapter Six, after the actual deployment of the selected devices in the case study homes is introduced in the next chapter.

Chapter 5: Pilot and Case Studies

5.1 Introduction

One objective of this research was to deploy the tested monitoring scheme in case study groups to generate effective raw data for the pre-processing and analysis. The previous chapter focused on the configuration and selection of monitoring systems and devices. This chapter builds on this by introducing the pilot and case study houses where the selected equipment was tested and deployed. Each house in the pilot and case studies was given the following unique code to be referred to hereafter throughout the thesis.

- Pilot studies: pilot study A and pilot study B
- Case study of Hockerton House Projects (HHP): HHP3, HHP4, and HHP5;
- Case study of Nottingham City Homes (NCH): NCHA and NCHB.

In addition to an application test of selected monitoring equipment and configured systems, pilot studies were conducted aiming to improve the mixed-method approaches to data collection, such as the identification of appropriate monitoring intervals for certain parameters and the use of occupancy diaries and manual utility meter readings. The two groups of case study houses, conventionally and unconventionally built respectively, had distinctive building characteristics and household profile features between groups but similar built form and family profiles within each group. The monitoring schemes, which featured low costs, less intrusiveness, flexibility, and repeatability in similar monitoring projects, were installed in the pilot and case study houses in phases, with slight variations in monitoring contents.

5.2 Pilot Studies

The testing of the feasibility of methods and procedures in a small-scale investigation for later use on larger scales is an epidemiological and statistical definition of ‘pilot study’ that was given by Thabane, et al. (2010), who examined the definition, rationale, limitation, and conduction of pilot studies from the clinical research perspective. Arain, et al. (2010), also approaching the subject from a clinical research perspective, pointed out the difference between feasibility studies and pilot studies, which were considered as equivalent to the pre-testing of a questionnaire and interview questions by some sociological researchers, such as Sproull (1995) and Bryman (2012). In addition to testing the feasibility of a sociological research instrument, a main contribution of feasibility studies to the main study design is to estimate the required sample size according to targeted confidence intervals (Arain, et al., 2010). One additional precondition that differentiates some pilot studies from pre-testing and feasibility studies resides in the study design aspect. If a pilot study is the first phase or a miniature version of a substantial main study, it should resemble the main study in many aspects in order to produce potentially applicable data in the final analyses. Pilot studies can be performed in both quantitative and qualitative studies (Thabane, et al., 2010), and are thus compatible with the mixed-method context of this research.

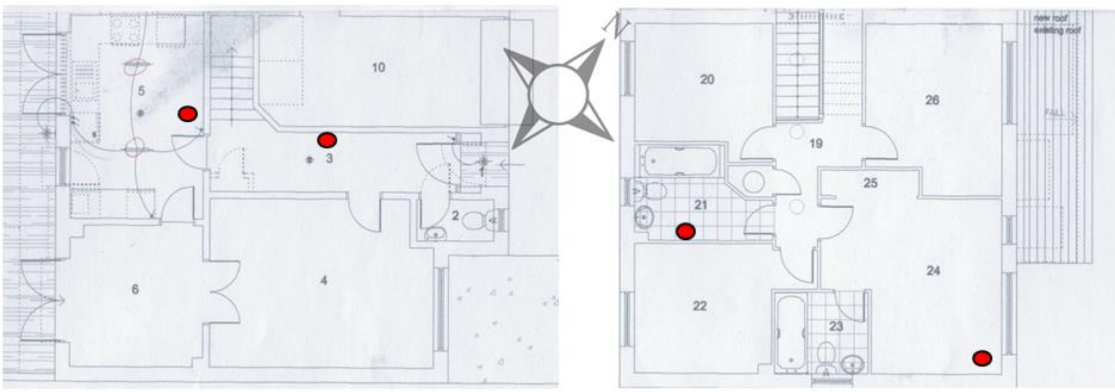
Reasons to conduct pilot studies, in terms of research process, resource demand, project management, and scientific results, were given by Thabane, et al. (2010), who also exemplified several misconceptions in justifying the conduction of pilot studies. The lack of resources, the similar procedures in other published studies, and the requirement from supervisors or bosses are among these misconceptions, which can potentially lead to poorly designed pilot studies that waste the effort and resources of researchers and participants. The pilot studies in this research were conducted based on thorough consideration of the four aspects listed by Thabane, et al. (2010). As the test-bed for monitoring devices and mixed-method approaches applied in the case studies, the experimental design of the pilot studies took into consideration every aspect of the main study. The non-intrusive and transferable features of the low-cost monitoring scheme enabled the reuse and relocation of certain pieces of the pilot studies' monitoring equipment in the long-term and longitudinal measurements carried out in the case studies. The other two aspects regarding project management and scientific results are individually presented in the following subsections. The monitoring contents and durations of the two pilot studies, which were respectively launched in September 2009 and August 2010, are listed in Table 5-1. Since conducting monthly site visits was infeasible, the data were downloaded by the residents in each pilot study home. The geographical locations, built forms and household profiles of the two pilot studies are different. The monitoring results thus had limited potential for cross-comparison. Data missing occasionally occurred in pilot studies. The problem-solving measures assisted in the establishment of an effective and properly conducted equipment maintenance protocol, which was important in acquiring data of a sufficient quality in the subsequent case studies.

Table 5-1 Monitoring contents in two pilot study homes

	Pilot study A	**Pilot study B**
location	Devon, UK	Derbyshire, UK
indoor T and RH	Sep.2009 to Mar.2012	Aug. 2010 to Feb. 2013
outdoor microclimate	Aug. 2010 to Mar.2012	Aug. 2010 to Feb. 2013
bi-hourly house electricity use	Dec. 2010 to Jan. 2011	Feb. 2011 to Mar. 2011
power draw at 10-minute intervals	Feb. 2011 to Sep. 2011	Mar. 2011 to Sep. 2011
power draw at five-minute intervals	Sep.2011 to Mar.2012	Sep.2011 to Mar. 2012
power draw of certain individual appliances at five-minute intervals	Oct.2011 to Mar.2012	Feb.2012 to Apr.2012

5.2.1 Pilot study A

The four-bedroom detached house was built with a 50 mm cavity between the 115 mm blocks, with plaster board on dabs internally and 20 mm render on the outside. The U-value was estimated between 0.96 W/m2K (assuming dense block materials) and 0.47 W/m2K (assuming thermal block materials). A fan-flued and non-condensing boiler served the central heating of the household consisting of an adult couple with two teenage children. T and RH were monitored using four Tinytag® TGU-4500 loggers in the four living zones as shown in Figure 5-1.



Ground floor plan **First floor plan**

Hygrothermal loggers in the hallway (room 3), kitchen (room 5), bathroom (room 21), and main bedroom (room 24)

Figure 5-1 Floor plans and logger locations in pilot study A

The residents downloaded loggers and examined battery conditions every few months. Different monitoring intervals over a range of five to 30 minutes were experimented with before the 10-minute interval was selected for the monitoring of indoor T and RH. Two batches of occupancy diaries were provided by the residents. The first batch was taken over a two-week period from 19 December 2010, when neither 10-minute nor five-minute power profiles were accessible. The occupancy diaries, which consisted of major energy-related activities and the starting times, were used to calibrate the extracted patterns in 10-minute hygrothermal profiles and bi-hourly electricity use. Some preliminary cross-comparison results were presented in a conference paper at the 7th International Conference on Intelligent Environments – IE'11. The second diary trial using the table format in Appendix One was taken on 22 December 2011 to calibrate the five-minute power profiles measured by Current Cost® IAMs. The cause of faulty power spikes was identified to be the lack of a signal-filtering mechanism in the IAM firmware design. Diaries in this format were collected from the subsequent case studies to assist in the data pre-processing that filtered the faulty measurements in power draws.

On 24 February 2012, an array of photovoltaic (PV) panels was commissioned in pilot study A. The five-minute power profile of house use at mains power was found to be severely distorted by the retrofitted PV microgeneration. Due to spatial restrictions imposed by the circuit arrangement, no position was available to relocate the Current Cost® current transmitter (CT) clamp in order to separate house use from PV microgeneration. This situation officially marked the end of the monitoring scheme in pilot study A. However, the problem-solving attempts performed by adjusting the CT positions contributed to the identification and implementation of proper solutions to a similar situation that appeared in case study home NCHB, where the retrofitted PV circuit was commissioned to the original wiring system in the same way as in pilot study A.

The monitoring trials in pilot study A made four major contributions to the research:

- Identifying proper measuring intervals for indoor hygrothermal monitoring;
- Applying occupancy diary as a sociological approach in data collection;
- Providing primary results in the first conference paper;
- Inspiring improvised solutions to separate retrofitted PV circuit from mains power by adjusting the CT deployment when permitted by circuit arrangements.

5.2.2 Pilot study B

The detached house of pilot study B had 100 mm polystyrene bead insulation inside the 100 mm Hemelite/Thermalite block as built in 1981. The house layout had been continuously altered since 1995, after a conservatory was added in 1991. The floor plans used during the monitoring period are shown in Figure 5-2.

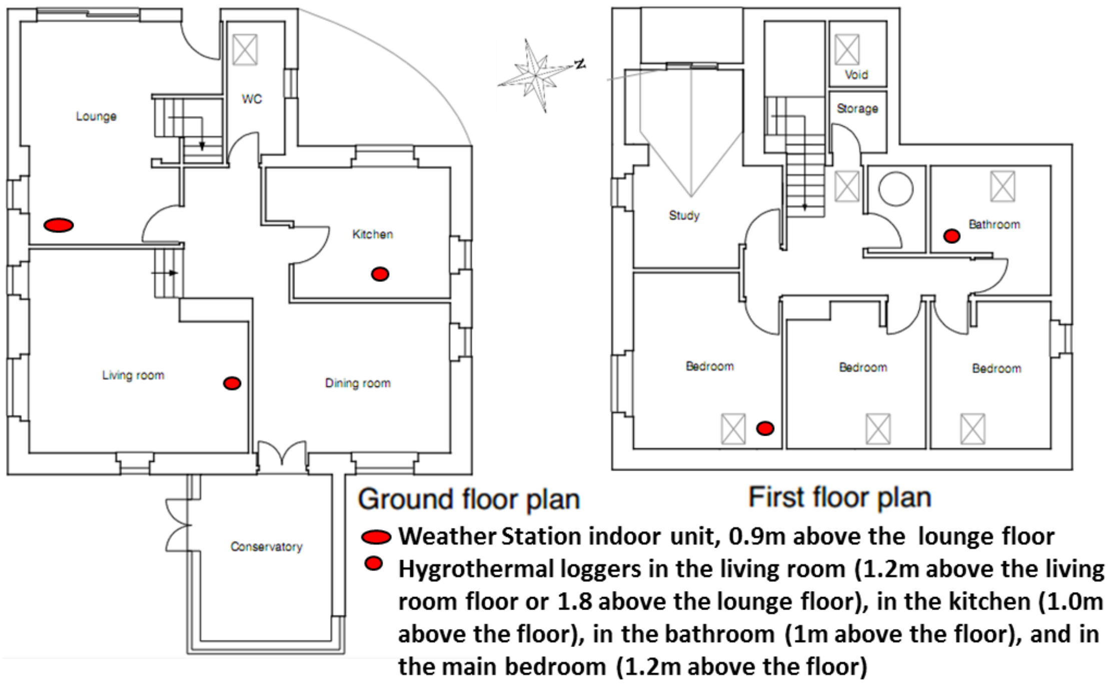


Figure 5-2 Floor plans and logger locations in pilot study B

In September 2010, which was one month after the indoor T and RH monitoring was conducted, an external insulation retrofit was conducted by creating an extra 100 mm cavity filled with blown Knauf glass-fibre. The section of external walls from exterior to interior was 100 mm natural sandstone, 100 mm knauf glass-fibre, 100 mm Hemelite / Thermalite block, 100 mm polystyrene bead insulation, and 12 mm lightweight plaster and skim. A U-value below 0.2 W/m^{2}K was estimated for the finished external walls. In addition to the external retrofit, a condensing boiler with weather compensation was installed on 14 October 2010 to replace a Band D non-condensing boiler with 78.7 per cent seasonal efficiency that was installed on 25 November 2004. It was a Band G non-condensing boiler with 65 per cent efficiency that had served the household for 23 years from October 1981 to November 2004. The household profile had changed over the previous two decades. When the on-site monitoring started in August 2010, the house was occupied by an adult couple.

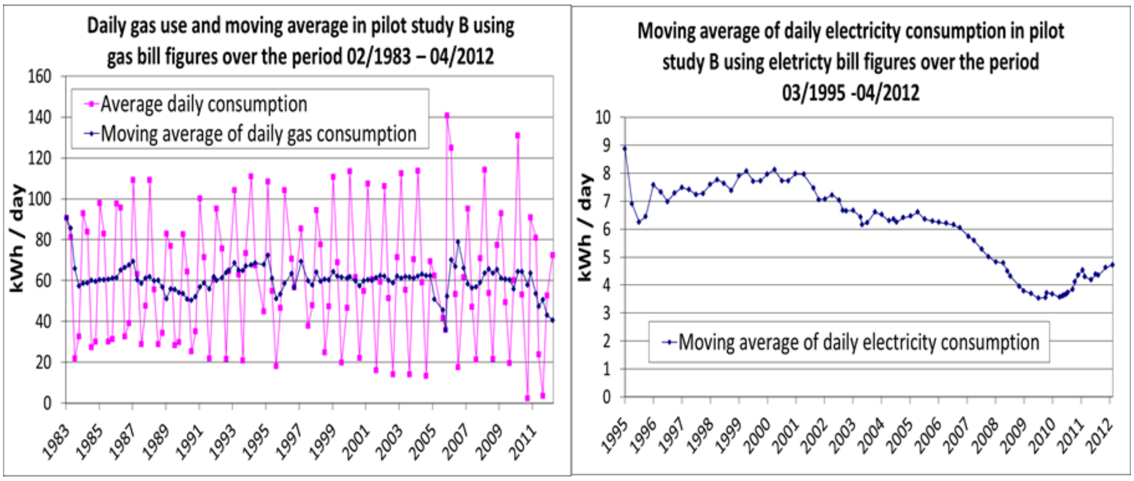


Figure 5-3 Moving average of daily energy use in pilot study B using figures on long-term utility bills

The residents had been keeping long-term manual records of electricity use since 1984 and gas use since 1982 based on the figures shown on the quarterly energy bills. The data profiles in Figure 5-3 present parts of the manual recordings, which contain the associated patterns regarding the changes of external-wall U-values, boiler efficiencies, and household profiles. The moving average of daily gas use was around 60 kWh and further decreased after the recent retrofit even during the extremely cold heating season, within the UK climate context, of 2010 to 2011. The average daily electricity use from the year 2010 ranged between four and five kWh, which was consistent with the Current Cost® measurements. The five-minute Current Cost® power profiles revealed that house power draws remained at a stable and low level for most of the occupancy periods. Other than base load components, major variations in power draws were sourced from the use of the washing machine since cooking was also fired by gas.

Compared to electricity use, gas consumption accounts for the major portion of energy use of the household.

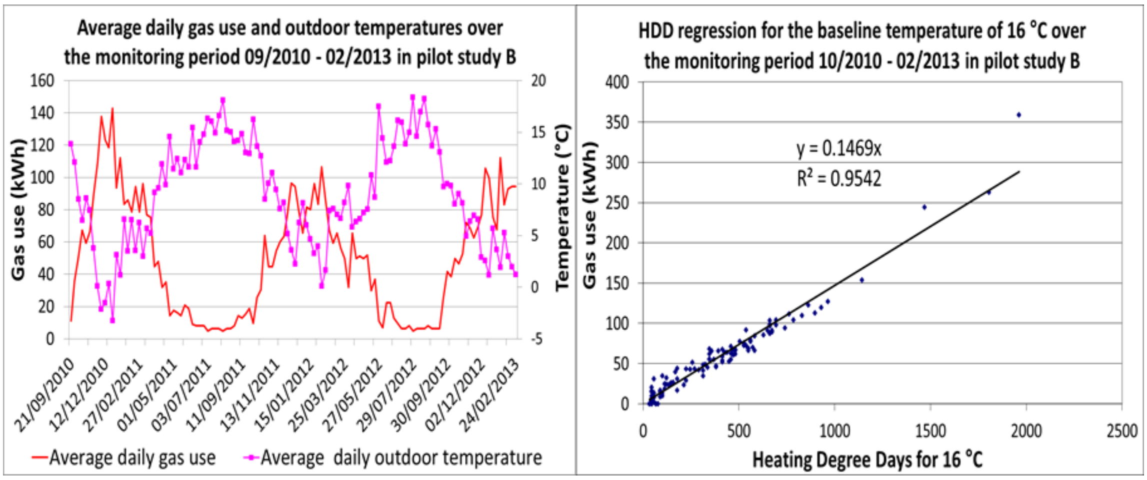


Figure 5-4 Average daily gas use and outdoor temperatures in pilot study B and HDD regression over the monitoring period

In addition to the quarterly bill records, to identify the effect of the recent retrofit on gas consumption, the residents started to manually record their gas use at weekly or bi-weekly intervals after 11 October 2010. Weather monitoring at consistent 30-minute intervals started from August 2010. The dedicated effort input from the residents helped to keep the most complete weather data profile among all pilot and case study houses in this research. Data were rarely lost due to battery failure or delayed download. The complete weather profile and frequent manual recordings of actual gas use facilitate the Heating Degree Days (HDD) analysis as demonstrated in Figure 5-4, which also presents the expected inverse-variations of gas use and outdoor temperatures. Statistically significant HDD regression was established using different baseline temperatures. Among all the temperature scenarios between 16 ºC and 18 ºC, the best fit regression was achieved for the baseline temperature at 16 ºC.

The major contributions to the research of the monitoring trials in pilot study B were as follows:

- Adopting manual energy recordings as a validation approach for electricity measurements and a supplementary approach for gas use analyses;
- Establishing protocols for equipment maintenance to keep relatively complete measurements.

5.3 Case studies

Case studies were justified as an appropriate research method in Chapter Three, which also discussed the selection criteria for case study groups. Based on the experiment conducted in two pilot study homes, the adjusted monitoring scheme was deployed in the two selected case study groups. The HHP case study consisted of three unconventionally built houses from the Hockerton Housing Project Trading Ltd.[5] (HHP). The NCH case study comprised two conventionally built social houses from Nottingham City Homes (NCH). The same level of monitoring was conducted in houses within each case study group to enable effective within-group comparison of the monitoring and analysis results. It was expected to pin-point the occupancy effects relating to the variations in domestic energy use and indoor environment in the process of within-group comparisons and to reveal the impact on energy use from the perspective of different building characteristics in the between-group comparison.

The HHP case study homes had diverse household profiles, including single occupant, couple-resident, and multi-occupant families. The major difference in energy use was expected to arise from the respective household compositions, since every home within the HHP community 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

[5] As a co-operative company, HHP is made up of all the adult occupants of the five families on site. The team members are responsible for the overall running and maintenance of the project and community services and equally paid for communal activities hours as required. Within and beyond its consultancy and educational business scope, HHP provides self-builders, researchers, students, local authorities and businesses with an investigation platform for sustainable living (HHP, 2013).

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.

5.3.1 Hockerton Housing Project (HHP) case study

5.3.1.1 Background of the autonomous houses

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’ as possible (Vale and Vale, 2000). As defined by one of the three highest environmental housing standards, autonomous houses / communities must meet the requirements of the other two top standards of zero CO_2[6] and zero heating[7] by utilising on-site renewable energy resources. Houses built to the autonomous standard are designed to be self-sufficient without the need for mains connection apart from grid-linked electricity. The water and sewage treatment, designed to be independent from the mains, and the building materials, selected from an environmental perspective, achieve excellence in environmental performance by allowing for more innovative solutions for the sustainable development of autonomous houses / communities. Technically, the autonomous standard is more comprehensive if compared with other commonly applied energy and building assessment methods that primarily measure the energy performance and ratings of houses. The philosophical and technical background of autonomous buildings has been discussed by the British architects Brenda Vale and Robert Vale, who designed and lived in the first autonomous house[8] in the UK and designed the five HHP houses afterwards.

[6] With no net carbon emissions from its annual energy use, a zero CO_2 house either only purchases renewable energy to meet its daily use or compensates for the non-renewable energy occasionally consumed by its own annually sufficient capacity of on-site renewable microgeneration (Energy Saving Trust, 1996).
[7] Space heating in a zero heating house is obtained from passive solar gains and the presence and activities of occupants. Supplementary heating can be occasionally used to meet the special demands of young children, elderly or disabled residents (Energy Saving Trust, 1996).
[8] The house, as built in 1993, is located in the Newark and Sherwood area. More information about the design and performance in use of this house development is available in Vale and Vale (2000).

Originating from concerns over resource depletion and environmental deterioration and the social and technological aspects of Utopian literature, autonomous buildings take the alternative-technology approach to simplifying design and enhancing performance in achieving a simple, robust and occupant-controllable built environment with a minimum environmental impact (Vale and Vale, 2000).

Living in an autonomous community demands certain levels of environmental responsibility to adjust to the non-conventional lifestyle. Three homes were selected out of five households for the case study. The long-term monitoring, including indoor / outdoor environment, energy use / generation, and occupancy status, was conducted on the scale of individual houses to the same extent. Rather than conducting a holistic environmental assessment of the self-sufficient HHP community, this case study was designed to investigate the domestic energy use activities that relate to the variations in energy use of each house. In addition, it was expected that the excellence in thermal performance of autonomous building characteristics would be reflected in the indoor / outdoor environmental monitoring results. Before discussing the application of monitoring schemes, it is necessary to briefly introduce the autonomous features of the HHP site and houses that are directly associated with the lifestyle and energy use activities of the monitored houses.

5.3.1.2 HHP site

Located in the northeast of rural Nottinghamshire, the Hockerton Housing Project is among the first multi-dwelling, earth-sheltered, and self-sufficient ecological housing developments in the UK (HHP, 2011). Designed in the year 1994 by Prof. Brenda Vale and Dr. Robert Vale[9], the five dwellings[10] were constructed in 1996 on a 25-hectare

[9] The UK's first sustainable autonomous town house in Southwell, UK was designed by and home to the architects Prof. Brenda Vale and Dr. Robert Vale and was constructed by the Hockerton Housing Project (HHP) Trading Ltd. in 1993. Convinced by the autonomous design, HHP commissioned the architects for the development of the five earth-sheltered autonomous dwellings (HHP, 2011).

[10] The office annex was designed and constructed to meet the same high standards as the dwellings at a later stage.

agricultural site outside the village of Hockerton. Off-grid from mains water, the site is self-sufficient in drinking water by using rainwater collection with high-standard filtrations and UV-light disinfection and in non-drinking water by using surface runoff collection with sand filtration. Off-grid from mains wastewater, the outflow from septic tanks is treated in a reed bed system, from which nutrient-rich water flows to an excavated lake for fishing, rowing, and other recreational and landscape uses in front of the five dwellings (see Appendix Three). The active eco-system created by the lake forms part of the unique microenvironment around the buildings. Separate water collection and storage system exist in food growing areas, which sustain over two-thirds of the community consumption of vegetables, fruit, eggs, meat, honey, and wine (HHP, 2011).

The original on-site microgeneration system includes two wind turbines that are rated at six kW each in the office annex area, and arrays of solar photovoltaic (PV) panels that are rated at 7.65 kW-peak on the house roof (see Appendix Four). Before the installation of PV panels in 2012 to meet the demand of the office annex and more electric cars in the future, the annual output of the on-site microgeneration was around 12,000 kWh[11], with an average annual shortfall of around 6,000 kWh being sourced from the national grid (HHP, 2011). The wind microgeneration was not included in the monitoring scheme of this research since power profiles of the office annex were beyond the scope of this research.

Six sets, 15 panels per set, of PV panels were mounted along the front parapet and down the side walls of the five south facing dwellings[12]. Each set of panels had an individual AC / DC inverter installed in the five houses, among which HHP4 had two inverters. Without on-site storage facilities, the grid-linked houses import the power

[11] The downwind design, coupled to a permanent magnet alternator, of the wind turbines should enable a quiet, flexible, and efficient operation of the wind turbines. However, only 40 to 50 per cent of the theoretical annual output (around 12,000 kWh from each turbine) is generated in practice due to the wind factors and invertor compatibility. The performance of solar PVs is close to the expected annual capacity of 6,000 kWh. Therefore, annual microgeneration is around 12,000 kWh in practice (HHP, 2006d).

[12] The peak output is 85 Watt-peak per panel, or 7.65 kW peak from the total 90 panels.

shortfall when house demand exceeds real-time supply from the PV microgeneration and export the excess to the grid in the reverse situation. To optimise the load balance of energy generation and consumption across three AC phases of the community power system, the mains power and two inverters of HHP4 were connected to a separated AC phase as shown in the power system sketch in Appendix Four. In addition to phase balancing, the inverter arrangement was selected out of the concern that HHP4 used to have a higher power demand than the other four houses at the time of PV installation, mainly because of the numbers of teenager residents living in the house (HHP, 2006e). The double amount of solar power generation from the two sets of panels can optimally match the higher demand of HHP4, before real-time power surplus being exported to the grid. Although the grown-up children left HHP4, the power connection structure remained unchanged. The PV microgeneration in each monitored house was measured along with energy use to provide further insights into the assessment of domestic energy profiles and associated activities.

5.3.1.3 HHP house

For the ease of construction and the efficiency in thermal performance, the houses were designed as a repeated modular-bay system of 3.0 metres in width per bay. Four houses have six bays and the centre house has seven bays. As shown in the layout diagram in Appendix Five, each bay is six metres deep with an average height of 2.8 metres when rising from 2.2 metres at the rear to over 3.3 metres at the front. Near to the apex of each bay is the 3.3 metres high and 1.8 metres wide glazed-area that connects with the south-facing conservatory / sun space that is 3.0 metres deep. The conservatory runs the full length of the house except for the first bay, where a porch area of 2.7[13] metres by 3.0 metres is placed, with a main entrance leading to the landing area and utility room. The buffer zones created by the porch and conservatory

[13] 150 mm glass wool insulation was used to insulate the walls surrounding the porch area, including the wall between the conservatory and the porch area. Thus the useable floor area of the porch was reduced from 3.0 by 3.0 metres to 2.7 by 3.0 metres.

introduce temperature gradients between indoor and outdoor environment by reducing heat loss from the front wall and main entry / exit point in winters and by decreasing extra heat gain in summers. The living zones where daylight is primarily needed, such as living room, kitchen, and bedroom, have been arranged adjacent to the glazed area, whilst those where daylight is less of an issue, such as bathroom, utility room, and entertaining and dining areas, have been placed at the rear of the house. The 1.8 metres wide glazed frame in each bay was well sealed and had trickle ventilation openings installed. Subdivided into upper French windows and lower French doors, all panes were triple-glazed, Argon-filled, and had an internal low-emissive coating surface.

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 as shown in Appendix Seven) and insulation, keeps the indoor environment within a stable comfort zone. Under the equilibrium status of heat gain and loss, energy stored in the thermal mass due to one degree of temperature increase throughout the mass of concrete and blocks can be sustained for nearly two days via the convective heat transfer between air and thermal mass, as estimated in Appendix Seven.

Appendices Five and Six show the sectional structure of the wall, roof, and floor slab of the earth-sheltered houses. The five dwellings were effectively enveloped by earth, damp proof membrane (dpm), reinforced concrete, and dense concrete blocks, except for the SSW-facing conservatory façade. The concrete, membrane and insulation were managed to be continuous in all directions of floor, roof, and rear and end walls along the terrace during the construction. Details were considered for the integrity of thermal performance, such as the thermal break in slab areas between buffer zones and the main house and the arrangement of service pipework without perforating the insulation and membranes (HHP, 2005). During severe winter seasons, soil temperatures only drop to 5.0 to 6.0 ºC, resulting in a maximum difference between indoor and outdoor temperatures of around 12.0 to 13.0 ºC in the free-floating houses (HHP, 2006b).

The highly air-tight design requires an effective ventilation system to prevent the deterioration of air quality from potentially excessive levels of moisture and pollutants. Natural ventilation is not adequate due to the terrace-bungalow design and the priority in reducing heat loss from the free-floating homes. A Mechanical Ventilation with Heat Recovery (MVHR) system is thus adopted when heat loss is a primary concern, while supplementary passive ventilation is applied mainly in warmer months. In addition to the operation of French windows and doors between main house and buffer zone areas, natural ventilation is assisted by the conservatory skylights adjacent to the corresponding French windows of each bay, the trickle ventilation openings on glaze frames of the main house, and the air bricks built in the conservatory walls. Blinds are manually operated in the conservatory to prevent over-heating from strong solar radiation in hot months when the passive stack created by skylights, windows, and doors is not adequate for quick heat exit. All HHP community members work in the office annex and are thus conveniently able to adjust the natural ventilation by coming back to the houses. The independent MVHR system in each house consists of clay ductwork, centrifugal impellers, motors, and a heat exchanger. Up to 70 per cent of the heat can be recovered from the stale air exacted from the wet areas such as the bathroom and kitchen (HHP, 2006c). An equivalent volume of pre-heated and filtered fresh air is supplied to major living areas such as the living room and bedrooms. Suspended from the ceiling, the inlet and outlet clay pipes run the full length of the house in parallel. All the other major MVHR components were housed in an air-handling casing near to the fresh air inlet in the porch area of each house (see Appendix Eight). The operating speed of the MVHR system used to be adjustable for different air change rates up to 400 cubic metres per hour. Although the system was rarely operated continuously at a low speed on 24 / 7 cycles, the HHP households ran various trials to lower energy consumption while ensuring the required air quality. When the monitoring scheme for this research started, the impellers and motors of the MVHR system in some houses had been replaced with a pair of standard fan-and-motors used for personal computers to lower the airflow rate by consuming as little as 3.0 watts. The noise level was also reduced following the change.

Hot Water System (HWS) of each house is a shell-and-coil indirect system that was originally designed to be powered by the air-to-water heat pump, which extracted the passive solar energy collected and stored in the conservatory (see Appendix Nine). A Coefficient of Performance (COP)[14] as high as three was expected initially, according to the brochure-based calculation, but was never reached[15] in practice even in seasons when warmer air was available in the conservatory for longer periods. The heated water flew between the heat pump and exchanger unit and the thermal store, which was a super-insulated tank[16] with conventional electric immersion heaters as a supplementary heating source. A thermostat control unit, similar to a space-heating thermostat, was used for on-and-off and temperature settings with a manual override function. Hot water in the storage tank, maintained at temperatures between 43 ºC and 47 ºC, was thus used to perform the secondary heat exchange with the running non-portable[17] water flowing through an extended series of coiled copper pipes immersed in the thermal store. Rapid heat transfer was conducted through the water-to-water heat exchange before the hot water was delivered through a microbore pipe to the taps of sinks, baths and showers at a temperature around 42 ºC. The indirect shell-and-coil

[14] The Coefficient of Performance (COP) is used to measure the effectiveness of energy output in relation to input of a system. For example, the COP of the air-to-water pump is the ratio of the delivered heat energy to the amount of electrical energy input used for running the pumping system. The COP of the 700 Watts Hockerton heat pumps was originally expected to be around three. Each kWh of electrical energy consumed was expected to deliver three kWh of heat energy in hot water (HHP, 2008).

[15] The COP for the heat pump was tested to be around 1.4. In the spring / summer, when the conservatory can provide warmer air for longer time periods, the COP will increase. However, it is unlikely the COP will be as high as three (HHP, 2008).

[16] The original water tank with a capacity of 1,500 litres was insulated by 300 mm expanded polystyrene around the base and sides. The tank was replaced by the 500-litre 'Hotsi®' tank that was developed by the HHP Ltd., when the heat pumps were replaced by the redesigned electric immersion heaters.

[17] The HHP site has separate collection and treatment system for portable and non-portable water use, as illustrated in Appendix Three.

system was adopted to remove the requirement to keep the thermal store at a temperature as high as 60 ºC to combat legionella growth (HHP, 2008). In cold seasons, heat pumps were required to operate for six hours per day, in contrast to four hours in warmer seasons to sustain the HWS. If taking the rated power of 700 watts as the constant power demand of the heat pump system, 3.5 kWh was theoretically used for daily HWS energy use. The HHP members conducted several rounds of experiments to compare energy use effectiveness of the HWS when using heat pumps and electric immersion heaters respectively. A new type of thermal tank was developed by the HHP Ltd. and named ‘Hotsi®’ tank. The indirect shell-and-coil feature remained but the super-insulated tank was downsized from 1,500 litres to 500 litres and heated by an electric immersion heater of one kWh instead of heat pumps. In one experiment undertaken in two five-resident houses, one house used the heat pump system and the other adopted the new Hotsi® tank. Over a sunny week period in February 2008, 3.1 kWh and 4.3 kWh were consumed respectively on average for the daily HWS energy use and a COP of 1.4 was reached by assuming the same amount of hot water was used by two houses (HHP, 2008). The energy efficiency achieved by using heat pumps was not proven to substantially outrace the efficiency obtained by using a Hotsi® tank. In practice, the maintenance of heat pumps is more complex and costly than that of immersion heaters. Without extra mechanical components, vibration and operational noise are absent from the immersion heater HWS. Therefore, when it needed to be replaced after a normal life cycle, the heat-pump HSW became obsolete and was gradually replaced by the Hotsi® tank in four houses, except for one home that was still using the original heat-pump HSW. All three monitored houses in this research adopted the new Hotsi® tank before the monitoring scheme started.

5.3.1.4 Energy Performance Certificate for the HHP houses

Appendix 10 is an excerpt of the Energy Performance Certificate (EPC) produced in 2008 for one HHP house using the Reduced Standard Assessment Procedure (RdSAP)

2005. The energy efficiency rating F mainly results from shortcomings in the assessment approach of the SAP and RdSAP (for existing dwellings) that fail to acknowledge heavy-weight thermal mass and passive solar gain that have been applied as energy-efficiency measures by the HHP house design and construction. Homes adopting similar design approaches 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. The Hockerton Housing Project, Ltd. has been appealing to the Building Research Establishment (BRE), the Department of Energy and Climate Change (DECC), and the Department for Communities and Local Government (DCLG), calling for them to reconsider the assessment principles by providing post-occupancy and operational evidence on the dwellings (HHP, 2012). The major design principles overlooked by the SAP and RdSAP include but not are limited to the following aspects:

- The inter-seasonal heat storage and release enabled by heavy-weight thermal mass are ignored, except for the diurnal heat storage;
- The role of passive solar gain as facilitated by appropriate manual ventilations is negated, since the whole house is considered to be unheated;
- The occasional use of electric mobile heaters to top up heat during severely cold seasons is instead assumed to constitute the primary heating;
- The hot water system using the Hotsi® tank with electric emersion heater is assumed to be energy inefficient due to overlooking the de-facto water-to-water heat exchange;
- No credit is assigned by the SAP and RdSAP to the autonomous community characteristics, such as the off-grid to water and wastewater mains.

The long-term monitoring scheme in the HHP case study sought collect more post-occupancy evidence of energy-related activities and associated impacts on indoor environment in the monitored houses. Through comparison to another case study conducted in two conventionally built and light-weight and timber-frame houses, the research aimed to investigate energy-related activities by comprehensively considering the building characteristics of the studied houses. Without diverting from the major research objective of examining targeted energy-related occupancy activities, the monitoring results were expected to provide the HHP residents with some post-occupancy evidence for their appeal process.

5.3.1.5 HHP monitoring

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 (see photos in Appendix Four). 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, the monitoring equipment was deployed in phases, as shown in Table 5-2. Prior to 25 June 2013, when the equipment was officially moved out of the HHP houses, the measurements of certain monitoring categories had either stopped or been overwritten since the final monthly site visit on 10 October 2012. The end date for each monitoring category of different installation phases in Table 5-2 has been selected as the time when all three monitored houses had relatively complete and valid measurements. The unit prices used for cost calculations in Table 5-2 were sourced from quotes provided by equipment suppliers at the time of procurement and may differ from current market prices. Software costs that were jointly shared by pilot and case studies are not included. The low-cost feature of configured monitoring schemes, especially for the electricity and power measurements, are directly reflected by the respective costs.

Table 5-2 Monitoring contents, installation phases and costs in the HHP case study

Phase	Logging contents	Logging intervals	Starting date	Ending date	Cost per monitored house
1	indoor T and RH	5-minute, 10-minute (adjustable)	16/12/2010	27/04/2013	HHP4 and HHP5: £119.00 * 4 = £476.00 HHP3: £119.00 *5 = £ 595.00
	house electricity use (kWh)	bi-hourly	19/12/2010	09/10/2012	£39.95
2	house PV microgeneration (kWh)	bi-hourly	14/01/2011	09/10/2012	£13.75
	outdoor microclimate	15-minute, 20-minute or hourly (adjustable)	12/01/2011	11/12/2012	£60.00 / 3 = £20.00 (one weather station worth £60.00 on site)
3	indoor illumination	10-minute (adjustable)	18/03/2011	27/04/2013	Included in the costs for indoor T and RH measurements
	use of doormat	real-time	12/02/2011	27/04/2013	£117.00
	house power draw (watt) averaged over the logging interval	10-minute (from the retired Google PowerMeter®)	12/02/2011	16/09/2011	£29.95 (Current Cost® NetSmart bridge)
4	doors facing sun space	real-time	13/04/2011	27/04/2013	HHP4 and HHP5: £73.00 * 5 = £365.00 HHP3: £73.00 * 6 = £438.00
5	residents' motions in the kitchen bay	real-time	11/07/2011	10/10/2012	£117.00
6	electricity use of certain appliances (kWh)	bi-hourly	09/09/2011	09/10/2012	£90.00
7	power profiles (watt) of house use, certain appliances, and house PV microgeneration	five-minute (from the Current Cost® dashboard)	HHP4 and HHP5: 07/10/2011, HHP3: 12/11/2011	27/04/2013	£14.99 (Pro service of Current Cost® NetSmart bridge) + £22.50 (separate display & receiver unit) = £37.49
8	windows facing sun space	real-time	02/05/2012	10/10/2012	Borrowed equipment
Total hardware cost per monitored house (excluding VAT and the costs of associated installation materials)					**HHP4 and HHP5: £1306.14 per house** **HHP3: £1498.14**

a) Energy use and microgeneration

Prior to deploying Current Cost devices® for the measurement of energy use and microgeneration, wiring systems of the HHP houses were investigated as shown in Figure 5-5.

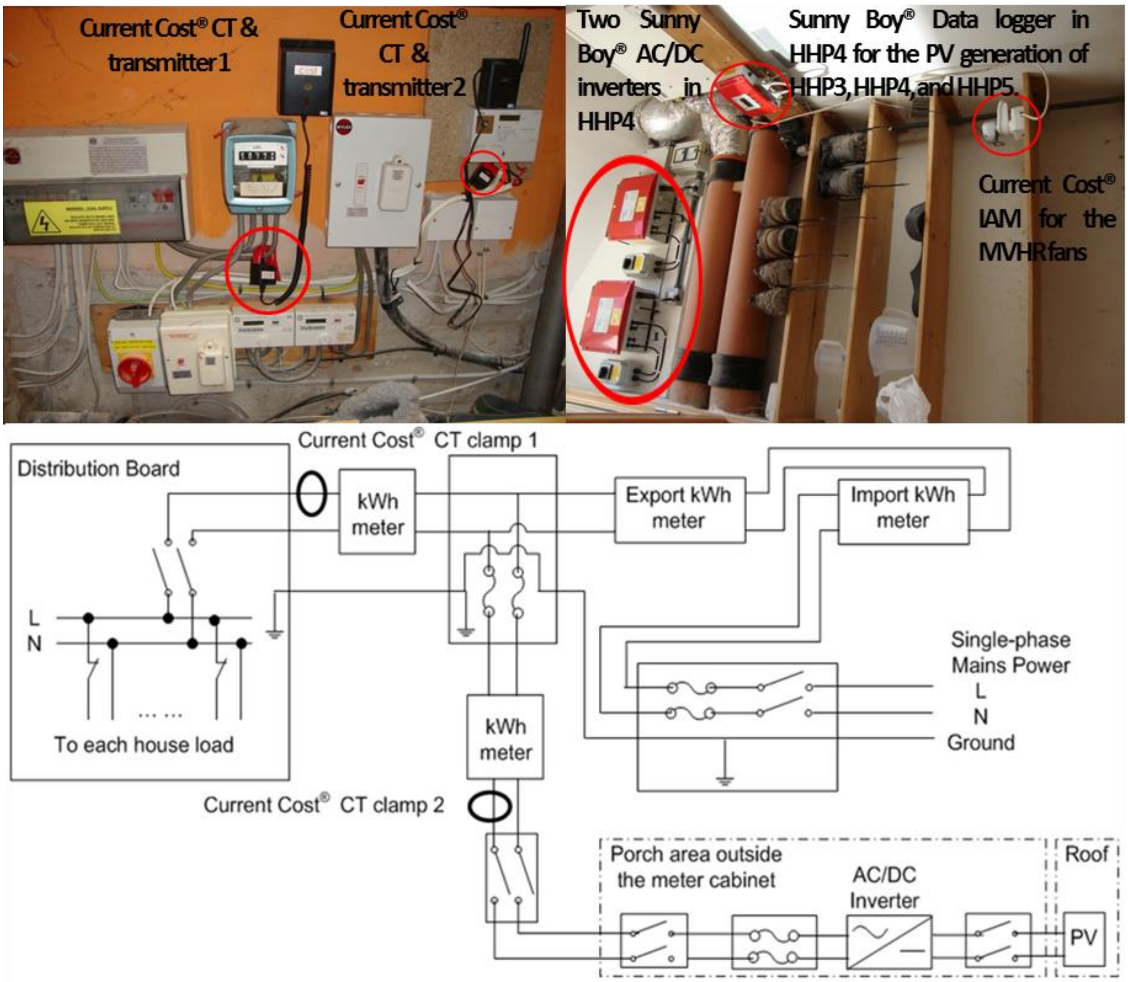


Figure 5-5 The meter cabinet in HHP3, the shelf area above meter cabinet in HHP4, and the wiring diagram drawn by the researcher in May, 2013

Some existing metering devices are components included in the solar microgeneration system, such as the Sunny Boy® PV inverters and data loggers. Some are the included components of already obsolete services, such as the air-to-water heat pump. The photo of the meter cabinet in Figure 5-5 was taken from HHP3, where the obsolete heat pump metering devices had already been removed. Also removed was the original

ELSTER® A1700 three-phase kWh meter, which was the legacy of previous monitoring schemes run by the HHP Ltd. and other research institutions. It was installed for three major functions, including the measurement of PV microgeneration, communication with import and export kWh meters, and remote transmission via the included GSM modem. After a non-repairable malfunction, it was replaced with a new ISKRA® single-phase meter in HHP3 in December 2011 to only record PV microgeneration. The original ELSTER® kWh meters are still in use in HHP4 and HHP5. The photo of the shelf area above the meter cabinet in Figure 5-5 was taken from HHP4, where two sets of Sunny Boy® PV inverters and data loggers were installed. The first CT & transmitter unit, 30 mm in diameter, was installed at the downstream side of the electromechanical induction kWh meter to measure house energy use and power profiles. The separate wiring circuit and metering of PV microgeneration enabled the individual measurement of solar power generation using the second CT & transmitter unit, 12 mm in diameter, at the upstream side of the ISKRA® electronic kWh meter. CT clamps with different resolution levels were selected according to cable diameters and associated installation space around the cables. Appropriate stream sides of the kWh meters were selected to remove the influence on CT measurements of the power draws of 1.0 to 2.0 watts by the kWh meters themselves.

The import and export kWh meters are two AMPY® 5196B single-phase meters that were crossly connected in order to distinguish directional current and store kWh values as energy export when current is running backwards through the meter and as energy import when current is running forwards. The HHP Ltd. has been keeping quarterly manual readings of all utility meters. The historical records from April 2008 to April 2013, which were provided by the HHP Ltd., are denoted as ‘HHP bills’ hereafter in this research. Two batches of occupancy diaries in the format shown in Appendix One were provided by each monitored house in the HHP case study to assist in data pre-processing and analyses.

The two CT & transmitter units used two out of the 10 RF channels that are enabled by the Current Cost® CC128 devices. The other eight channels were used by Individual Appliance Monitors (IAMs) that were moved among appliances in each house for various plug-loads in different seasons. For example, mobile electric space heaters were occasionally used in HHP3 and HHP4 from November to February. The IAM connected with the space heater can be moved to other appliances outside of these periods. One IAM, which was used for MVHR fans in HHP4, is shown in Figure 5-5. Another IAM, which was moved to the immersion heater of Hotsi® water tank in HHP3 on 8 December 2011, contributed to identifying the improper installation of the CT clamp around the mains cable. The not completely closed CT clamp could not perform proper electromagnetic induction to measure the total amount AC current flown through mains power. The flawed data of house use and power draws were remedied and validated by using the IAM-measured resistive power profiles of the immersion water heater and the HHP bills as explained in the pre-processing approaches in Chapter Six. From January 2012, manual readings of the HHP houses' utility metering devices were recorded during site visits to validate the Current Cost® metering results. Compared with the quarterly HHP bills, monthly recordings assisted in more effective measurement validations to prevent similar CT installation errors from reoccurring.

Prior to installing the IAMs, an appliance audit was conducted in each monitored house. The rated power of major domestic appliances was compiled into an appliance inventory, which was updated continuously during the monthly site visits. The philosophy of autonomous community is not to advocate a primitive lifestyle by avoiding all modern facilities, unless the associated service or appliance has an unsatisfactory environmental performance in energy and resource efficiency (HHP, 2011). Washing machines were used in all three HHP houses, where air-drying in the conservatory was utilised instead of tumble dryers. A dishwasher was used in HHP5, but not in HHP3 and HHP4. Multi-ownership of refrigeration appliances existed in all three houses.

b) Indoor and outdoor environment

Indoor environmental conditions were measured by four hygrothermal loggers in the kitchen, living room, bathroom, and conservatory areas of the six-bay HHP4 and HHP5. Undrinkable hot water for shower and tap use comes from the Hotsi® tank. Shower events are identifiable from the hygrothermal conditions rather than from power draw variations as in the case of electric shower use. An extra logger was put in the separate shower room that only exists in the seven-bay HHP3. Tinytag® TGU-4500 hygrothermal loggers were used for the first two months until they were replaced in February 2011 by Hobo® U-12 data loggers that can measure the T and RH and instantaneous ambient light intensity at logging moment depending on the logging interval settings. Figure 5-6 features some of the deployment photos.

The instantaneous light intensity recorded by the Hobo® U-12 loggers was used as an indicator for the use of artificial lighting. Relatively stable light intensity over a given time period represents the use of artificial lighting. Together with the recordings of power draws and occupancy statuses, the idle use of artificial lighting over a non-occupied period is potentially indefinable. Erratically high and largely fluctuating intensity recordings were used to identify the influence of direct solar radiation on loggers that needed to be relocated to other places in order to keep reasonable recordings of indoor hygrothermal conditions. Loggers placed in the sun space and living room were more susceptible to direct solar radiations. The living room logger in HHP4, as shown in the upper middle photo in Figure 5-6, was moved to behind the picture frames after a solar radiation effect was discovered. The sun space logger in HHP3, as shown in the lower right photo in Figure 5-6, was put in a recess space that was free of solar radiation influence.

Figure 5-6 The Tinytag® TGU-4500 loggers in HHP3, the subsequently applied Hobo® U-12 loggers in HHP4, and the indoor and outdoor Easy Weather® station units

Multiple weather variables were recorded by the portable Easy Weather® Station, although the outdoor T and RH values were the major variables used in the analysis. The thermal performance assessment was enabled by comparing indoor and outdoor hygrothermal conditions in various seasons. The indoor component was in the HHP3 living room as shown in the lower left photo in Figure 5-6. The outdoor unit was fixed to the HHP3 garden fence. A Tinytag® TGP-4500 T/RH logger was used from 2 November 2012 to 22 February 2013 to provide relatively valid outdoor temperature recordings since the Easy Weather® Station could not be downloaded in time after the final monthly site visit on 10 October 2010.

c) Occupancy statuses

Prior to the five-minute power profile being accessible, the occupied or non-occupied statuses of the HHP houses were directly monitored by the passive infrared (PIR) motion / light intensity detection box bound to the HVAC clay duct in kitchen bay, the doormat pressure detector in front of the main entrance, and the door / window status detector on the French door / window of each bay. Figure 5-7 depicts the installation of occupancy status loggers. The motion logger and doormat use detector were configured by wiring the three-state Hobo® U-11 data logger with PIR sensors and a pressure mattress respectively. The open / closed statuses of French doors / window were recorded by mounting the one-state Hobo® U-9 data logger on one door frame, and the included magnet strip on the other. The monitoring results of three types of detectors were comprehensively used to overcome the limits of one single type of state measurement.

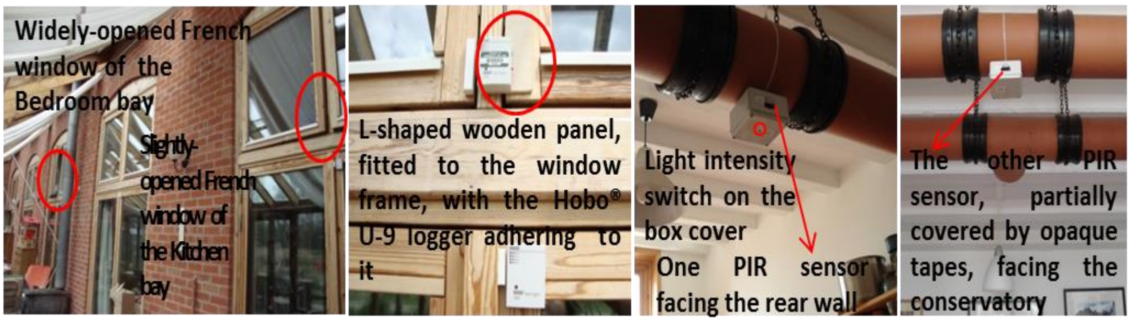


Figure 5-7 Window / door status detectors and motion & light intensity detection box in the HHP houses

Over a one-month period with a moderate level of detectable motions, one PIR sensor needs to be powered by at least three AA batteries. Frequent recordings of detectable events can potentially terminate the logging process due to the capacity limits of either the logger's internal memory or the AA batteries. Therefore, the single-occupant house HHP3 had relatively complete measurements compared to the other two homes. The entry or exit events relating to occupancy statuses were originally designed to be directly measured by using the doormat pressure detectors. However, rather than using the main entrance in the porch and landing area bay, residents and visitors sometimes exited / entered the house using one of the two external conservatory doors and any

French door of each bay. In HHP4, which had pet dogs living in the porch area, the doormat pressure detector was frequently moved away by the residents to prevent the sensor and cable from being chewed by pet dogs. Under such circumstances, the doormat pressure detectors can potentially fail to record the actually occurring entry and exit events. Therefore, Hobo® U-9 loggers were used on the French doors. The alternation frequency between the open / closed status was used to indicate the door use. Within a detectable distance of the magnet field, the magnet strip can interact with the internal reed switch within the U-9 logger that sets logger's input channel to 'open' and 'close' corresponding to the open / closed statuses of the monitored door. If the mounting distance is beyond the detectable range, which is around one centimetre, a status of 'open' is wrongly recorded when the door is actually closed. An ambiguous status when the monitored door remains slightly open can thus be potentially recorded as 'open'.

Being more convenient to manually operate than the upper French windows, the French doors were more frequently used for natural ventilation in addition to use for entry and exit. To examine the natural ventilation events or habits, the statuses of French windows were monitored by U-9 loggers from 2 May 2012 to 10 October 2012. The HHP residents tended not to frequently operate the French windows during hot seasons to prevent overheating of the house. Instead, the windows were used more frequently in the early evenings of sunny days in autumn and early winter to utilise the heat stored in conservatory during the daytime. The window use habit was reflected by the monitoring results to some extent.

The monthly site visits, associated tasks, and main findings over the entire monitoring period in the HHP case study are recorded in Table 5-3, which includes most of the monitoring project's key events from December 2010 to April 2013.

Table 5-3 Dates, tasks and main findings in the monthly site visits to the HHP case study houses

Site visit Date	Purposes	Main Findings
16/12/2010	The installation of Current Cost® devices for house electricity monitoring in the three HHP homes; The installation of Tinytag® TGU-4500 loggers in the three HHP homes. The HHP5 sun space was not monitored due to logger shortage.	Appraisal of wiring systems of the HHP houses inside and beyond the meter chamber; First-time walkthrough in the HHP homes; First-time rapport-building with the resident in the single-occupant HHP3.
13/01/2011	Installation of the Easy Weather® station in the HHP3 yard; Installation of the second set of Current Cost® CT clamps for the measurement of PV microgeneration in the three HHP homes; The loggers were downloaded.	Incomplete electricity use data if the Current Cost® display and receiver unit was not properly downloaded via button pressing; The sun space of HHP3 and HHP4 had similar hygrothermal measurements and justified that the HHP5 sun space could remain unmonitored until extra logger was available.
11/02/2011	The replacement of Tinytag® TGU-4500 loggers with Hobo® U12-012 loggers in the three houses. The HHP5 sun space was still not measured and the HHP5 living room Tinytag® logger was not replaced due to logger shortage; The Current Cost® bridge, which was not upgraded to the NetSmart bridge at this time, was installed in the three houses to acquire 10-minute house use data from the Google PowerMeter® dashboard; The installation of Hobo® U9-001 loggers on the more frequently operated doors in kitchen and main bedroom bays of the three HHP houses; The installation of a Hobo® U11-001 logger, which was connected with a mattress pressure detector, in each HHP house for the monitoring of main entrance use; The loggers were downloaded.	The HHP3 house use that was measured by Current Cost® was found to be lower than the other two houses. This was assumed to be caused by the single-occupant status of HHP3; The PV microgeneration in HHP4 was nearly twice of that in HHP3 and HHP5; The Current Cost® bridges in HHP3 and HHP4 started working from 11/02/2011, but that in HHP5 had malfunctioned; The improper operation of the Google PowerMeter® dashboard for the first-time on-line data download made the HHP3 data invalid until 23/02/2011 when the 10-minute data became accessible on line.
15/03/2011	The installation of an extra Hobo® U12-012 logger in the HHP5 sun space; The replacement of malfunctioning Current Cost® bridge in HHP5; The loggers were downloaded.	The replaced Current Cost® bridge in HHP5 started working from 18/03/2011.

Site visit Date	Purposes	Main Findings
13/04/2011	The installation of extra Hobo® U9-001 loggers to cover every French door in the three houses; The installation of an extra Hobo® U12-012 logger in the HHP5 living room to replace the Tinytag® TGU-4500 logger; The loggers were downloaded.	The 10-minute energy use from the Google PowerMeter® dashboard showed that HHP3 not only had a lower energy use but also had a house use power draw level, during the time-of-use of the 1,000-watt immersion water heater, of around 700 watts.
11/05/2011	An appliance audit was conducted in the three houses for the preparation of Current Cost® IAM monitoring of electricity use by certain selected appliances; The loggers were downloaded.	Erratic light intensity readings were given by the Hobo® U12-012 loggers in the sun space of all three houses, probably due to direct solar radiations on the loggers; The problematic power draw measurements remained unchanged in HHP3, with the integrated Google PowerMeter® data and downloaded Current Cost® data matching each other.
10/06/2011	The relocation of sun space Hobo® U12-012 loggers in all three houses to relatively shaded areas to prevent the impact of direct solar radiations on hygrothermal measurements; The loggers were downloaded.	The feedback given by the HHP3 resident, regarding the low energy use and problematic power draw during water heating, was that the immersion water heater, rated at 1,000 watts, might be partially malfunctioning. Emptying the Hotsi® water tank for a status check was infeasible.
11/07/2011	The installation of Hobo® U11-001, which was connected with a stand-alone toolkit consisting of two motion (PIR) detectors and a light switch, in the kitchen bay of every monitored HHP house to detect residents' motions and to supplement other event loggers, including the door sensors and the mattress pressure sensor; The loggers were downloaded.	The light intensity readings given by the sun space Hobo® U12-012 loggers in all three houses returned to relatively normal levels, except for the occasionally erratic readings due to short-term direct solar radiation.
10/08/2011	Opaque stripes were applied on the PIR sensors in HHP3 and HHP4 to partially prevent the impact of pets' motions on the monitoring; Adjustment of the light intensity switch in the stand-alone toolkit that consisted of motion detectors and a light switch The loggers were downloaded.	The battery of the Easy Weather® station was changed on 26/07/2011 by the residents without notifying the researcher to download the data beforehand. The volatile internal memory of the weather station caused the missing data from 11/07/2011 to 25/07/2011.

Site visit Date	Purposes	Main Findings
09/09/2011	The installation of eight pieces of Current Cost® IAMs in each of the three houses, since the first two RF channels among the 10 permitted ones were taken by the CT-based house use and PV microgeneration monitoring; The loggers were downloaded.	The Hobo® U11-001 loggers, which were connected with the stand-alone toolkit consisting of two motion detectors and a light switch in the three houses, were found to have stopped logging prior to the subsequent site visit due to the frequent logging triggered by the two PIR sensors and one light intensity sensor. This situation was most obvious in the multi-occupant HHP5 that had more motions to be detected.
07/10/2011	The visualisation-based examination of five-minute power data after 10/10/2011, when the Current Cost® bridge was upgraded to the NetSmart bridge to transmit the measurements of 10 RF channels with no data download permitted; The deactivation of one PIR detector and the light intensity sensor in the toolkit to save the internal memory capacity; The loggers were downloaded.	The HHP3 resident returned on 15/09/2011 from a long holiday starting on 18/08/2011; The different categories of variables that were acquired under the unoccupied circumstances in HHP3 matched each other, such as energy consumption and use statuses of the mattress and doors; The bi-hourly IAM-measurements were found to be erratic with the sum of IAM measurements exceeding the simultaneously measured house use; Faulty spikes were discovered in the power profiles on the Current Cost® dashboard for most IAM-measured appliances.
07/11/2011	The visualisation-based inspection of five-minute power data continued, since the download was not supported by Current Cost® dashboard until one year later; The Current Cost® IAMs were moved to different appliances to test the faulty power spikes that might have caused the overestimated bi-hourly IAM measurements; The loggers were downloaded.	The HHP3 Current Cost® bridge failed the first-time upgrade to NetSmart bridge and was not able to transmit five-minute measurements until 12/11/2011; There was no further evidence regarding the status of the immersion water heater in HHP3, since no power profiles were available from 16/09/2011 when the Google PowerMeter® dashboard retired.

Site visit Date	Purposes	Main Findings
08/12/2011	Certain Current Cost® IAMs in HHP3 and HHP4 were moved to mobile heaters that did not exist in HHP5 until the winter of 2012 to 2013; One Current Cost® IAM was moved to the immersion water heater in HHP3 on 8/12/2011 and gave readings of around 1,000 watts; The loggers were downloaded.	A house power draw of around 700 watts was given by the Current Cost® dashboard of HHP3 around the period of immersion water heater use; The similar levels of readings were given by the Current Cost® dashboard and the retired Google PowerMeter® dashboard; The immersion water heater was thus found to be not partially malfunctioning and the wrong measurement was due to the small aperture at the opening of CT clamp around the mains power cable; Both house use and IAM-measured immersion heater readings returned to normal after 20/12/2011 when the CT clamp was adjusted by the HHP3 resident at the researcher’s request.
06/01/2012	A procured professional device, NZR® Standby-Energy-Monitor (SEM) LOG16+, was placed between the immersion heater socket and the associated Current Cost® IAM to validate the effectiveness of the CT-clamp adjustment; The meter readings started to be manually recorded from the meter chamber from this site visit onwards; The loggers were downloaded.	Frequent motions occurred in all three houses during the Christmas and New Year period. Therefore, the memory of the Hobo® U11-001 logger, which was connected to the stand-alone toolkit was almost used up in all three houses, although one PIR detector and the light intensity switch were already deactivated.
06/02/2012	The HHP quarterly bills, which contain meter readings every three months by the HHP residents, were requested; The loggers were downloaded.	The Easy Weather® station was found to have no effective recordings over most of the winter period from late December 2011; The situation was not improved after replacing the weather station’s batteries, partially due to the cold weather; An effort was made to acquire weather data from third-party monitoring sites that were close to the HHP site.
06/03/2012	The loggers were downloaded.	The IAMs connected to the mobile heaters in HHP3 and HHP4 were moved to other appliances. For example, the HHP4 heater IAM was moved to test the MVHR fans.

Site visit Date	Purposes	Main Findings
02/04/2012	The indoor Hobo® U12-012 loggers were adjusted to avoid direct solar radiations; The kitchen Hobo® U12-012 loggers in the three homes were moved to be closer to the cooking hobs, to examine the parameter variations relating to cooking events; The loggers were downloaded.	The sun space hygrothermal measurements were cross compared with those taken over the same period in the previous year (2011) to examine the effect of direct solar radiation on logger recordings.
02/05/2012	Empty diary copies in the format as shown in Appendix One were given to the HHP residents to validate the Current Cost® IAM measurements; The Hobo® U9-001 sensors borrowed from other institutions were used to cover every French window in all three houses to examine associated ventilation habits; The loggers were downloaded.	The Hobo® U12-012 loggers in the kitchen bays recorded more frequent variations due to the impact of cooking-related events; Exploration of possible methods to remedy the flawed measurements of house use and individual appliances that were caused by improper installation of the CT-clamp in HHP3.
12/06/2012	The diaries were collected from three houses; Extra Hobo® U12-012 loggers were installed in the kitchen and shower room of the three houses with the monitoring interval being set at five minutes to examine the influence of monitoring frequency levels on hygrothermal measurements; The loggers were downloaded.	The diaries were collected from three houses and new blank copies given to the residents who could randomly select any convenient time and day to fill the diaries; The readings given by the French window sensors showed that the windows were not frequently open during the hot summer seasons to prevent residual heat in the sun space from entering the indoor areas.
6/07/2012	The diaries were collected from three houses; The loggers were downloaded.	The cross-comparison between the five-minute and 10-minute hygrothermal data in the kitchen and shower room did not show any significant difference; The borrowed Hobo® U9-001 loggers on the French doors were found to either not have many recordings due to the lack of window operations or have no effective readings due to the dropping of loggers onto the ground.
20/08/2012	ditto	ditto

Site visit Date	Purposes	Main Findings
10/10/2012	This was conducted as the last official site visit. Removal of the borrowed Hobo® U9-001 loggers from the French windows to return them to the lending institutions; The Easy Weather® station was set to log at hourly intervals to save internal memory capacity until the next visit, which was the final one to remove all monitoring devices; A Tinytag® TGP-4500 logger, having a dust and water proof level of IP68, was deployed in the HHP4 yard under the shed roof as a monitoring backup to the Easy Weather® station; The loggers were downloaded.	The HHP4 household profile had changed from a two-occupant house to a single-resident home since July 2012; The borrowed Hobo® U9-001 loggers were not found to generate specifically featured measurements since the monitoring time was over the hot summer period when the French windows in each house tended to be closed; The Current Cost® dashboard started to support data download for all RF channels.
25/06/2013	Final site visit to remove all monitoring devices from the HHP houses; The loggers were downloaded.	A new household moved into HHP4 from early April 2013; Most of the loggers stopped recording in April due to the used-up internal memory capacity; HHP5 started to use a mobile heater in the winter period of 2012 to 2013; The HHP5 residents voluntarily moved one Current Cost® IAM to the mobile heater, the power use of which was thus recorded.

5.3.2 Nottingham City Homes (NCH) case study

5.3.2.1 Project background

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. Energy efficiency and fuel poverty were one of the four social, environmental and economic research strands of the Decent Homes Impact Study of SWM programme, with the other three strands being crime and security, health and wellbeing, and local economy and employment. To meet the target of the Nottingham City Council's Energy Strategy, a 37.6 per cent reduction in CO_2 emissions is required from domestic energy use by 2020 (NCH, 2012). From the year 2008 to 2015, the initiative aimed to bring the entire portfolio of 28,500 council homes that account for a quarter of the housing stock in Nottingham up to or above the national Decent Homes standard (NCH, 2012). The retrofitting installations, applied to various extents across the council homes, included double glazing, central heating controls, and loft and wall insulation (NCH, 2011). In addition to the boost in energy efficiency, these retrofitting installations are expected to reduce fuel poverty through the improvement of dwelling characteristics. Although social housing tenants are vulnerable to fuel poverty because of their lower incomes and higher sensitivity to the increase in fuel prices, social housing properties are generally more energy efficient due to the maintenance and retrofit provided by local authorities or social landlords (Department of Energy & Climate Change, 2012). However, a recent study about social housing retrofit programmes (Gentoo, 2011 cited in NCH, 2012, p.31) showed that only about 40 per cent of the expected energy efficiency and cost savings were evidenced due to the differences between theoretical predictions and the realities of occupants' behaviours.

The energy efficiency and fuel poverty strand of the SWM programme aimed to investigate the impact of NCH's significant retrofit investment from the post-occupancy perspective. The monitoring scheme, starting from January 2011, was deployed in two selected case study council homes, NCHA and NCHB. In association with the Nottingham City Homes partners, three interviews were conducted with the tenants, who also provided several daily and weekly self-report diaries on their energy-related activities to calibrate the monitoring results. The report documents of NCH (2011) and NCH (2012) were produced using the first-phase monitoring data from January to April 2011. Prior to the official end of the monitoring project in August 2012, the monitoring contents were gradually extended to cover the five-minute power profiles of the entire house and certain home appliances, the statuses of frequently operated windows, the use of doormat, and the manually recorded gas use.

5.3.2.2 Household composition and building type

Three major criteria in selecting case study homes were discussed by the university and NCH partners. Firstly, to identify efficiency variations from the occupancy perspective, the two houses needed to be of identical building type and age with the same extent of retrofit. Secondly, the household compositions needed to be similar to each other in order to identify efficiency-proving potentials from similar daily activity routines. Finally, the householders' willingness to participate actively into the monitoring scheme was critical for the data quality of occupancy-related studies. Although the scheme adopted non-intrusive or less-intrusive monitoring systems, certain devices needed to be locally rebooted from the power supply points when researchers could not access the houses. Therefore, it was hoped that a certain level of assistance and amount of dedication from the monitored households would effectively maintain the data coherence and reduce the frequency of site visits by researchers. In addition to device reboots, the Hobo® loggers have buttons that can be manually pressed to record a targeted event such as leaving the house unoccupied or switching on the heating system. Although it showed that this type of more obtrusive and demanding monitoring cannot produce accurate recordings even with some dedicated pilot-study participants, supportive and responsible householders can still make a difference to the monitoring results. Since the real-time gas consumption was not automatically recorded by advanced meters, it was suggested that houses served only by mains power should be selected, in addition to the three major criteria. However, no council homes from the SWM programme met all of these requirements. Gas use was manually recorded during each site visit.

Since their construction around 1977, the two selected houses of NCHA and NCHB have been the homes of two retired couples. The building age and social house characterisers of the NCH case study homes make it difficult to locate the original architecture drawings and associated Planning and Building Control documents. Enquires were made to the relevant Nottingham City Council departments that are only obliged to keep the related records for maximum 15 years from the date of project completion. Neither the original architect nor the contractor was found to be accessible for construction associated details. The mid-terrace houses were designed as bi-level homes with two ground floors to utilise the sloping terrain (see Appendix 11). The main entrance porch with a meter chamber and a built-in garage to each side is on the lowest level. A full flight of stairs in the porch leads to the landing area, via which the patio on the second ground floor is accessible from a patio door at the end of the landing. The entrance to living room, kitchen and guest water closet are connected by the hallway around the staircase and arranged clockwise when facing the patio door. Another full flight of stairs leads to the top floor where a smaller bedroom, two bigger bedrooms with the water cylinder cabinet in between, and the bathroom are located clockwise after the landing.

Both NCH houses were developed by Walter Llewellyn and Sons Ltd. in Eastbourne according to the Building Research Establishment (BRE) publications, including BRE

282 (Covington, et al., 1995), BRE284 (McIntyre and Stevens, 1995), and BRE469 (Harrison, et al., 2004), which were recommended by the Information Specialists from the Planning and Building Control department of Nottingham City Council. The timber-frame dwelling is one type of non-traditional housing system that boomed after the Second World War in the UK (Covington, et al., 1995). 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). To present an appearance similar to that of traditional construction, the plywood that sheathed the timber stud was clad with brickwork. Alternatively, tiles were hung on the timber battens backed with bituminous felt and breather membrane for the upper storeys (Covington, et al., 1995). According to McIntyre and Stevens (1995), some Quikbild dwellings used 25 mm of mineral fibre between the frame studs (estimated U-value around 1.3 W/m^2K); others had foam plastic insulation in the 50 mm cavity between the sheathing panel and the brickwork (estimated U-value around 0.6 W/m^2K). The separating walls between dwellings of the terraced Quikbild houses comprised a timber stud frame cavity wall faced with three layers of plasterboard. The 50 mm cavity was filled with 25 mm of paper-laminated mineral fibre insulation to eaves level. The partition walls within the house were timber stud faced with plasterboard.

The bi-level NCH case study houses, exemplifying one commonly adopted type of Quikbild construction, have brickwork cladding on the first-ground and second-ground floor façade and tiles hanging on the timber battens above (see Appendix 11). The Energy Performance Certification (EPC) shown in Appendix 12 was produced by Nottingham City Homes after the SWM programme. The EPC assumed partial insulation in external walls, not knowing the types of partial insulation used during the construction[18]. The relatively lightweight feature facilitates heat transfer within a house

[18] Maximum thermal transmittance (U-value) for external walls remained unchanged at 1.7 W/m^2K in the building regulations from 1966 to 1975 (McIntyre and Stevens, 1995) and decreased to 1.0 W/m^2K in 1976 (Smith, et al., 1982). Considering the construction year around 1977 of the two NCH case study houses, the partial insulation in the external wall should be in compliance with the regulations of 1976.

and between neighbouring homes. 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.

The EPC stated that the original mineral wool roof insulation was topped up from 100 mm to 250 mm. Both NCHA and NCHB, double-glazed in the year 2001, respectively received a heating system upgrade in March and January 2011 as part of the SWM programme. Prior to the heating upgrade, a gas fire with a G-rated back boiler was located in the living room, where both families spent most of their time beyond sleeping hours. A jacketed indirect cylinder on the top floor was used for hot water storage. Two double-bank radiators, powered by the back boiler, were installed respectively in the kitchen and the hallway between living room and kitchen. The SWM programme replaced the entire heating system with an A-rated boiler and central heating controls, a well-insulated water cylinder, six radiators in the main hallway on the second ground floor and every room except for the guest room water closet. The central heating controls included programmable water and space heating, a hot water cylinder thermostat, a wall-mounted room thermostat in the main hallway, and thermostatic radiator valves (TRVs) on all radiators except for that in the hallway on the second ground floor. As requested by the tenants of NCHA, the hallway radiator that was planned to be on the second ground floor was installed next to the main entrance on the first ground level. The tenants living in NCHB preferred the upgrade plan that kept the main entrance level unheated, so they could continue to utilise it as a larder space in winter time.

The transcripts of interviews with both households were partially quoted in the NCH report (NCH, 2011). It showed that both families were content with the original heating system, although only the second ground floor of the house was heated. During heating seasons, they kept the doors of the upstairs bedrooms and bathroom open to utilise the rising heat from radiators. Both families converted the space within the cylinder cabinet into ‘clothes dryer’ shelves, using the heat dispersed from the cylinder jacket. When necessary, the tenants in both houses used the gas fire in the living room and turned it off when the room was warm. The residents in NCHA left the back boiler on a medium setting over the cold nights, whilst the tenants in NCHB preferred to turn it off at bedtime. Their heating use habits remained unchanged before and after the retrofit programme. The monitoring scheme in the retrofitted NCHA and NCHB was deployed to reveal energy use differences from the perspective of post-occupancy activities, including heating and ventilation habits and domestic appliance use.

5.3.2.3 NCH monitoring

The NCH case study started one month later than the HHP monitoring project, in January 2011. The installation phases and associated costs of the low-cost monitoring scheme are listed in Table 5-4, which shows the unit prices that were sourced from quotations provided by equipment suppliers at the time of procurement. The costs of software that was used for both the pilot and case studies are not included.

a) Indoor and outdoor environment

Four Tinytag® hygrothermal loggers were used for indoor T and RH measurements in the living room, kitchen, bathroom and main bedroom of each house. Without the extra light intensity parameter, the Tinytag® loggers had a slightly lower unit price than the Hobo® loggers that were used in the HHP case study. A monitoring interval of 10 minutes was used for most of the monitoring period and a 20-minute interval was adopted when monthly site visits were not feasible. A five-minute interval was used from 26 April 2012 till the end of the monitoring scheme for the purpose of cross-comparison with the five-minute power draw profiles. The Easy Weather® Station was installed in NCHB to measure the outdoor hygrothermal conditions at 10-minute intervals, which were enabled by more frequent site visits than in the HHP case study.

Table 5-4 Monitoring contents, installation phases and costs in the NCH case study

Phase	Logging contents	Logging intervals	Starting date	Ending date	Cost per monitored house
1	indoor T and RH	Five- / 10- / 20-minute (adjustable)	27/01/2011	22/08/2012	£99.00 * 4 = £396.00
	house electricity use (kWh)	bi-hourly			£39.95
2	outdoor microclimate	10- / 15- / 20- / 30-minute (adjustable)	14/02/2011	22/08/2012	£ 60.00 / 2 = £30.00 (one weather station worth £60.00 on site)
	use of doormat	real-time			£117.00
	use of two windows in the main bedroom and living room of NCHA and two windows in the main bedroom and kitchen of NCHB	real-time		25/04/2012	£73.00 * 2 = £146.00
3	electricity use of certain appliances (kWh)	bi-hourly	07/09/2011	22/08/2012	£90.00
4	power draw (watt) of house use and certain appliances	five-minute (from the Current Cost® dashboard)	10/10/2011	22/08/2012	£29.95 (Current Cost® NetSmart bridge) + £14.99 (Pro service of NetSmart bridge) + £22.50 (separate display & receiver unit) = £67.44
5	PV microgeneration (kWh) in NCHB	bi-hourly	14/02/2012	22/08/2012	£14.45 (12 mm Current Cost® CT & transmitter unit)
	power profiles of (watt) PV microgeneration in NCHB	five-minute (from the Current Cost® dashboard)			
Total hardware cost per monitored house (excluding VAT and the costs of associated installation materials)					**NCHA: £886.39** **NCHB: £900.84**

b) Occupancy statuses

Since covering all external windows was infeasible, only the two most frequently operated windows were selected to be monitored in each NCH home by the Hobo® U-9 loggers. According to the information acquired in informal interviews conducted during the monthly site visits, the NCHA residents tended to frequently open the windows in heating seasons when space heating was continuously in use. The deployment of window status loggers was expected to capture this energy-related occupancy behaviour. The entry / exit events were recorded by the configured doormat pressure detector at the main entrance on the first ground floor, although both retired couples tended to stay at home for most of time periods.

c) Energy use and microgeneration

Prior to October 2011, when the Internet service became available in NCHB, 10-minute or five-minute power profiles were not accessible other than the manually downloaded bi-hourly and daily electricity use. The electricity utility meter readings were manually recorded from January 2011 during every site visit to validate the Current Cost® measurements. The gas utility meter readings were also manually recorded from February 2011 to facilitate the HHD analysis.

The CT & transmitter unit that was not properly clamped around the mains cable of NCHA flawed the house use measurements until 15 June 2011. The pseudo-power draws and subsequently integrated energy use were calculated by using partially inducted current values that were about one quarter of the actual figures. Similar installation-associated errors happened in the HHP3 case study, where five-minute power profiles of the immersion water heater assisted in the identification of a relatively effective linear coefficient to scale up the flawed measurements. However, five-minute power profiles were not available in NCH houses until October 2011. In addition, NCHA had no such IAM-connected resistive load to identify a linear coefficient in a similar approach. Instead, the monthly manual recordings taken from the electricity utility meter were used to remedy and validate the flawed house use measurements as discussed in Chapter Six. Both CT & transmitter units that caused flawed measurements in HHP3 and NCHA were initially installed properly but were moved by a third party afterwards for various reasons. The lack of effective protocols for equipment examination and measurement validation was a major reason for the belated correction of the CT installation. The lesson that was learnt from the experience in the two case studies was the importance of establishing proper protocols when acquiring field monitoring results to a sufficient quality standard.

On 2 December 2011, the SMW programme of Nottingham City Homes installed an array of photovoltaic (PV) panels for NCHB. The eight PV panels had a total peak output of 1.88 kW that was monitored by a second CT & transmitter unit from 13 February 2012 as shown in Figure 5-8. Unlike the separate microgeneration circuit of HHP houses, previously shown in Figure 5-5, the NCHB microgeneration circuit was directly wired into the distribution board. Prior to the PV installation, the CT & transmitter unit was clamped around the mains cable on the downstream side of the digital kWh meter to remove the influence of power draws of 1.0 to 2.0 watts that sustain the running of utility meter.

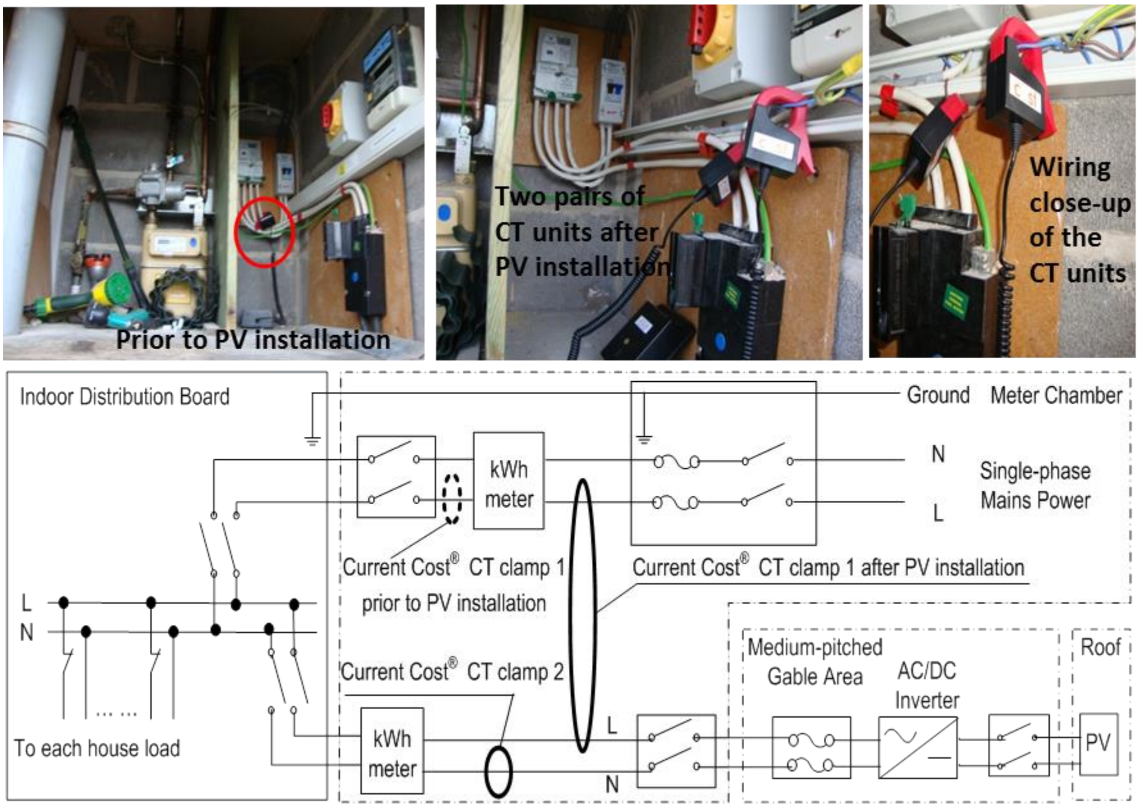


Figure 5-8 NCHB meter chamber photos prior to and after PV installation and wiring-diagram drawn by the researcher in May, 2013

Unable to detect current directions, the Current Cost® CT & transmitter unit in the original position could not correctly measure house use after PV installation. 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 as shown in Figure 5-9. From the initial commission of PV microgeneration in December 2011, the PV microgeneration was never near to its peak output capacity due to the weak solar radiation in winter seasons. The impact on house use was not detected and removed until the second CT unit was installed on 14 February 2012.

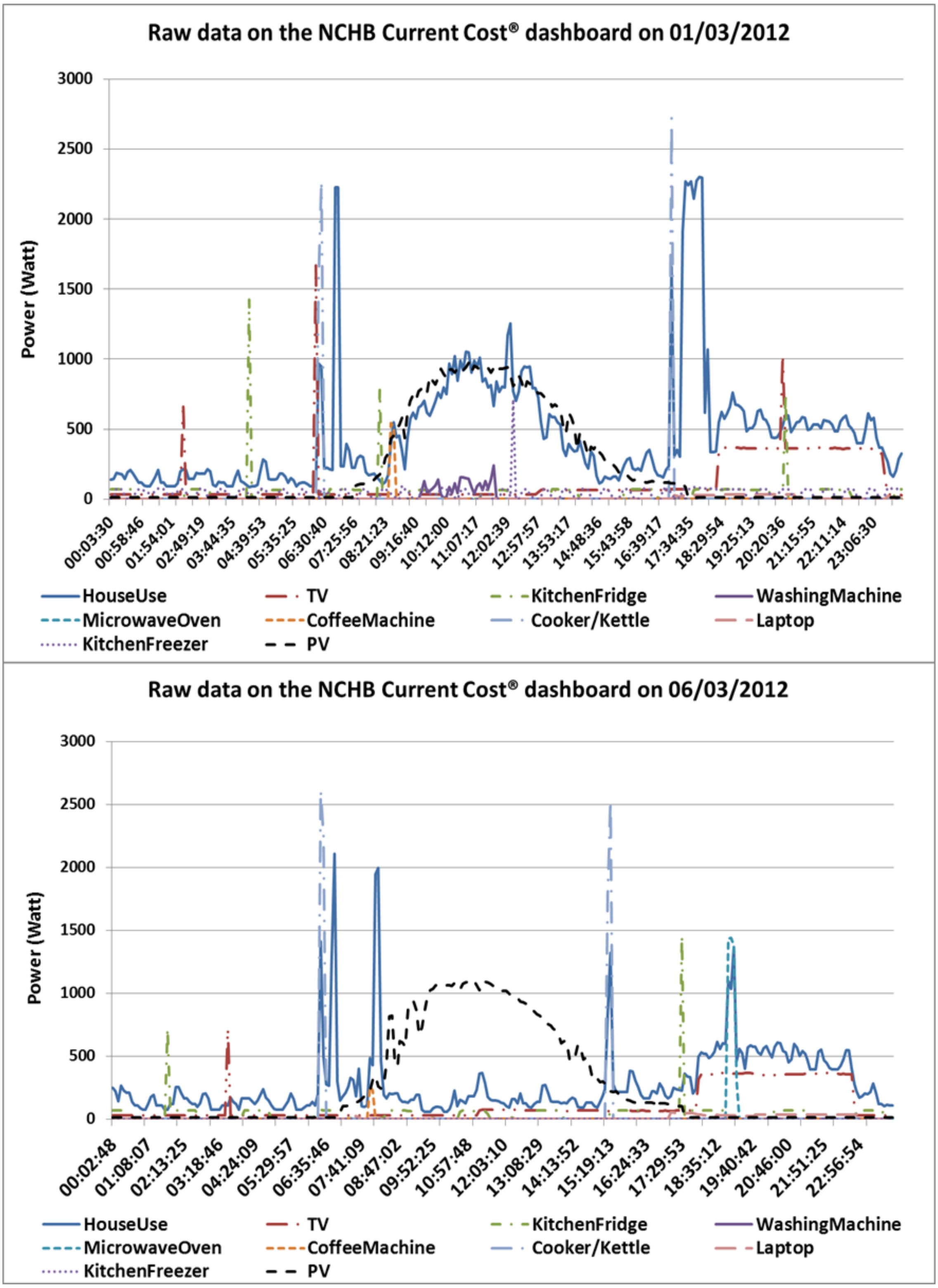


Figure 5-9 Raw power-profile data from the NCHB Current Cost® dashboard prior to and after the CT & transmitter unit being repositioned

The distortion of the house use data is clearly expressed by the microgeneration curve in Figure 5-9 upper graph, which provides the raw power-profile data taken from the NCHB Current Cost® dashboard on 1 March 2012. After the CT & transmitter unit was repositioned on 2 March 2012 by using the approach demonstrated in Figure 5-8, the influence was removed, as shown in the raw power-profile data for 6 March 2012 that are co-presented in Figure 5-9. The clamping of mains power cables and PV feed-in within one CT unit is an improvised solution that applies Ampère's circuital law of electromagnetic induction. When house use exceeds microgeneration, extra power input flows from the grid to the house. The two cables in the CT clamp have identical current direction. The total house use current is inducted by adding input from the grid and PV feed-in. When more energy is generated than being used, the current direction in the mains cable is reversed to feed into the grid as net microgeneration. Under this circumstance, the two cables within the CT clamp have opposite current directions and produce opposite magnetic fields via 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 is correctly measured without the influence of PV microgeneration.

Two types of circuit arrangement are commonly used when PV microgeneration is connected into the existing domestic power system. One is to directly feed the PV input into the distribution board as in the case of NCHB. Another connection type is to arrange a junction box prior to the distribution board for the mains power and PV feed-in. Although requiring more electrical wiring effort, the latter type is the most cost-effective wiring method for the separate metering of house use, net export, and total microgeneration. The repositioning of the CT unit as shown in Figure 5-8 was an improvised solution since it was not possible to alter the circuit arrangement of NCHB after the first connection approach was taken by the PV installer. The precondition, which was met in the case of NCHB, to utilise this improvised solution is to have two such cables that are adjacent to each other and clamped by one CT unit. However, the only position on the mains power cable to be clamped together with a PV feed-in cable was the section prior to the mains kWh meter of NCHB. The power draws of 1.0 to 2.0 watts to sustain the utility meter were thus counted into the total house use when power was imported from the grid. The circuit arrangement in the previously introduced pilot study A, which had the same PV installation wiring approach as the study conducted on NCHB, could not meet the precondition to effectively separate PV microgeneration from house use.

The spikes in raw power-profile data shown in Figure 5-9 exemplified some faulty IAM-measurements resulting from the lack of signal-filtering functions in the firm-ware design of Current Cost® IAMs. Therefore, appropriate pre-processing procedures are required to remove the faulty signals prior to using the data for further analyses. The pre-processing procedures for raw data of various categories in this research are discussed in Chapter Six, with an emphasis on those of raw power-profile data.

The multi-node communication enabled by the SRD RF wireless technique of Current Cost® devices was used in the NCH case study since the Internet service was only available in NCHB. Two sets of display & receiver units were connected with the Internet router in NCHB as shown in Figure 5-10. One unit was paired with the transmitter-equipped sensors, including a CT & transmitter unit and nine IAMs, in the neighbouring NCHA. The other unit was paired with those transmitter-equipped sensors in NCHB, including two CT & transmitter units and eight IAMs. In each house, a separate display & receiver unit was deployed as a Human Machine Interface (HMI) to present energy use feedback to the residents. The HMI was also used for manual download during monthly site visits without the interruption of real-time data transmission via Internet router to the Current Cost® dashboard, since only one RJ45 serial output port is available on the display & receiver unit for connection with either an Internet router or a PC.

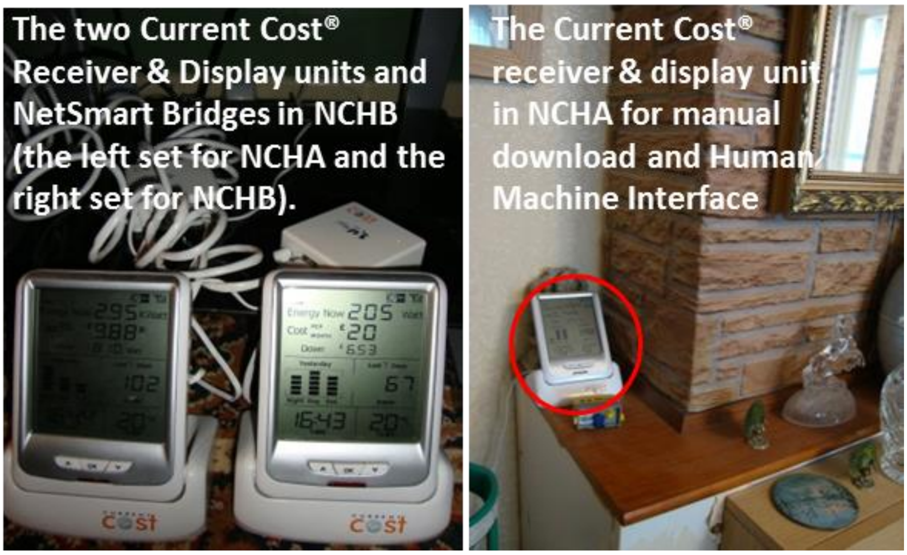


Figure 5-10 Application of multi-node communication using Current Cost® devices in the NCH case study

The monthly site visits, associated tasks, and main findings over the entire monitoring period in the NCH case study are listed in Table 5-5, which includes most of key events of the monitoring project from January 2011 to December 2012. In certain months, site visits were individually conducted in the two NCH homes due to the two households having different schedules.

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Table 5-5 Dates, tasks and main findings in the monthly site visits to the NCH case study houses

Site visit Date	Purposes	Main Findings
27/01/2011	The installation of Current Cost® devices for house electricity measurements in the two NCH homes; The installation of Hobo® U12-012 loggers in the two NCH homes; The gas meter readings started to be manually recorded from the meter chamber from this site visit onwards; First jointly conducted and semi-structured interview, along with project partners from the social housing association, regarding heating use, health conditions, and satisfaction towards the SWM retrofit programme (NCHA was pre-retrofitted and NCHB post-retrofitted at this time).	Assessment of wiring system and the types of utility meter of NCH houses inside and beyond the meter chamber; First-time walkthrough in the NCH homes; First-time rapport-building with the residents.
9/02/2011	The removal of the Hobo® U12-012 loggers, which were intended for use in the HHP case study to utilise the extra light intensity parameter; Download of data loggers.	The electricity use data was incomplete if the Current Cost® display and receiver unit was not properly downloaded via button pressing.
14/02/2011	The installation of an Easy Weather® station in the yard of NCHB; The deployment of Tinytag® TGU-4500 loggers that were taken back from the HHP case study on 11/02/2011; The deployment of a Hobo® U11-001 logger, which was connected with a mattress pressure detector, in each NCH house for the monitoring of main entrance use; The deployment of Hobo® U9-001 loggers on the most frequently operated windows of each houses (a window in the NCHA living room, a window in the NCHB kitchen).	The NCHA house use measured by Current Cost® was found to be lower than that of NCHB, although more intensive energy use activities were noted in NCHA during the first-time walkthrough. The low-level recordings were assumed to be caused by the malfunctioning Current Cost® display and receiver unit.
04/03/2011	The replacement of the Current Cost® display and receiver unit in NCHA; The electricity meter readings started to be manually recorded from the meter chamber from this site visit onwards.	

Site visit Date	Purposes	Main Findings
16/03/2011	The deployment of an additional Hobo® U9-001 logger on the other frequently operated window of each house (a main bedroom window was selected for each home); Download of data loggers.	The problematic house use measurements in NCHA remained unchanged after the new Current Cost® display and receiver unit was replaced.
11/04/2011	The replacement of the Current Cost® display and receiver unit in NCHA; Second jointly conducted and semi-structured interview, along with project partners from the social housing association, regarding the changes in heating use and health conditions, and the satisfaction towards the SWM retrofit programme; Download of data loggers.	
09/05/2011	Download of data loggers.	
10/06/2011	An appliance audit was conducted in the two houses for the preparation of Current Cost® IAM monitoring of electricity use by certain selected appliances; Download of data loggers.	The problematic house use measurement in NCHA remained unchanged after the Current Cost® display and receiver unit was replaced twice; It was assumed that the faulty readings might be caused by the improperly closed CT-clamp around the mains power cable.
15/06/2011 to NCHA	The examination of the CT-clamp installation in NCHA.	The aperture at the opening of the CT-clamp set that was located at the top of the NCHA meter chamber was discovered.
08/07/2011	Download of data loggers.	The house electricity use in NCHA returned to a reasonable level.
05/08/2011	Download of data loggers.	
02/09/2011 to NCHB 07/09/2011 to NCHA	The installation of nine Current Cost® IAMs in each of the three houses, since the first RF channel among the 10 permitted ones was taken by the CT-based house use monitoring; Download of data loggers.	Possible methods to remedy the flawed measurements of house use that were caused by the installation of CT-clamp were explored.
29/09/2011 to NCHB 03/10/2011 to NCHA	Download of data loggers.	The bi-hourly IAM-measurements were found to be erratic with the sum of IAM measurements exceeding the simultaneously measured house use.

Site visit Date	Purposes	Main Findings
10/10/2011	The multi-node installation of two Current Cost® Net Smart Bridges, each of which was connected to a display & receiver unit, in NCHB. The bridge and display set for NCHA was firstly paired with the NCHA Current Cost® IAMs and the CT unit around the NCHA mains power cable prior to connecting to the Internet router in NCHB.	
09/11/2011	Download of data loggers.	
13/12/2011	Download of data loggers.	Faulty spikes were discovered in the power profiles on the Current Cost® dashboard for most IAM-measured appliances.
04/01/2012	Download of data loggers.	
01/02/2012	Download of data loggers.	The retrofitted PV microgeneration system in NCHB was found to have been put in use since 01/12/2011; The manually downloaded house use data for NCHB were thus flawed due to the retrospectively inseparable PV power profiles.
13/02/2012	The installation of a second Current Cost® clamp around the output cable of the NCHB PV microgeneration.	The power profiles on the Current Cost® dashboard attested to the reason behind the flawed measurements of house use due to the retrofitted PV circuit.
02/03/2012	An improvised solution shown in Figure 5-8 was applied to the NCHB wiring system; Download of data loggers.	The Easy Weather® station was found to have taken no effective recordings over most of the winter period around February 2011.
28/03/2012	Download of data loggers.	The data relating to power draws and electricity use returned to normal after the improvised solution was implemented to separate PV microgeneration from house use.
25/04/2012	Empty diary copies in the format shown in Appendix One were given to the NCH residents to validate the Current Cost® IAM measurements; A five-minute interval was used for T and RH measurements for the purpose of cross-comparison with the five-minute power draw profiles; Download of data loggers.	An effort was made to acquire third-party weather data from monitoring sites that were close to the NCH site.

Site visit Date	Purposes	Main Findings
23/05/2012 to NCHB	Download of data loggers.	
01/06/2012 to NCHA	Download of data loggers.	
29/06/2012	Download of data loggers.	NCHB had visitors over the summer period of June to July; The changes in occupancy statuses of NCHB were revealed by the monitoring results, especially by the more frequently appearing power draw patterns for electric shower use.
27/07/2012	The collection of occupancy diaries from the two homes; Download of data loggers.	
22/08/2012	This was conducted as the last official site visit. The Easy Weather® station was set to log at hourly intervals to save the internal memory capacity until the next visit, which was the final one to remove all monitoring devices; The Tinytag® TGP-4500 logger, having a dust and water proof level of IP68, was deployed in a location adjacent to the NCH site as a monitoring backup to the Easy Weather® station; The removal of monitoring equipment from NCHA; Download of data loggers.	NCHB agreed to keep the hygrothermal loggers and the multi-node Current Cost® system until December 2012.
11/12/2012	The removal of monitoring devices from NCHB.	

5.4 Chapter summary

Starting with a justification for conducting pilot studies, this chapter introduced the two case study groups that were selected by following the case study selection criteria announced in Chapter Three. The HHP and NCH case study groups featured unique building characteristics. The project background, built form, and household composition of the two groups were introduced, followed by a description of how the selected monitoring schemes were implemented. Compared to the Energy Saving Trust's monitoring configuration, which cost £1,900 per household (EST, 2009), the monitoring scheme in this study utilised distributed and off-the-shelf products to lower costs, reduce intrusiveness, and increase deployment flexibility. The transferable monitoring techniques are applicable to any other similar project and the equipment can be reused and relocated. In addition, the direct measurements of occupancy statuses and the involvement of more monitored indoor zones are features that do not exist in the EST protocol (2009; 2011). The tasks and main findings relating to the monthly site visits conducted in this research have been tabulated for each case study groups in Table 5-3 and Table 5-5. Improvised solutions were conducted in the NCHB case study house to separate house power profiles from retrofitted PV microgeneration profiles. Certain restrictions in the low-cost monitoring system produced some incomplete or flawed measurements that require effectively pre-processing prior to being used for data presentation and analysis. The pre-processing procedures for each variable category in the raw data are introduced in the next chapter.

Chapter 6: Data Pre-processing

6.1 Introduction

Chapter Four and Chapter Five introduced the equipment selection and system configuration and the deployment of experimental work in pilot and case study homes. As discussed, the monitoring scheme implemented in this research was convenient in terms of maintenance and featured low costs, less intrusiveness, and repeatability in other similar projects. However, potentially flawed raw data from field measurements acquired by applying the low-cost monitoring scheme require certain levels of pre-processing prior to being used in the subsequent analyses. Appropriate pre-processing procedures and tools are critical in handling flawed raw data, especially when flawed measurements have been caused by either equipment-inherent or installation-associated factors. This chapter dwells on the processing of each variable category from the following four aspects:

- The synchronisation and primary processing of raw data that feature sufficient levels of completeness, continuity, and accuracy;
- The signal-filtering processing of raw data that contain erroneous measurements due to equipment-inherent factors;
- The remedial processing of raw data within which the flawed measurements can be artificially corrected to an acceptable standard;
- The removal processing of raw data within which missing data, due to either failure in wireless data communication or depletion of equipment's memory capacity, have no appropriate substitute.

It is important to use effective media and tools when applying pre-processing procedures onto the large volumes raw data collected in long-term field measurements. The Matlab® environment and associated toolbox products were selected in this research given the advantage they offer in terms of programming flexibility, dataset capacity, and compatibility with other commonly used software such as Microsoft® products.

6.2 Indoor hygrothermal data

Three characteristics were revealed by the hygrothermal measurements taken at different logging intervals. Firstly, the changes in T and RH values do not immediately respond to energy-related occupancy activities in the same way as electrical power draw variations. For example, the increase in temperature and accumulative water contents due to electric shower use take longer time periods to be reflected from the variations in T and RH variables than from the associated power draw profiles. Secondly, although some instant fluctuations in T and RH variables are only visible from more frequent recordings, logging frequencies have no obvious impact on time-series characteristics such as trend and seasonality and statistical properties such as mean and variance. A 10-minute interval can meet the monitoring requirement of this research, although 20-minute and five-minute intervals were experimented with in the pilot and case studies. Thirdly, as interval variables, the T and RH do not follow linear regressions between two adjacent recordings in the same way as ratio variables such as the averaged power draws. Linear interpolation approaches, such as artificial value-insertion using the arithmetic average value between two adjacent actual measurements, are applicable to ratio variables but not to interval ones. Therefore, hygrothermal measurements at a higher frequency can be artificially converted to lower frequency ones by removing the middle values. This type of pre-processing approach is referred to as sparse-treatment hereafter. If required, the sparse-treatment can be conducted multiple times to further enlarge the intervals in actual measurements. It is however infeasible to conduct the reversed conversion from lower to higher frequencies by inserting artificially calculated values for T and RH variables.

Three versions of pre-processed data profiles were compiled for subsequent analyses based on the aforementioned three characteristics of T and RH variables. The first version only included indoor hygrothermal parameters by synchronising the simultaneously measured raw data of each living zone. The measuring intervals in original recordings remained unchanged to keep the information contained in measuring results to the largest extent. This version of data profiles was used to examine the within-group and between-group variance depending on the defining factor of groups, such as living zones, houses, and case studies. Once the outdoor hygrothermal conditions were synchronised with the pre-processed indoor data profiles, the second version was formed to examine the tracking trajectory of indoor environment to weather conditions. In addition to building characteristics, factors relating to the use of natural ventilation and space heating can be inferred from the tracking trajectory. In most circumstances, the indoor parameters were measured at a relatively high frequency compared to the outdoor variables due to the capacity limits of the Easy Weather® station. The sparse-treatment was thus applied to high-frequency indoor measurements prior to the synchronisation with lower-frequency outdoor measurements. The third version of pre-processing consisted of artificially calculated statistical features of the first two versions of indoor / outdoor parameters, such as mean, variance and range. For example, the mean value of simultaneously measured values in different living zones was used to represent the average indoor conditions in the studied house. The third version was used to perform a cross-comparison of indoor hygrothermal conditions between different houses when the average indoor conditions were required.

All three versions of the pre-processed measurements were arranged to vertically follow the sequence of time and date. The data were converted to the Dataset Arrays format, which is a statistical data organising approach within the Matlab® environment. The missing data were flagged with ‘Not a Number’ (NaN) in order to apply the relevant

Matlab® statistical functions that facilitate calculations by ignoring missing values. Calendar days were used in the purpose-built Matlab® programme as the unit to split data profiles into daily Matlab® Dataset Arrays, which included extra information such as the count of daily data entries and basic statistics.

6.3 Outdoor hygrothermal data

Among the measurable weather parameters, T and RH were major outdoor environmental variables used in this research to represent the micro-environments adjacent to the studied houses. To validate the measurements and to examine the impact from direct solar radiations on outdoor sensors, Easy Weather® recordings were averaged into daily T and RH values and then superimposed with daily data from two Met Office weather stations A and B, as shown in Figure 6-1. The ground-based stations A and B are located near to Nottingham and Southwell, which are where the two case studies in the research were situated. Daily data from these two stations were available[19] from 1 January 2010 to 30 June 2012. Over longer sampling periods such as daily intervals, recordings from sites further apart tended to look increasingly similar. The hygrothermal recordings of the two case studies significantly correlated with the professional measurements taken from Met Office sites A and B, as shown in Table 6-1. Compared to the temperature recordings, RH measurements varied to a larger extent from one site to another due to the influence of installation conditions. For example, the Easy Weather® station was installed adjacent to the case study buildings, whereas Met Office stations are located in open-ground settings. Nevertheless, patterns of trend and seasonality exhibited similarities among recordings from different sites. The significantly positive correlations between measurements of different sites confirmed the feasibility of data supplementing and replacement when data loss occasionally occurred in any case study due to the volatile and limited internal memory of Easy

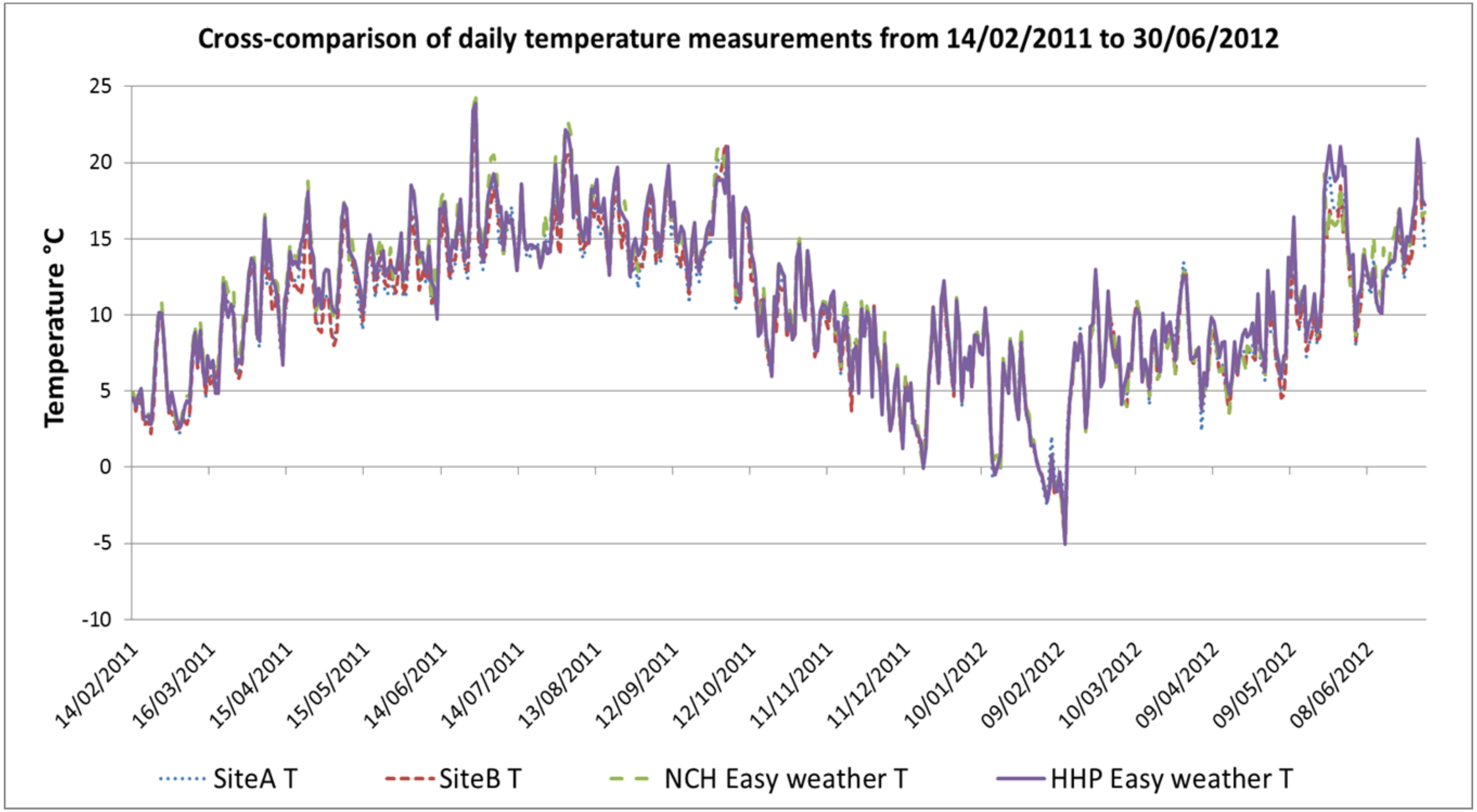
[19] Courtesy of the Centre for Renewable Energy Systems Technology of Loughborough University

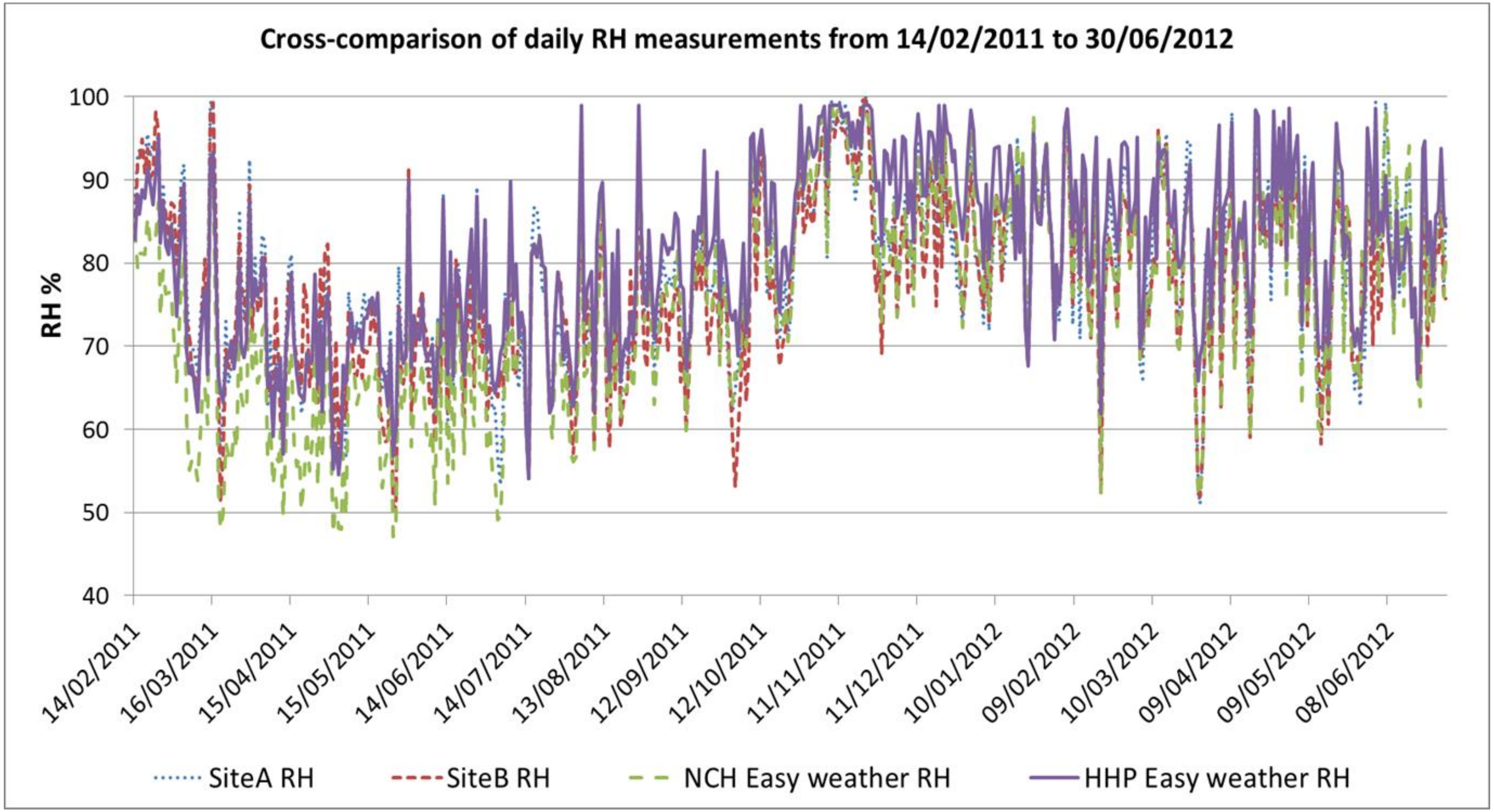
Weather® station. The similarity in outdoor hygrothermal conditions at the HHP and NCH case study sites justified the between-group comparison of respective tracking trajectories of indoor and outdoor conditions that closely related to the thermal performance of different building characteristics.

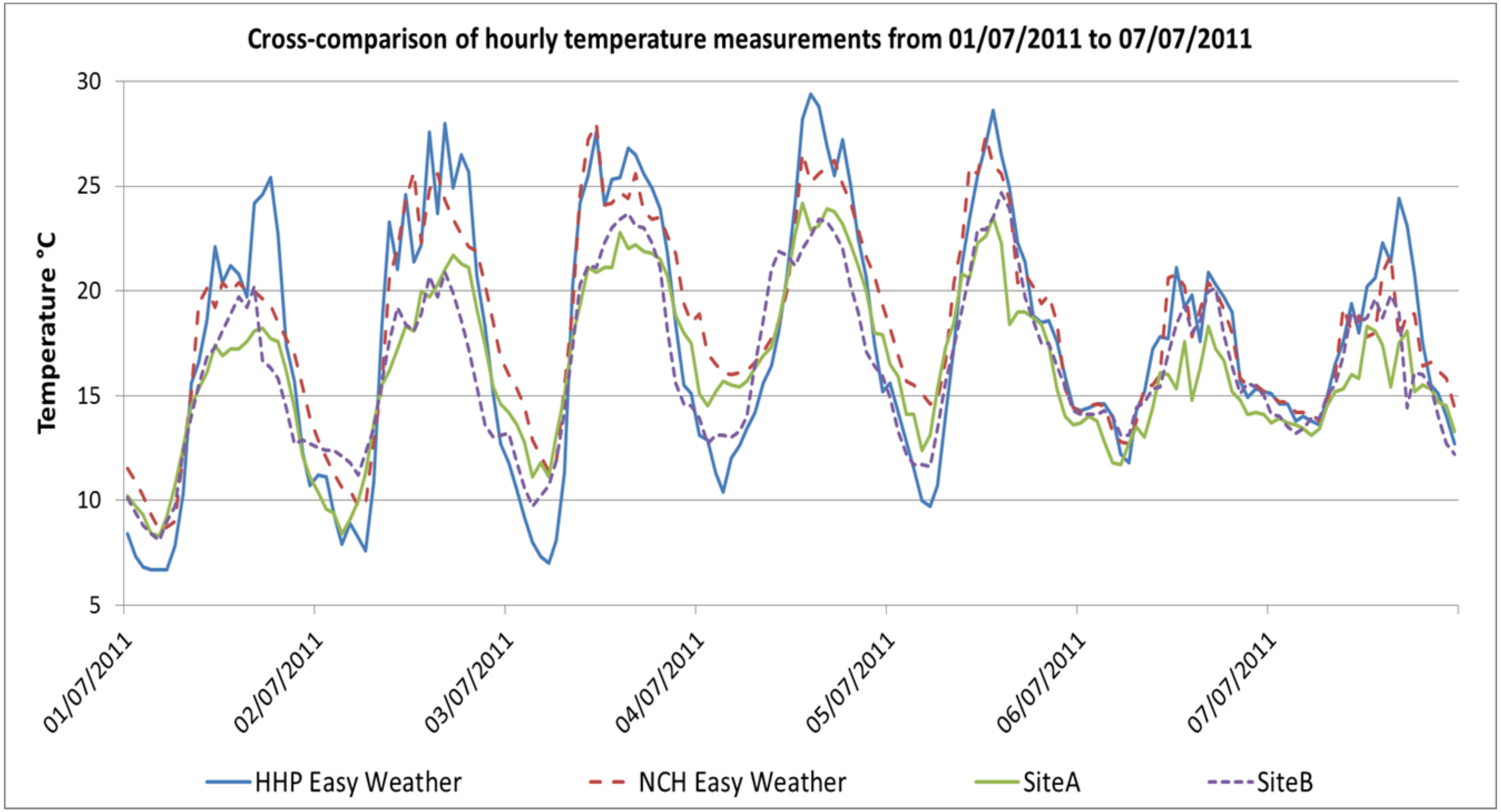
Table 6-1 Correlation coefficients of daily hygrothermal measurements of two Met Office weather stations and the Easy Weather® stations for both case studies

	SiteA/SiteB	SiteA/NCH	SiteA/HHP	SiteB/NCH	SiteB/HHP	NCH/HHP
T	0.991	0.991	0.989	0.991	0.987	0.987
RH	0.921	0.925	0.908	0.889	0.882	0.940

Over shorter sampling periods such as hourly intervals, differences in recordings from sites that were further apart were larger, as demonstrated in Figure 6-1 by the superimposed hourly temperature measurements over seven sunny summer days in July 2011 and seven cold winter days in February 2012. The NCH weather station malfunctioned over the latter winter period and thus no recordings were available for inclusion in the graph for that period. The impact of direct solar radiations on the grey-coloured weather case of outdoor hygrothermal sensors made the midday and afternoon measurements of the Easy Weather® station in the HHP case study approximately 5.0 ºC higher than those of the professional Met Office stations A and B. The lighter colour of the NCH Easy Weather® station weather case reacted to direct solar radiations better, although the measured temperatures were still higher than those recorded by the professional stations. The measurements from the Met Office sites and case studies overlapped when outdoor temperatures were around 15 ºC. The night measurements of Easy Weather® stations were affected by the opposite issue. Due to the less-professional weather case, the readings were lower than the actual temperatures, approximately cancelling out the higher recordings that were taken during daytime period.


Cross-comparison of daily temperature measurements from 14/02/2011 to 30/06/2012
Temperature °C
25
20
15
10
5
0
-5
-10
14/02/2011
16/03/2011
15/04/2011
15/05/2011
14/06/2011
14/07/2011
13/08/2011
12/09/2011
12/10/2011
11/11/2011
11/12/2011
10/01/2012
09/02/2012
10/03/2012
09/04/2012
09/05/2012
08/06/2012
SiteA T
SiteB T
NCH Easy weather T
HHP Easy weather T


Cross-comparison of daily RH measurements from 14/02/2011 to 30/06/2012
RH %
100
90
80
70
60
50
40
14/02/2011
16/03/2011
15/04/2011
15/05/2011
14/06/2011
14/07/2011
13/08/2011
12/09/2011
12/10/2011
11/11/2011
11/12/2011
10/01/2012
09/02/2012
10/03/2012
09/04/2012
09/05/2012
08/06/2012
SiteA RH
SiteB RH
NCH Easy weather RH
HHP Easy weather RH


Cross-comparison of hourly temperature measurements from 01/07/2011 to 07/07/2011
Temperature °C
30
25
20
15
10
5
01/07/2011
02/07/2011
03/07/2011
04/07/2011
05/07/2011
06/07/2011
07/07/2011
HHP Easy Weather
NCH Easy Weather
SiteA
SiteB

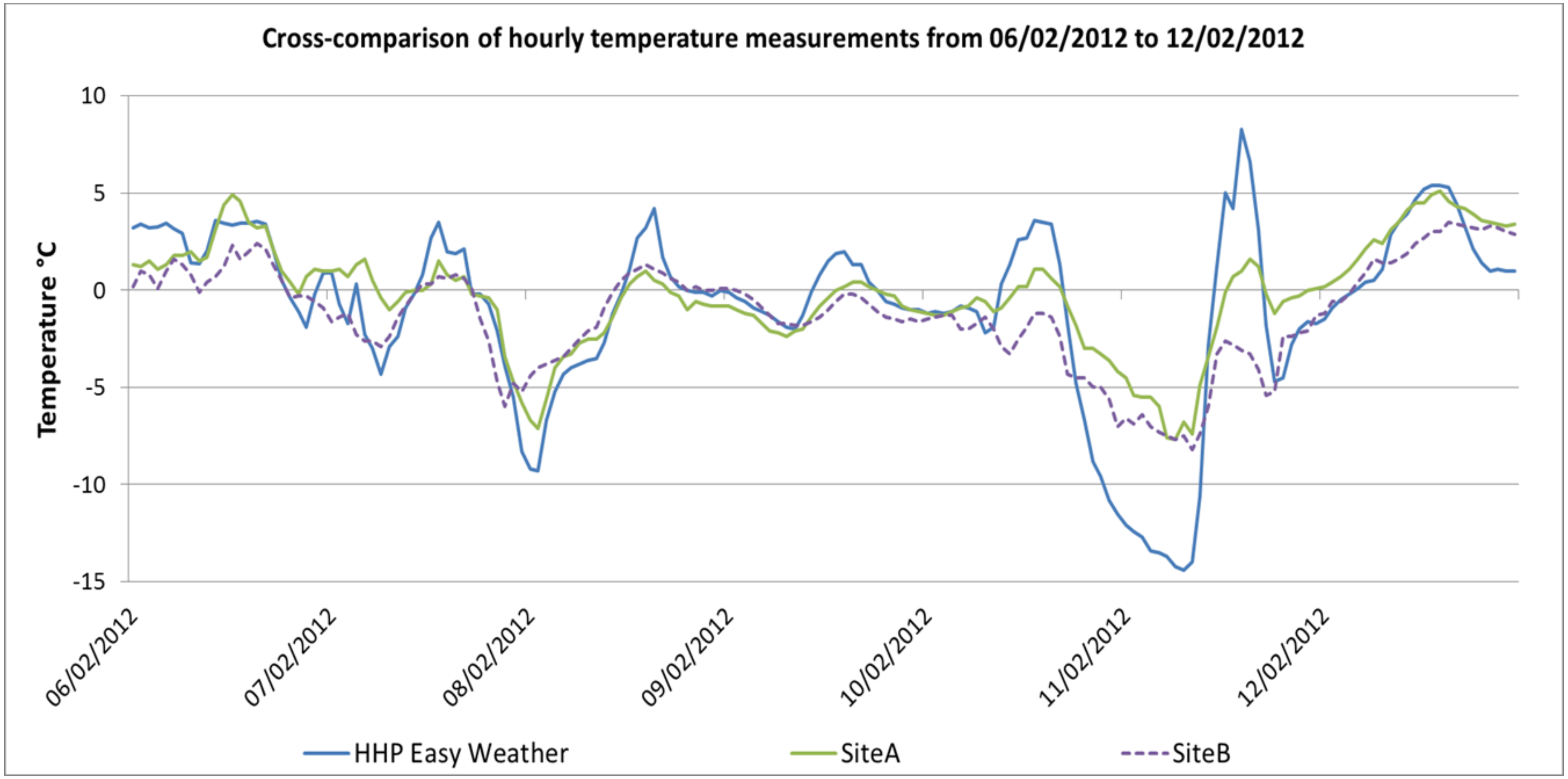


Figure 6-1 Superimposed hygrothermal measurements of Met Office weather stations A and B and the Easy Weather® stations at two case study sites

Tinytag® TGP-4500 hygrothermal loggers were used to measure the outdoor T and RH in both case studies from November 2012 as a backup to the Easy Weather® station when site visits were less frequently arranged. The Tinytag® TGP-4500 is not designed for the purpose of weather monitoring although its dust and water proof level at IP68 enables outdoor use. Without the purpose-built weather case to buffer any interference from the wind and other weather conditions, the RH measurements fluctuated largely between zero and 100 per cent. The temperature measurements were generally reasonable as demonstrated in Figure 6-2, which shows the superimposed daily average temperatures recorded by the Tinytag® TGP-4500 loggers and Easy Weather® stations at two case study sites over the same time period.

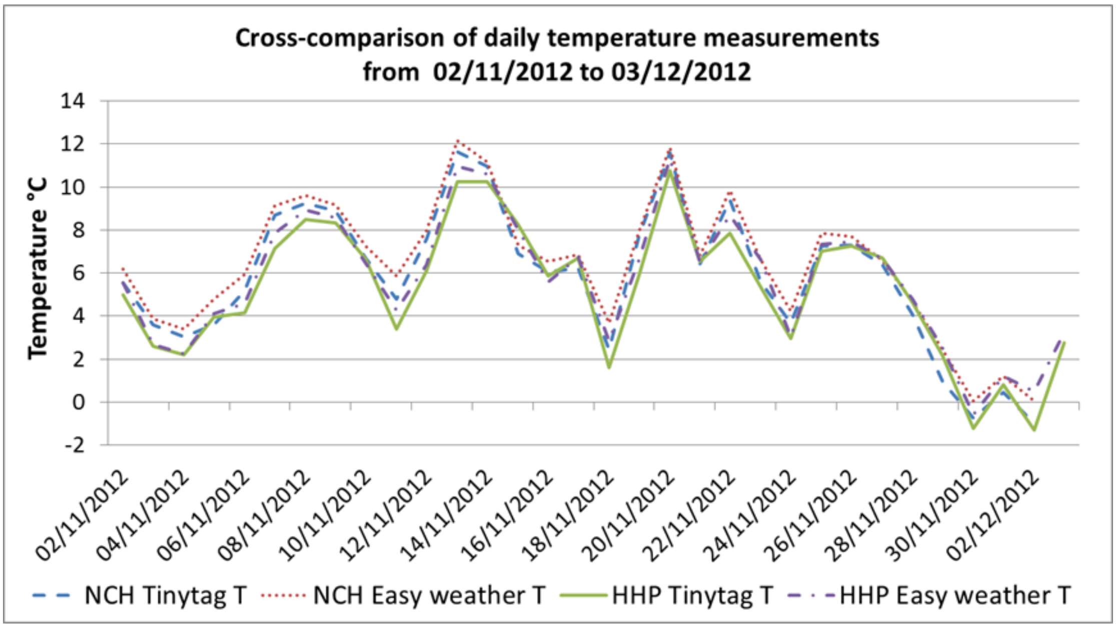


Figure 6-2 Superimposed daily outdoor temperatures measured by the Tinytag® TGP-4500 loggers and the Easy Weather® Station at two case study sites

The correlation coefficients between the Tinytag® and Easy Weather® temperature measurements taken during the HHP and NCH case studies were 0.989 and 0.997 respectively. In addition, the temperature measurements recorded by Easy Weather® stations were slightly higher than those recorded by Tinytag® TGP-4500 loggers in both case studies. Measurements taken from the same site, whether with Tinytag® or Easy Weather® equipment, showed that outdoor temperatures in the suburban environment of the HHP case study tended to be 0.5 to 2.0 ºC lower than temperatures in the city of Nottingham over the same time period.

6.4 Power draws and electricity use data

Flawed measurements were caused by different factors in the field monitoring of both case studies. Equipment-inherent factors included the absence of internal batteries to prevent clock-drifting in the Current Cost® display & receiver unit and the lack of signal processing functions in the circuit design of Current Cost® IAMs to filter faulty signals under power surges. Installation-associated issues included the improperly clamped CT units that produced flawed measurements. Uncontrollable factors, such as the infeasibility of accessing monitored homes over certain time periods, also caused electricity use data loss due to the limited internal memory capacity of Current Cost® display & receiver units.

Not all situations where measurements were incomplete or inaccurate were remediable by pre-processing procedures, which can artificially alter certain types of flawed data to an acceptable extent for the subsequent analyses. Irremediable examples are the gaps in daily electricity use recordings caused by clock-drifting or limited memory capacity and the data loss in power draw profiles due to instable network telecommunications. No effective solutions existed for such circumstances except for the use of monthly manual recordings of utility meters as a supplementary approach. Inaccurate measurements in house use power draws and integrated energy use due to the improperly installed CT clamp around the mains power cable were potentially rectifiable if a rational linear coefficient can be identified. The faulty spikes in power profiles measured by the IAMs were artificially removable by purpose-built signal-filtering programmes based on individual appliance characteristics. However, the integrated energy use of IAM-measured appliances was not retrospectively modifiable and should be discarded.

6.4.1 Pre-processing of power profiles

6.4.1.1 Pre-processing principles

Current Cost® power profiles consist of the average power draws of house use and monitored appliances over five-minute periods. Random variations in house power draws can occur over a period of five minutes, except for the time between midnight and early dawn when less energy-related occupancy activities take place. Some appliances have different operational settings, such as combinations of water temperature, spinning speed and washing mode for domestic washing machines. The power draws of such appliances vary largely under different operational modes. The average power draws of the same appliance under the same operational modes are not consistent depending on the location of the associated five-minute time window within the operational cycle. For example, electric shower use causes instant power draws above nine kW and average power draws over five minutes ranging from four to eight kW. Therefore, extra consideration was given to the pre-processing of incomplete and inaccurate power draw measurements.

Data replacement using existing power draw patterns or arithmetically interpolated values was infeasible when dealing with the data missing from the Current Cost® measurements. Even for the missing data relating to night-time sleeping periods, direct data replacement by transplanting the power profiles for the same time period on other days in the same house can be problematic. Indeed, the power draw patterns of major end use, such as a cold appliance or multiple cold appliances, were not consistent. Therefore, zero watt was artificially assigned to the time periods where data were missing. If the Current Cost® measurements were interrupted for a relatively long time period that potentially featured active energy use events, the associated daily power profiles were discarded.

Inaccurate measurements of power profiles using Current Cost® devices stemmed from two issues. The overestimated house power draws were due to the calculation principle of pseudo real power without a simultaneously measured real-time AC voltage and power factor. The false power draws of some individual appliances corresponding to power surges were due to the lack of signal filtering mechanism in the IAM firmware design. The pseudo real power profiles, although having larger values than actual power draws, contained the features of energy use activities in the monitored house. When the measurements were relatively complete, the data profiles could meet the pattern extraction requirement of this research without extra pre-processing. Energy-related activities could potentially be disaggregated from the house power profiles by applying appropriate algorithms. In contrast, the false signals in the IAM-measured power profiles required artificial removal prior to being used for the purpose of pattern extraction.

6.4.1.2 Raw data characteristics

Each batch of raw data downloaded from the Current Cost® dashboard included seven days of monitoring results at most, as confined by the web portal capacity. Each downloaded file consisted of the data recorded by 10 radio frequency (RF) channels, with each channel's data vertically arranged in series by days. Once the RF communication was successfully established between the display & receiver unit and the CT & transmitter unit and transmitter-equipped IAMs via pairing procedures, the channel order were fixed in the downloadable files that were in the format of comma separated values (CSV). Therefore, when the successfully paired IAM was moved to different appliances during the monitoring period, the sequential tag of the IAM channel appeared unchanged in the downloaded comma separated values (CSV) files although the measurement results came from different appliances. Manual data compilation was thus required to categorise the downloaded IAM data per type of appliance. The advantage of the fixed tagging mechanism was that the residents in case study houses could move the IAMs to any plug-in type of appliance when required by the researchers if they could not perform the IAM movement in person between two monthly site visits. For example, when the original IAM on a washing machine was found to be potentially malfunctioning from the Current Cost® dashboard, residents were able to move the IAMs placed on other appliances having relatively regular power draw patterns, such as refrigerators, to the washing machine, prior to replacing the broken IAM. The disadvantage of flexibility in moving the IAMs among monitored appliances was the extra effort required during the subsequent semi-automatic data compilation.

Over a time period when network problems occurred, such as the disconnection of Internet routers and the frozen status of Current Cost® bridges, the missing data were directly omitted from the downloaded data files. Zero watt was automatically entered in the downloaded data files over the time period when the network service still functioned properly but no measurable power readings existed. The main RF channel for house use was relatively stable compared to the channels for individual appliances. Among the nine IAM channels allowed by the Current Cost® devices, the first three channels operated more stably. Without a reboot of the network peripheral devices, the IAM data loss could last for several days.

Since each piece of five-minute power data took a fractional second to be buffered, transmitted and received by Current Cost® devices, the timestamp of each piece of data could not follow the integral number of seconds, such as 'YYYY-MMM-DD HH:MM:00' as in the monitoring of the indoor environment. A purpose-compiled Matlab® programme was applied to convert data timestamps for the purpose of synchronisation with other monitoring parameters. In the programme, the timestamps between HH:MM:01 and HH:MM:30 were artificially allocated with a new timestamp of

HH:MM:00 and that between HH:MM:31 and HH:MM:59 with HH:(MM+1):00. When the MM part was 59 minutes, the timestamp was rounded up to (HH+1):00:00. When the HH part was 23 hours, the timestamp was returned to 00:00:00 with the associated date being increased by one day. If the interface was the last day of a month, similar rounding-up procedures were implemented to alter the month (MMM) and Day (DD) elements in the timestamp. Similarly, the minute fraction of M1, M2, (M-1)8, and (M-1)9 was rounded up to M0, and that of M3, M4, M6, and M7 to M5, where the first digit of the Minute element (M) could be any number between zero and five included. The newly created timestamps were thus allocated to each power draw entry with unchanged power values. Gaps within timestamp series were inevitable since the daily raw data rarely contained exactly 288 entries due to the fractional second of time delay of each piece of data. To fill in the gaps, another purpose-compiled Matlab® programme was applied to identify the gap positions prior to filling in the required timestamps and the power values using arithmetic average power draws of two adjacent values. However, the artificially interpolated values could severely alter the actual energy use values even though the transformed power draw profiles facilitated the synchronisation with other monitoring variables. Therefore, this type of processing was not carried on. Instead of attempting to approximate the timestamps of all measurements in power profiles to the integral interval of five minutes, both values and timestamps of the raw data were kept unchanged.

6.4.1.3 Pre-processing procedures

The pre-processing of the power profiles that were downloaded in batches from the Current Cost® dashboard involved four major steps. Step one was to synchronise the data from 10 channels using the timestamp of each piece of data as a reference. The raw data that were organised vertically by channels were converted to a multi-column dataset of power profiles with each column representing one RF channel. Step two was to concatenate processed data from different batches by following the sequence of data and time. Special procedures were taken to adjust the timestamps during time periods of alternation between GMT and DST. Step three was to identify and alter the faulty power signals due to power surges as experienced by the IAM measurements. Rules were compiled using Matlab® tools in the signal-filtering process, such as the comparison of power draw amplitudes of house use and monitored appliances. IAM measurements of certain appliances can be considered as false power draws if largely exceeding the simultaneous power draws of house use. Retrospective examinations on processed results and continuous adjustment of programmed rules were critical for effective signal filtering. For certain types of appliances, such as TVs and entertainment appliances, filtering rules were relatively easy to compile since the power draws remained at a relatively low and stable level. False measurements over 400 watts, for instance, can be either removed or replaced with a reasonable estimation depending on other values adjacent to the false measurements. For energy-intensive events, such as the use of dishwasher and electric kettle that featured larger variations in power draws, the filtering rules were relatively complicated. Therefore, the pre-processing of power draw profiles in step three was conducted semi-automatically according to the different power draw features of monitored appliances. Figure 6-3 shows the raw and processed data of house use and seven IAM-measured appliances in the NCHA case study house, after the three processing steps were applied. The other two IAM channels were not included in the data files since they were not used consistently by specific appliances when the IAMs were moved among different appliances. The highlighted figures in the raw and processed dataset in Figure 6-3 demonstrate the alterations made to the associated power draw values by purpose-compiled Matlab® programmes.

Raw data

DateTime	House	FriFree	DishW	BreadM	Kettle	Dryer	WashingM	TV
29/11/2011 12:34	394	39	0	0	0	0	0	236
29/11/2011 12:39	435	110	0	0	0	0	0	0
29/11/2011 12:44	439	116	0	7	0	0	0	223
29/11/2011 12:49	483	102	0	0	0	0	0	214
29/11/2011 12:54	417	0	0	0	0	0	0	231
29/11/2011 12:59	436	0	0	0	0	0	0	217
29/11/2011 13:04	503	0	0	29	2776	0	0	253
29/11/2011 13:09	1186	56	0	37	1218	0	0	226
29/11/2011 13:14	920	119	0	0	46	0	0	236
29/11/2011 13:19	848	121	0	0	0	0	0	224
29/11/2011 13:24	478	114	0	0	0	0	0	168
29/11/2011 13:29	483	112	0	0	0	0	0	196
29/11/2011 13:34	546	109	0	18	0	0	0	212
29/11/2011 13:39	1467	66	0	0	0	316	0	238
29/11/2011 13:45	2465	1	0	260	0	2445	0	222
29/11/2011 13:50	2612	0	0	592	0	1943	0	199
29/11/2011 13:55	2050	745	0	534	0	1310	0	142
29/11/2011 14:00	1883	58	0	1272	0	1302	0	194
29/11/2011 14:05	2003	115	0	542	0	1295	0	201
29/11/2011 14:10	1736	113	0	269	0	1304	0	156
29/11/2011 14:15	1726	110	0	268	0	1299	0	178
29/11/2011 14:20	1696	87	0	300	0	1290	0	185
29/11/2011 14:25	1668	0	0	345	0	1291	0	210
29/11/2011 14:30	1337	0	0	282	0	1100	0	212
29/11/2011 14:35	614	0	0	227	0	130	0	187
29/11/2011 14:40	650	83	0	215	0	80	0	211
29/11/2011 14:45	655	112	0	154	0	0	0	229
29/11/2011 14:50	549	0	0	81	0	0	0	230
29/11/2011 14:59	910	0	0	0	0	0	0	0
29/11/2011 15:04	444	0	0	0	0	0	0	212

Processed data

House	FriFree	DishW	BreadM	Kettle	Dryer	Washing	TV
394	39	0	0	0	0	0	236
435	110	0	0	0	0	0	229.5
439	116	0	7	0	0	0	223
483	102	0	0	0	0	0	214
417	0	0	0	0	0	0	231
436	0	0	0	0	0	0	217
503	0	0	29	0	0	0	253
1186	56	0	37	777	0	0	226
920	119	0	0	46	0	0	236
848	121	0	0	0	0	0	224
478	114	0	0	0	0	0	168
483	112	0	0	0	0	0	196
546	109	0	18	0	0	0	212
1467	66	0	0	0	316	0	238
2465	0	0	260	0	2445	0	222
2612	0	0	592	0	1943	0	199
2050	0	0	534	0	1310	0	142
1883	58	0	538	0	1302	0	194
2003	115	0	542	0	1295	0	201
1736	113	0	269	0	1304	0	156
1726	110	0	268	0	1299	0	178
1696	87	0	300	0	1290	0	185
1668	0	0	345	0	1291	0	210
1337	0	0	282	0	1100	0	212
614	0	0	227	0	130	0	187
650	83	0	215	0	80	0	211
655	112	0	154	0	0	0	229
549	112	0	81	0	0	0	230
910	112	0	0	0	0	0	221
444	0	0	0	0	0	0	212

Figure 6-3 An example of the raw and processed NCHA power profiles

The final pre-processing step was to convert the filtered power draw data from the excel datasheet to Matlab® Dataset Arrays prior to splitting the dataset processed in step three into daily datasets for later analyses. As shown in Figure 6-4, an extra 'DateNum' column was added by converting the timestamps into Matlab® numeric format. The durations of targeted energy-related activities can be calculated by directly computing the numeric timestamps. After the four pre-processing steps, the measured house use remained unchanged to keep the actual power draw features. The IAM measurements were processed by using purpose-compiled rules for each type of appliance to remove or alter the identified false signals that were due to power surges. The dataset in the format of Matlab® Dataset Arrays contained information on the counts of daily data entries of house use power profiles since not all RF channels of IAMs were as stable as the main RF channel for house use measurements.

	DateNum	House	FriFree	DishW	BreadM	Kettle	Dryer	WashingM	TV
29-Nov-2011 12:34:00	7.3484e+005	394	39	0	0	0	0	0	236
29-Nov-2011 12:39:00	7.3484e+005	435	110	0	0	0	0	0	229.5
29-Nov-2011 12:44:00	7.3484e+005	439	116	0	7	0	0	0	223
29-Nov-2011 12:49:00	7.3484e+005	483	102	0	0	0	0	0	214
29-Nov-2011 12:54:00	7.3484e+005	417	0	0	0	0	0	0	231
29-Nov-2011 12:59:00	7.3484e+005	436	0	0	0	0	0	0	217
29-Nov-2011 13:04:00	7.3484e+005	503	0	0	29	0	0	0	253
29-Nov-2011 13:09:00	7.3484e+005	1186	56	0	37	777	0	0	226
29-Nov-2011 13:14:00	7.3484e+005	920	119	0	0	46	0	0	236
29-Nov-2011 13:19:00	7.3484e+005	848	121	0	0	0	0	0	224
29-Nov-2011 13:24:00	7.3484e+005	478	114	0	0	0	0	0	168
29-Nov-2011 13:29:00	7.3484e+005	483	112	0	0	0	0	0	196
29-Nov-2011 13:34:00	7.3484e+005	546	109	0	18	0	0	0	212
29-Nov-2011 13:39:00	7.3484e+005	1467	66	0	0	0	316	0	238
29-Nov-2011 13:45:00	7.3484e+005	2465	0	0	260	0	2445	0	222
29-Nov-2011 13:50:00	7.3484e+005	2612	0	0	592	0	1943	0	199
29-Nov-2011 13:55:00	7.3484e+005	2050	0	0	534	0	1310	0	142
29-Nov-2011 14:00:00	7.3484e+005	1883	58	0	538	0	1302	0	194
29-Nov-2011 14:05:00	7.3484e+005	2003	115	0	542	0	1295	0	201
29-Nov-2011 14:10:00	7.3484e+005	1736	113	0	269	0	1304	0	156
29-Nov-2011 14:15:00	7.3484e+005	1726	110	0	268	0	1299	0	178
29-Nov-2011 14:20:00	7.3484e+005	1696	87	0	300	0	1290	0	185
29-Nov-2011 14:25:00	7.3484e+005	1668	0	0	345	0	1291	0	210
29-Nov-2011 14:30:00	7.3484e+005	1337	0	0	282	0	1100	0	212
29-Nov-2011 14:35:00	7.3484e+005	614	0	0	227	0	130	0	187
29-Nov-2011 14:40:00	7.3484e+005	650	83	0	215	0	80	0	211
29-Nov-2011 14:45:00	7.3484e+005	655	112	0	154	0	0	0	229
29-Nov-2011 14:50:00	7.3484e+005	549	112	0	81	0	0	0	230
29-Nov-2011 14:59:00	7.3484e+005	910	112	0	0	0	0	0	221
29-Nov-2011 15:04:00	7.3484e+005	444	0	0	0	0	0	0	212

Figure 6-4 An excerpt of the NCHA daily power profile of processed data in Matlab® Dataset Arrays format

6.4.2 Pre-processing of electricity use

6.4.2.1 Flawed energy use measurements in HHP3

At the researcher’s request, the position of the CT clamp around the mains cable in case study house HHP3 was adjusted by the residents in March 2011. The confined space between the mains cable and rear wall in the meter cabinet left an aperture at the clamp opening following the adjustment. The single-occupant household profile in HHP3 featured a lower level of daily electricity use relative to the other monitored homes in the HHP autonomous community. Therefore, the flawed measurements were not discovered in time.

The Hotsi® water tanks in the three monitored HHP houses were heated by electric immersion heaters rated at one kW. The use of an immersion heater is a *resistive* load featuring an approximate power factor of one, which is the default power factor value used by the Current Cost® CT & transmitter unit. When properly monitored, the power demand of the entire house should fluctuate based on a plateau of power draws around one kW over the water heating period. However, house power draws around 700 watts, instead of one kW, were measured by the CT & transmitter unit. It had once been assumed that the immersion heater in HHP3 had partially malfunctioned since it was not practical to empty the water tank to examine the coils and other heating elements as demonstrated in the site-visit tasks and findings in Table 5-3 (see Chapter Five).

In December 2011, when an IAM was moved to the immersion heater in HHP3, the five-minute IAM-measured power draws were around one kW as shown in Figure 6-5. The discrepancy in the power draw magnitudes between the simultaneous power profiles of house use and IAM measurements in HHP3 was further examined. Power draws around one kW were also measured by the IAMs on immersion heaters in the other two HHP case study houses, in which the power profiles of house use had always been above the plateau of one kW during water heating periods. All Current Cost® devices in HHP3 were individually examined until the CT installation problem was discovered. After readjusting the CT clamp, a professional appliance monitor, the NZR® Standby-Energy-Monitor (SEM) LOG16+, was applied between the IAM and immersion heater to calibrate the new measurements as shown in Figure 6-6. The five-minute IAM measurements of the immersion heater prior to and after the readjustment of the CT clamp assisted in the identification of an approximately linear coefficient 1.73 to modify the flawed data of the energy use and power draws of HHP3.

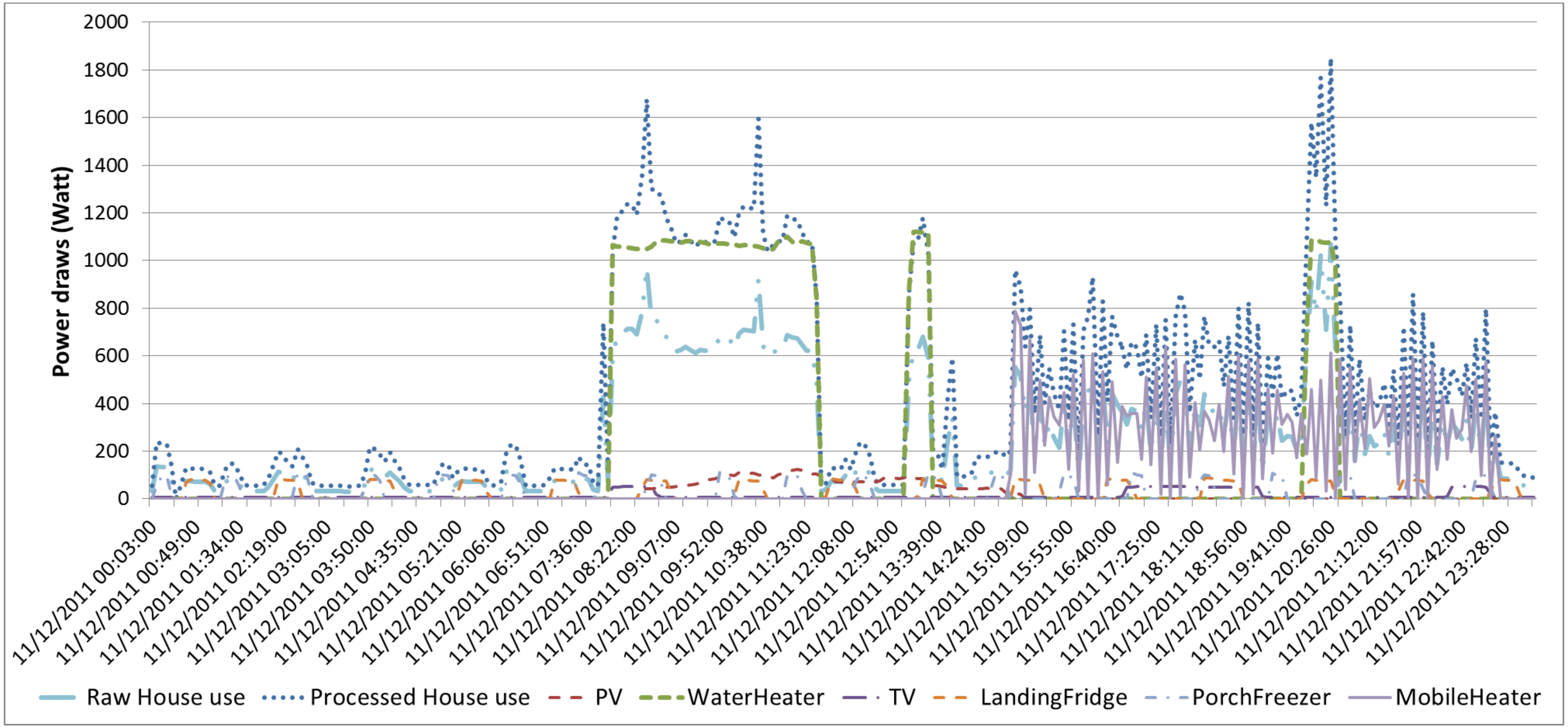


Figure 6-5 A power-profile example of the flawed and processed measurements of house use and the processed IAM measurements in the HHP3 case study

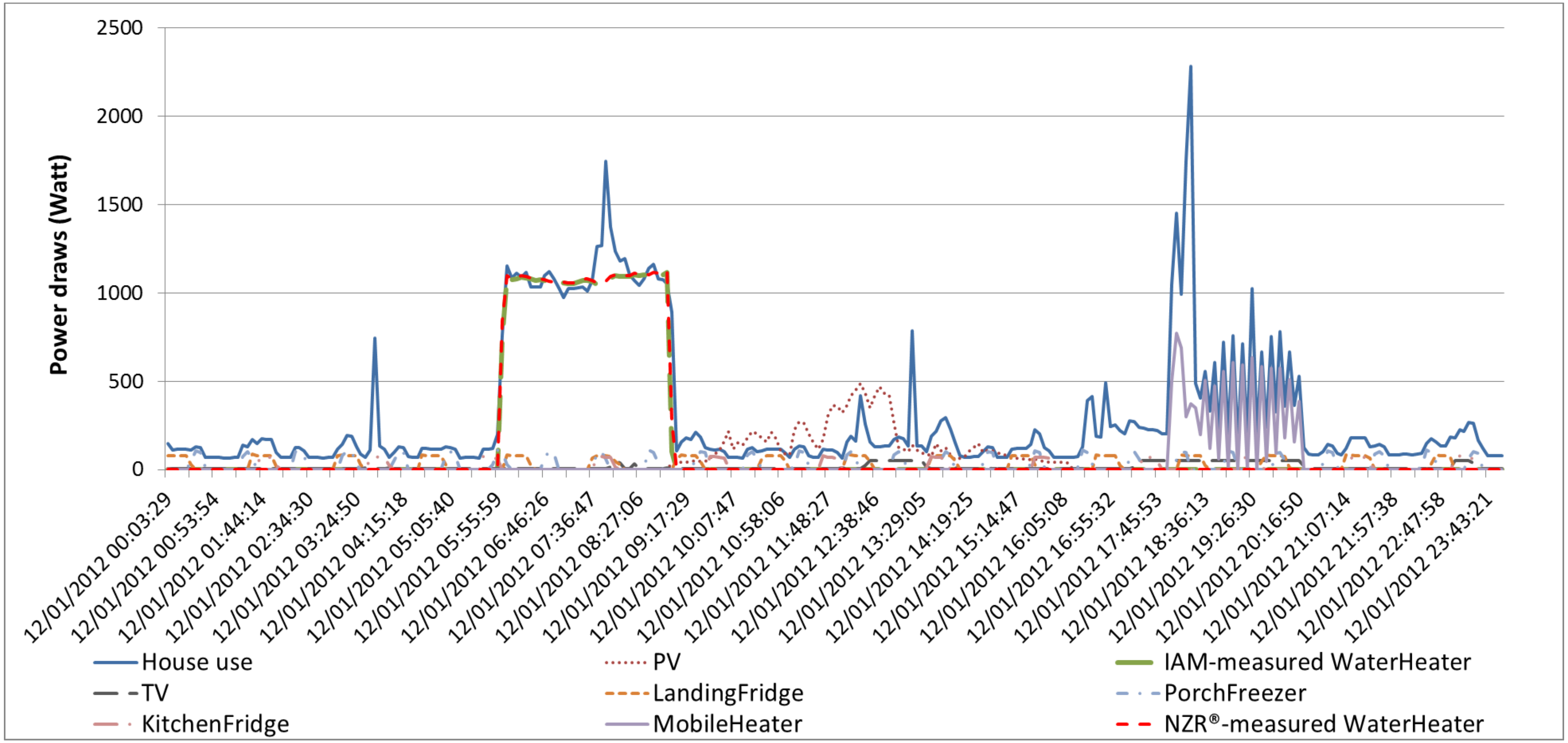


Figure 6-6 Power-profiles of CT-measured house use, IAM-connected appliances, and NZR®-validated water heater after adjusting the CT installation in HHP3

One major advantage of using a linear coefficient to modify flawed raw data, in addition to simplicity and practicality, is that it keeps the raw data's statistical features. For example, both mean and standard deviation of the dataset remains unchanged after each piece of data is multiplied by a constant coefficient. The manually downloaded daily electricity use was the sum of 12 entries of bi-hourly consumption that derived from the integrated power demand over a period of two hours. Therefore, the coefficient 1.73 was expected to work for the integrated energy use in the same way as for the real-time pseudo power draws. The power draw and electricity use patterns thus remained unchanged except for the scaled-up magnitude. This facilitated the extraction of energy use activities and the cross-comparison of electricity use in different homes. Figure 6-7 demonstrates the pre-processing of HHP3 results over the period of inaccurate measurements using the identified coefficient.

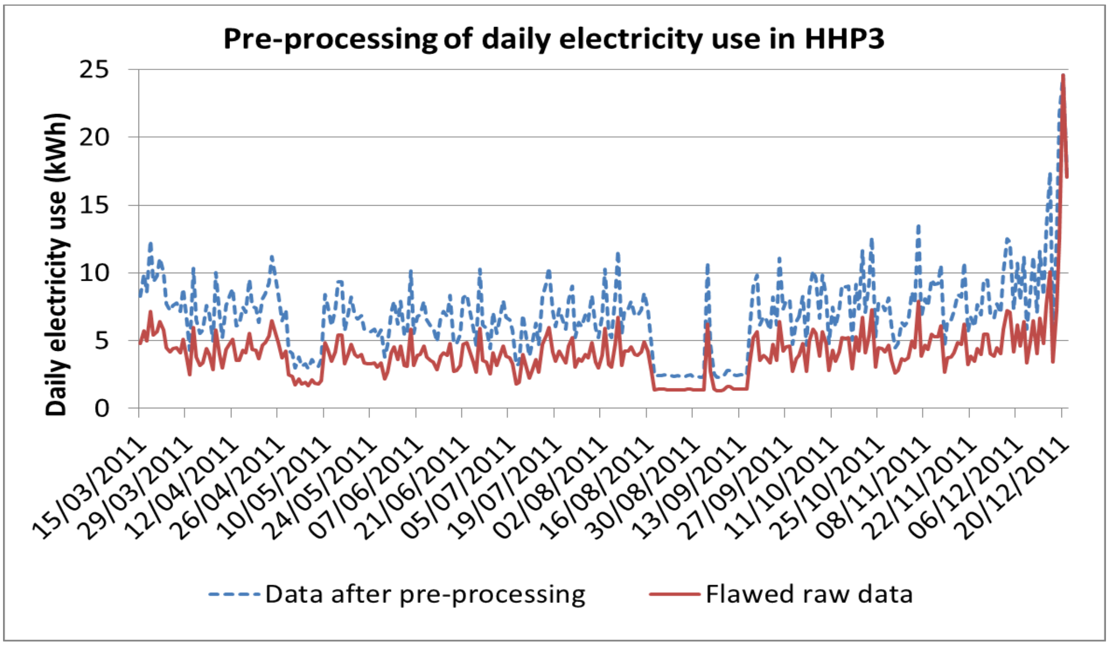


Figure 6-7 Modification of HHP3 daily electricity measurements using the identified coefficient 1.73

In practice, not all power loads are purely resistive and have a constant power factor of one. The proportion of real power within the apparent power relies on the actual power factor of the house mains power at the measuring moment, and is difficult to estimate retrospectively without the real-time measurements of power factor. The pseudo real power recorded by Current Cost® tended to be larger than the actual power draws. Therefore, the coefficient was actually a moderate estimation. The quarterly HHP bills were used to validate the effectiveness of the identified coefficient by comparing the modified energy use against the HHP residents' manual meter readings. The validation results are presented in Table 6-2, in which the raw data for HHP4 and HHP5 and the modified data for HHP3 are compared against the quarterly manual recordings. For three consecutive quarters, the modified daily energy use in HHP3 was the closest to the manual recordings among the three monitored houses. Therefore, the selected coefficient was attested to suit various data scales from five-minute power profiles to long-term electricity use. The manual energy recordings in the HHP bills played an important role in the validation process. To have more frequent meter readings than the quarterly HHP bills, manual readings of utility metering devices of the monitored HHP houses started to be recorded during the subsequent site visits from January 2012 onwards.

Table 6-2 Validation of energy use measurements in HHP4 and HHP5 and modified energy use in HHP3 using quarterly HHP bills

Date	House	Modified /Raw Data (kWh)	Manual recordings (kWh)
22/03/2011-28/06/2011	HHP3	**685**	681
	HHP4	798	716
	HHP5	920	986
28/06/2011-28/09/2011	HHP3	**534**	533
	HHP4	742	698
	HHP5	807	876
28/09/2011-10/01/2012	HHP3	**1010**	1004
	HHP4	1098	1120
	HHP5	1209	1284

The wireless communication of RF signals established between the display & receiver unit and the CT & transmitter unit around the mains power cable in HHP5 was not as stable as that in the other two HHP houses. The unstable communication resulted in relatively low measurements compared to the manual recordings, as shown in Table 6-2. On the contrary, relatively high Current Cost® measurements of house use compared with the quarterly manual readings were witnessed in HHP4. The discrepancy mainly arose from the difference between the actual real power and the measured pseudo real power. For example, assuming that a freezer with a rated current capacity of one Ampere and an average power factor of 0.5 is the only domestic appliance in operation over the midnight period when the AC voltage is around 240 V. The actual power draws should be around 120 watts during operational cycles if it is measured by a professional device such as the NZR® Standby-Energy-Monitor (SEM). The pseudo real power measured by the Current Cost® CT & transmitter unit would be as high as 240 watts. Therefore, the integrated daily energy use would be twice as much as the actual energy used by the freezer. Since the power factor at the measurement point of mains power is no greater than one, the discrepancy would not be enlarged indefinitely along with the involvement of multiple appliances, but instead be accumulated over a longer time period such as weeks or months, as in the case of energy use in HHP4 shown in Table 6-2. Other equipment-inherent issues of the Current Cost® devices, such as low consistency in monitoring accuracy of different equipment sets, can also potentially result in a discrepancy between the acquired raw data and the manual recordings taken in the HHP houses. In general, the difference was within an acceptable scope, especially for the short-term figures in this study that were less influenced by accumulated errors. It was not the research objective of the monitoring project to calibrate Current Cost® devices against either manual recordings or utility billing systems. After being processed with the validated coefficient 1.73, the daily energy use of HHP3 was superimposed with the Current Cost® measurements of HHP4 and HHP5 as shown in Figure 6-8.

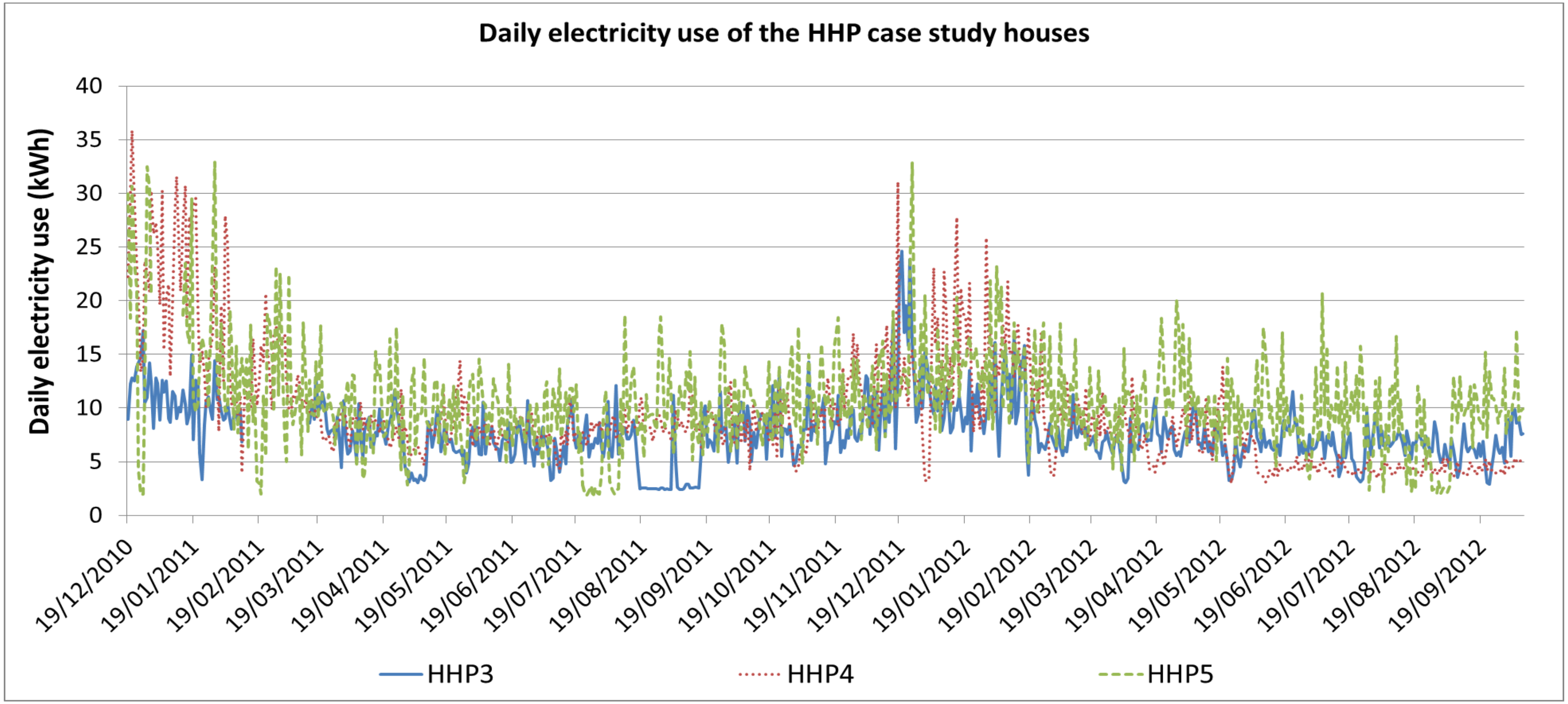


Figure 6-8 Daily electricity use of the HHP case study houses over the monitoring period 19/12/2010 to 09/10/2012

Gaps within the time series of energy use in each house represent the days with missing measurements due to either failed RF communication or lack of memory capacity. Since electricity was the only energy source used in the HHP community, the energy use time series in Figure 6-8 present obvious seasonality. The multi-occupant HHP5 did not use electric space heaters like the other two monitored households until the winter of 2012 to 2013. Unlike the other two houses, the residents in HHP5 preferred to use a thermostat, instead of a programmable timer, to control the Hotsi® water tank, given the hot water demand by young children in the house. The immersion heater started working whenever the hot water temperature fell below the set values. More frequent use of water heating was thus required in winter seasons. Therefore, seasonality of energy use was also recognisable in the time series of energy use in HHP5. HHP5 was the only household using a dishwasher in the HHP community. More frequent use of the washing machine compared to the other two houses, together with the factors of dishwasher use and hot water demand, made the energy use of HHP5 the highest, followed by the double-occupant HHP4 and then the single-occupant HHP3. Other than seasonality, no clear trend relating to the increase or decrease in electricity use was witnessed from the monitoring results, since the occupancy status and domestic appliance ownership in all three houses remained the same over the monitoring period. Another reason for the lack of trend features in electricity consumption over the monitoring period was the energy-conscious lifestyle of the HHP residents.

The long-term daily use in Figure 6-8 provides a macro-scale background to cross compare energy use in different houses. Key features identified from macro-scale presentations can be used in micro-scale inspections of power draw profiles in Chapter Seven. For example, over the periods 29 April 2011 to 9 May 2011 and 18 August 2011 to 15 September 2011, the energy use in HHP3 was relatively fixed around the base load of two or three kWh per day. Together with the measurements given by other categories of loggers, these days were identified as unoccupied periods, which were later confirmed by the house resident.

Three key aspects in keeping long-term and valid measurements were summarised from the experience of pre-processing and validating energy use measurements:

- An appropriate protocol to examine and maintain effective statuses of monitoring devices and system;
- An inspection approach, such as the use of more professional monitoring devices, to identify the causes of flawed measurements;
- An extra data source, such as the manual reading of energy meters, to validate the effectiveness of problem-solving.

6.4.2.2 Flawed energy use measurements in NCHA

Similar instances of inaccurate measurements of daily energy use were experienced in NCHA. The CT unit was improperly clamped around the mains cable from 28 January 2011 to 15 June 2011 when the Internet service had not been available in NCHB to facilitate five-minute power profiles. In addition, no *resistive* loads, such as the immersion water heater in HHP3, existed in NCHA to be monitored by IAMs for the identification of a linear coefficient. Unlike the HHP residents who had been keeping quarterly meter readings for over a decade, the tenants of the NCH houses had no other forms of historical recordings of energy use except for the quarterly energy bills from utility suppliers. Actual meter readings were usually taken once every half a year by utility suppliers, who provided an estimated use in two other quarterly bills. Therefore, the figures that were quoted on utility bills were an inadequate remedy to the discrepancy between actual use and inaccurate Current Cost® daily measurements.

Manual readings of electricity and natural gas meters in the two NCH homes were recorded by the researcher from March 2011 in each monthly or half-monthly site visit.

The manual recordings were used to modify the inaccurate measurements that had occurred in NCHA. Four batches of manual recordings, shown in Figure 6-9, were listed in parallel with the flawed raw data that were integrated according to the actual dates when meters were manually read. An averaged coefficient of 5.87 was thus identified to modify the inaccurate Current Cost® recordings from March 2011 to June 2011. Considering the features of pseudo real power as measured by Current Cost® devices, 5.87 was also a moderate estimation.

Date	Manual log	Coefficient	Actual use	Raw data
04/03/2011	29919			
16/03/2011	30126	5.682	36.43	207
11/04/2011	30507	5.959	63.932	381
09/05/2011	30920	5.913	69.841	413
10/06/2011	31388	5.935	78.855	468

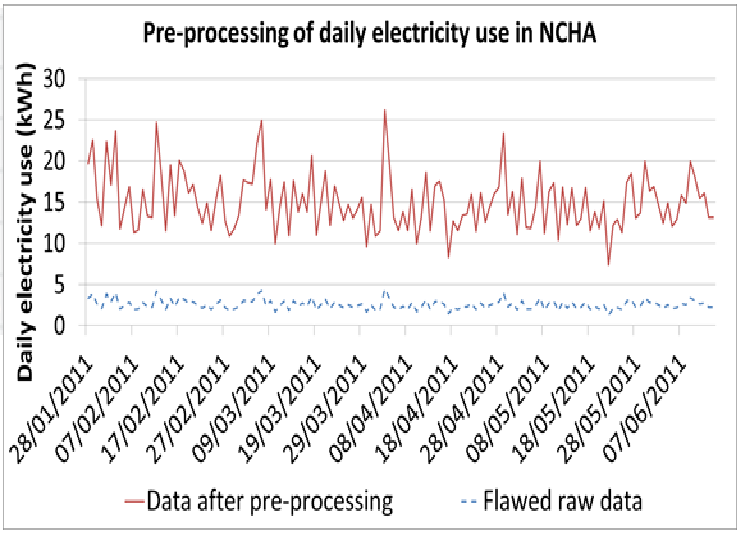


Figure 6-9 Modification of daily electricity measurements in NCHA using the identified coefficient 5.87

Although the modified measurements cannot be validated to the same extent as they were in the case of HHP3, the features of processed daily use fit in the long-term time series of electricity use in NCHA and NCHB as shown in Figure 6-10.

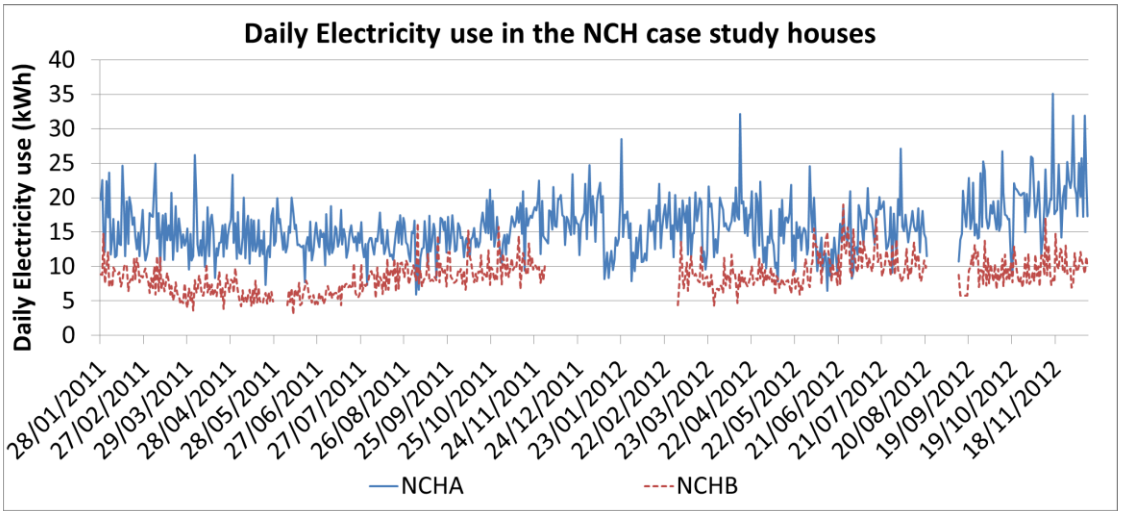


Figure 6-10 Daily electricity use of the NCH case study houses over the monitoring period 28/012011 to 10/12/2012

After the processing, NCHA had more complete data profiles than NCHB. The time period between the final two site visits exceeded the internal memory capacity, which is 90 days for daily records, of Current Cost® devices. Therefore, data loss during the period 22 August 2012 to 11 September 2012 occurred in both houses. Two other instances of data loss occurred in NCHB. The first one over the period 28 May 2011 to 5 June 2011 was caused by the signal blockage of RF communication between the transmitter and receiver units. The second one over the period 2 December 2011 to 1 March 2012 was because of the retrofitted PV microgeneration that distorted house use measurements as previously shown in Figure 5-8 and Figure 5-9 (see Chapter Five). NCHA, which featured intensive energy use activities, had an electricity-use level at least double that of NCHB. The major difference is revealed via micro-scale inspections in Chapter Seven. Electricity was not the only energy source in the NCH case study houses, which used gas-fired space and water heating and partially gas-fired cooking. Therefore, seasonality in the time series of electricity use was not as apparent as that of the HHP case study. The relatively stable status of household profiles and ownership of domestic appliances over the monitoring period explain the stable levels of electricity use.

6.5 Pre-processing of occupancy statuses

Multiple event loggers were comprehensively deployed in the HHP case study to detect residents' presence and motions, light intensity, entry / exit, and door / window statuses. In contrast, the occupancy statuses monitoring in the NCH case study only included the entry / exist detection and the open / closed statuses of two frequently operated windows. The processing procedures discussed in this subsection focus on the HHP monitoring results.

The statuses were logged in real time to capture the actual moment of event occurrence. The raw data were expressed as a series of ones and zeros corresponding to respective timestamps. The frequency of digit alternations and the duration in between were selected as the focus of processing procedures in the compiled Matlab® programmes. If the status alterations occurred at relatively high frequencies, the timestamps and recorded statuses were artificially integrated into the required durations. For example, when the door statuses were frequently swopping between the digits of zero and one, this stood for consecutive entry / exist events via the monitored door. In some circumstances, the information required for activity extraction related to specific events, such as a door remaining open for a period exceeding one hour for the purposes of natural ventilation. The real-time timestamps were first altered to follow the integral time step of one hour. When no status alternation from closed to open occurred in the specific hour, one was assigned to the respective result. If at least one status-swopping event happened within the hour, the respective result was zero. Other information can be similarly extracted, such as the events of doors remaining closed for a time period longer than one day. The processed results in the HHP case study were categorised as follows:

- Windows / doors: open statuses over a duration longer than two minutes or five minutes; closed statuses over a duration longer than one day or two days;

- Pressure doormat: no entry / exit by stamping on the doormat adjacent to the main entrance over a period longer than five minutes or one day;
- PIR motion detection: no motion activities over a duration longer than five minutes or one day;
- Light intensity switch: dim indoor environment over a period longer than one hour or three hours; light indoor environment over a period longer than five minutes or one hour.

The results in the above four categories can be used for the comprehensive extraction of occupancy statuses of the house. For example, the door / window open statuses over a duration exceeding two or five minutes can be used to detect natural ventilation behaviours. The closed statuses over a duration exceeding one day or two days of all monitored doors were fused with the results of pressure doormat and PIR detectors to extract unoccupied statuses of the house. Some long-term unoccupied statuses over holiday periods were identified from such a sensor fusion process. The extracted results should match the recordings of daily electricity use and power profiles. One example is given in Figure 6-11, which is an excerpt from one conference paper prepared by the researcher and her team. Positive correlations were established between the extracted occupancy statuses and daily electricity use. A two-step quick cluster analysis was applied to the daily electricity use over a period of two months. The statistically significant Pearson bivariate correlation attested the impact of occupancy status on actual electricity use.

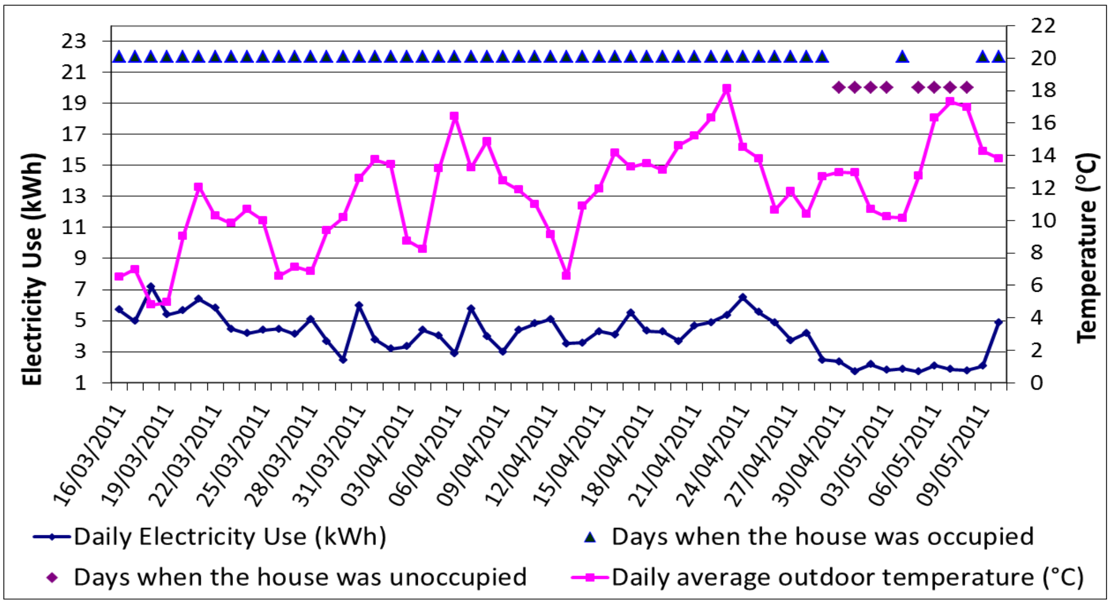


Figure 6-11 Superimposed daily electricity use, outdoor temperature and occupancy status from 16/03/2011 to 10/05/2011 in HHP3

The light intensity switch was applied for a relatively short time period. The unconventional design of the autonomous HHP houses and the 100 per cent low-energy lighting in each home made the indoor environment remained at a relatively dim level for most of the occupancy period. This feature was proven by the processed measuring results of light intensity switch. A positive correlation was discovered between the PV microgeneration and light intensity results. When the PV microgeneration approached the upper limit of generation capacity, the indoor environment was detected to remain light over most of the associated time periods. It indirectly evidenced the effective use of natural light in the HHP design and partially explained the low level of electricity use for lighting activities in the HHP homes.

6.6 Chapter summary

This chapter follows on from Chapters Four and Five that respectively focused on the design and deployment of experimental work. The equipment-inherent and installation-associated factors introduced in the previous two chapters resulted in incomplete or inaccurate field measurements. The pre-processing procedures and tools have been exemplified in this chapter that preludes subsequent analyses in the following chapters. Considering the characteristics of different monitoring categories under various situations, the raw measurements have undergone pre-processing as below:

- Indoor hygrothermal data: synchronisation and sparse-treatment (to be converted to lower frequencies than the actual measurements);
- Outdoor hygrothermal data: the validation against professional measurements of Met Office stations to justify data replacement in data loss occasions and cross-comparison of thermal performance of two case studies;
- Power draw profiles: the alteration of faulty IAM measurements via signal-filtering process and the direct removal of missing data;
- Electricity use data: the identification of approximately linear coefficients to scale up the house use measurements flawed by improperly installed CT clamps; the direct removal of missing data of house electricity use; and the discarding of IAM-measured electricity use.

Some of the pre-processing producers were conducted by the purpose-compiled Matlab® programmes in a semi-automatic approach, since manual examinations of interim results were indispensable in the process of effective data pre-processing.

Chapter 7: Visualisation-based Examinations

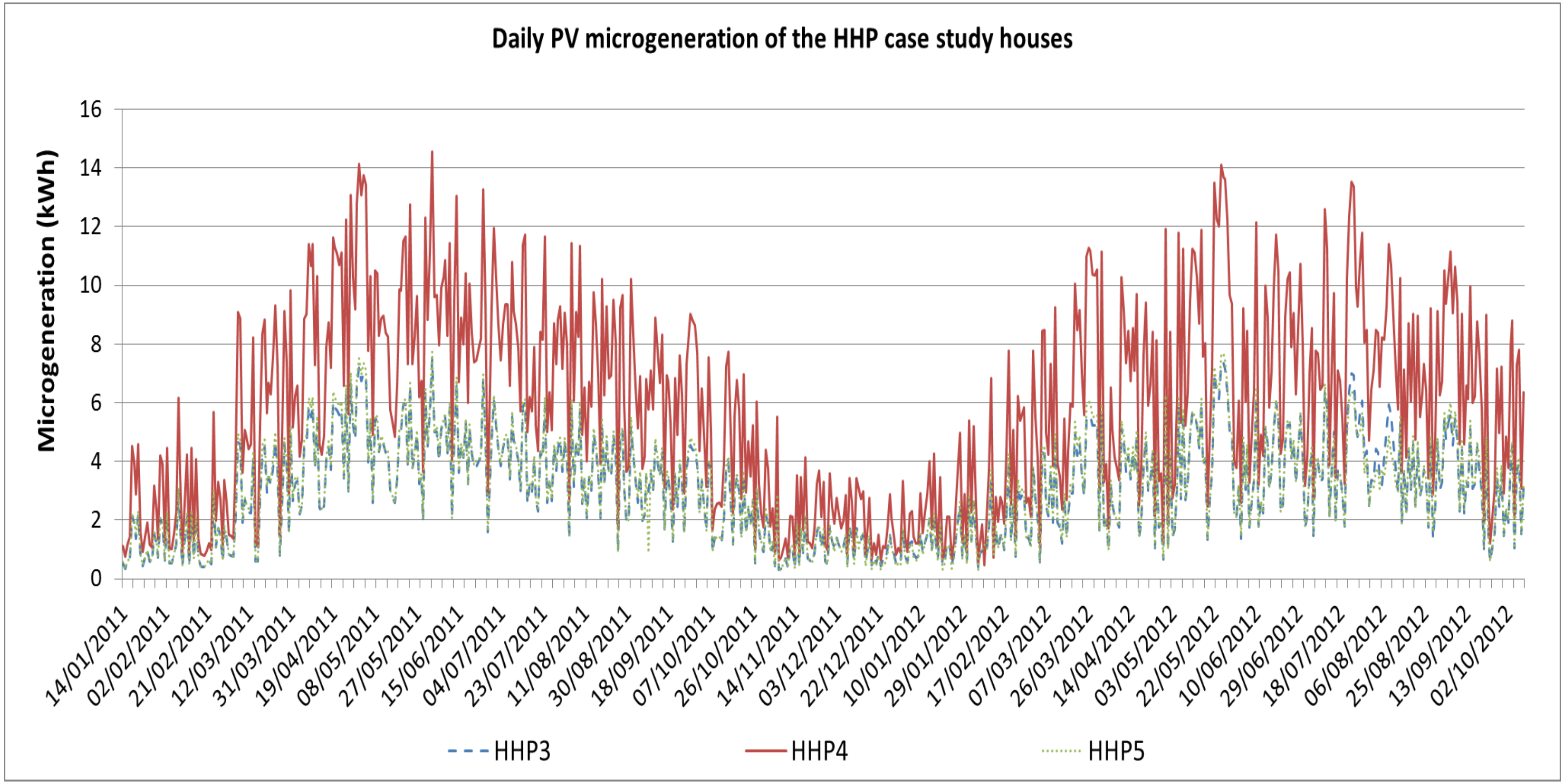
7.1 Introduction

The purpose of data collection and pre-processing discussed in previous chapters is to facilitate appropriate approaches to data presentations and analyses by comprehensively examining the multi-category measurements of each case study. This chapter focuses on the visualisation-based examinations of measurements in each case study to reveal the impact of energy-related occupancy activities. The major data categories are separately examined prior to the comprehensive and micro-scale inspections conducted on measurements of exemplary days that feature special weather conditions and relatively complete data profiles for each case study. More systematic analyses based on visualisation-based examinations are arranged in the next chapter that explores two types of algorithm-based inspection methods.

7.2 HHP case study

7.2.1 House electricity use and PV microgeneration

The pre-processed daily electricity use data of the HHP case study houses was displayed in Figure 6-8 and validated against the HHP bills in Table 6-2 (see Chapter Six). Followed subsequently by the two-occupant HHP4 and single-resident HHP3, the multi-occupant HHP5 had the highest electricity use due to higher demand for hot water, more frequent use of washing machine, and the use of a dishwasher that was only present in HHP5. The trend features were not as obvious as the seasonality characteristics in the time series of daily electricity use due to the consistent household profiles and appliance ownership levels over the monitoring period in three HHP houses. To present a holistic electricity audit, the PV microgeneration on the household scale is demonstrated in Figure 7-1.


Daily PV microgeneration of the HHP case study houses
Microgeneration (kWh)
16
14
12
10
8
6
4
2
0
14/01/2011
02/02/2011
21/02/2011
12/03/2011
31/03/2011
19/04/2011
08/05/2011
27/05/2011
15/06/2011
04/07/2011
23/07/2011
11/08/2011
30/08/2011
18/09/2011
07/10/2011
26/10/2011
14/11/2011
03/12/2011
22/12/2011
10/01/2012
29/01/2012
17/02/2012
07/03/2012
26/03/2012
14/04/2012
03/05/2012
22/05/2012
10/06/2012
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25/08/2012
13/09/2012
02/10/2012
HHP3
HHP4
HHP5

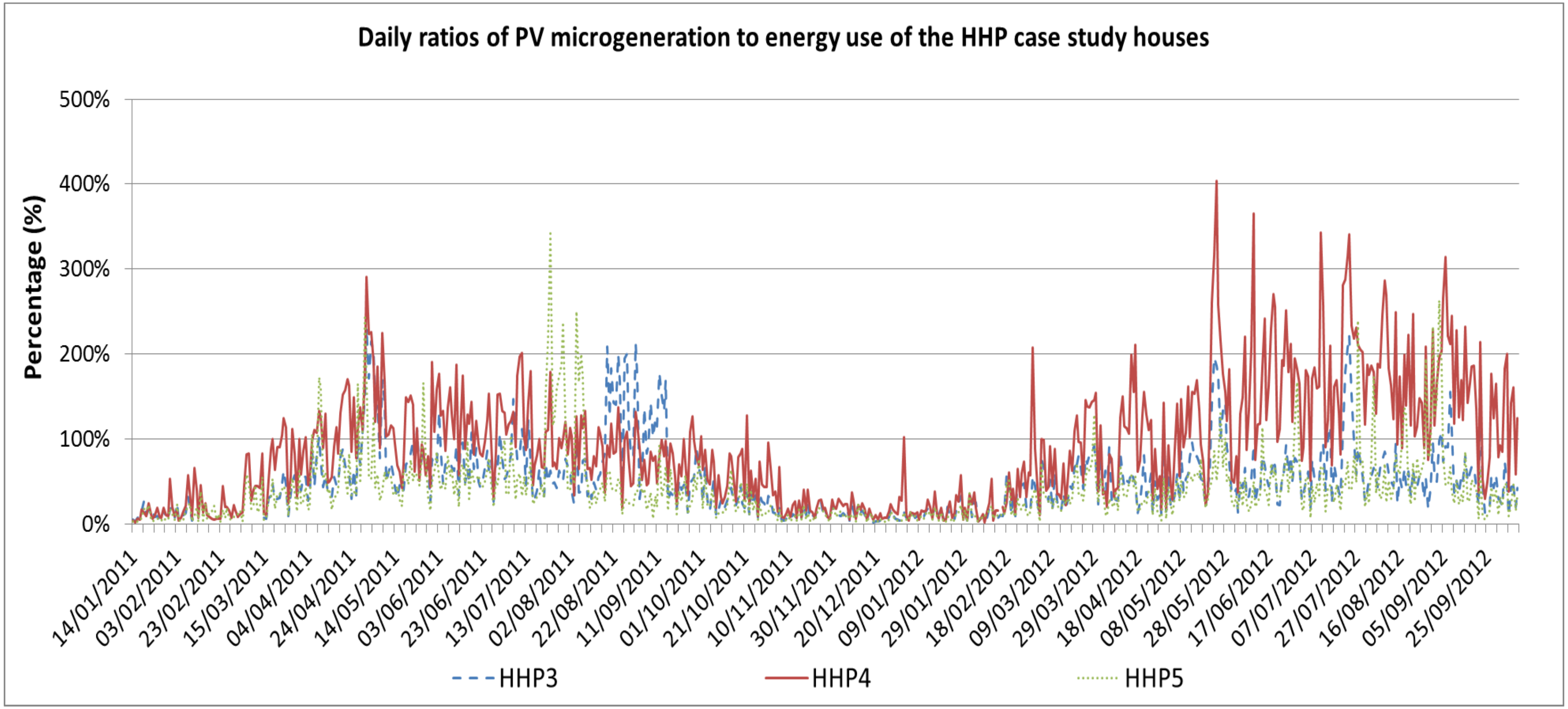


Figure 7-1 Daily PV microgeneration of the HHP case study houses over the monitoring period 14/01/2011 to 09/10/2012

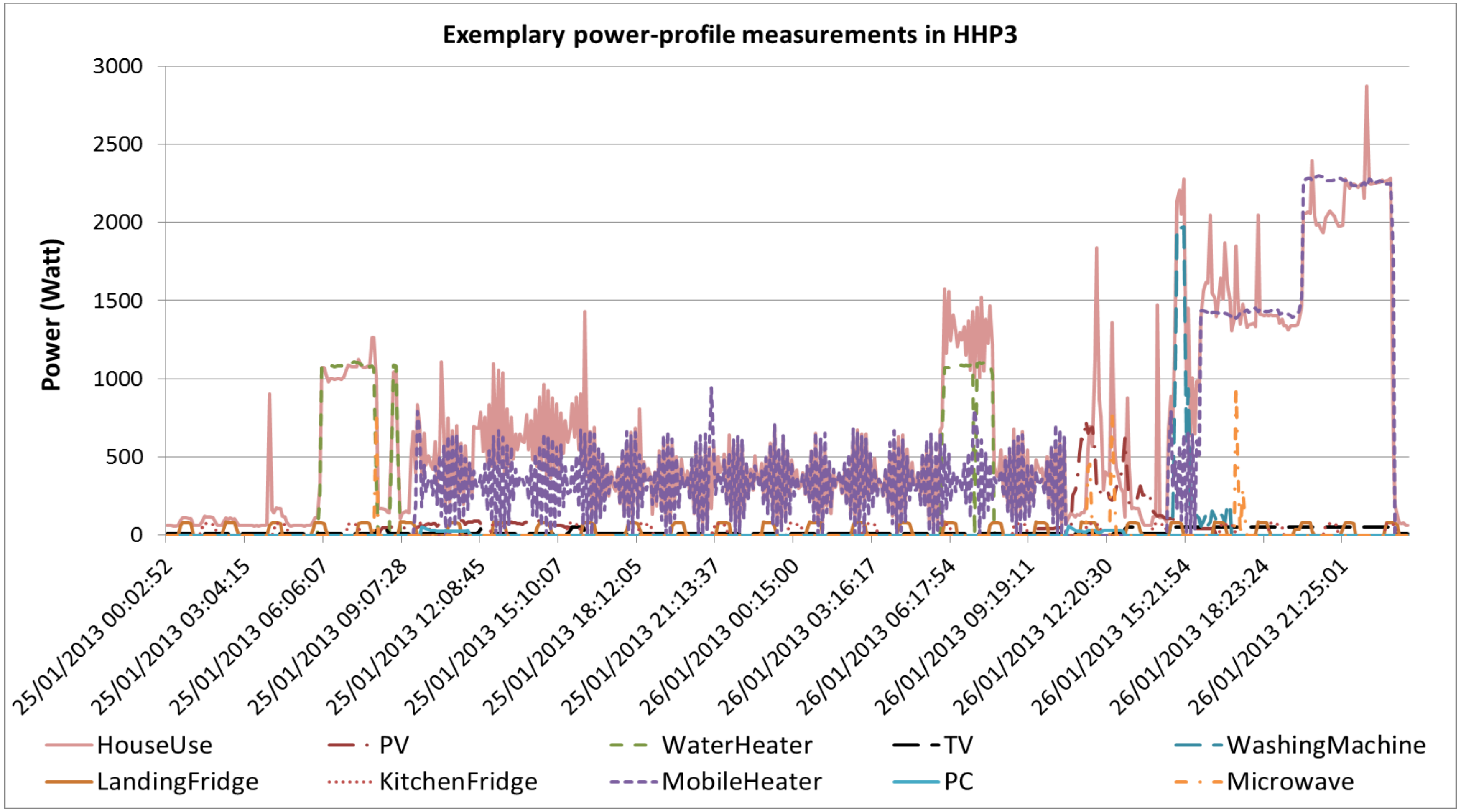
The output cable leaving the PV kWh meter has a downsized diameter compared to the diameter of the mains power cable. The PV microgeneration was thus measured by a Current Cost® mini CT & transmitter unit (12 mm of CT diameter and 98 per cent of accuracy). The mini unit also features stability in RF wireless communication to keep relatively complete measurements compared to the 30 mm CT unit used for house use monitoring. The clutch-mechanism in the design of the CT closure effectively prevents the occurrence of the CT unit aperture opening due to improperly clamped installations, as experienced in two case study houses in this research. Therefore, no extra pre-processing procedures were required for PV microgeneration data.

As validated by the cross-comparison with manual recordings of PV kWh meter, the Current Cost® measurements were larger than the actual microgeneration. Over the time period when no solar radiation was available to stimulate PV microgeneration, the inverter and metering system were sustained by power drawn from the grid. The CT unit, which cannot distinguish current directions, counted the power demand as microgeneration. Accumulating over longer time periods, the discrepancy between measurements and actual microgeneration increased but remained within an acceptable range over the monitoring period. Over the period 15 March 2011 to 09 October 2012, the ratios of measured PV microgeneration to monitored house electricity use in HPP3, HHP4, and HHP5 were 43 per cent, 77 per cent, and 33 percent respectively. The double capacity of PV installation in HHP4 was attested by the two-fold installation capacity in HHP4. High daily ratios of PV microgeneration to electricity use appeared in summer time, a season that features longer and stronger solar radiation and lower energy demand for house use. Higher ratios also emerged when the houses were in the non-occupancy status such as during holiday seasons. Another potential use of microgeneration data was to identify solar radiation conditions in certain days, since solar radiation was not a measurable parameter of the Easy Weather® Station.

7.2.2 Power draw profiles of house use and appliances

Appendices 13, 14, and 15 present the overall processed results of Current Cost® power profiles in the three HHP houses. The gaps in house use graphs represent data loss occasions when Internet peripheral devices were not rebooted in time following the interrupted network service. The gaps in IAM-measured graphs are either due to the IAMs being moved among different appliances or because of the measurements being interrupted by network associated disruption. The PV microgeneration in each house used the first of the 10 IAM channels, among which the first three were more stable than the others. The micro-scale inspection can be conducted on power profiles by enlarging the graphs in Appendices 13, 14, and 15 to various scales, such as the exemplary power profiles over the two winter days in Figure 7-2 when mobile space heaters were used in all three HHP houses.

The incompleteness of IAM-measured power profiles and the irremediable daily energy use of IAM recordings disenabled statistical analyses regarding the operation frequency and total energy use of IAM-monitored appliances over the entire monitoring period. Table 7-1 demonstrates the energy use proportions of major appliance categories within respective daily house use based on the calculation of exemplary power profiles in Figure 7-2. In addition to being used for micro-scale examinations of appliance electricity use and associated proportions in house use, such relatively complete power profiles were mainly used for two other types of presentation and analysis. The extraction of targeted energy use activities using the algorithm-based method will be discussed in Chapter Eight. The cross-comparison against indoor and outdoor hygrothermal parameters is discussed in the following subsections of this chapter.


Exemplary power-profile measurements in HHP3
Power (Watt)
3000
2500
2000
1500
1000
500
0
25/01/2013 00:02:52
25/01/2013 03:04:15
25/01/2013 06:06:07
25/01/2013 09:07:28
25/01/2013 12:08:45
25/01/2013 15:10:07
25/01/2013 18:12:05
25/01/2013 21:13:37
26/01/2013 00:15:00
26/01/2013 03:16:17
26/01/2013 06:17:54
26/01/2013 09:19:11
26/01/2013 12:20:30
26/01/2013 15:21:54
26/01/2013 18:23:24
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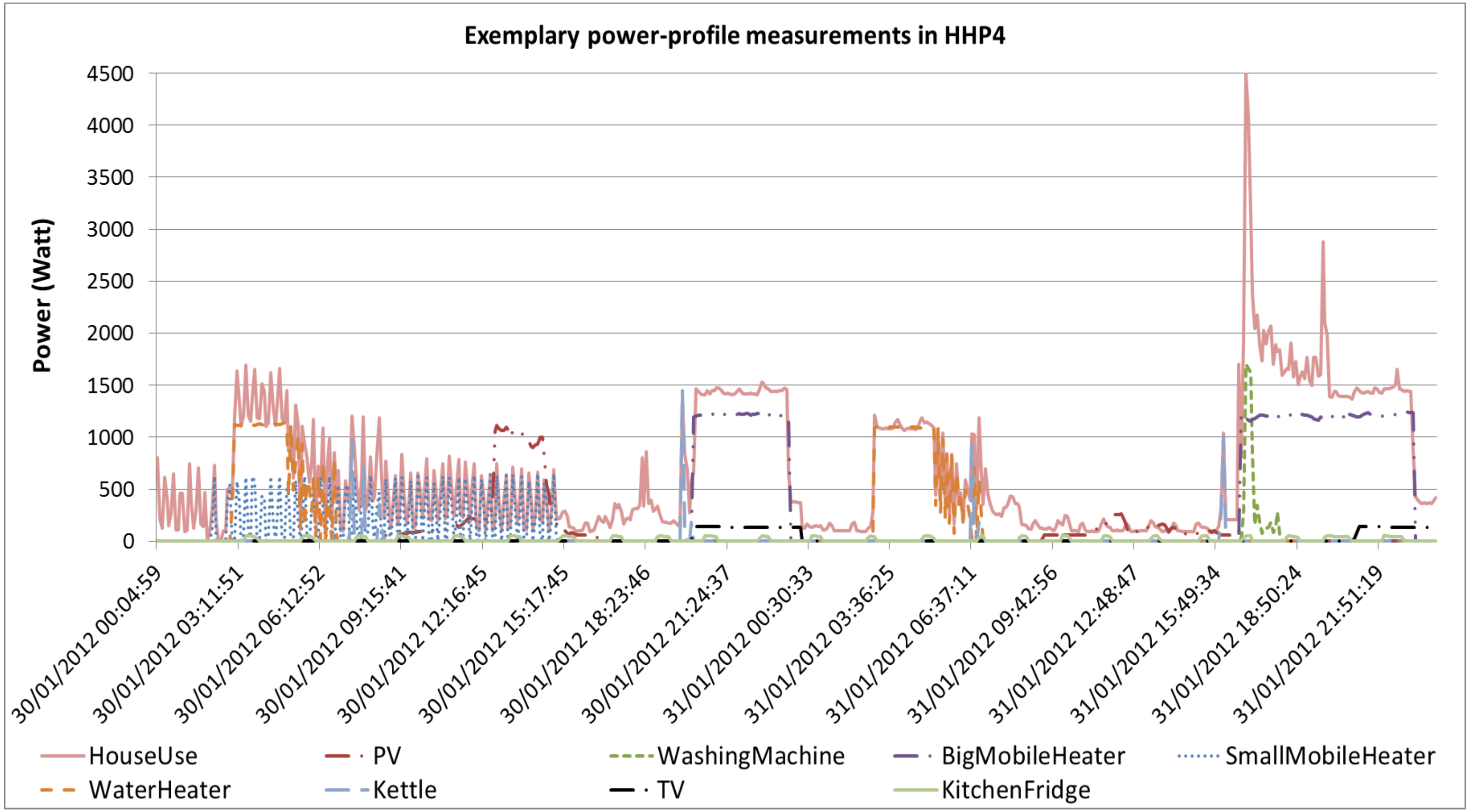
TV
WashingMachine
LandingFridge
KitchenFridge
MobileHeater
PC
Microwave



Exemplary power-profile measurements in HHP4
Power (Watt)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
30/01/2012 00:04:59
30/01/2012 03:11:51
30/01/2012 06:12:52
30/01/2012 09:15:41
30/01/2012 12:16:45
30/01/2012 15:17:45
30/01/2012 18:23:46
30/01/2012 21:24:37
31/01/2012 00:30:33
31/01/2012 03:36:25
31/01/2012 06:37:11
31/01/2012 09:42:56
31/01/2012 12:48:47
31/01/2012 15:49:34
31/01/2012 18:50:24
31/01/2012 21:51:19
HouseUse
PV
WashingMachine
BigMobileHeater
SmallMobileHeater
WaterHeater
Kettle
TV
KitchenFridge

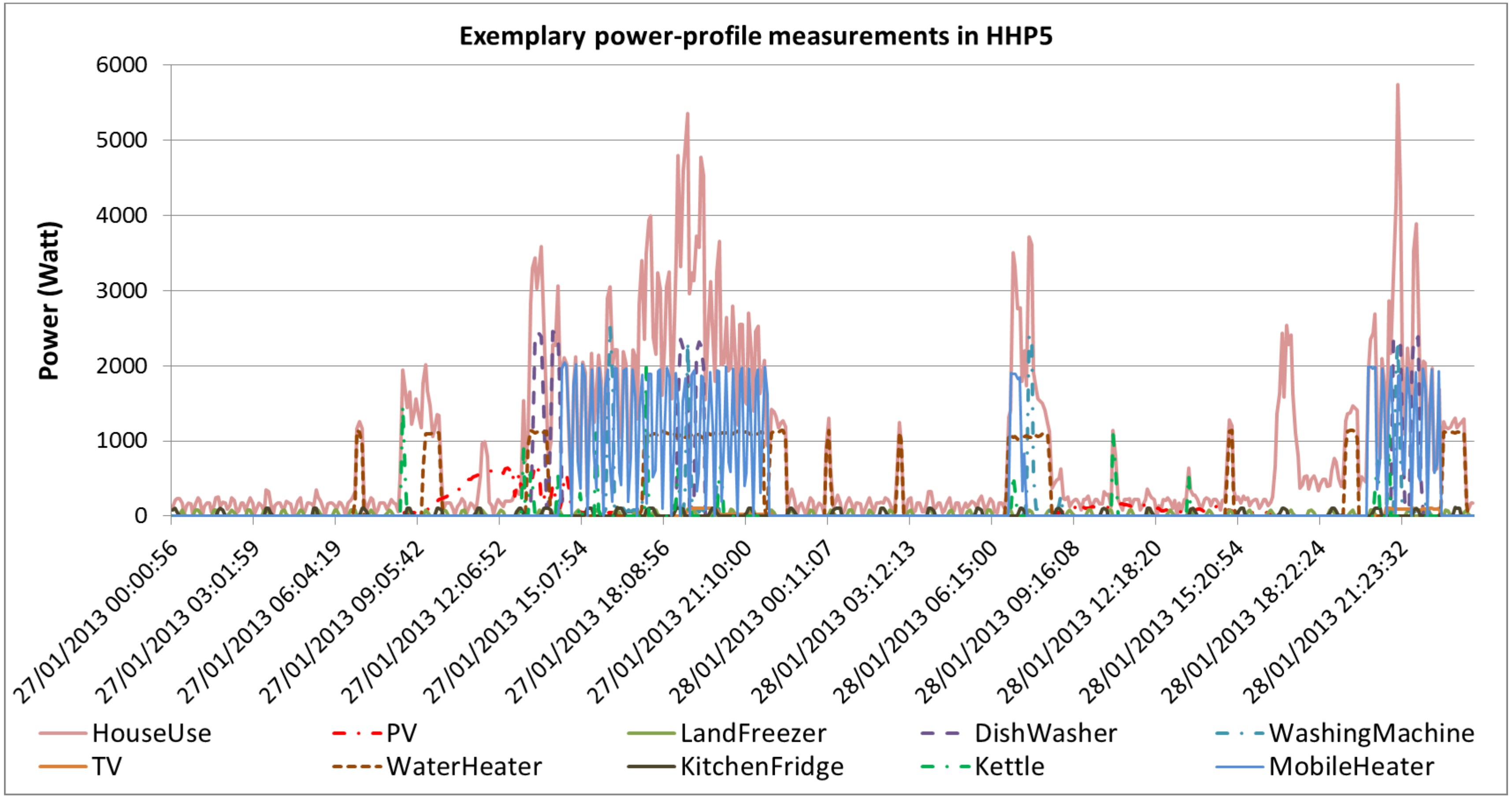


Figure 7-2 The exemplary power-profile measurements in the HHP houses during winter time periods

Table 7-1 HHP electricity use per appliance category and associated proportions of respective house use on the days given in Figure 7-2

House	House use (kWh)	Daily use (kWh) of appliances and the proportions of respective house use						
HHP3		**Cold Appliances**	**TV**	**Water Heater**	**Mobile Heater(s)**	**Washing Machine**	**PC & Internet**	**Other**
	25/01/2013 10.288 kWh	1.396	0.213	2.599	4.922	0	0.306	0.851
		14%	2%	25%	48%	0%	3%	8%
	26/01/2013 21.896 kWh	1.477	0.564	2.046	15.567	1.071	0.314	0.856
		7%	3%	9%	71%	5%	1%	4%
HHP4		**Cold Appliances**	**TV**	**Water Heater**	**Mobile Heater(s)**	**Washing Machine**	**PC & Internet**	**Other**
	30/01/2012 14.925 kWh	0.714	0.508	3.105	7.486	0	0.25	2.862
		5%	3%	21%	50%	0%	2%	19%
	31/01/2012 17 kWh	0.739	0.440	3.217	7.739	0.667	0.25	3.948
		4%	3%	19%	46%	4%	1%	23%
HHP5		**Cold Appliances**	**TV**	**Water Heater**	**Mobile Heater(s)**	**Washing Machine**	**Dish Washer**	**Other**
	27/01/2013 26.491 kWh	0.903	0.168	7.417	9.169	1.451	3.551	4.239
		3%	1%	28%	35%	4%	13%	16%
	28/01/2013 16.975 kWh	0.808	0.191	3.839	4.201	1.088	1.722	5.126
		5%	1%	23%	25%	6%	10%	30%

The home office set, including the computer and Internet peripheral devices, was not directly monitored in HHP5, where the associated IAM channel was used for the measurement of dishwasher use. The operation of cold appliances featured relatively stable electricity use as expected. The three refrigerator and freezer appliances in HHP3 used more cold-load associated electricity compared to HHP4 and HHP5 that each owned two cold appliances. TV was less frequently used in HHP5, which featured relatively low electricity use for this category. The immersion water heater was controlled by thermostat in HHP5 instead of by timers as in HHP3 and HHP4. The water heater power draw patterns for HHP5 were thus not as consistent as those of the other two houses. In line with the occupant numbers, the electricity used by immersion water heaters in the three houses was in the descending order HHP5, HHP4, and HHP3. The same order of electricity use levels was evidenced for the use of washing machine, which was used more frequently by the multi-occupant HHP5. From 18

January 2013 to 1 April 2013, a mobile heater was used for space heating in HHP5 that had not used this type of supplementary heating in the preceding heating seasons. Therefore, the two exemplary daily power profiles of HHP5 were selected from this time period as shown in Figure 7-2. The electricity use by mobile heaters in the three houses counted for the largest proportion of total house use among all types of end-use in winter periods as shown in Table 7-1. Power profiles beyond the winter seasons remained relatively stable for other types of end-use except for the absence of mobile heater use. The end-use included in the ‘other’ category of Table 7-1 refers to electricity use that is not measureable by the plug-in IAMs, such as the electricity used by cooking equipment and artificial lighting. This energy use category in HHP4 and HHP5 featured higher figures and proportions than that in the single-occupant HHP3.

7.2.3 Indoor and outdoor hygrothermal conditions

The raw data of indoor T and RH recordings at the original measuring intervals are presented in Appendices 16, 17, and 18, and the Easy Weather® hygrothermal measurements in Appendix 19. Except for the absence of light intensity measurements prior to the replacement of Tinytag® loggers by Hobo® loggers on 11 February 2011, gaps in the indoor hygrothermal and light intensity measurements correspond to the data missing instances due to either battery failures or the running-out of logger capacity. The official site visit to the HHP case study ended on 10 October 2012, when the loggers were launched for the last time before all monitoring devices were removed on 25 June 2013. The non-volatile internal memory of indoor hygrothermal loggers lasted until 27 April 2013, which was the last day being included in the graphs of Appendices 16, 17, and 18. The volatile internal memory of the Easy Weather® station was used up by 11 December 2012 when the weather data were downloaded by the HHP residents. No effective recordings were conducted over the following winter period by the weather station due to deficient battery conditions. A Tinytag® TGP-4500 was used on 10 October 2012 in the yard of HHP4 as a substitute to the weather station.

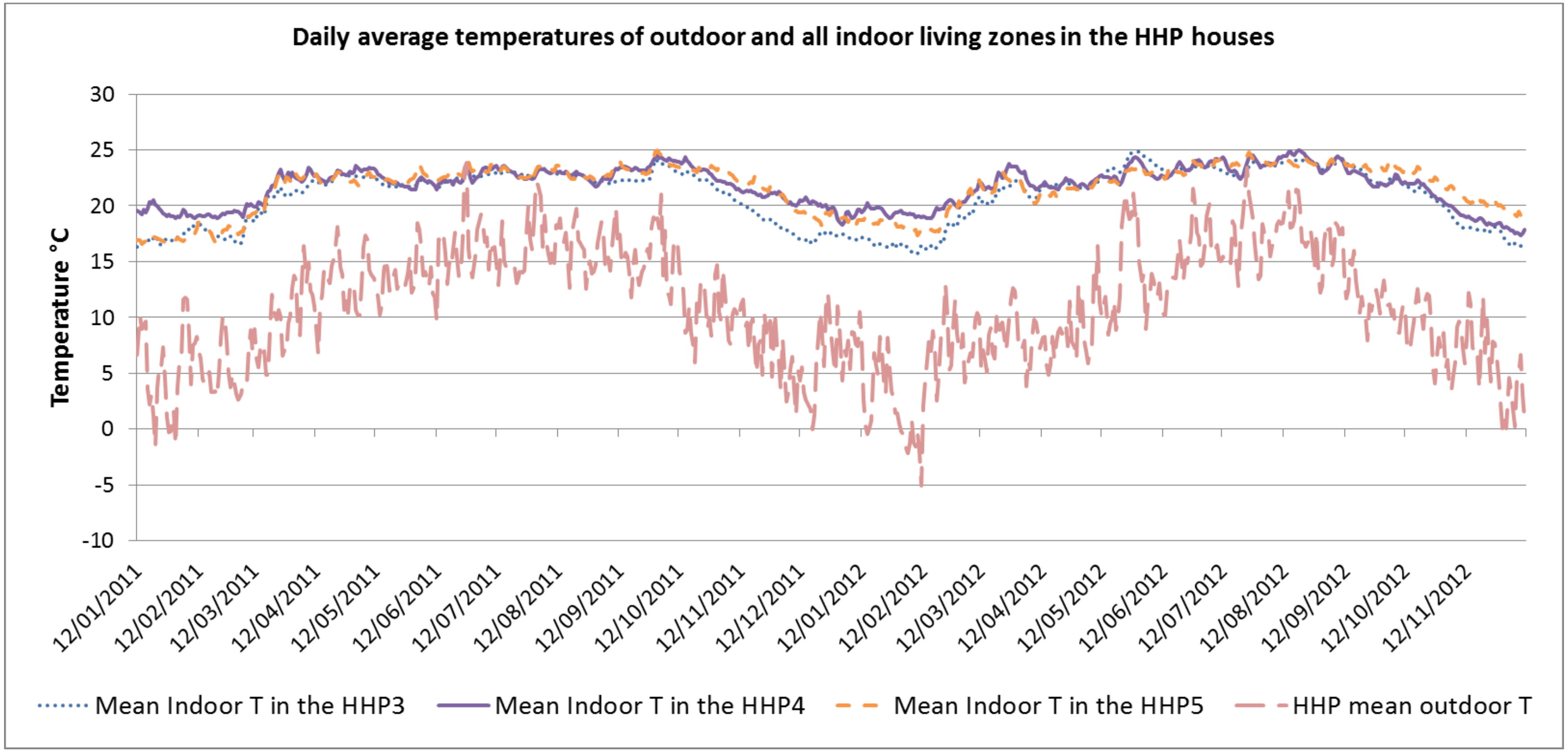
Not designed for the use of weather monitoring, the severely fluctuating RH measurements cannot be used as the substitute for outdoor RH conditions. The temperature recordings from 1 November 2012 until 22 February 2013 were found to be rational, as partially evidenced in Figure 6-2 (see Chapter Six). In general, over the monitoring period from 12 January 2011 to 11 December 2012, the measurements taken in 700 days were relatively complete.

The seasonality characteristics in long-term hygrothermal measurements are clearly visible in the graphs of Appendices 16 to 19. A negative correlation between the T and RH variables in both indoor and outdoor environments is another clearly presented feature. It takes a relatively long time period to store and release heat via the convective heat transfer between the air and heavy-weight thermal mass. The heavy-weight thermal mass of the HHP houses that performed inter-seasonal heat storage and releasing contributed to the relatively stable hygrothermal conditions across all living zones. Over the period of 700 days, the living room temperatures in all three homes remained within the scope of 15 to 25 ºC, if not considering the impact of the adjacent kitchen bay which occasionally experienced higher temperatures than 25 ºC due to cooking events and the frequent-operation of the French door in the kitchen bay. Therefore, no trend features were discovered from the indoor hygrothermal time series.

The hygrothermal measurements in sun space tracked the outdoor recordings over most of monitoring periods. Some unusually high temperature recordings, occasionally above 40 ºC, were caused by the direct hit on sun space loggers by strong solar radiations as evidenced by the simultaneously measured light intensity levels. Some high temperature measurements over relatively long time periods indicated the de-facto ambient hygrothermal conditions in sun space. For example, when the skylight windows in the sun space were kept closed over the unoccupied summer holiday period, the heat trapped in the sun space increased ambient temperatures. The influence exerted in this circumstance on indoor hygrothermal conditions are examined at a micro scale in the next subsection from the perspective of inter-seasonal heat storage and releasing that are featured by the heavy-weight thermal mass of HHP houses.

The daily average temperatures of all monitored zones, except for the sun space, were horizontally averaged across the zones to produce a representative indoor mean temperature. The further-compressed daily average data are presented in Figure 7-3, together with the daily mean values of outdoor hygrothermal conditions. The averaging process was performed by the Matlab® statistical functions that allow analyses to be conducted on the dataset having missing values (flagged as Not a Number) involved. Some features extracted from Figure 7-3 can be used for the subsequent micro-scale examinations on specific daily measurements. For example, the daily average outdoor temperature on 11 February 2012 was discovered to be as low as -5.1 ºC. The average indoor temperature of all three houses approached the lower limit of seasonal variations around 15 ºC. The indoor environment around 11 February 2012 was examined at a micro scale to assess the energy performance of the houses under extreme weather conditions in the context of the British climate. The impact of occupancy activities are co-presented in the micro-scale inspections by cross-comparing against the simultaneously measured power profiles in the next subsection.

The winter seasons between November and March featured distinguishable indoor hygrothermal levels across the three houses because of the difference in energy use related activities, such as the use of mobile heaters and MVHR system. Beyond winter seasons, the indoor T and RH were generally stable at relatively similar levels in all three houses. As revealed in Figure 7-3, the indoor hygrothermal condition of HHP4 featured relatively high T and RH levels in the winter season of 2011 to 2012.


Daily average temperatures of outdoor and all indoor living zones in the HHP houses
Temperature °C
30
25
20
15
10
5
0
-5
-10
12/01/2011
12/02/2011
12/03/2011
12/04/2011
12/05/2011
12/06/2011
12/07/2011
12/08/2011
12/09/2011
12/10/2011
12/11/2011
12/12/2011
12/01/2012
12/02/2012
12/03/2012
12/04/2012
12/05/2012
12/06/2012
12/07/2012
12/08/2012
12/09/2012
12/10/2012
12/11/2012
Mean Indoor T in the HHP3
Mean Indoor T in the HHP4
Mean Indoor T in the HHP5
HHP mean outdoor T

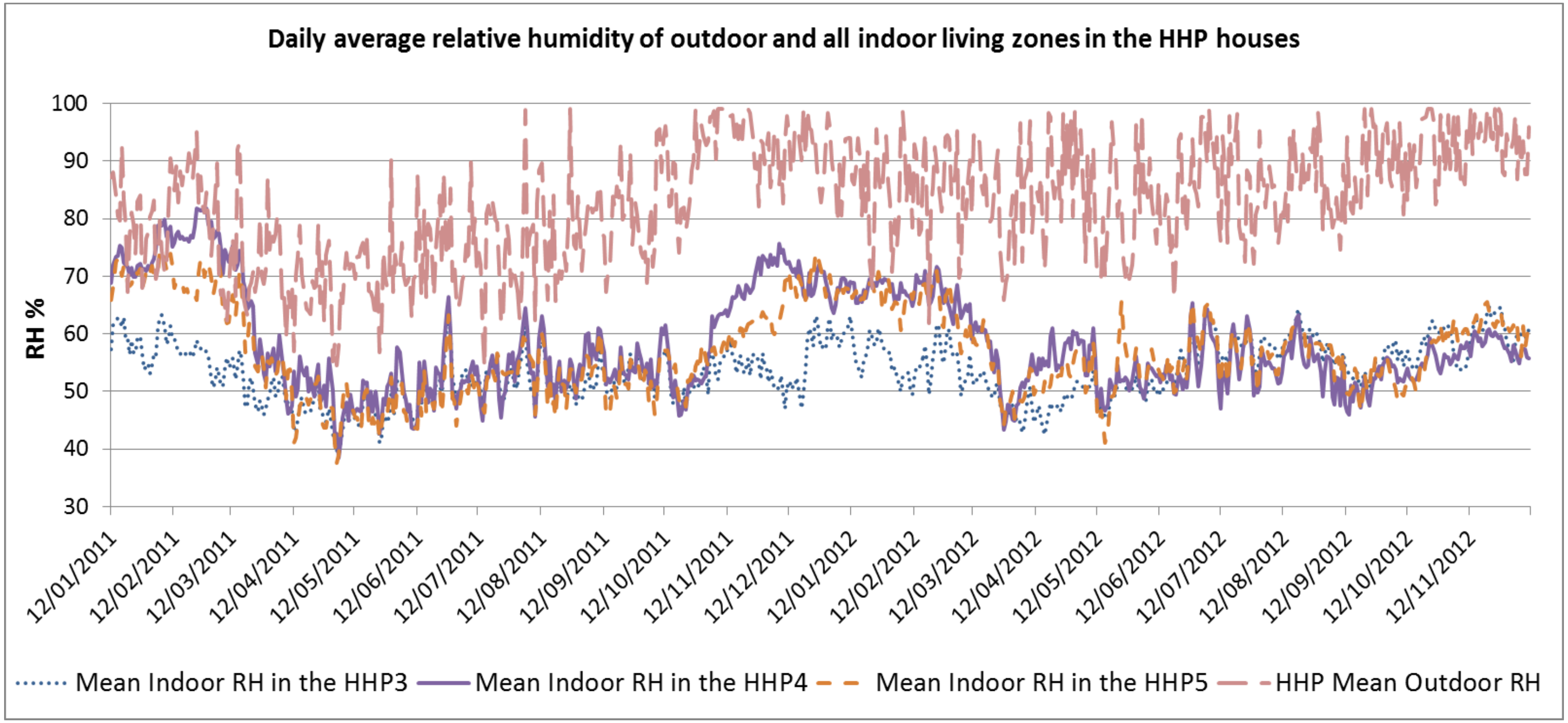
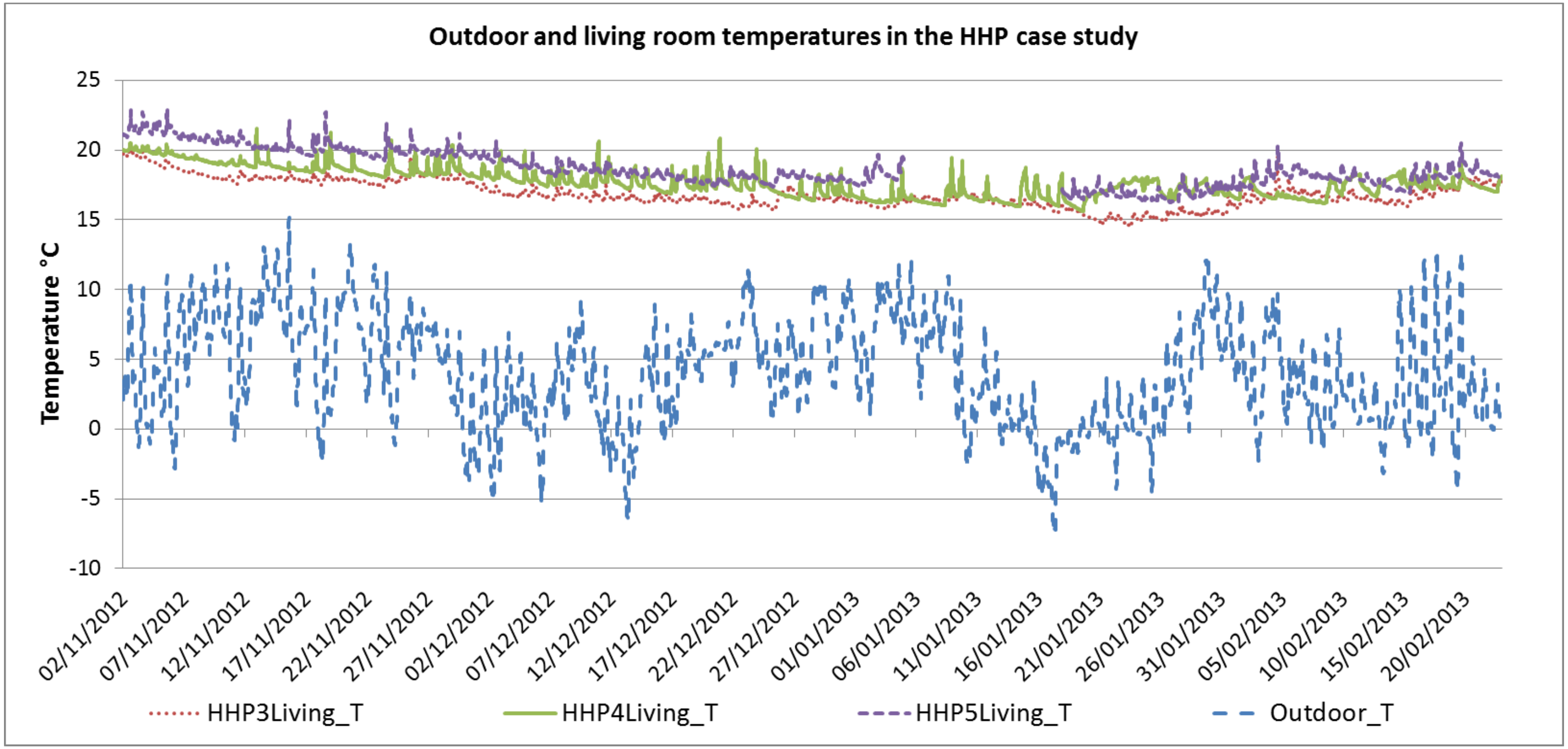


Figure 7-3 Daily average T and RH of outdoor and all indoor living zones in the HHP Houses over the monitoring period 12/01/2011 to 11/12/2012

The cross-checking with monitored power profiles and acquired occupancy information during site visits shows that the aforementioned patterns in HHP4 mainly resulted from the relatively frequent use of mobile heaters and clothes-drying adjacent to the heaters. One resident in the house preferred not to operate the MVHR system as frequently as the other two households due to her sensitiveness concerning the noise level of the system. The accumulated water contents in the air increased the RH levels although the ambient temperature levels in HHP4 were also higher than those in the other two houses. More frequent use of mobile heaters in HHP4 was demonstrated in the Current Cost® power profiles provided in Appendix 14 over the winter period 2012 to 2013, when only outdoor temperatures were rationally measured by the Tinytag® TGP-4500, as shown in Figure 7-4. The living room temperatures rather than the averaged indoor temperatures across monitored living zones were used for superimposition with the Tinytag®-measured outdoor temperatures because the measurements in some living zones taken during the final monitoring period after 10 October 2012 were not complete. The household profile in HHP4 had changed from a two-occupant to single-resident home since the summer of 2012. Consequently, the hygrothermal condition patterns relating to occupancy habits in the winter season of 2011 to 2012 changed in that of 2012 to 2013. For example, the more frequently operated MVHR system in HHP4 changed the RH levels from the highest to the lowest among the three houses. HHP5 started to use a mobile heater in the winter of 2012 to 2013 as evidenced in the power profiles provided in Appendix 15. The change in space heating activities made the indoor temperatures in HHP5 higher than those in the other two houses. The power draw profiles were not available in the winter season of 2010 to 2011, when the monitoring scheme was initially deployed in the HHP case study as shown in Table 5-3 (see Chapter Five), to produce valid cross-checking information for hygrothermal measurements. Therefore, the measurements in certain days of the following two heating seasons of 2011 to 2012 and 2012 to 2013 were selected to perform the micro-scale examinations that are presented in the next subsection.


Outdoor and living room temperatures in the HHP case study
Temperature °C
25
20
15
10
5
0
-5
-10
02/11/2012
07/11/2012
12/11/2012
17/11/2012
22/11/2012
27/11/2012
02/12/2012
07/12/2012
12/12/2012
17/12/2012
22/12/2012
27/12/2012
01/01/2013
06/01/2013
11/01/2013
16/01/2013
21/01/2013
26/01/2013
31/01/2013
05/02/2013
10/02/2013
15/02/2013
20/02/2013
HHP3Living_T
HHP4Living_T
HHP5Living_T
Outdoor_T

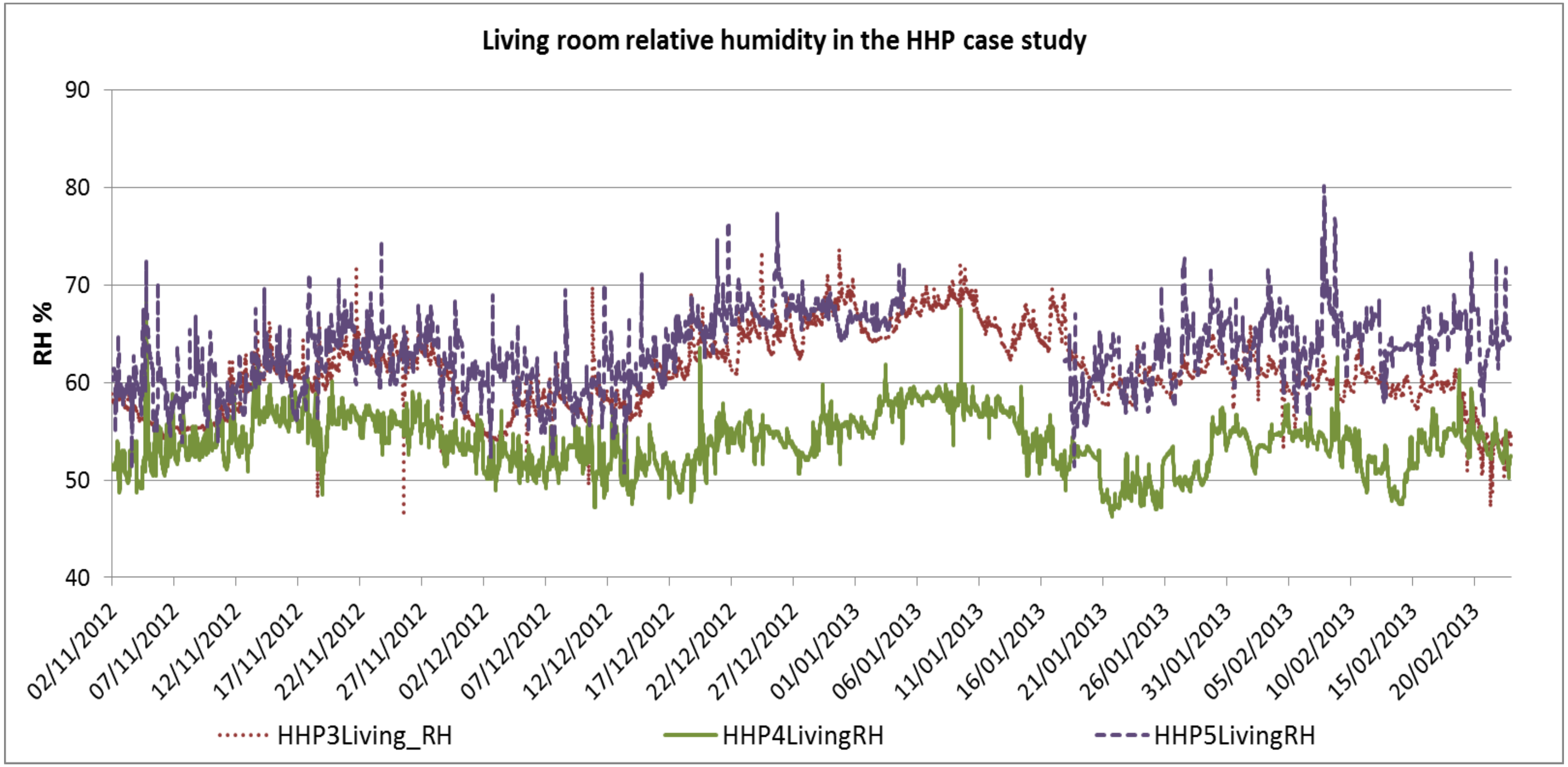


Figure 7-4 Tinytag®-measured outdoor temperatures and T and RH of living room in the HHP Houses over the last monitored winter period 02/11/2012 to 22/02/2013

7.2.4 Micro-scale examinations on the HHP data

Three aspects of micro-scale investigations are conducted in this subsection based on the overall measurements of energy use, power draws, and indoor and outdoor hygrothermal conditions displayed in the previous subsections. Each of the following aspects is examined by cross-comparing the multi-category data on a daily scale:

- The impact of direct solar radiations on sun space hygrothermal measurements;
- The influence of high temperatures caused by accumulative heat over sunny summer periods in the sun space on indoor living areas; and the effectiveness of natural ventilation measures;
- The building energy performance and the impact of occupancy behaviours on indoor environment and energy use against cold weather backdrop.

When sun space loggers were installed in the three HHP houses, the probable influence of direct solar radiations was not fully considered until 10 June 2011, when the loggers were moved to relatively shaded areas. The changes in measured light-intensity levels from over 30,000 Lux to below 5,000 Lux are reflected in the sun space measurements presented in Appendices 16, 17, and 18. Two sets of comparable daily data in summer sunny days prior to and after the relocation of sun space loggers are presented in Figure 7-5. The solar microgeneration in the previous Figure 7-1 shows that both days featured high-level PV microgeneration approximating the peak capacity of solar panels. The highest outdoor temperature measured on 3 June 2011 and 23 July 2012 approached 30 ºC, although the actual peak temperatures were approximately 5.0 ºC lower if considering the impact of direct solar radiations on the less-professional weather case of the Easy Weather® station.

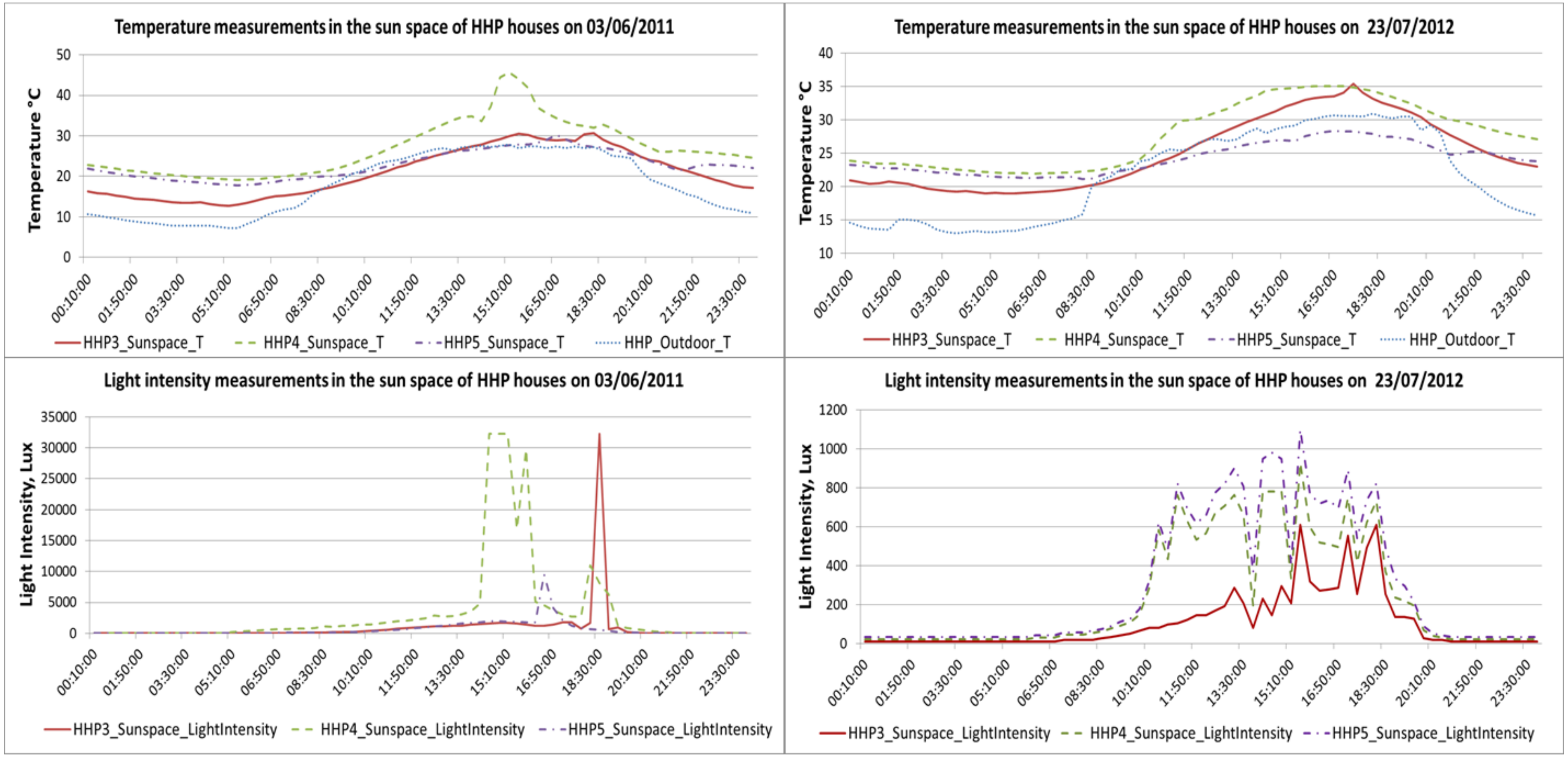


Figure 7-5 Impact of direct solar radiations on the HHP sun space hygrothermal measurements

The impact of solar radiations on sun space temperature measurements on 3 June 2011 were the most obvious in HHP4, where light intensity levels around 30,000 Lux had been recorded by the Hobo® sun space logger for over three hours. As a result, a temperature as high as 45 ºC was recorded by the HHP4 sun space logger. The strong solar radiations that hit the HHP3 and HHP5 loggers lasted for shorter time periods and resulted in similar measurements tracking the outdoor temperature measured by the Easy Weather® station. The relocation of sun space loggers made the sun space temperature measurements less influenced by direct solar radiations and more associated with occupancy statuses and natural ventilation activities as shown in Figure 7-6 and Figure 7-7.

All three HHP houses were occupied on 3 June 2011, as evidenced by the processed occupancy-status data. Among monitored doors and windows, the French door in kitchen bay was the most frequently operated door for purposes of ventilation or entry / exit in each of the three houses. The associated door statuses are co-presented in Figure 7-6, which examines the impact of accumulative heat in sun space on indoor temperatures. The digit zero stands for an open status and one for a closed state for monitored doors. Except for showering events that were featured by short-term temperature variations in the shower room, no other occupancy-related activities had any visible impact on the temperature conditions in the shower room (and an extra bathroom in the seven-bay HHP3) at the rear of the houses. The temperatures in the living room and kitchen that are facing sun space were largely influenced by natural ventilation activities, as featured by the use of French doors and windows in each bay.

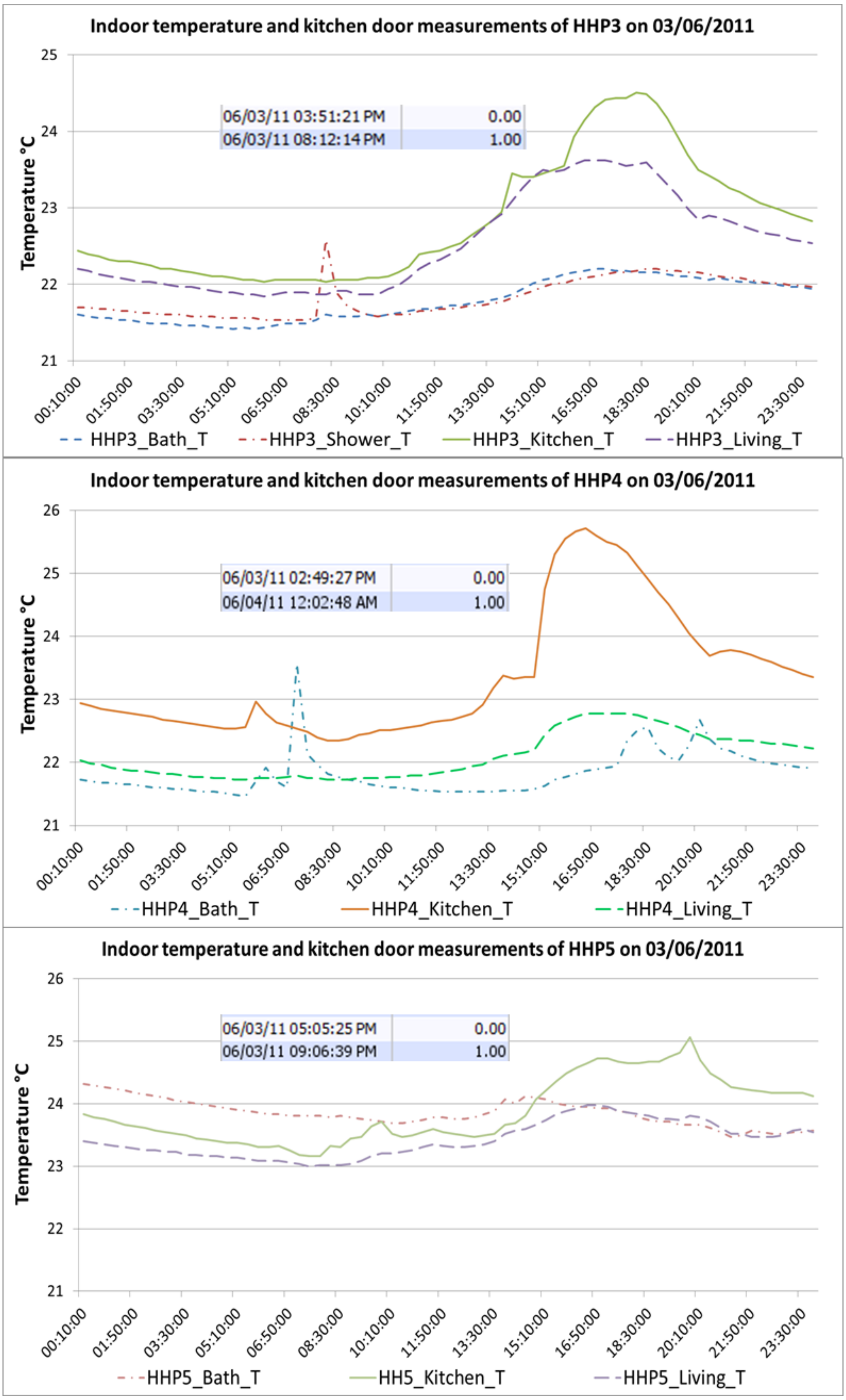


Figure 7-6 Impacts of accumulative heat in the HHP sun space and associated natural ventilation measures on the indoor temperatures on 03/06/2011

The actual time of door operations shown in Figure 7-6 is related to the starting and ending time points and the amplitude of associated temperature variations. The lengths of time periods over which the kitchen doors remained open are directly associated with the time lengths of temperature variations. For example, the kitchen door in HHP4 was open from 14:49:27 when the sun space had the highest temperatures and levels of accumulative heat. If taking the sun space measurements in HHP3 and HHP5 as approximate temperatures in the HHP4 sun space to remove the influence of direct solar radiations as shown in the previous Figure 7-5, the actual temperatures in the HHP4 sun space were approaching 30 ºC around 15:00:00. As a result, the associated changes in kitchen temperatures started around 15:00:00 with the increased temperature amplitude approaching 26 ºC in the HHP4 kitchen. Similar patterns existed in the living room that openly connects with the kitchen. The HHP4 kitchen door remained open until midnight when the diurnal heat storage and releasing facilitated by the heavy-weight thermal mass caused another round of temperature increase with smaller amplitude during the evening and night-time of 3 June 2011. The kitchen doors in HHP3 and HHP5 were closed earlier and caused no extra temperature variations over the same time period. Figure 7-7 presents the similar indoor temperature variations and operations of associated doors on 23 July 2012, one year after the influence of direct solar radiations on sun space loggers was removed by relocating the associated loggers.

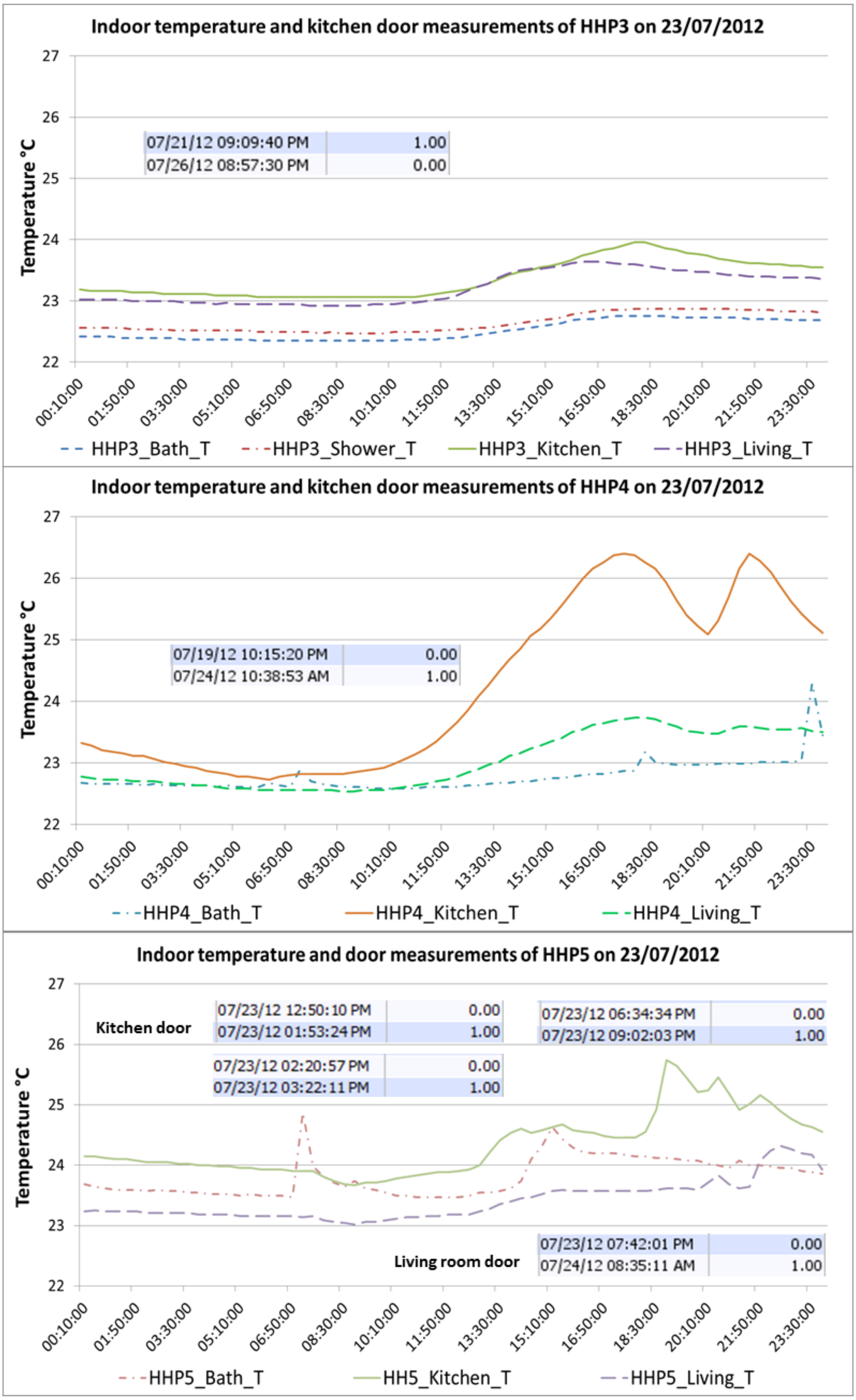


Figure 7-7 Impacts of accumulative heat in the HHP sun space and associated natural ventilation measures on the indoor temperatures on 23/07/2012

The measurements of occupancy statuses and power draw profiles show that HHP3 was not occupied on 23 July 2012. For example, the HHP3 kitchen door was not operated over this time period, as shown in Figure 7-7. The skylights in the sun space and sun space windows facing outdoors remained slightly open although all French doors and windows between the sun space and indoor zones were closed when the HHP3 resident was away. Therefore, the indoor temperatures across all indoor living zones, especially the shower room and bathroom areas at the rear of the house, remained relatively stable. The HHP4 kitchen door remained slightly open from 19 July 2012 until 24 July 2012 as demonstrated in Figure 7-7. The accumulative heat in the sun space directly influenced the indoor temperatures through the open kitchen door. In addition, skylights in the HHP4 sun space were not operated as frequently as in the other two households, which had relatively low temperatures in both living zones and sun space. The three time periods when the HHP5 kitchen door remained open for a period longer than one hour are presented in Figure 7-7. Each door-opening event corresponded to variations in kitchen temperatures. The living room French door remained open overnight in HHP5, which experienced another increased variation in living room temperatures due to the diurnal heat storage and releasing enabled by the heavy-weight thermal mass.

The sun space was designed to effectively create hygrothermal gradients between indoor and outdoor environments to assist in maintaining stable and comfort indoor conditions in various weather situations. To examine the post-occupancy performance of the autonomous HHP houses in heating seasons, a relatively cold day that features complete data profiles of different monitoring categories for all three houses was selected. The outdoor measurements show that 11 Febuary 2012 featured the lowest daily average outdoor temperature at -5.1 ºC and the lowest measured temperature at -14.4 ºC over the entire period of 700 days that have relatively complete Easy Weather® recordings. In general, the temperatures in the sun space tracked outdoor conditions as shown in Figure 7-8. The daytime measurements were influenced by various factors, such as the occasionally direct solar radiations on loggers and occupancy-related activities. The night-time reordings in each house were approximiately identical. The heat storage in heavy-weight thermal mass successfully maintained sun space tempatures at the level of 3.9 to 4.6 ºC over the cold dawn period. The temperature difference at the level of 17.3 to 18.3 ºC in this circumstance is a very evidential feature for the energy performance of free-running autonomous HHP houses.

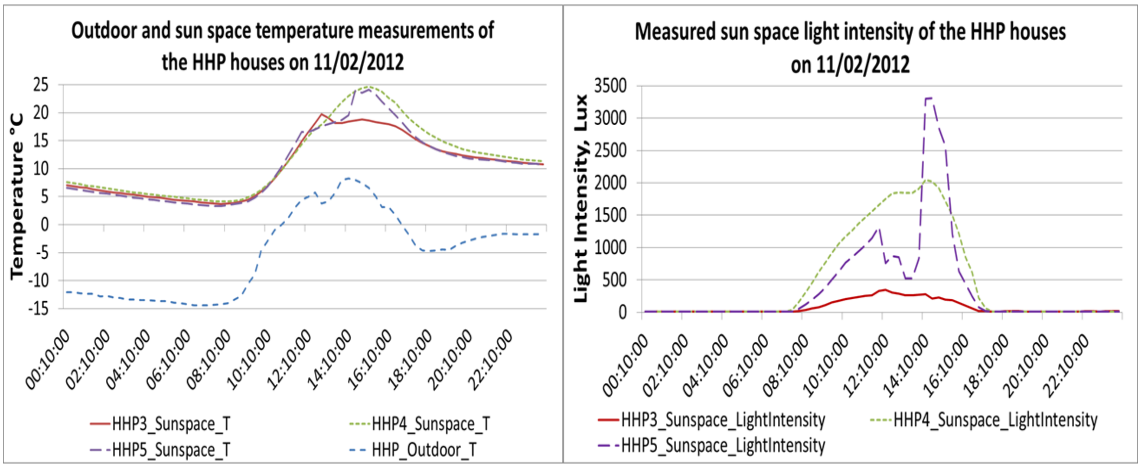
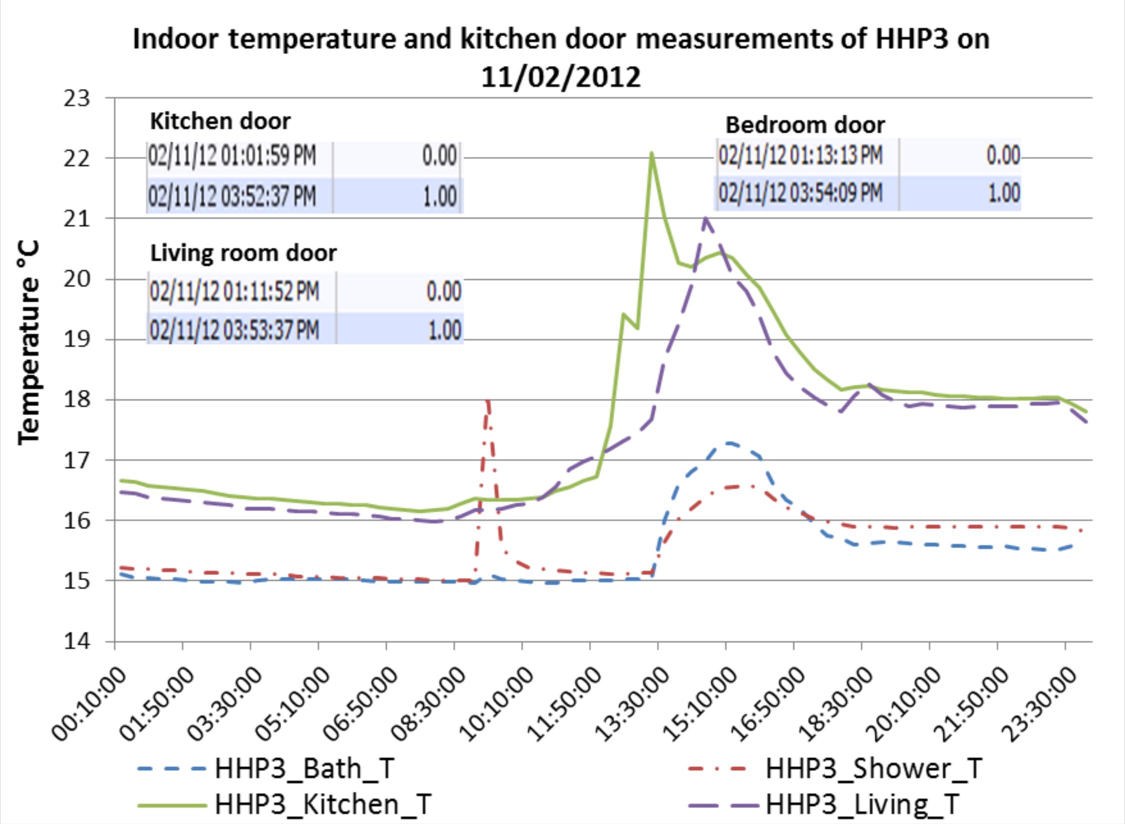
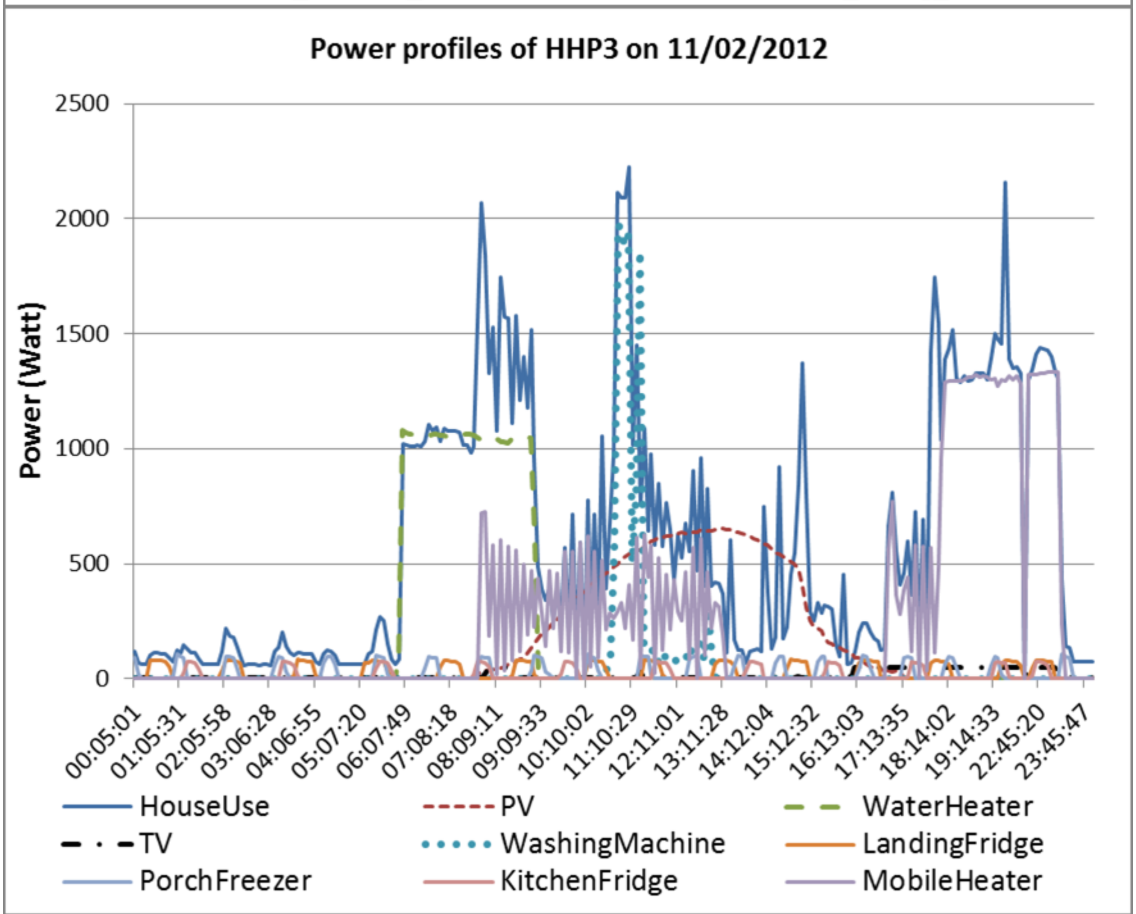
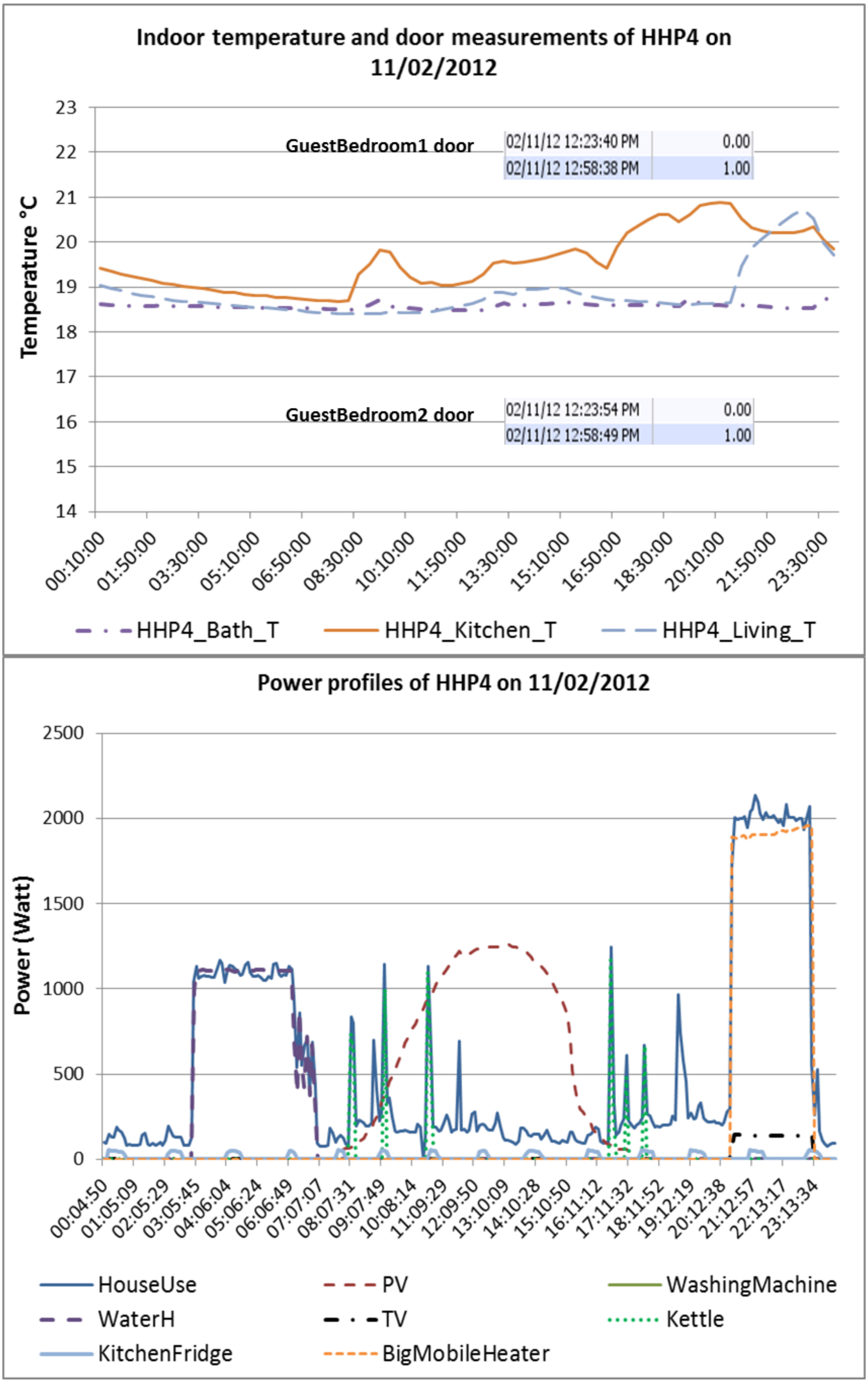


Figure 7-8 Hygrothermal and light intensity measurements in the HHP sun space on 11/02/2012

The pre-processed power profiles for 11 Febuary 2012 are co-presented with the indoor temperature measurements of each house in Figure 7-9. The PV power profiles attested that it was a cold but very sunny day on the HHP site on 11 Febuary 2012. The passive solar heating during the daylight period made the temperatures in the sun space of every house at least 10 ºC higher than the simultaneous outdoor conditions, if using the recordings in the HHP3 sun space that were not influenced by direct solar radiations as a reference. The influence of accumulated heat in the sun space on indoor conditions were examined together with measurments of power profiles and associated door use.


Indoor temperature and kitchen door measurements of HHP3 on 11/02/2012
Kitchen door
02/11/12 01:01:59 PM 0.00
02/11/12 03:52:37 PM 1.00
Living room door
02/11/12 01:11:52 PM 0.00
02/11/12 03:53:37 PM 1.00
Bedroom door
02/11/12 01:13:13 PM 0.00
02/11/12 03:54:09 PM 1.00
Temperature °C
23
22
21
20
19
18
17
16
15
14
00:10:00
01:50:00
03:30:00
05:10:00
06:50:00
08:30:00
10:10:00
11:50:00
13:30:00
15:10:00
16:50:00
18:30:00
20:10:00
21:50:00
23:30:00
HHP3_Bath_T
HHP3_Shower_T
HHP3_Kitchen_T
HHP3_Living_T


Power profiles of HHP3 on 11/02/2012
Power (Watt)
2500
2000
1500
1000
500
0
00:05:01
01:05:31
02:05:58
03:06:28
04:06:55
05:07:20
06:07:49
07:08:18
08:09:11
09:09:33
10:10:02
11:10:29
12:11:01
13:11:28
14:12:04
15:12:32
16:13:03
17:13:35
18:14:02
19:14:33
22:45:20
23:45:47
HouseUse
PV
WaterHeater
TV
WashingMachine
LandingFridge
PorchFreezer
KitchenFridge
MobileHeater


Indoor temperature and door measurements of HHP4 on 11/02/2012
Temperature °C
GuestBedroom1 door
02/11/12 12:23:40 PM 0.00
02/11/12 12:58:38 PM 1.00
GuestBedroom2 door
02/11/12 12:23:54 PM 0.00
02/11/12 12:58:49 PM 1.00
23 22 21 20 19 18 17 16 15 14
00:10:00 01:50:00 03:30:00 05:10:00 06:50:00 08:30:00 10:10:00 11:50:00 13:30:00 15:10:00 16:50:00 18:30:00 20:10:00 21:50:00 23:30:00
HHP4_Bath_T
HHP4_Kitchen_T
HHP4_Living_T
Power profiles of HHP4 on 11/02/2012
Power (Watt)
2500 2000 1500 1000 500 0
00:04:50 01:05:09 02:05:29 03:05:45 04:06:04 05:06:24 06:06:49 07:07:07 08:07:31 09:07:49 10:08:14 11:09:29 12:09:50 13:10:09 14:10:28 15:10:50 16:11:12 17:11:32 18:11:52 19:12:19 20:12:38 21:12:57 22:13:17 23:13:34
HouseUse
PV
WashingMachine
WaterH
TV
Kettle
KitchenFridge
BigMobileHeater

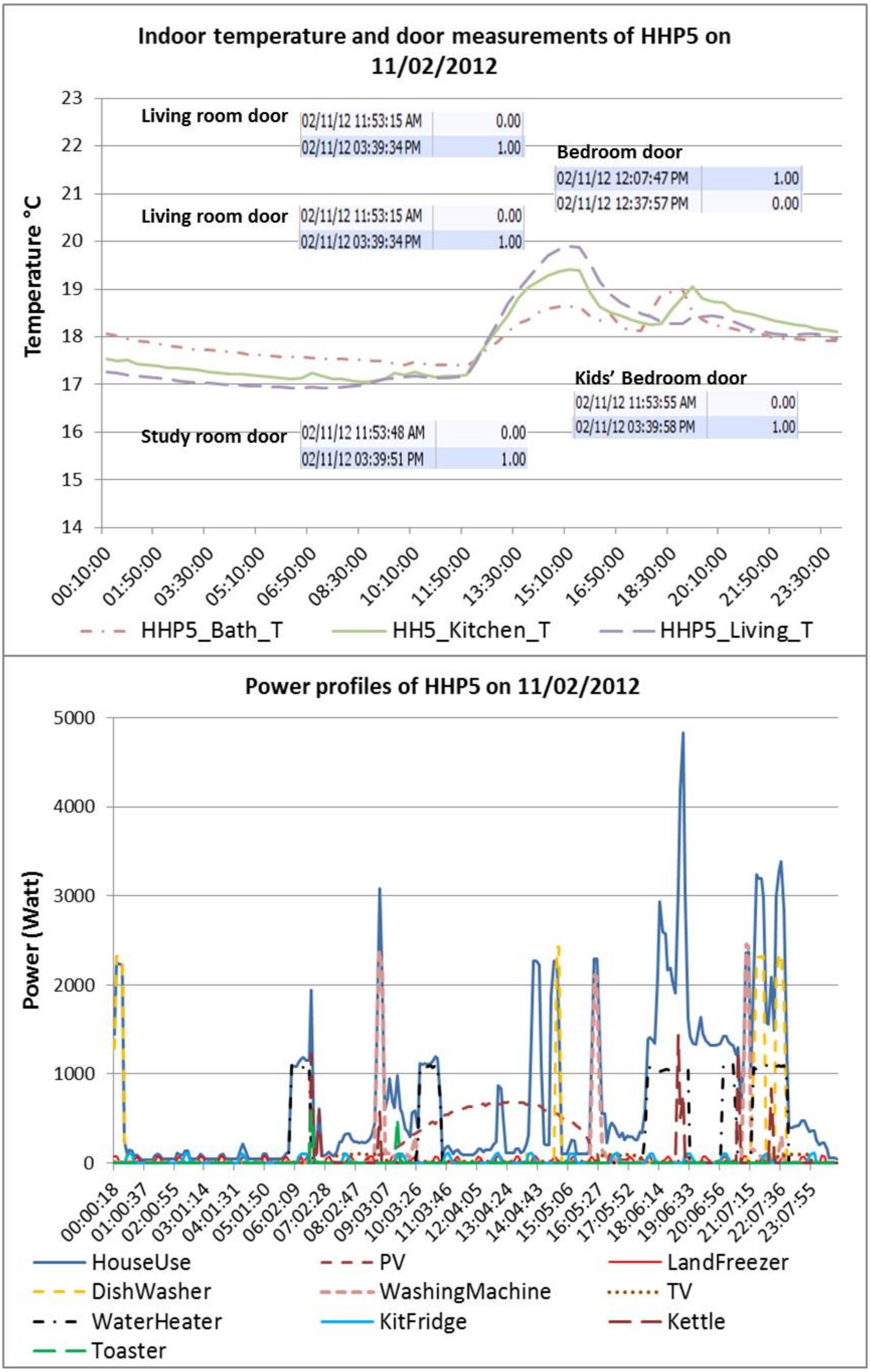


Figure 7-9 Effects of the HHP sun space and the usage of natural ventilation and mobile heater on indoor temperatures on 11/02/2012

The single-occupant and seven-bay HHP3 house is one bay larger than the other two families' homes. Figure 7-9 shows that HHP3 had the lowest indoor temperatures among the three houses although the mobile heater was in use, with a thermostat-controlled mode during the daytime period and a continously heating mode in the evening and night time, during the most non-sleeping hours. The centralised heating using a mobile heater made the temperature gradient across different living zones of HHP3 the largest among the three houses. Three French doors in the kitchen, living room, and main bedroom were open for almost three hours when the sun space temperature was approaching 20 ºC. The heat transfer was reflected in the temperature increase across all indoor zones.

The double-resident HHP4 had two mobile heaters in use, one small and one big as previously shown in Figure 7-2, although only the big heater was used on 11 Feburary 2012 during the occupied evening time. The heater use quickly increased the living room temperature. The temperatures in the adjacent kitchen area were more associated with cooking events that were reflected in the house use power profile since the use of cooking hobs is not IAM-measurable. The doors in the two guest bedroom areas were open for around half an hour and thus had less impact on the indoor environment than was the case in HHP3. Another factor that contributed to the relatively stable temperature across all living areas in HHP4 is that the resident preferred the use of flax-textured curtains on all French doors and windows during winter time. The use of curtain partially explained the relatively high levels of RH measured in the winter season of 2011-2012 as shown in the previous Figure 7-3. The indoor temperatures across all living zones in HHP4, including the daytime hours when the heater was not being used, was the highest among the three houses. HHP4 is positioned in the centre of the three monitored HHP houses and has one bay less than HHP3. Therefore, the nearly 5 ºC difference in indoor temperatures on 11 February

2012 between HHP3 and HHP4 can be explained by multiple factors, including occupant numbers, house size and location, and the use of mobile heaters.

HHP5 had a thermostat-controlled towel rail to warm the bathroom for the daily baths of two young children in winter seasons. No mobile heaters were used in the house until the heating season of 2012 to 2013 as shown in the previous Figure 7-2. Therefore, the indoor temperatures of HHP5 on 11 February 2012 were stable and similar across all living zones. Similar to HHP3, the passive solar heating increased the indoor temperatures when the French doors remained open for over three hours. The cooking and bathing events also increased the temperatures although to a small extent. Unlike the other two houses, the immersion water heater in the HHP5 Hotsi® tank was controlled by thermostat rather than timer. The evening bath event was recognisable from the increased indoor temperatures and the IAM-measured water heater power profiles shown in Figure 7-9.

In this subsection, micro-scale examinations were conducted on the hygrothermal conditions in the indoor, outdoor and buffer zone areas, five-minute power profiles, and occupancy status measurements to assess building performance in the hot and cold weather situations. The occupancy statuses and ventilation behaviours had a visible impact on the indoor environment and energy use as shown in the examination processes. In sunny summer time, the French doors and windows were closed for most of the time periods to maintain a cooler indoor environment. In sunny winter time, the French doors and windows were open over the noon time period to utilise passive solar heating. The weather conditions of exemplary days selected for the examinations featured either highest or lowest outdoor temperatures over the monitoring period. The thermal performance of the autonomous HHP houses was discovered to be closely associated with the diurnal and inter-seasonal heat storage and releasing of the heavy-weight thermal mass. The electricity use of mobile heater and immersion water heater accounted for the greatest proportion of daily house energy use ranging 10 to 27 kWh as shown in Table 7-1. Outside of heating seasons, the daily house use would drop to 5 to 15 kWh due to the removal of electricity use by mobile heaters. Without mains gas on site, these kWh ranges have been for the total energy use if not considering the extra PV microgeneration. The discussion in Chapter Nine is set to compare the thermal performance and energy use of the HHP houses with the retrofitted timber-frame social houses of the NCH case study, on which macro-scale and micro-scale examinations are conducted in the next subsection.

7.3 NCH case study

7.3.1 House energy use and microgeneration

The two NCH case study homes were served by both natural gas and electricity. Gas was used for the space and water heating. All cooking utilities, including the hobs and oven / grill, in NCHA were gas fired. Electric oven / grill and gas-fired hobs were used in NCHB. The gas and electricity utility meter readings were manually recorded during each monthly site visit. The average daily use and the calculated ratios of NCHA and NCHB are presented in Figure 7-10. The gas use in imperial units was converted to kWh using the equation given by the utility supplier[20] of NCH homes.

The daily electricity use in NCHA was twice that of NCHB on average due to the difference in ownership and usage of domestic appliances. Seasonal variations in electricity use were associated with the length of space heating periods. Boiler pumping system power loads around 200 watts had a cumulative effect on the integrated electricity use during heating seasons. The second peak of electricity use in NCHB in July 2012 was caused by the more frequent use of the electric shower by multiple visitors. Compared with the relatively stable level of electricity use, the average daily gas consumption in both houses had clear seasonal variations.

[20] Gas use in kWh = imperial units x 2.83 x 3 9.3 x1.20064 + 3.6

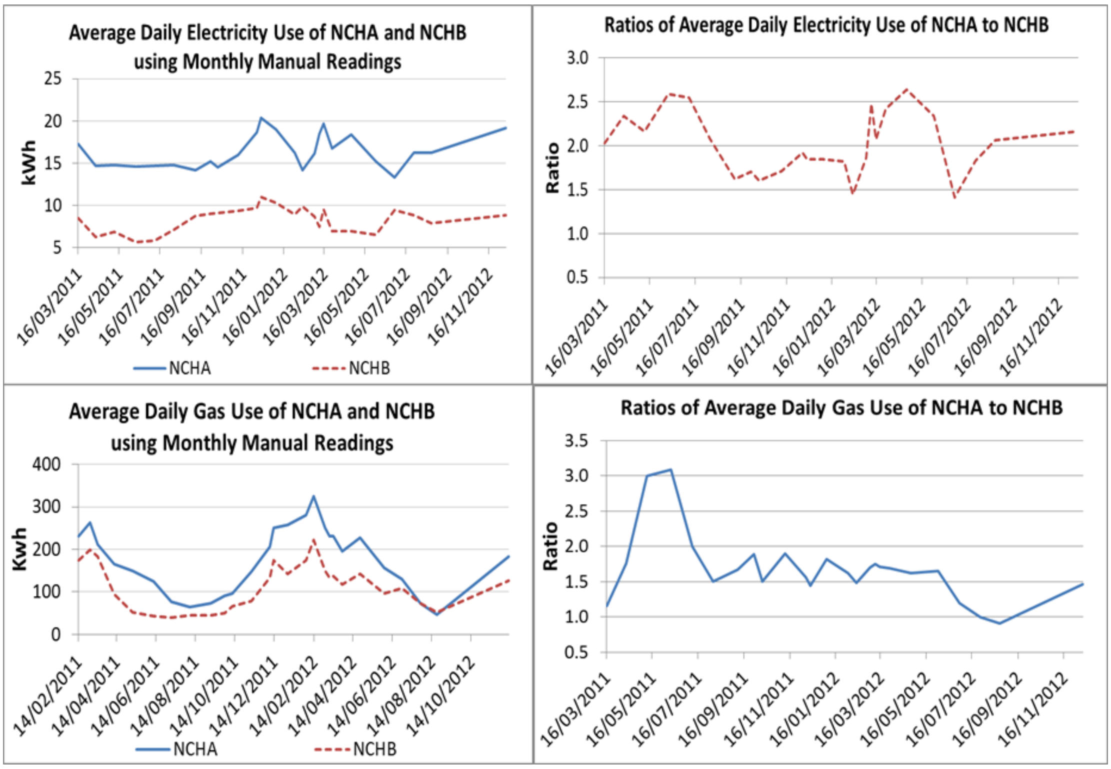


Figure 7-10 Average daily energy use and ratios of NCHA and NCHB using manual meter readings over the period 14/02/2011 to 11/12/2012

The partial heating systems in NCHA and NCHB were respectively upgraded in March 2011 after the start of monitoring and January in 2011 prior to the start of monitoring as part of the Secure, Warm, Modern (SWM) programme of Nottingham City Homes. NCHB gradually stopped using the post-retrofitted system for space heating from early March 2011. In contrast, NCHA used the pre-retrofitted system till March 2011 and continued with the use of space heating after the retrofit program over the entire summer season in 2011 until the next summer period in 2012. The prolonged use of space heating was out of concern for the health and medical condition of one resident in NCHA. As a result, the ratio of gas use of NCHA to NCHB was as high as over 3.0 in May and June 2011 when NCHA continued with the use of space heating. For most of the time periods during heating seasons, the ratios of gas use fluctuated within a relatively stable range of 1.4 to 2.0 since the residents of the two homes kept their heating use and ventilation habits unchanged prior to and after the upgrade programme. The ratio figure dropped to around 1.0 from late May 2012 when NCHA finally stopped gas use for space heating, using it only for cooking and occasional water heating. The ratio approached 1.5 once again when the heating season of 2012 started. The gas-fired cooking in NCHA and partially gas-fired cooking in NCHB made some difference in the gas use. However, compared to the major gas use for water and space heating, gas consumed for cooking activities influenced the gas use ratio between the two homes to a very limited extent. This is attested by the relatively stable ratios over heating seasons and the ratio around 1.0 when no space heating was used in either home.

The pre-processed daily electricity measurements of NCHA and NCHB were displayed in Figure 6-10 (see Chapter Six). To present a holistic picture of electricity use and PV microgeneration in NCHB, the Current Cost® measurements over the time period 2 March 2012 to 10 December 2012 when the PV microgeneration was successfully separated from the house electricity use are presented in Figure 7-11. The measurement gap was caused by the limited internal memory capacity of Current Cost® devices between the last official site visit on 22 August 2012 and the final visit to collect the monitoring devices on 11 December 2012. Prior to the measurement gap, the total microgeneration accounts for 60 percent of the total house use; after the gap, 31 per cent.

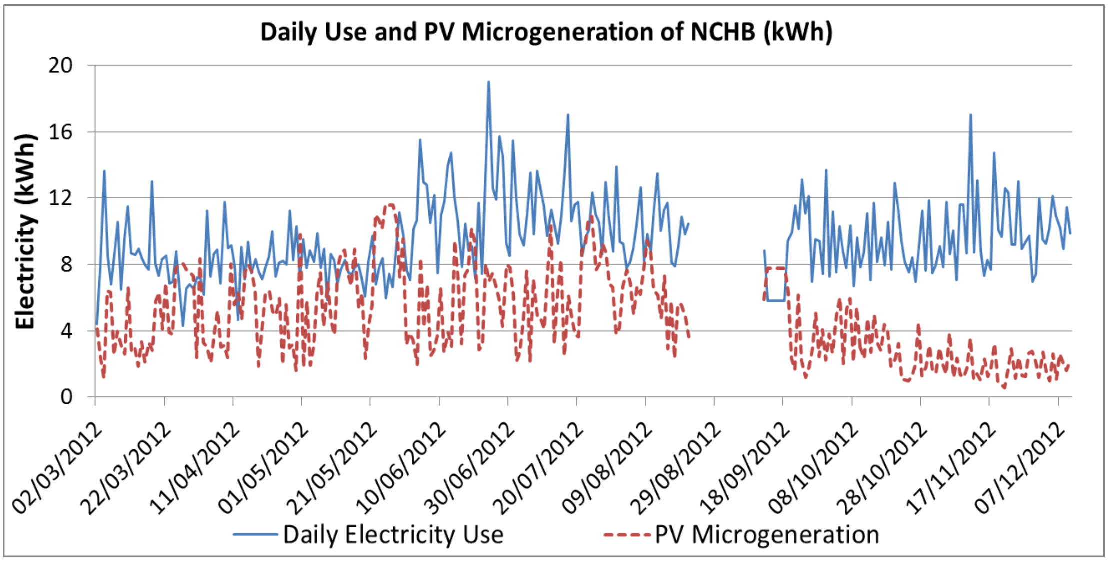


Figure 7-11 Measurements of daily electricity use and PV microgeneration of NCHB over the period 02/03/2012 to 10/12/2012

The manually recorded gas use was taken monthly or half-monthly (in certain months) although the weather parameters were monitored at 10-minute intervals for most of the monitoring periods. Therefore, no sufficient gas use recordings were available to facilitate the Heating Degree Days (HDD) analysis to a similar extent as in pilot study B, where weekly or bi-weekly gas use had been manually logged since the year 2010. Instead, daily average outdoor temperatures of the NCH site were used to calculate the HDDs by applying four baseline temperatures of 15.5 ºC, 18 ºC, 19 ºC and 20 ºC. The calculated HDDs were then integrated over each monthly or half-monthly period that had manually recorded gas meter readings. The integrated HDDs and the associated meter readings were used to establish linear regressions as shown in Figure 7-12. The best-fit regression among the four scenarios for NCHA is at the temperature of 20 ºC. The R^2 of the HHD linear regressions for NCHB cannot improve as much as that of NCHA when the temperature scenario moves from the best-fit temperature 18 ºC to 20 ºC. This result is consistent with NCHA’s relatively long space heating period when the outdoor average daily temperature is below 20 ºC.

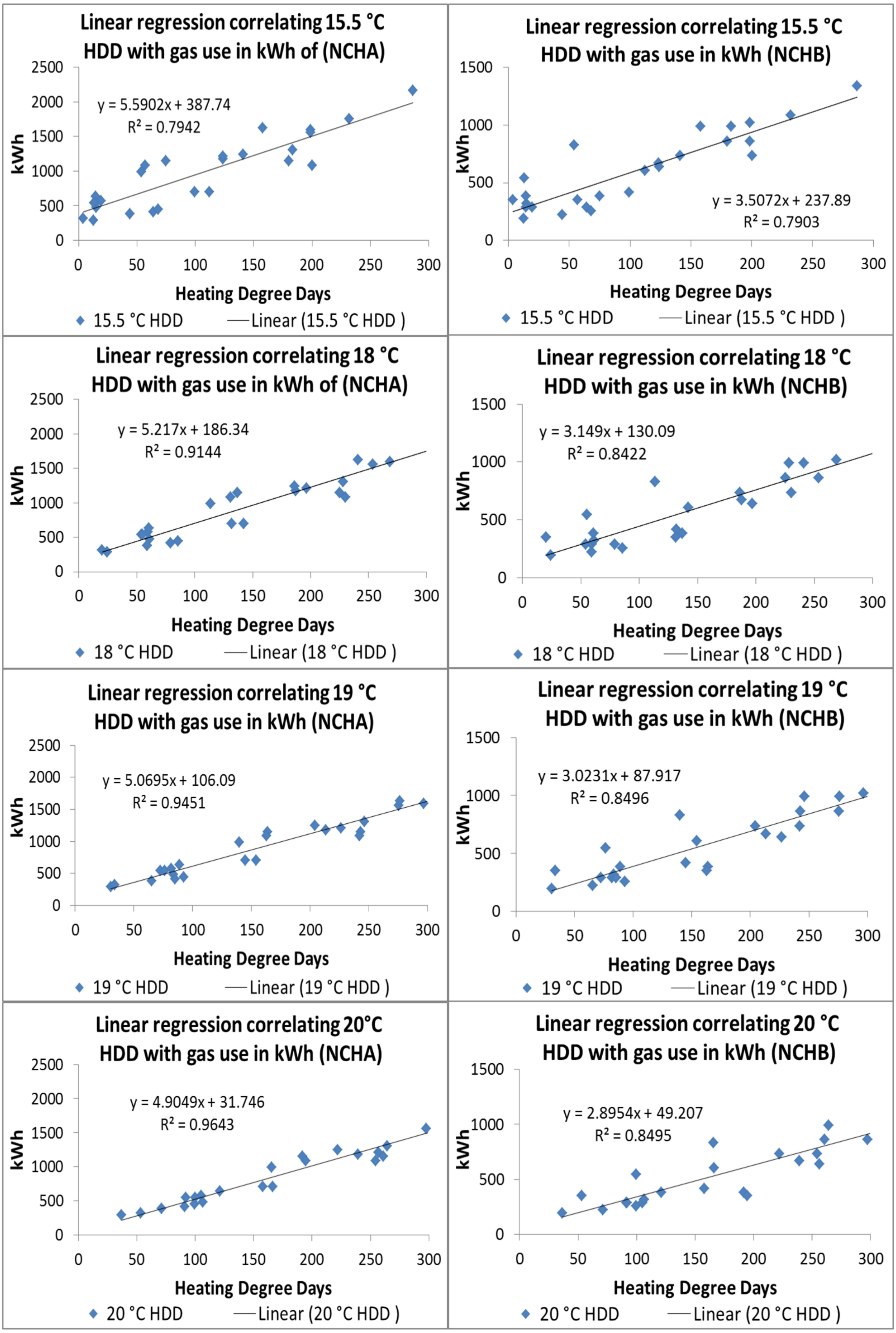


Figure 7-12 HDD linear regressions under 15.5 ºC, 18 ºC, 19 ºC and 20 ºC scenarios over the monitoring period in NCHA and NCHB

7.3.2 Indoor and outdoor hygrothermal conditions

The HDD analyses have identified the best-fit regression at the base temperature of 20 ºC and 18 ºC respectively for NCHA and NCHB. The higher best-fit base temperature and larger amount of gas use of NCHA are attested, in this subsection, by the higher indoor temperature measurements and the cross-comparison of gas bills of the two homes. The raw data of indoor hygrothermal measurements at the original logging intervals are presented in Appendices 20 and 21 and the outdoor recordings in Appendix 19. The measurement gap between 8 February 2011 and 15 February 2011 was caused by the replacement of loggers.

As shown in Appendices 20 and 21, the main bedroom and shower room on the top floor shared similar hygrothermal patterns except for the fluctuations relating to zone-related activities, such as shower events; the living room and kitchen on the second ground floor shared similar patterns except for the cooking events. The frequent and wide-range variations in the indoor T and RH conditions cannot reveal the seasonality features to the same extent as the associated measurements of the HHP case study as shown in Appendices 16, 17, and 18. The variations revealed certain levels of difference in the building performance between the light-weight timber frame buildings of NCH houses and the heavy-weight autonomous HHP houses against similar outdoor hygrothermal conditions. Between the two NCH houses, the difference in occupancy activities relating to space heating and natural ventilation caused NCHA to have larger daily temperature variations as shown in Figure 7-13. To remove the localised variations, the measurements across different living zones were averaged prior to calculating the daily mean temperatures and associated variation ranges. The indoor temperatures in NCHA were higher than those in NCHB for most of the monitoring period. The daily mean temperatures of the two homes did not converge until late May 2012 when the NCHA residents stopped using space heating.

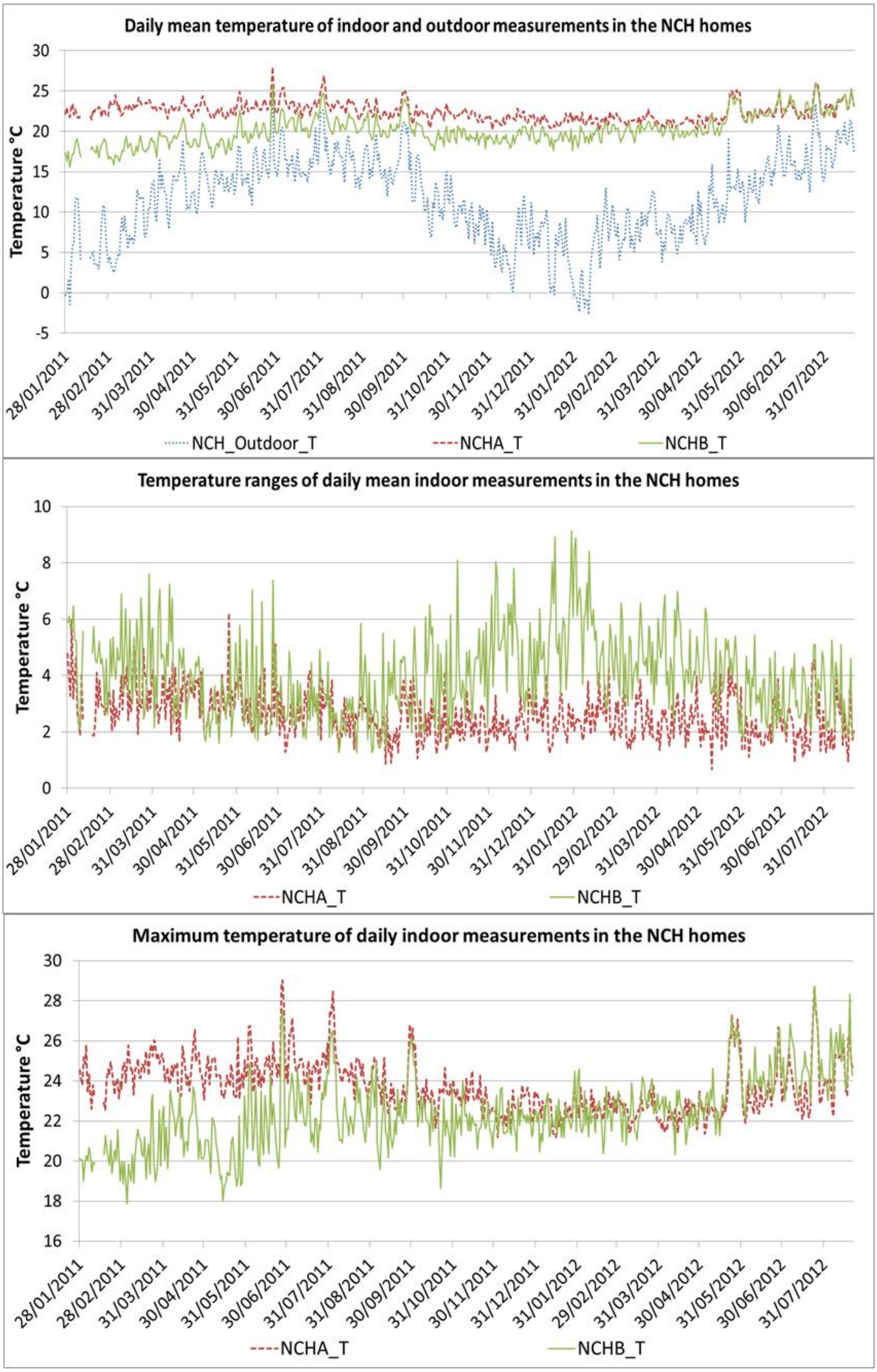


Figure 7-13 Daily mean and maximum temperatures and variation ranges of NCH measurements over the monitoring period 28/01/2011 to 21/08/2012

The less-intensive use of space heating in NCHB partially caused the larger variations in the indoor hygrothermal conditions than those in NCHA. After the retrofit programme, the NCHB residents kept their previous habit of space heating and opted not to heat the upstairs space, except for the guest bedroom of the visiting granddaughter. The monitoring of the most-operated windows assisted in revealing some impact of occupancy-related ventilation behaviours on the energy performance of the two identically retrofitted houses. The main bedroom and bathroom on the NCHB top floor were not only unheated but frequently ventilated by opening the windows. The variations in T and RH of these two monitored living zones closely tracked that noted in the outdoor hygrothermal conditions. A unique occupancy habit of the NCHB residents was their preference to keep the bedroom window open during night-time. Over the night-time period of cold winters, the bedroom temperatures were lower than 10 ºC since the space heating was not used overnight. The variation ranges of indoor temperatures over these days were around nine ºC as shown in Figure 7-13. In contrast, the NCHA residents preferred to heat the entire house continuously for relatively consistent indoor temperatures and to open the windows frequently when the space heating was in use. The continuous and frequent use of space heating narrowed the range of variations in hygrothermal conditions across different living zones but resulted in gas use being approximately 1.5 times that of NCHB, as shown in the previous Figure 7-10.

The NCHA residents gradually chose to use low-level space heating for upstairs areas by adjusting the Thermostatic Radiator Valves (TRVs), which were installed as part of the SWM retrofit programme. In addition to the reduced gas use ratios of NCHA and NCHB in heating seasons from over 3.0 to approximately 1.5 as previously shown in Figure 7-10, the energy-saving effect from the improved efficiency of the upgraded heating systems was demonstrated by the excerpts of gas bills provided in Appendix 22. Using the converted kWh as the unit of gas use, the difference at a relatively significant level was revealed by the bar charts that depicted the quarterly use and the use in the same quarter of the previous year. The gas consumption in both homes decreased consecutively over the two heating seasons when the residents became more familiar with the retrofitted system. However, gas use over non-heating seasons increased since both homes used gas for separate water heating that cannot be facilitated by the pre-retrofitted system. Both homes selected to switch on the water heating for one hour prior to their demand of hot water use following the advice of the boiler installation technicians of the SWM programme of Nottingham City Homes. Using a similar water heating approach, the difference between the two homes in their gas use over heating seasons was mainly caused by the different space heating and natural ventilation behaviours of the two homes.

The daily maximum temperatures of the two NCH homes on certain monitored days shown in Figure 7-13 were approaching the overheating threshold temperatures that are defined in the CIBSE Guide A[21], if using the measured indoor temperatures as the substitute for the operative temperatures. Some potential overheating occasions in NCHA were also identified in the pre-retrofit heating season in January 2011. Unlike the concept of overheating against a hot weather backdrop, the instance during the heating time period in NCHA are potentially identifiable as one source of energy waste caused by the overuse of space heating. Considering that the NCHA boiler system was not retrofitted until March 2011, the less-efficient heating system and the window-opening habit of NCHA residents explained the higher gas use in NCHA.

To examine the overheating issues, the raw data of indoor temperature measurements were examined as shown in Figure 7-14. Digit one denotes a measurement larger than the threshold temperature, 26 ºC for bedroom and 28 ºC for all other rooms (CIBSE, 2006), and digit zero the opposite situation.

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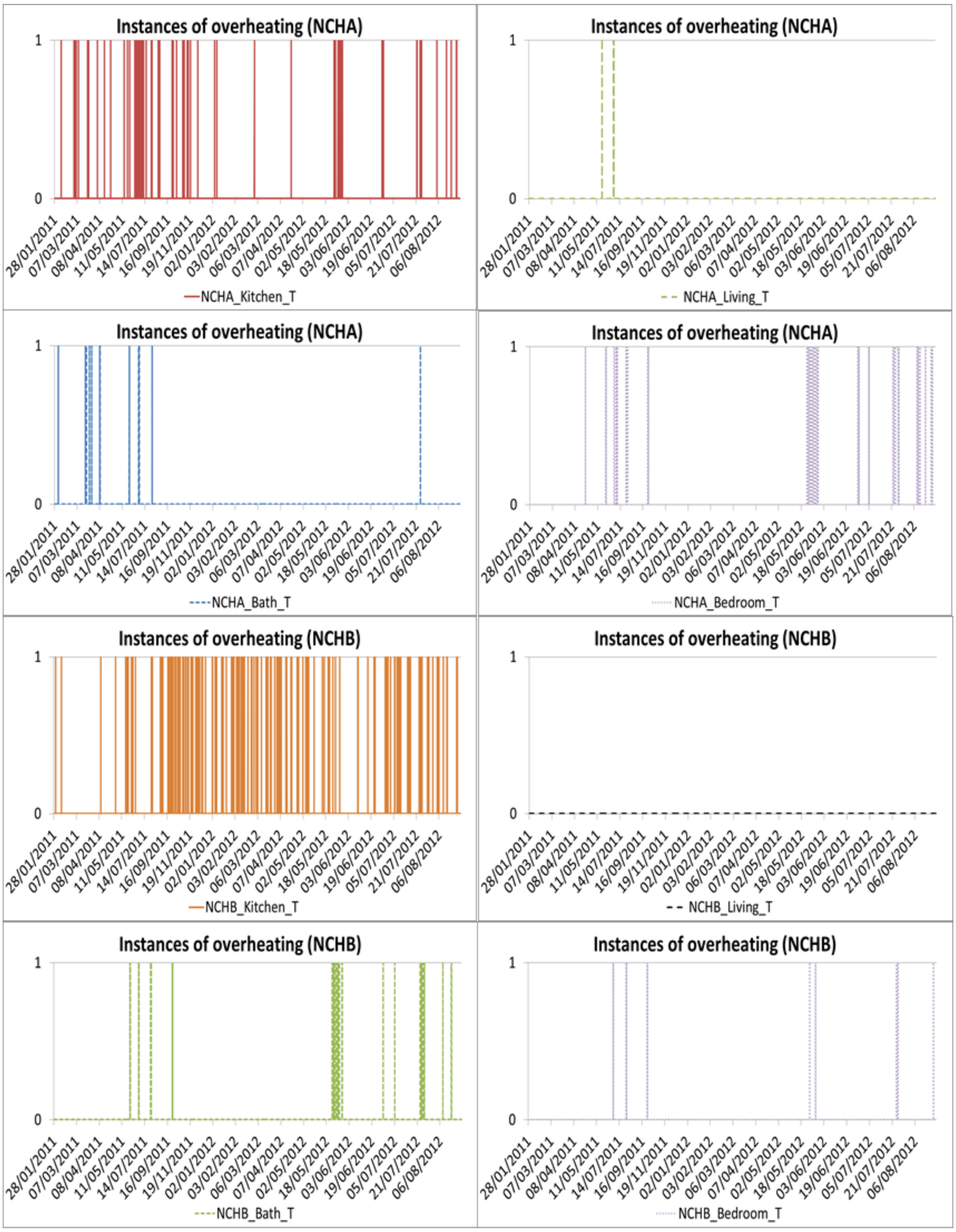
[21] The overheating single criterion in the CIBSE Guide A is based on operative temperature. If the threshold temperature, 26 ºC for bedroom and 28 ºC for all other rooms, is exceeded over the time period for longer than one per cent of occupied hours per year, then the living zone is testified to be under overheating conditions (CIBSE, 2006).



	Kitchen	Living room	Bathroom	Bedroom
Temperature	> 28 °C	> 28 °C	> 28 °C	> 26 °C
NCHA	0.81%	0.30%	0.40%	2.68%
NCHB	1.66%	0.00%	0.60%	0.48%

Figure 7-14 Instances of overheating NCHA and NCHB over the monitoring period 28/01/2011 to 21/08/2012

Most of the overheating instances occurred during summer months, except in the kitchen area that frequently experienced temperatures exceeding the temperature threshold beyond the summer season. In addition to the passive heat source of cooking events, the major cause of overheating was space heating activities. Both homes maintained their pre-retrofit heating habit of centrally heating the kitchen areas, which is where the only radiator was located prior to the retrofit. More frequent cooking in NCHB meant there was a relatively even distribution of overheating instances in the NCHB kitchen over the entire monitoring period. The proportion of overheating time periods in each monitored living zone of the two houses in the total monitoring time period are given in Figure 7-14. The NCHA bedroom and NCHB kitchen were attested to have overheating issues since the proportions exceeded the one per cent as defined by the CIBSE Guide A (CIBSE, 2006).

7.3.3 Power draw profiles of house use and appliances

The processed power draw profiles of NCHA and NCHB are presented in Appendices 23 and 24. The power draws by most of the IAM-measurable appliances are categorised as cold and active loads. Most cold loads from refrigerators and freezers have a rated power demand ranging 60 to 110 watts. The associated power draw patterns depend on the operational cycle and the brand of cold appliances. Only one cold appliance, a combined refrigerator and freezer in the kitchen, was used in NCHA. Three cold appliances, including two separate sets of refrigerator and freezer in the kitchen and one refrigerator in the porch landing area, were used by the NCHB residents. NCHB, although having multiple cold appliances, had a lower base load than NCHA. As the daily minima in house use profiles, the base load values depend on the composition of cold loads, continuous loads, and stand-by loads in the household power profiles. Some Current Cost® IAMs were deployed to monitor the stand-by loads from appliances such as the TV, the TV set-top box, and other entertainment sets in the two NCH houses for various lengths of time periods. The amount of monitored stand-by power draw was around 20 watts in the two houses and further reduced following the advice given by the researcher during site visits. Some stand-by loads from unknown sources, which were not IAM-measurable but recognisable from the daily house use power profiles, were 90 to 160 watts in NCHA and zero to 70 watts in NCHB. The larger amount of stand-by power demand in NCHA was partially caused by the occasional usage of heated towel rail in the bathroom.

An Internet service was only available in NCHB, which enabled the multi-node communication of Current Cost® devices. The Internet peripheral devices and the monitoring equipment set up in NCHB continuously drew 20 to 30 watts. The continuous power draws relating to monitoring devices were around 10 watts in NCHA. In general, the proportion of power draws by the monitoring devices remained at a relatively negligible level against the total amount of power load in each house.

The major active power draws of NCHA were sourced from multiple energy-intensive appliances, including the washing machine, tumble dryer and dish washer. Some of these appliances were used more than once per day over the monitoring period. The washing cycles at relatively high water temperatures were frequently selected by the NCHA residents in contrast to the cold water washing preferred by the NCHB residents. The maximum power draw values of the washing machine are directly associated with the selection of washing temperatures. As shown in the graphs of washing machine power draw profiles in Appendices 23 and 24, the amplitude of washing machine power draws in NCHB rarely exceeded 500 watts over the entire monitoring period. In contrast, most of the maximum values of the washing machine power draw profiles in NCHA were larger than 1,500 watts. To visualise the power profiles of house use and IAM-measureable appliances in the two houses, the pre-processed power profiles for two selected days are presented in Figure 7-15.

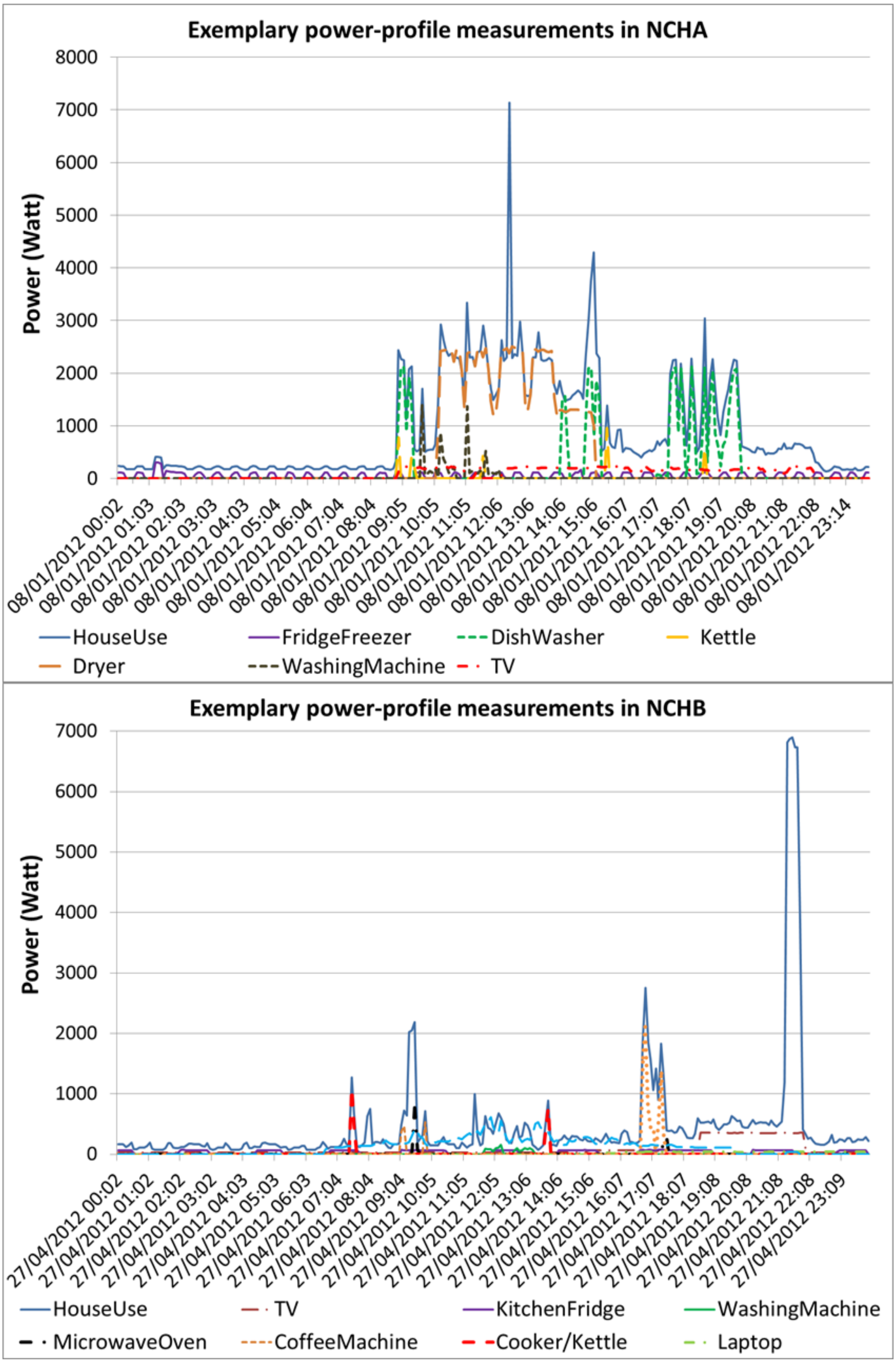


Figure 7-15 Exemplary power-profile measurements for the two NCH homes

Among different categories of power loads in Figure 7-15, the active loads with large amounts of power demand are directly recognisable in the house use power profile. Examples are the shower event that was not IAM-measureable and the usage of certain IAM-measureable energy intensive appliances. The selected power profiles contained typical electricity use activities that did not necessarily occur to the same extent on a daily basis. For example, the tumble dryer in NCHA was used four times and the dishwasher three times on 8 January 2012. The daily electricity use of 21.71 kWh was relatively high compared to other NCHA daily use shown in Figure 6-10 (see Chapter Six). Although containing the energy use of a shower event of relatively long duration on 27 April 2012, the daily electricity use of 10.85 kWh in NCHB was nearly half of the amount used by NCHA on 8 January 2012. Most of the NCHB daily use was below 10 kWh over the entire monitoring period as shown in Figure 6-10 (see Chapter Six). As shown in Figure 7-15, the PV microgeneration profile of NCHB was successfully separated from the house use power profile by using the solution previously illustrated in Figure 5-8 (see Chapter Five).

7.3.4 Micro-scale inspections of the NCH data

The use of space heating and the associated indoor environment are the focus of micro-scale examinations of the measurements for retrofitted NCH case study homes. Therefore, the relatively cold 11 February 2012 that was selected for the micro-scale inspection of the HHP case study data is presented in this subsection. The graphs in Figure 7-16 demonstrate the use of frequently operated windows and the indoor temperatures against the outdoor temperatures that were below zero degree for most of the time and lower than minus five degrees during the dawn time period. Where the window status is concerned, the digit zero stands for the window opening and the digit one for the window closing.

The variation patterns in the indoor temperature profiles and the window-status data segments were consistent with the information on ventilation and space heating use acquired from informal interviews during the site visits. As shown in Figure 7-16, the NCHA residents used the space heating continuously across all living zones where the temperatures varied within a relatively narrow range of five degrees. The monitored living room windows were opened three times, each of which corresponded to the temperature variations in the living room and the adjacent kitchen area. The monitored window in the upstairs main bedroom remained open for the most of the daytime period when the heating was continuously in use. The temperatures in the bedroom and the adjacent bathroom over the window-opening period were around 20 ºC, with the heat loss being compensated by the continuous use of space heating and the heat transfer from the kitchen and living room on the second ground floor.

Heating use in NCHB was relatively more intense during the daytime period of 11 February 2012 when most of the windows were closed on this relatively cold day. The heated areas on the second ground floor had relatively high temperatures around 25 ºC, approximately five degrees higher than the unheated top floor areas. The dawn to monitoring period had witnessed the lowest indoor temperatures around six ºC in the bedroom, resulting from the NCHB residents’ preference for opening the window during night-time. The monitored bedroom window remained open from the evening time on 10 February 2012 when the space heating was switched off. The space heating was put in use after the residents got up and closed the windows to minimise unnecessary heat loss. Compared to the space heating and window use in NCHA on the same day, the associated gas use in NCHB was relatively efficient.

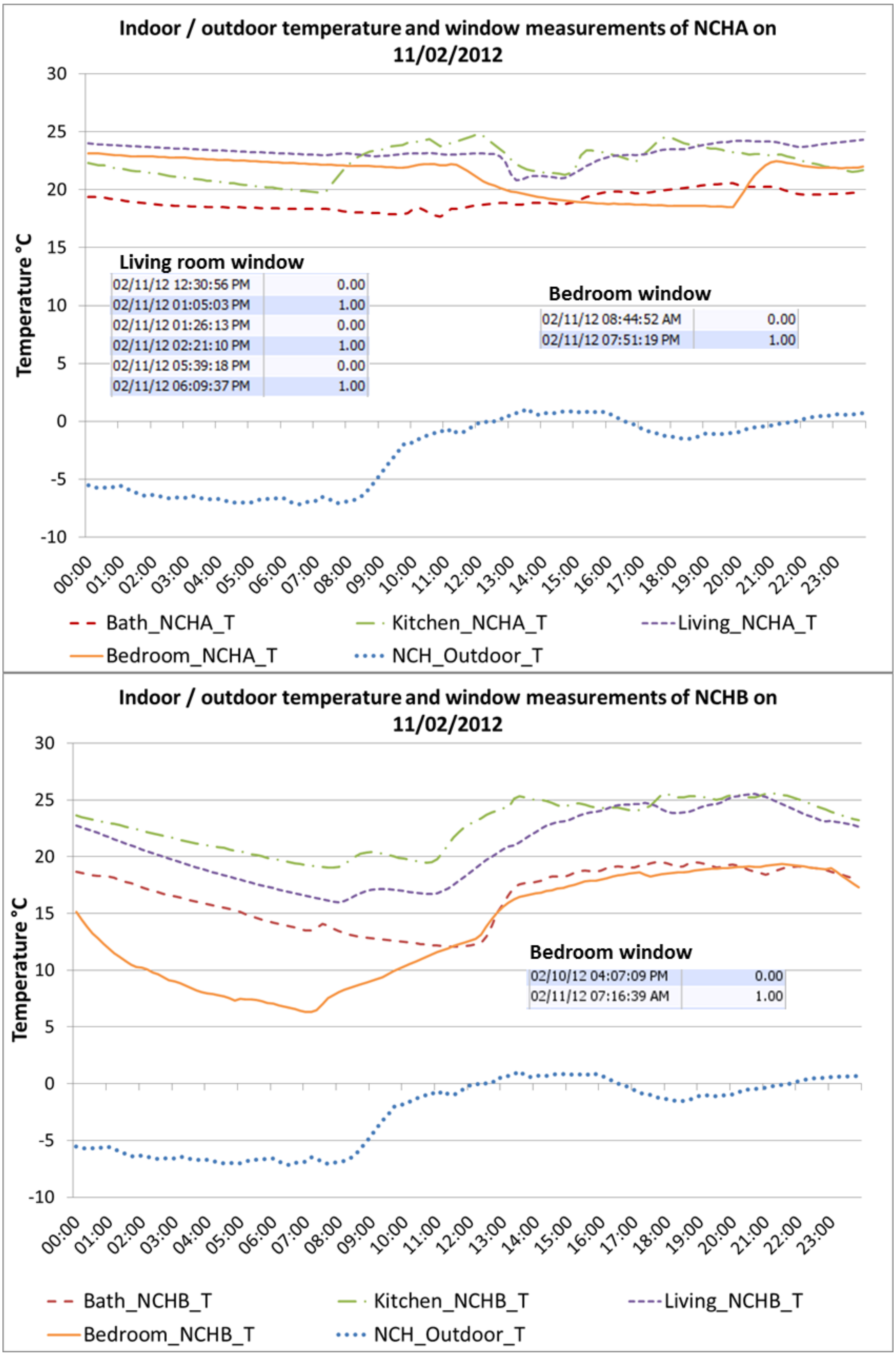


Figure 7-16 Indoor / outdoor temperature and window status measurements taken on 11/02/2012 for the NCH homes

Another feature relating to the building characteristics was revealed by comparing Figure 7-16 with the preceding Figure 7-9 that presents the HHP data of the same day. The free-running autonomous houses of the HHP case study experienced a relatively stable indoor environment. The frequently occupied areas facing the sun space reached temperatures around 20 ºC by utilising passive solar heating and supplementary mobile use. In contrast, the light-weight NCH houses experienced larger temperature variations depending on the use of space heating and the operation of windows. A relatively large potential of gas saving was revealed by the comparison of the two NCH homes. This can be achieved if it is feasible to alter the associated occupancy activities.

7.4 Chapter summary

Building on the preceding chapters on the experimental work and data pre-processing of the two case study groups, this chapter has described the visualisation-based inspections conducted on the multi-category measurements. The micro-scale examinations of certain representative days revealed the case study features that related to the variations in energy-related activities within the same case study and the difference in building characteristics between the two case study groups. The visualisation-based examinations have the advantage of directly testing the effectiveness of pre-processing and the validity of measured results. The lack of systematic strength is one of the disadvantages of the visualisation-based inspection. This is a relatively time-consuming process to examine small-scale data, such as the daily measurement profiles of certain days. To explore the potential of meeting the requirements of systematic analyses, algorithm-based quantitative examinations are conducted in the next chapter.

Chapter 8: Algorithm-based Examinations

8.1 Introduction

This chapter is built on the preceding Chapter Seven, which described the visualisation-based inspections performed on the pre-processed measurements of power draws, hygrothermal parameters, and occupancy statuses of the two case study groups. Systematic and quantitative examinations were respectively conducted on the hygrothermal data and power profiles using the Analysis of Variance (ANOVA) and Adaptive Neuro-Fuzzy Inference System (ANFIS) methods. Like the methodological trials, algorithm-based analyses were conducted on the selected data profiles over exemplary periods. The methods are applicable to data profiles over any preferred time periods in the pre-processed database following the same approach.

8.2 Inspections of hygrothermal data

Analysis of Variance (ANOVA) was introduced in Chapter Three as a statistical approach aiming to attest variation sources of grouped data by comparing between-group mean and within-group mean. Conventionally, ANOVA is used to attest data from unknown sources. If the between-group mean is significantly larger than the within-group mean, then it is statistically safe to reject the null hypothesis that all groups of data are sampled from the same population. The application of ANOVA in this research aimed to investigate the difference in indoor environments relating to energy use and building characteristics. Hygrothermal parameters in this research can be grouped by multiple factors, such as living zones, houses, and case study groups. However, the already-known difference regarding building characteristics, energy sources, and occupancy statuses of each case study house had made two-way or n-way AVOVA results predicable without conducting actual analyses. One-way ANOVA was thus selected for application to temperature measurements that were grouped by living zones across all house subjects. The ANOVA results were not used to attest null hypotheses but to quantitatively confirm the visualisation-based examination results that have been exemplified in the preceding Chapter Seven.

Another predicable feature of ANOVA results in this research was the influence of house layout on data grouped by living zones. For example, the measurements of two adjacent living areas share similar temperature variation patterns. The *p*-value in ANOVA results regarding adjacent living areas is potentially larger than the threshold value of 0.05. The null hypothesis that assumes the temperature measurements were taken from the same areas would thus be accepted although the data were actually sourced from different living zones. If ANOVA is applied to measurements in two distinctive areas that feature either unique occupancy activities or different building characteristics, the *p*-value is potentially smaller than 0.05. Therefore, the *p*-value was not the investigation focus of the ANOVA process in the context of this research. In contrast, the box plots and mean comparison graphs that were produced by using the Matlab® ANOVA function were used to inspect temperature data of different living zones in the two case study groups.

The temperature measurements of NCH and HHP case studies taken on 11 February 2012, which featured the lowest outdoor temperature recordings, were examined individually in Chapter Seven. To verify the results of visualisation-based inspections, the indoor temperature measurements for this day were examined using one-way ANOVA. The information extracted from visualisation-based inspections, such as temporal and spatial variations in indoor temperatures relating to heating and ventilation activities, was used to interpret the ANOVA results. The *p*-values of the ANOVA results of temperature recordings taken on 11 February 2012 and the associated box plots and mean comparison graphs for two case studies are shown in Figure 8-1.

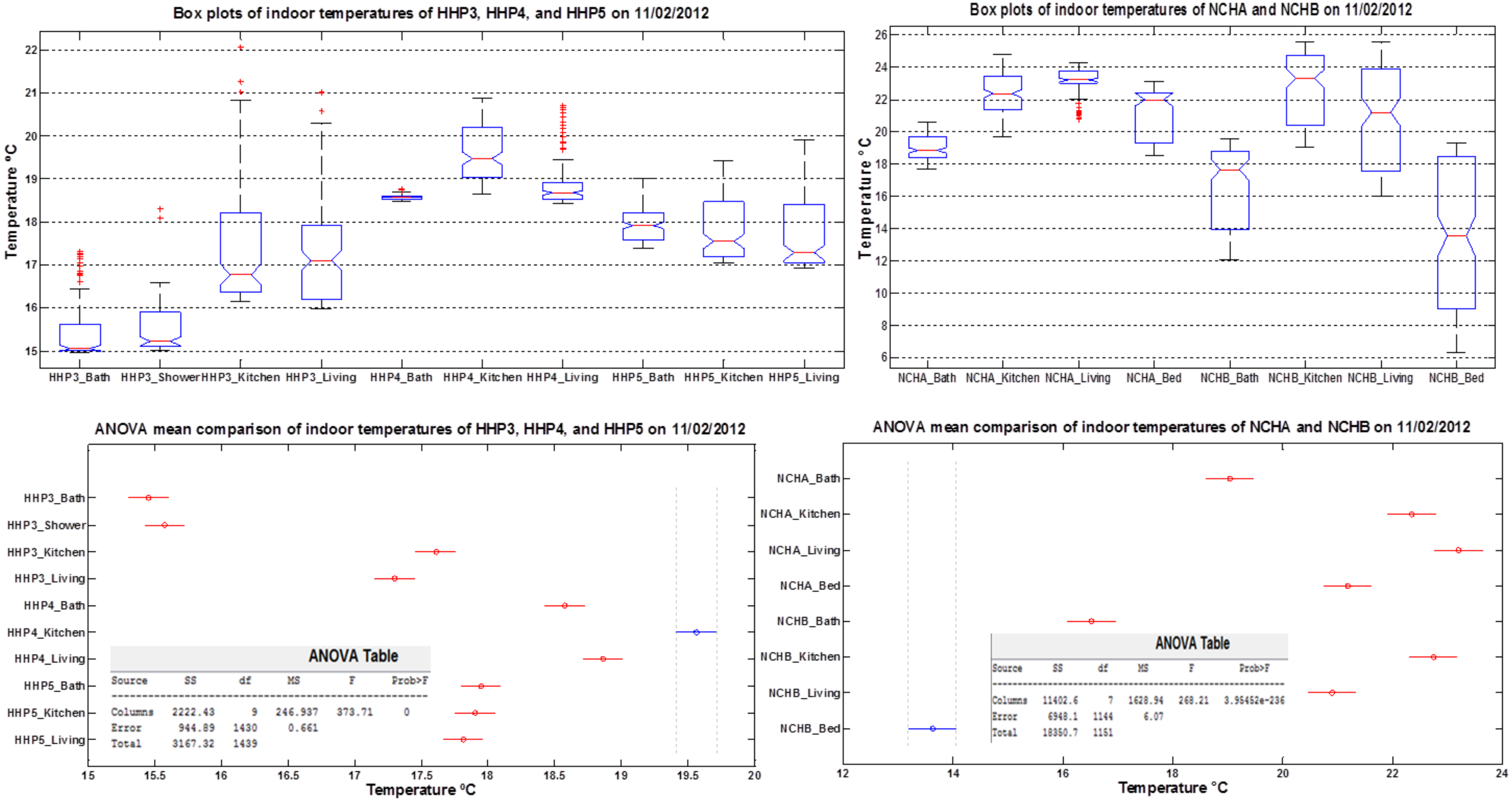


Figure 8-1 Box plots and mean comparison graphs of the two case studies using ANOVA results of the temperature measurements in each monitored living zone on 11/02/2012

The notch line in the middle of each box plot is the median temperature in the monitored area. The quartile divisions of 75 per cent and 25 per cent are denoted by the top and bottom bars, between which the distance is the interquartile range. The temperature values that are more than 1.5 times the interquartile range are considered as the outliers and denoted using the '+' markers by the default settings of the Matlab® ANOVA function. The stable indoor hygrothermal environment corresponds to the short interquartile range and fewer outliers. For example, the interquartile range of the NCHB bedroom on 11 February 2012 was as large as 10 ºC since the bedroom window remained open during the unheated period of early dawn, as shown in the visualisation-based examination in Figure 7-16 (see Chapter Seven). The interquartile range of each monitored living zone of NCHB was larger than the same zone of NCHA that continuously heated the house on 11 February 2012. The window opening activities while using space heating in NCHA were reflected by multiple outliers below the bottom bar of the living room box plot.

Although more outliers appeared in the box plots of HHP3 and HHP4, the major difference between the HHP and NCH indoor environments against similar outdoor conditions resided in the difference in the temperature scales of box plots. The box plots of the HHP case study used one degree as the major unit for the temperature axis, compared to two degrees in the NCH box plots. Therefore, the HHP houses actually had a shorter interquartile range in each monitored living zone. The outliers in the HHP3 box plots, from left to right in Figure 8-1, corresponded to the energy use related occupancy activities that were displayed in Figure 7-9 (see Chapter Seven), such as a shower event in the morning, a cooking event during the noon time period, or the use of mobile heater during the daytime and evening periods. The outliers in the HHP4 box plots mainly applied to the living room and corresponded to the use of a big mobile heater in the evening. HHP5, where no mobile heater was used until the winter of 2012 to 2013, had the most stable indoor temperatures across all living zones as proven by interquartile ranges of less than two degrees and no outliers. Representing the targeted occupancy activities relating to energy use in this research, the outliers in box plots were not treated as in other pieces of research that attempted to remove the unusual values prior to further analyses. Instead, the interquartile range and outliers were two major aspects in the examination of indoor environments using box plots. Box plots can be considered as an alternative to the conventional display of time-series data as in the visualisation-based inspections in Chapter Seven. The two approaches are complementary to each other and both demand a reference to multi-category measurements, such as power draw profiles and occupancy statuses.

The ANOVA process compares the means, rather than the medians, to reach the *p*-value based results. The mean comparison graphs and associated *p*-values shown in Figure 8-1 were generated by comparing the means of each group in a one-way ANOVA of each case study. Since the ANOVA test was conducted on the measurements of all houses in each case study group rather than on data taken from the same house, the *p*-values less than 0.05 in Figure 8-1 stand for the de-facto difference in the temperature data grouped by monitored living zones in all houses. Compared to the *p*-value based results, the mean comparison graphs are more important for the inspections of indoor environments in the context of this research, since the graphs provide information about which pairs of means are significantly different and which pairs are not.

Unlike the medians used in box plots, the centre points of each monitoring zone in the mean comparison graphs in Figure 8-1 are the respective group means, such as the mean temperature of the living room. The intervals in the graph were computed by the Matlab® ANOVA function based on the ANOVA statistics. If the intervals of two groups of data are disjoint, the two groups are significantly different from each other. If the intervals overlap, the groups are not significantly different. For example, a temperature lower than six degrees in the NCHB bedroom due to window opening during the unheated early dawn period on 11 February 2012 made the mean temperature significantly different from all the other groups in the NCH case study. Similarly, the NCHB bathroom mean was also significantly different from all other groups, since the NCHB residents maintained their pre-retrofit space heating habit of not heating the top floor areas. The NCHA house that was heated continuously had less-scattered group means. Although the living room windows were open during space heating periods, the mean temperature of the living room was the highest among all NCHA living zones. Although they gradually started to use TRVs in the top floor areas, the NCHA residents still preferred to open windows in the top floor bedroom and bathroom, which had significantly different group means.

Like the comparison of box plots, the difference in temperature scales is also a key point to compare the mean comparison graphs of the NCH and HHP case study. Compared to the two degrees that features as the major unit of temperature axis in the NCH graph, 0.5 ºC is the major unit in the HHP graph. Although group mean values of certain living zones in the HHP houses were displayed further apart in Figure 8-1, the maximum mean difference between two living zones of HHP3 and HHP4 were around four degrees. The intervals of all living zones in HHP5 overlapped with each other. There was nearly no distinctive difference in temperatures across all the living zones of HHP5 that did not use mobile heaters until the winter of 2012 to 2013. Cooking events and mobile heater use in HHP4 increased the mean temperatures in associated living zones. There was a mean temperature difference of around two degrees between the front and rear living zones of the single-occupant HHP3, which is one bay larger than the other two homes.

The box plots and mean comparison graphs of the ANOVA examinations are also applicable to long-term measurements in addition to the specific daily temperature profiles. Figure 8-2 and Figure 8-3 present the plots and graphs of ANOVA inspections of daily mean temperatures and variation ranges of all monitored living zones in the two case studies over the entire monitoring periods. The difference in indoor environment relating to energy use and building characteristics was thus revealed from the macro-scale examination of long-term temperature measurements. The calculated values of daily mean temperatures and variation ranges in the pre-processed database of hygrothermal measurements were used in Figure 8-2 and Figure 8-3. The box plots of HHP daily mean temperatures in Figure 8-2 have no outliers across all living zones in each house. The interquartile of each living zone covered all the calculated daily mean temperatures. The median values of daily mean temperatures in all living zones were located within the stable and narrow range of 20 to 22 ºC. Except for the bathroom and shower room in the single-occupant and seven-bay HHP3, all the other living zones of the three HHP houses shared similar group means within a range of one degree in the mean comparison graphs of the daily mean temperatures. In contrast, the NCH box plots in Figure 8-2 present multiple outliers in most of the monitored living zones expect for the NCHB kitchen that featured frequent cooking events involving residual heat from the use of an electric oven and grill. In addition to the frequent cooking events, the NCHB residents also kept their pre-retrofit space heating habits unchanged and preferred to centrally heat the kitchen area by turning the kitchen radiator TRV on to the highest level. As shown in the mean comparison graphs in Figure 8-2, the kitchen and adjacent living room in NCHB had the largest mean values. The mean of daily average temperatures was around four degrees higher than that in the unheated bathroom and bedroom. Considering the window-opening habit of the NCHA residents when space heating was in use, the larger amount of gas use caused by the heat loss was indirectly reflected in the ANOVA examination in Figure 8-2.

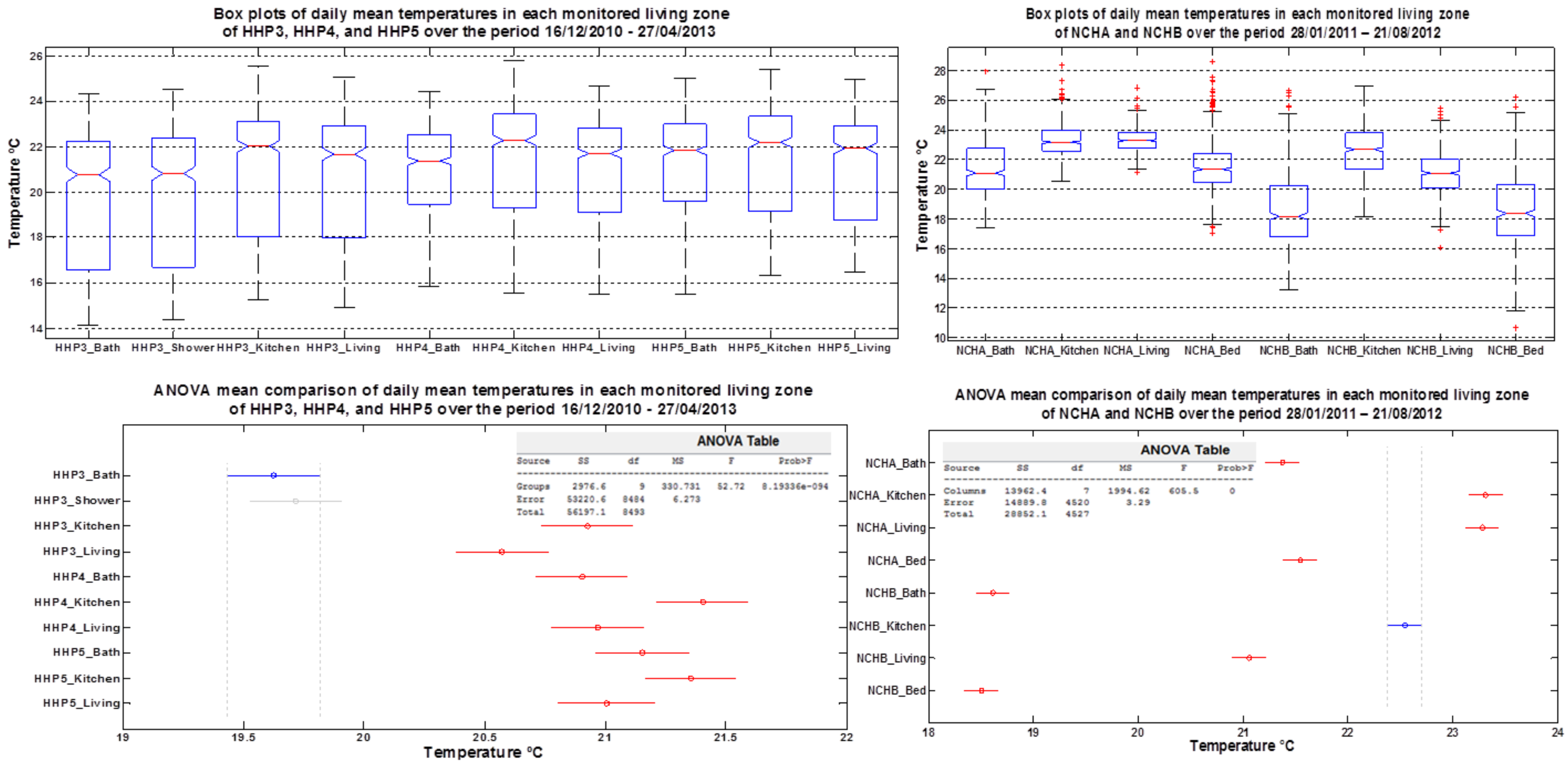


Figure 8-2 Box plots and mean comparison graphs of daily mean temperatures in each monitored zone of the two case studies using ANOVA results of the long-term measurements over the entire monitoring periods

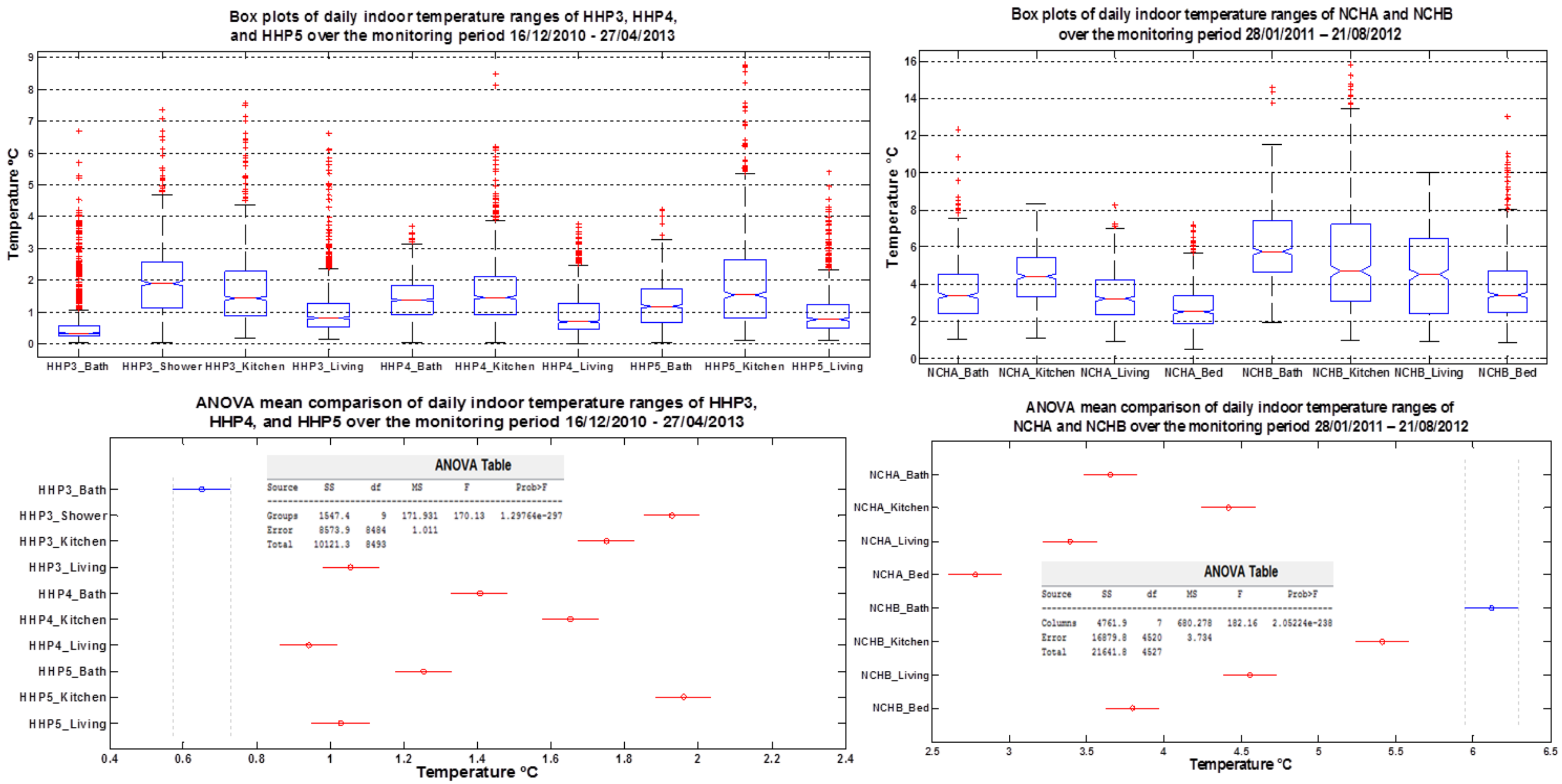


Figure 8-3 Box plots and mean comparison graphs of daily temperature variation ranges in each monitored zone of the two case studies using ANOVA results of the long-term measurements over the entire monitoring periods

The difference in building performance of the heavy-weight thermal mass in autonomous HHP houses and the light-weight thermal mass in timber-frame NCH houses was revealed by the box plots and mean comparison graphs regarding daily temperature variation ranges in Figure 8-3. The diurnal and inter-seasonal heat storage and releasing characteristics of the HHP houses made the temperature variation ranges stay within a narrow scope that was nearly half that of the NCH houses. The frequent use of passive solar heating via sun space caused the outliers, most of which occurred in sunny days, in temperature variation ranges. The extra bathroom in the seven-bay HHP3 had the smallest mean value of variation ranges, less than 0.7 ºC, since the shower events more frequently occurred in the adjacent shower room. In contrast, the largest mean value of variation ranges was more than six degrees in the NCHB bathroom, resulting from the temperature contrast between the time periods of shower events and the usually unheated periods. The largest variation range outlier appeared in the NCHB kitchen box plot. Although having the highest median temperature for daily mean temperatures as shown in the box plots in Figure 8-2, the NCHB kitchen experienced the largest temperature variations caused by the contrast between the concentrated space heating period and the unheated night-time period in the wintertime. The timber-frame NCH houses are quick to heat up and cool down, compared to the free-running HHP houses. Considering the significantly correlated outdoor conditions as demonstrated in Figure 6-2 (see Chapter Six), the two case studies had relatively similar microclimatic conditions to facilitate cross-comparison of the variations in different responding features of the indoor environment to outdoor one. The advantage in stable indoor environment with less energy use in the autonomous HHP houses was revealed in the ANOVA process in Figure 8-3.

The box plots and mean comparison graphs generated by the ANOVA process are effective analysis approaches to enhance the visualisation-based examinations described in Chapter Seven. The *p*-value based ANOVA result is not as critical as in other research since the measurements were knowingly taken from carefully selected case study groups rather than from unknown experimental subjects. However, the outliers and interquartile in box plots and the intervals in mean comparison graphs can assist in revealing the targeted occupancy activities and building performance that are closely related to the difference in actual energy use.

8.3 Investigations into power draw profiles

As shown in the power draw graphs in Appendices 13, 14, 15, 23, and 24, the IAM measurements of some monitored appliances were not as continuous as the simultaneous house use measurements over the entire monitoring period. In addition to the factor of equipment design that prioritises the communication stability of the first three IAM channels, the incompleteness was also caused by the movement of associated IAMs among different appliances. The house use power profiles outlined in the Appendices excluded the days when no measurements were taken due to the interrupted Internet service. Some included daily profiles had incomplete recordings over certain periods when the temporarily stopped Internet peripheral devices were not rebooted in time. Therefore, the conventional statistical analysis cannot be directly conducted on the power measurements, such as the use frequency of certain monitored appliances.

The pre-processed power measurements can be 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 load disaggregation process requires appropriate pattern extraction methods that suit the flawed power data in this research. The computationally intensive algorithms of the Non-intrusive Appliance Load Monitoring (NIALM) process, which is based on the accurately acquired power draw features at super-high sampling frequency, are not necessarily applicable in this research. One similarity between the examinations of the power measurements in this section and the conventional NIALM process resides in the load disaggregation principle, which requires an Intrusive Appliance Load Monitoring (IALM) phase that intrusively measures targeted end-use activities prior to the non-intrusive phase of NIALM. The installation of Current Cost® IAMs in this research to monitor the actual use of certain domestic appliances is essentially an IALM phase. The acquired features in IAM measurements are used to extract targeted energy use occupancy activities, which refer to the use of certain energy-intensive appliances in this section.

The Adaptive Neuro-Fuzzy Inference System (ANFIS) was selected as a methodological trial to extract targeted appliance use. One major advantage in applying ANFIS resides in the aspect of *learning* capability to process the flawed power measurements. In addition to the incompleteness issues, the power measurements in this research cannot distinguish real power and reactive power. Although the pre-processed IAM measurements approximate the actual real power demand, the CT-measured house use is pseudo real power that is calculated by using the default values of power factor and AC voltage. The defective measurements of five-minute power draws thus have very limited features, such as start time, duration, and power draw values, for use in the pattern recognition process. These features relating to the occurrence of targeted electricity use activities can be used to establish a pattern library for the purpose of *supervised* learning of the established ANFIS.

Considering the incomplete and discontinuous nature of IAM measurements, appropriate data segment needs to be taken from the entire monitoring period. An appropriate data section should include continuous measurements of house use and IAM-connected appliances. In addition, relatively fixed components should feature a selected section that includes identical appliances monitored by IAMs. The selected data segment of pre-processed power draws is then split into three sections for the purposes of training, testing, and checking of the ANFIS process, which requires sufficient numbers of qualified data profiles. Since the IAMs were moved among different appliances in the case study homes, it is challenging to locate a temporally continuous section of data that meets the aforesaid requirements. One potentially feasible solution is to artificially establish the data segment by connecting different data sections that are not temporally continuous but qualified in terms of data contents.

In addition to the appropriate dataset, properly selected input and output contents of the ANFIS are key issues for successful pattern extraction. Theoretically, the power profiles of house use and all simultaneously monitored appliances can be used as ANFIS inputs. In practice, the input numbers are controlled to be around six to save computing resources. The involvement of unnecessary input items from appliances without effective power draw features cannot assist in extracting targeted output, except for exponentially increasing the numbers of Neuro nodes, parameters of membership functions (MFs), and fuzzy rules in the ineffective ANFIS structure.

The pre-processed IAM measurements of energy-intensive appliances, such as water immersion heater and tumble dryer, are selected as targeted ANFIS outputs of the exemplified HHP5 and NCHA in this section. The power draws by other appliances, such as TVs and refrigerators, are not sufficiently high to be separated from the house use power profiles under the influence of other energy use events with intensive power demand. Appliances featuring intensive but short-period power draws, such as electric kettles and toasters, are not valid as targeted ANFIS outputs either. The short-term use of these appliances results in relatively low levels of power draws with varied values depending on the start time of appliance use within the associated five-minute time window over which the power draws are averaged. The targeted output is the converted digital series of ones and zeroes, which stand for the on and off states of the targeted appliance. The extraction process aims to determine the use status of appliances rather than the actual power draw values. The power draw and energy use of the appliance can be estimated based on the knowledge of operational cycles acquired from the IAM measurements of targeted appliances.

Unlike the *IF-THEN* structure in the conventional Boolean logic, such as '*IF* the power value is above 5,000 watts *AND* the duration is around 15 minutes, *THEN* a shower event occurs', the rule-based Fuzzy Inference System (FIS) allows a certain ambiguity in the rules to simulate the inferring process of human beings. The aforesaid rule example is thus re-expressed as '*IF* the power amplitude value is *relatively* high *AND* the duration is *medium*, *THEN* a shower event *probably* occurs'. The ambiguous lingual expression, such as '*relatively* high' and '*medium*', is numerically expressed by the Membership Functions (MFs) that map the input over the *universe of discourse*, which is the input space, to a membership degree within the probability range of zero to one. The lingual description depends on the context of each input space, which is the power draw range in this research. For example, the power value of 5,000 watts in the NCHA house use profiles is considered as a relatively high power demand. Although the instantaneous power demand of an electric shower use can exceed 9,000 watts depending on the water temperature settings, the averaged power draws over the five-minute period are usually lower than the instantaneous power figures.

Unlike the arbitrary settings of MFs in the FIS, the ANFIS adds a *learning* capability dimension to the FIS by introducing the '*Adaptive Neuro*' element that assists in assigning appropriate parameters to the MFs. The ANFIS reiterates the optimisation process in the order of input, processing, feedback and rectification, and output to automatically adjust the MFs' parameters. The reiteration stops either when the selected epoch numbers are reached or when the errors between the actual output and ANFIS output fall within a tolerance scope. Therefore, the appropriate numbers and types of MFs for each input are important to effectively produce the ANFIS result by efficiently utilising computing resources. Based on the spectrum of the power draws relating to house use and individual appliances, the *universe of discourse* is split automatically by the ANFIS to produce adaptively acquired parameters for MFs. Only sufficient numbers of MFs can initiate the ANFIS extraction processes. However, unnecessarily complicated MFs demand large computing resources without necessarily achieving better ANFIS results. The numbers and types of MFs were selected to be two trapezoidal functions for each input for the ANFIS trials in this subsection.

Among the three HHP case study houses, the multi-occupant HHP5 used more electricity than the other two homes due to the frequent use of the washing machine, dish washer and thermostat-controlled immersion water heater. The power measurements in HHP5, which did not use mobile heaters over most of the monitoring period except of the winter of 2012 to 2013, also featured a relatively high level of temporal continuity since the IAMs were not frequently moved among appliances in different seasons. HHP5 was thus selected for the HHP case study ANFIS trial. The use statuses of immersion water heater, which features relatively stable and high power draw levels over the period of thermostat-controlled use, were selected as the ANFIS output. The six inputs included the power draws of house use, immersion water, and four other energy-intensive appliances.

Based on the power draw graphs in Appendix 15, the measurements taken between 21 October 2011 and 8 January 2013 were selected and split into three sections. The two sections 21 October 2011 to 4 March 2012 and 25 July 2012 to 8 January 2013 were respectively used for the ANFIS training and checking purposes. The middle section running from 5 March 2012 to 24 July 2012, which includes unoccupied periods during the summer holidays, was used to test the established ANFIS. The ANFIS structure with the selected inputs and output and the associated parameter numbers are shown in Figure 8-4, which also presents the training, testing, and checking results and the training and checking errors.

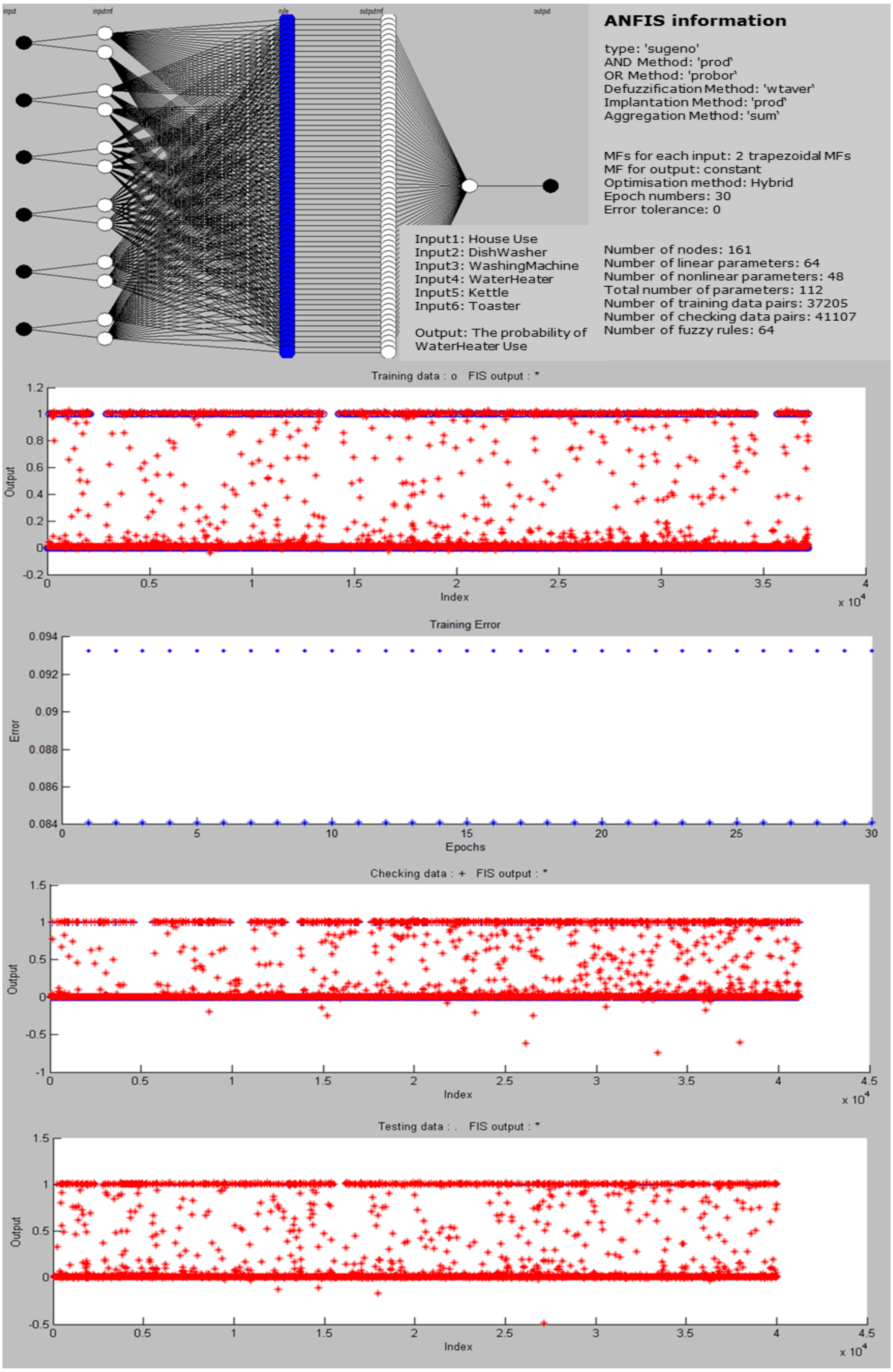


Figure 8-4 ANFIS structure established for power measurements of HHP5 and training, checking, and testing results for immersion water heater use statuses

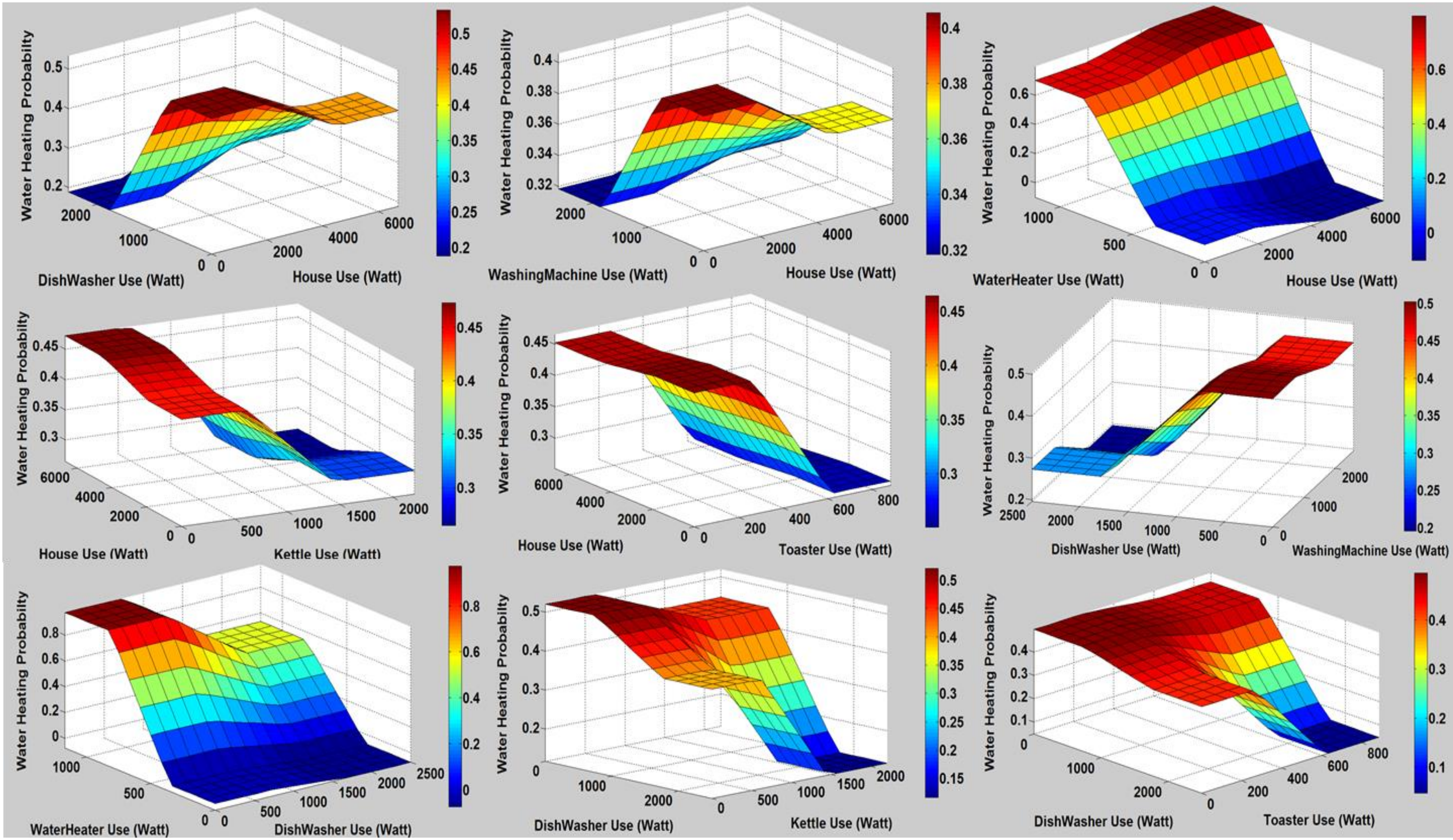
The checking errors were less than 0.094 and the training errors were around 0.084 over the 30 epochs. The trained ANFIS thus had no overfitting risks, signalled by a first decreasing, then increasing trend in the checking errors. Most of the immersion water heater use statuses were thus extracted correctly. The dots between zero and one stand for the fuzzy output of probable statuses other than zero and one. The purpose of using a testing dataset, which is sufficiently distinct from the training and checking datasets due to the included unoccupied periods, is to check the generalisation capability of the trained ANFIS.

The ANFIS output values were then approximated to either zero or one using the threshold of 0.5. When the probability output was smaller than 0.5, it was assigned to zero; otherwise to one. Out of the 4,843 ‘on’ statuses of the in-use immersion heater in the testing dataset, 4,475 were correctly emulated with the rate of correct extraction as high as 92 per cent. Most of the 368 erroneous results appeared at the start and ending points of the immersion water heater’s operational cycles. Over the relatively long sampling interval of five minutes, most of the averaged power draws over the first and last five-minute intervals in one operational cycle of the heater were lower than the rated values. The ANFIS thus categorised the heater’s state as ‘off’ although the actual power draws were not zero watt. The established ANFIS was thus attested to be effective with sufficient generalisation capability following its relatively high rate of successfully extracted testing results.

The reason 0.5 was selected as the threshold to approximate the ANFIS output to either zero or one was based on the examination of the interrelations between the potentially simultaneous power draws of different appliances and the probability of immersion heater use. The 15 surface plots were generated by the established ANFIS as shown in Figure 8-5. The real-time house use is associated with the simultaneous use status of every end-use in the household, although no linear relations exist due to the difference between the power factor of each end-use and the power factor at the mains power. The horizontal axes in each surface plot stand for the input space, which is the *course of universe* of the ANFIS input, of each pair of end-use. The vertical axis in the surface plot assigns probability values to the immersion water heater usage regarding the combination of potentially simultaneous power draws of each pair of appliances or that of house use and an appliance.

The surface view is used to examine the interrelationship between the power draws of different types of electricity end-use. For example, in all graphs that include house use as one of the two inputs, only when the house use approaches a relatively high level and the other input has no featured power draws, are the occurrence probabilities of an in-use status for the immersion water heater displayed as approximating or exceeding the 0.5 threshold. When two energy-intensive appliances are being simultaneously used, the immersion water heater usage probability is relatively low. This interrelationship is consistent with the actual instances of hot water use in HHP5, where the washing machine and dishwasher were directly connected to the cold water rather than to the Hotsi® tank. Therefore, the use of washing machine and dishwasher has no direct connection with the immersion water heater usage. Controlled by a thermostat, the immersion water heater in the HPP5 Hotsi® tank is associated with other hot water use events, such as showers and cooking activities.

The ANFIS results, including the surface view graphs, cannot replace the visualisation-based examination process of the daily power draws described in Chapter Seven. However, the ANFIS method provides an alternative approach to inspecting the interrelationship between house use and energy-intensive end-use. The accurate level of ANFIS extraction results also depends on the power draw features of the selected output. A similar ANFIS process was also applied to the NCHA data, although the successfully extracted testing results were not as high as the immersion heater ANFIS in HHP5.


Water Heating Probabilty
DishWasher Use (Watt)
House Use (Watt)
WashingMachine Use (Watt)
WaterHeater Use (Watt)
Kettle Use (Watt)
Toaster Use (Watt)

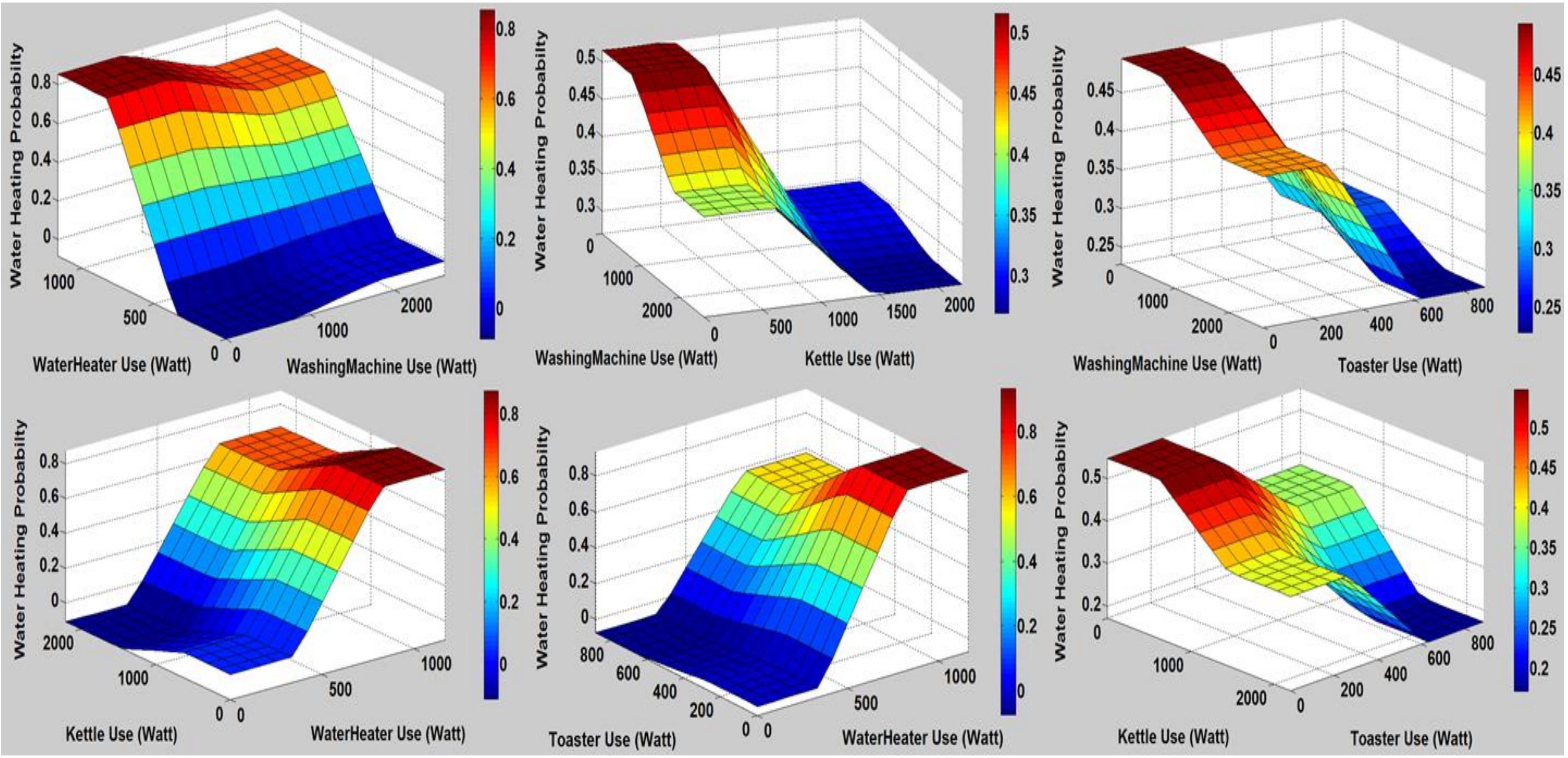


Figure 8-5 Surface view graphs of the ANFIS established for use statuses of immersion water heater in HHP5

Of the two NCH case study houses, NCHA used more electricity than NCHB due to the frequent use of washing machine, dish washer and tumble dryer and preference for high-temperature washes when using the washing machine. Power measurements in NCHA also featured relatively high levels of temporal continuity since the house did not experience the flawed measurements resulting from the retrofitted PV microgeneration that affected NCHB. NCHA was thus selected for the NCH case study ANFIS trial. The use statuses of the tumble dryer, which features relatively fixed power draw levels and relatively high power draw values compared to other appliances, were selected as the ANFIS output. The five inputs included the power draws relating to house use, tumble dryer, and three other energy-intensive appliances.

Based on the power draw graphs in Appendix 24, the measurements taken between 14 December 2011 and 23 August 2012 were selected and split into three sections. The two sections from 14 December 2011 to 6 March 2012 and from 27 May 2012 to 23 August 2012 were used for the ANFIS training and checking respectively. The middle section, 7 March 2012 to 26 May 2012, was used to test the established ANFIS as shown in Figure 8-6. The checking errors were less than 0.102 and the training errors were around 0.095 over the 100 epochs. The parameters of HHP5's immersion water heater ANFIS were less than 0.094 for the checking errors and around 0.084 for the training errors over the 30 epochs. Therefore, with more iteration numbers for the optimisation process of the established ANFIS, the errors between the ANFIS output and the actual use status of the NCHA's tumble dryer were still larger than those of the HHP5 immersion heater. The ANFIS training result had no overfitting risk.

The ANFIS output values were then approximated to either zero or one using the same threshold of 0.5. When the probability output was smaller than 0.5, it was assigned to zero; otherwise to one. Out of the 2,051 'on' state of the in-use tumble dryer in the testing dataset, 1,494 were correctly emulated with the rate of correct extraction at 73 per cent. This is lower than the 92 per cent in the HHP5's immersion heater ANFIS.

Most of the 557 incorrect results appeared at the starting, ending, and flexion points of power draw profiles over the tumble dryer's operational cycles. Over the relatively long sampling interval of five minutes, most the averaged power draws over the first, the last, and the flexional five-minute intervals in one operational cycle of the dryer were relatively low and not fixed. The statuses over some of these intervals were thus categorised by the ANFIS as 'off' although the actual power draws were not zero watt. In contrast to stable power draws of around 1,000 watts during the use period of the immersion water heater in HHP5, the power draw profiles of the tumble dryer have flexion points that depend on the selected drying temperature and duration. For example, a stable power draw level might be maintained for the entire drying cycle if the selected operational mode is a 40-minute normal drying cycle with medium temperatures. In contrast, if the operational mode is a 90-minute intensive drying cycle with relatively high temperatures, the power draw levels are automatically changed by the thermostat control of the dryer. The flexion points thus occur in the consequent power profiles. The irregularity in the occurrence of flexion points resulted in a relatively lower accuracy level of ANFIS results, as attested by the larger training and checking errors over larger epoch numbers and the lower rate of successful extraction for the NCHA's dryer ANFIS.

The 10 surface view graphs showing the ANFIS results for the NCHA's tumble dryer use statuses were presented with the testing results in Figure 8-7. Compared to the HHP5's water heater, the testing results are more scattered across the probability range of zero and one. This testing graph is consistent with the successful extraction rate, which was 73 per cent. Similarly, the patterns of power draw interrelationships can be identified from the surface view graphs.

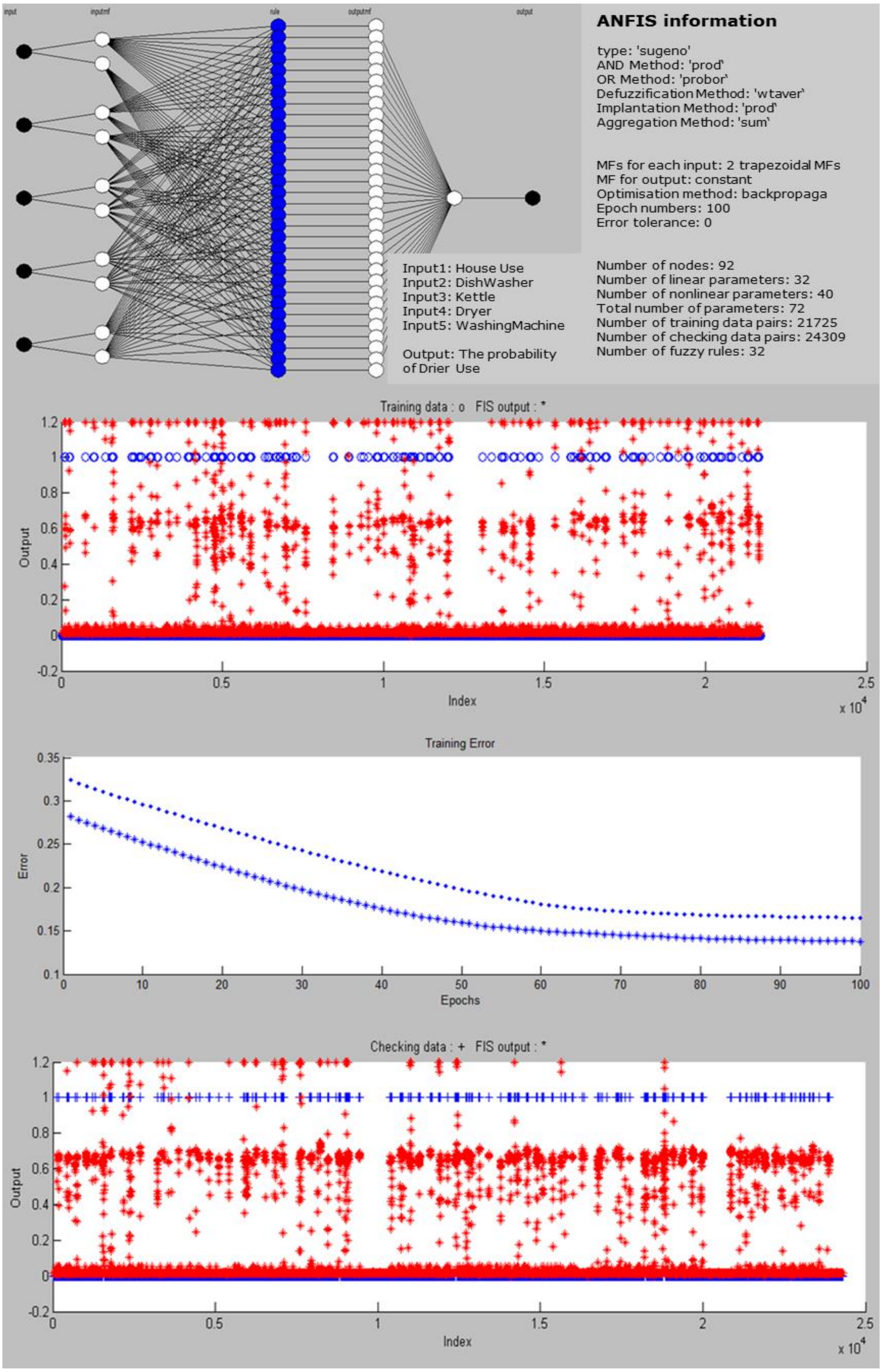


Figure 8-6 ANFIS structure established for power measurements of NCHA and training, checking, and testing results for the dryer use statuses

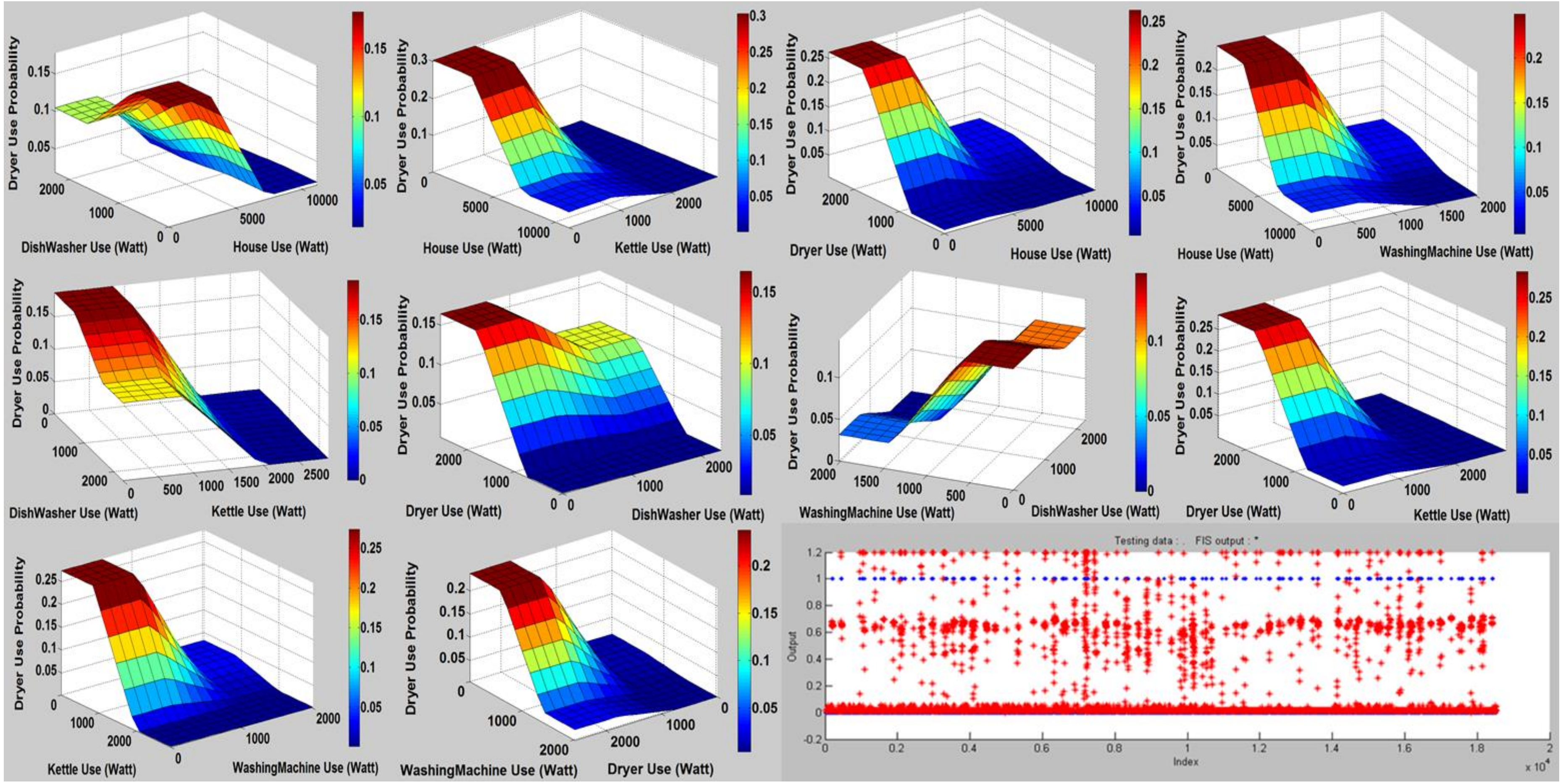


Figure 8-7 Surface view graphs of the ANFIS established for use statuses of tumble dryer in NCHA

Most of the surface view graphs in Figure 8-7 have a probability scale of zero to 0.3, which is lower than that in Figure 8-5. It is consistent with the relatively low level of interrelations between house use and individual end-use. Larger use probabilities applying to the tumble dryer do not occur when the house use approximates the maximum power draw around 10 kW that was usually caused by a shower event. Since the electric shower was not IAM-measurable, no individual power draws relating to a shower event were used as one of the ANFIS inputs to verify this assumption. To certain extent, the absence of this most energy-intensive end-use in the NCHA power measurements partially explains the lower accuracy levels of the established ANFIS.

8.4 Chapter summary

This chapter described a methodological trial of algorithm-based approaches sourced from the fields of statistics and computational science. ANOVA was applied to hygrothermal data to compare the means and medians of actual measurements in all living zones. It was also applied to the artificially calculated means and ranges of measurements. The living zones were taken as the grouping factor in the one-way ANOVA. The ANOVA results effectively assisted in revealing the hidden regularities in the large number of long-term measurements. The method can be applied to data on various scales from daily profiles to measurements over the entire monitoring period. The ANOVA tables containing *p*-values and *F* statistics are not as significant and straightforward as the presentation of data using box plots and mean comparison graphs. Not only the energy-related occupancy activities but also the building characteristics can be explained by examining the box plots and mean comparison graphs.

ANFIS was applied on selected power draw measurements in HHP5 and NCHA, which featured comparatively intensive energy use and relatively complete measurements in the respective case study groups. The use status probabilities of selected appliances, which are the water immersion heater in HHP5 and the tumble dryer in NCHA, were used as the respective ANFIS outputs. The extraction results were consistent with the actual operational situations of appliances in each house. Since the power draws of immersion water heater have fewer uncertainties, such as flexion points, compared to those of the tumble dryer, the extraction results of the HHP5 ANFIS were more accurate than those of the NCHA ANFIS. The presentation of ANFIS results, such as the training, testing, and checking parameters and the surface view graphs, assisted in revealing the interrelationships of power draws by house use and individual appliances.

Though unable to replace the micro-scale and macro-scale visualisation-based inspections described in Chapter Seven, the ANOVA and ANFIS processes laid out in this chapter provided an alternative approach to examining mixed-method measurements and the associated effectiveness of data pre-processing results. From a methodological perspective, the visualisation-based inspections were improved, in terms of the interpretation of pre-processed measurements, by the use of ANOVA and ANFIS to conduct algorithm-based examinations.

Chapter 9: Discussion and Future Work

9.1 Summary and discussion

This study has investigated the energy-related occupancy activities in purposefully selected case study homes. The 'mixed methods research' (Bryman, 2012) approach underpinned the methodology justification process. The strengths of qualitative and quantitative research strategies were combined for the study of this socio-technical research topic. Long-term and longitudinal approaches were selected for data acquisition with reference to the Retrofit for the Future (RFF) and Building Performance Evaluation (BPE) programmes of the Technology Strategy Board (TSB). The research design applied and enhanced certain aspects given in the whole-house carbon and energy monitoring protocol and the occupant evaluation guidance of the Energy Saving Trust (EST) (2009; 2011; 2014). Case study was selected as the research approach with reference to the systematic discussion on case studies as a research method by Yin (2014). 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. Following the conventional and visualisation-based data presentation, multidisciplinary and analytical approaches were sourced from the fields of statistics and Artificial Intelligence (AI) to undertake algorithm-based data examinations. 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 configuration and implementation process of the monitoring schemes that feature low costs, less intrusiveness and transferable techniques in this study has comprehensively answered the research questions raised in Chapter Three.

The experimental work, data pre-processing, presentation and analysis have been respectively covered in Chapter Four to Chapter Eight, regarding the HHP and NCH case study groups. Utility meter readings taken from each house over the same monitoring period are used in this subsection to present the actual difference in energy consumption. Manual readings that cover electricity use and natural gas consumption can provide a holistic energy use scenario, since natural gas use was not automatically measured in this study. Findings from previous chapters are resorted to in order to explain the impact of energy-related occupancy activities on actual energy use. Manual meter-readings of all case study homes were compared in Figure 9-1, in which renewal microgeneration figures for the HHP houses and NCHB were not included. The seven consecutive quarterly periods over which both case studies have complete manual meter recordings were selected for presentation. Gas use in the two NCH homes was converted into kWh consumption prior to being added to the electricity use. The second graph in Figure 9-1 separately presents the electricity use and gas consumption of the two NCH homes, with kWh as the unit. The distinctive contrast of the actual energy use between both case study groups illustrated in Figure 9-1 exemplifies the difference in building design and energy-related occupancy activities. Daily energy use in the free-floating autonomous HHP houses was approximately one tenth of that in the retrofitted timber-frame NCHB, which consumed nearly half the amount of energy used by NCHA. The natural gas that was used in the two NCH houses, mainly for the purpose of space heating, counted for 85 to 95 per cent of the total energy use depending on the seasonality. The ratios of the total energy use between NCHA and NCHB range around 2.0 across all seasons except for the summer period in 2012, when the NCHA residents stopped using space heating. The two houses, which featured similar household profiles and identical built form, have been retrofitted the same standard. Without considering the impact of occupancy activities, the same or similar assessment or simulation results would be produced for the two retrofitted homes.

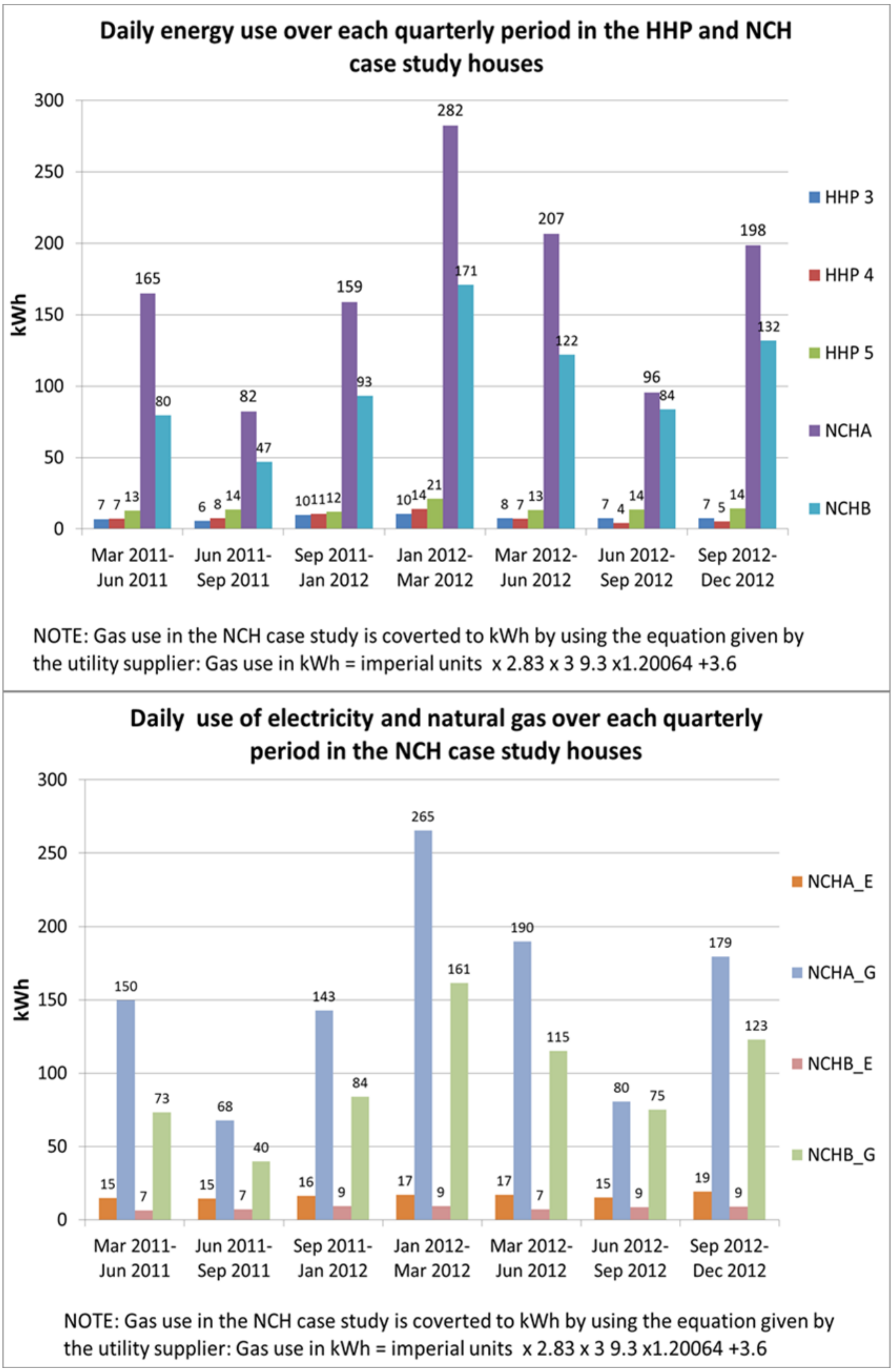


Figure 9-1 Daily energy use over the period of seven quarterly periods from March 2011 to December 2012 in the five houses of the two case studies

The distinctive difference in actual energy use within the NCH case study group was consistent with the monitoring results. Although gas use was not directly measurable, the HDD regressions previously depicted in Figure 7-12 (see Chapter Seven) presented a difference in the baseline outdoor temperatures of the two NCH homes, 20 ºC for NCHA and 18 ºC for NCHB. The two ºC difference in baseline temperatures reflects 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 as previously revealed in Figure 7-13 (see Chapter Seven). 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 on 11 February 2012 were respectively presented in Figure 7-16 (see Chapter Seven) and in Figure 8-1 (see Chapter Eight). 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 shown in Figure 7-15 (see Chapter Seven) 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. As shown in Figure 9-1, the average daily electricity use in NCHB over each quarterly period was approximately the same as that of the singly occupied HHP3.

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. The preference for this space heating and ventilation approach was out of concern for the health condition of one resident and consideration for their pet cats. Although feedback and energy-saving advice was provided to the residents during several site visits, the only observed change in the heating and ventilation activities in NCHA was the gradually adopted use of Thermostatic Radiator Valves (TRVs) settings on the heated top floor. Over the quarterly period from June 2012 to September in 2012, the NCHA residents stopped using space heating for the first time since the retrofit programme in March 2011. These changes were recognisable from the converging patterns in indoor average temperatures of two NCH homes as shown in Figure 7-13 (see Chapter Seven).

The natural gas use in both NCH homes actually increased after the retrofit programme, as shown in Figure 9-1. The gas bill excerpts in Appendix 22 presented the same changing patterns. The higher gas use in both NCH homes can be partially explained by the water heating use in summer time and the higher indoor temperatures during winter time. As pointed out in Section 2.4.2 (see Chapter Two), *temperature takeback* or *actual energy consumption* in this post-retrofit circumstance are not suitable for categorisation as thermally related rebound effect, since the price-related effect is not clear. The feedback given by the NCHB residents in some site visits showed their tendency to use more energy than in the pre-retrofit stage, especially after the PV microgeneration was installed.

In contrast, by removing the need for a space heating system in the autonomous 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 as shown in Figure 7-2 and Table 7-1 (see Chapter Seven). 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 9-1 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 visualisation-based presentation and the ANOVA application discussed in Chapter Seven and Chapter Eight was shown in Figure 7-9, Figure 8-1, Figure 8-2, and Figure 8-3 (see Chapter Seven and Chapter Eight). The similarity in outdoor conditions of the case study groups was attested in Figure 6-1 and Table 6-1 (see Chapter Six). 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). Appendices 10 and 12 show the EPC excerpts that were produced for one HHP case study house and one post-retrofit NCH case study house. The energy efficiency and environmental impact ratings for the HHP house are F and E, whilst those for the retrofitted NCH house are C and C. 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.

9.2 Knowledge contributions and research impact

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 and longitudinal monitoring and selected analysis techniques that feature in this study made knowledge contributions from practical and methodological perspectives.

Contributions from practical perspectives were mainly exemplified in the configuration and implementation of long-term and longitudinal monitoring schemes in two purposefully selected case study groups. Both off-the-shelf products and self-configured elements were selected in the system configuration. Featuring low cost, less intrusiveness, convenient maintenance, and transferable redeployment, the monitoring schemes were proven to be adaptable for different building characteristics. Without visible aesthetic impact and environmentally psychological influence upon monitored occupants, the monitoring schemes were able to acquire multi-category parameters for the extraction of energy-related occupancy activities. This low-cost and transferable monitoring approach effectively bridged the research gap identified in Chapter One. In the majority of existing households that cannot be covered by projects requiring major investment, such as the RFF and BPE programmes of the TSB, the monitoring technique can be utilised for the instigation of energy-related occupancy activities and associated indoor environmental conditions.

Contributions from a methodological perspective mainly reside in the multidisciplinary approaches that were sourced from various research fields. A mixed methods research approach was selected and enhanced in this study on the socio-technical research subject of energy-related occupancy activities. The combination of research strengths from qualitative and quantitative perspectives was recommended by Bryman (2012). The quantitative strategy discussed by Bryman (2012) emphasised the application of statistical methods to survey results. The quantitative methods in this study were expanded to the research field of statistics and Artificial Intelligence (AI). ANOVA and ANFIS methods were applied in the algorithm-based data examinations in Chapter Eight on the basis of the visualisation-based inspections undertaken in Chapter Seven. Regarding the supplementary sociological research methods, occupation diaries were used and informal interviews conducted, with reference to the whole-house carbon and energy monitoring protocol and the occupant evaluation guidance of the Energy Saving Trust (EST) (2009; 2011; 2014). Therefore, methodological contributions were made in the aspects of both data analysis and data acquisition. The process of applying multi-disciplinary approaches to explain the actual energy use difference has been demonstrated in this chapter's discussion section. The results demonstrated in Chapter Seven and Chapter Eight were proven able to effectively interpret the actual difference in energy use and indoor environment within and between case study groups from the perspective of energy-related occupancy activities.

The research impact of this study resides in the major results and findings derived from the two case studies. The NCH case study results are of importance for the participants of retrofitting programmes, such as the Green Deal scheme, to utilise information from empirical case studies as in this research in order to secure both efficiency gains and financial gains. The results of the HHP case study, on the other hand, revealed an aspect that was overlooked by the building assessment system, regarding low-tech autonomous house design. A low-tech built form that features heavy-weight thermal mass has been proven to outperform the retrofitted timber frame buildings, although the ratings given by assessment systems such as the EPCs produce a completely different conclusion. The evidential results of this empirical study can potentially influence certain decision making processes in the field of building design, retrofit, and assessment.

The research impact is also embodied in the process of or potential for disseminating the multidisciplinary research techniques and associated results to achieve large-scale effects in energy savings and carbon mitigations. The project partner, social landlord Nottingham City Homes, published two batches of project reports on the 'Secure Warm Modern' programme in Nottingham on the purpose-built website (NCH, 2011; NCH, 2012). Certain data and results of the NCH case study were quoted in the reports. The reports have been referenced by another similar project that was conducted by a similar consortium of universities and social landlords[22]. The subsequent data and analysis results can contribute to future reports such as the NCH ones. The HHP case study partner, the Hockerton Housing Project Trading Ltd. (HHP), has started the appeal process for a more comprehensive and objective set of assessment principles by providing post-occupancy and operational evidence on the dwellings (HHP, 2012). The evidential results in this study and associated future publications can potentially be disseminated to a wide range of building-related sectors, including academia and the industry, in the process of supporting HHP's appeal.

9.3 Limitations and future work

The major limitations in this study relate to the available research resources in term of time and funding for data acquisition and analysis. The low-cost data acquisition using the selected monitoring system effectively bridged the identified research gap. However, the measuring accuracy and sensitivities were compromised to certain extent. Most of research resources were thus spent on the data pre-processing aspects. The trade-off between low-cost monitoring and professional analysis largely restricted the research

[22] One example is the KTP project conducted by the consortium of Wulvern Housing Ltd and Manchester Metropolitan University. The project was initiated in March 2013, with the purpose of identifying key issues of energy affordability faced by social landlords and tenants – from the perspective of behavioural changes.

strengths, especially with regards to data analysis. For example, the incompleteness of and discontinuity in the measured power profiles of the targeted end-use negated the possibility of statistical analyses relating to the use frequency of the end-use on time domains. The infeasibility in acquiring more frequent recordings of natural gas use restricted the gas use analysis to the HDD method. The time-keeping mechanism of the low-cost Current Cost® equipment cannot support proper synchronisation with the simultaneously measured T and RH parameters. The application of the sensor-fusion approach, which extracts information from data acquired by different sensors through automatic and computationally-intelligent methods, was thus infeasible. As a result, the ANOVA and ANFIS methods were separately applied to the indoor temperatures and power draw profile data in this study. However, these very limitations contributed to providing this research with an alternative perspective on developing suitable analysis methods for the data acquired from actual living environments.

Some future work, depending on the available research resources, can be envisaged from the following aspects:

- Improving the technological approaches to adopting cost-effective monitoring products that facilitate the application of targeted analysis methods whilst keeping the low-cost, less-intrusive and transferable features;
- Applying feasible computationally-intensive methods for the purpose of system modelling, in addition to data presentations;
- Incorporating certain building-related aspects, such as the improvement of building simulation, building assessment, and energy audit methods;
- Using sociological surveys to triangulate major findings from field monitoring and data analysis;
- Introducing extra research perspectives, such as the price-related rebound effect.

Chapter 10: Conclusion

Aiming to investigate energy-related occupancy activities in actual residential buildings, this study adopted a mixed methods research approach, which features qualitative and quantitative strengths, in the processes of data acquisition and analysis. A case-study based research method was applied in the research design, in which two case study groups featuring different building characteristics and household profiles were purposefully selected. The HHP case study was conducted in the autonomous community of the Hockerton Housing Project, Ltd. (HHP) in Southwell Nottinghamshire. The HHP is among the first multi-dwelling, earth-sheltered, self-sufficient ecological housing developments constructed in the UK. The three monitored households featured different family profiles, including a single occupant, an adult couple, and a young couple with children. The NCH case study was conducted in two conventionally-built and identically-retrofitted social houses, which are home to two families composed of pensioners. Long-term and longitudinal monitoring schemes were configured and deployed in the case study houses. The low-cost, less-intrusive, and transferable monitoring techniques were proven to have effectively bridged the identified research gap. Most existing households cannot be covered by projects requiring major investment, such as the Retrofit for the Future (RFF) and Building Performance Evaluation (BPE) programmes of the Technology Strategy Board (TSB). The monitoring and analysis techniques in this study can be effectively and conveniently applied to these households for low-cost investigations of energy-related occupancy activities.

The major conclusion points of this empirical research are:

- Conducting a cost-effective study on energy-related occupancy activities on the scale of this study was proven to be feasible by applying long-term and longitudinal monitoring approaches;

- The socio-technical characteristics of the research topic 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;
- Improvised problem-solving techniques are important to manage low-cost monitoring schemes. For example, the electromagnetic induction principle was applied to cost-effectively separate the power profiles of PV microgeneration from that of house use in the NCHB case study house;
- Effective pre-processing procedures are important to manage the incomplete or flawed raw data from field measurements;
- Appropriate data analysis methods that suit the features of acquired and processed data need to be widely sourced from multidisciplinary research fields, such as Statistics and Artificial Intelligence (AI) in this study;
- According to the specific analysis requirements, selected analysis methods need to be rationally tailored for the research context. One example in this study is the unconventional application of ANOVA to groups that are known to

be different. The other example is the use of methodological trials using ANFIS to inspect interrelationships of end-use power draws;

- There is huge potential for some commonly applied building assessment methods, such as the Standard Assessment Procedure (SAP) and Reduced Standard Assessment Procedure (RdSAP) that are used to produce Energy Performance Certificates (EPCs), 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;
- A potential exists for energy savings from the perspective of altering energy-related occupancy activities. For example, the two identically retrofitted NCH homes that featured the same built form and household profiles had an actual energy use ratio ranging from 1.2 to 2.4 in different monitoring seasons.

In general, this empirical study has made knowledge contributions from practical and methodological aspects, including the low-cost and transferable monitoring techniques, the multidisciplinary data acquisition approaches, and the methodological trials of algorithm-based methods. The evidential results and findings in this study have the potential to influence a wide range of building-associated fields through knowledge transfer and dissemination jointly conducted with the project partners.

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<u>Appendix</u>

Appendix 1 An example of the design of manually recorded occupancy diaries in a monitored home

Time	Kettle		Microwave Starting time & duration	Washing Machine		Tumble dryer		Dishwasher		Entertainment		Shower or Bath Starting time & duration	Other (Hoovers, carpet cleaner, etc.)
	Starting time & duration	Water amount		Temp & other setting	Start & duration	Temp & other setting	Start & duration	setting	Start & duration	type	Start & duration		
05am – 06am													
06am – 07am													
07am – 08am													
08am – 09am													
. . .													
08pm – 09pm													
09pm – 10pm													
10pm – 11pm													
11pm – 12pm													

Note: The appliances vary among the monitored homes. The diary is in an hourly format that covers 20 hours per day, from 05:00 to 24:00.

Appendix 2 Acknowledgement letter issued by the Hobo® logger supplier regarding the contribution to product development of the latest series of compact loggers

Measurement Systems Limited
16 Kingfisher Court
Newbury, Berkshire RG14 5SJ

Telephone: +44 (0)1635 576800
Fax: +44 (0)1635 31023
E-mail: info@measys.com
Web : http://www.measurementsystems.co.

To: Jia (Michelle) Cui and Professor Steve Goodhew

Dear Michelle & Steve,
This letter is to acknowledge the helpful feedback and comments resulting from the use of Hobo Data Loggers during your research into energy savings and occupancy patterns.

We are grateful for all feedback, which we discuss with the design teams. This communication may, when combined with similar responses, help to ensure future products, such as the latest Hobo UX series data loggers, provide even more information and benefits for our customers.

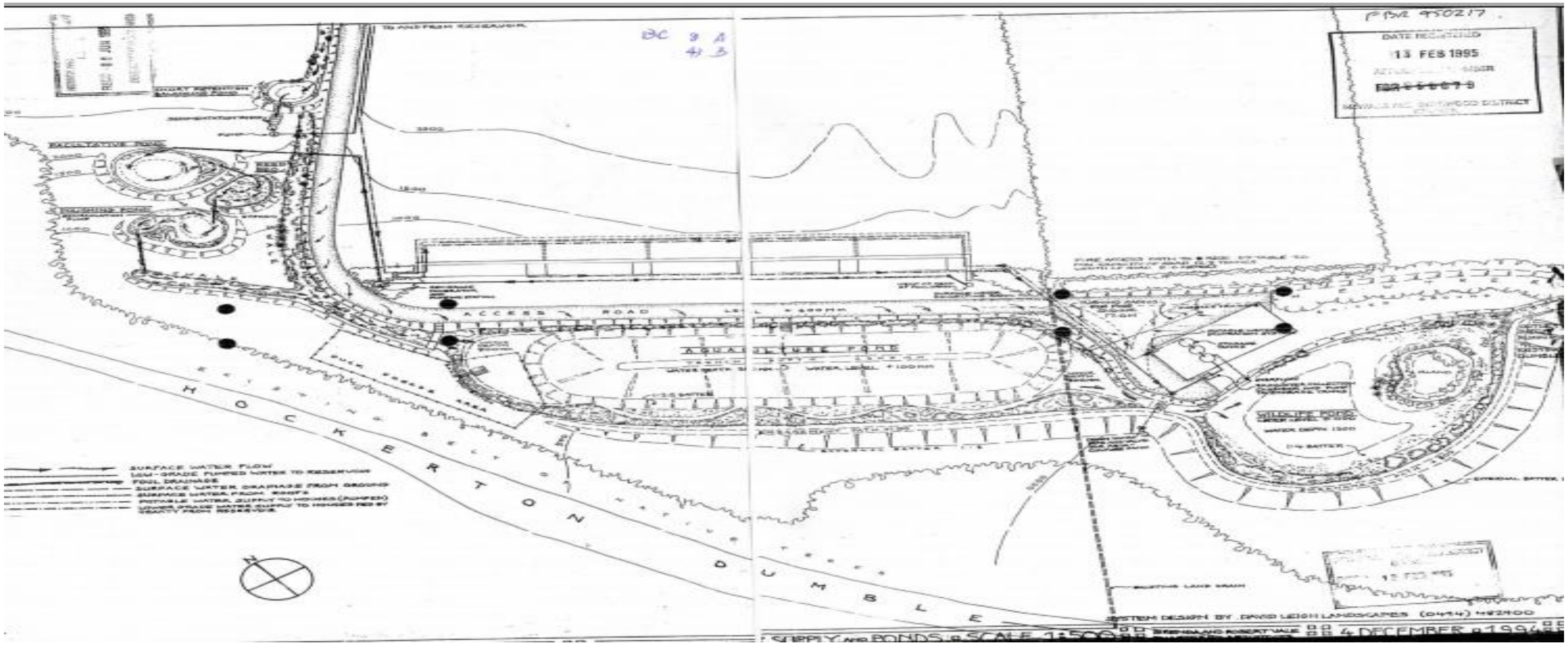
Yours faithfully

Mark Jenkins

HOBO UX90 Occupancy/Light Logger - UX90-006M

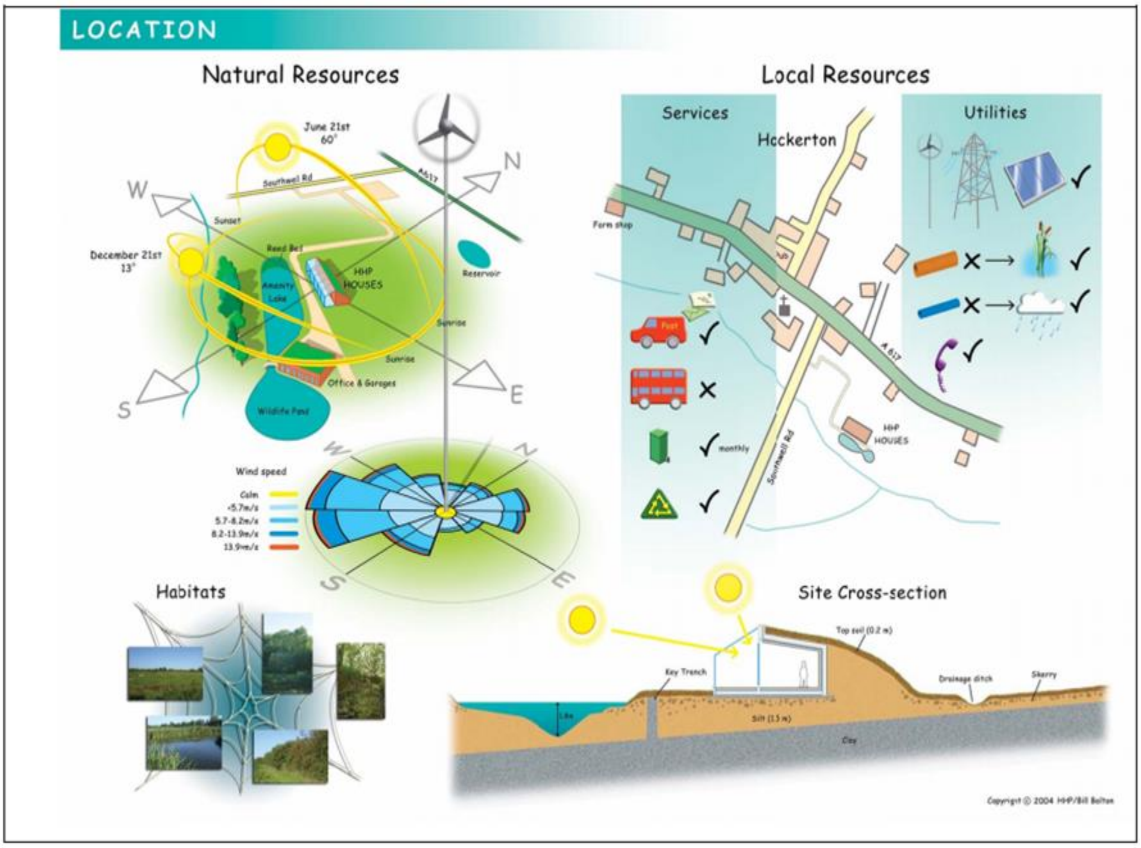
Appendix

Appendix 3 Landscape planning and water / sewage treatment of the HHP development



Landscape planning document of HHP development (courtesy of the Building Control Department in Newark & Sherwood District Council, July 2011)

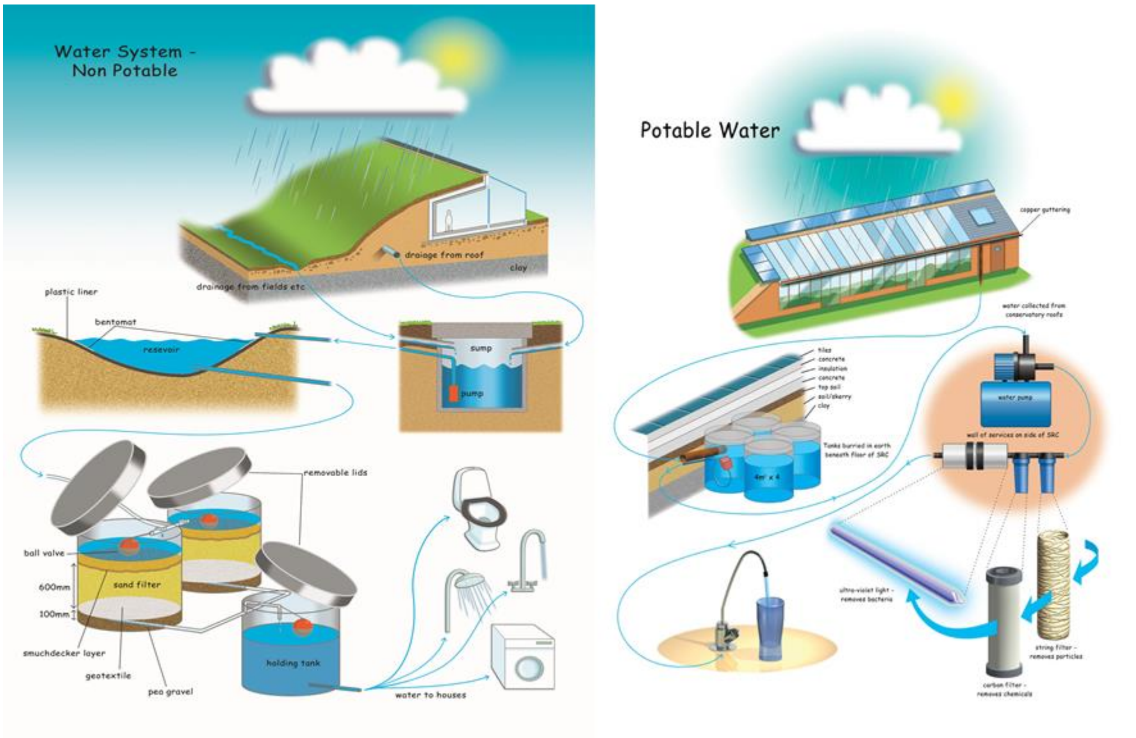
Appendix



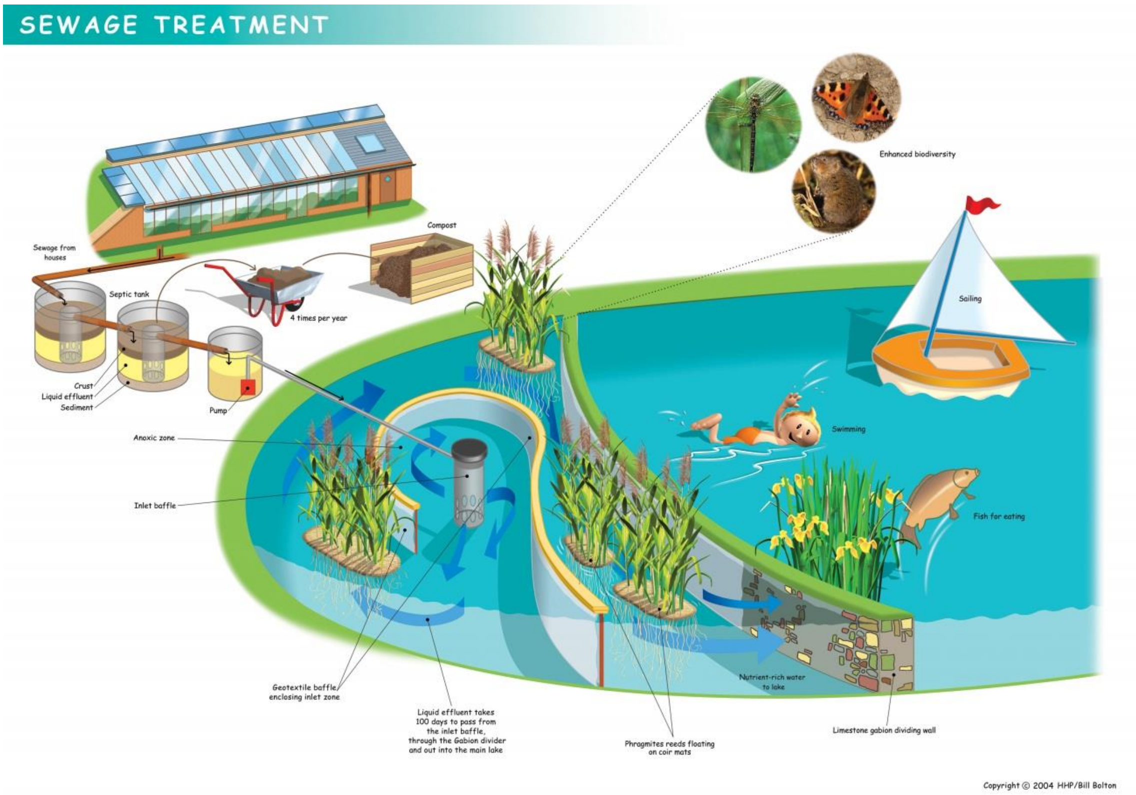
HHP site layout diagrams. Copyright© 2004 HHP/Bill Bolton.

An aerial view of the earth-covered HHP development (Source: HHP, 2006a).

Appendix



Water supply system using rainwater and surface runoff water for portable and non-portable water respectively in the HHP development. Copyright© 2004 HHP/Bill Bolton.



Sewage treatment using a reed-bed system in the HHP development. Copyright© 2004 HHP/Bill Bolton.

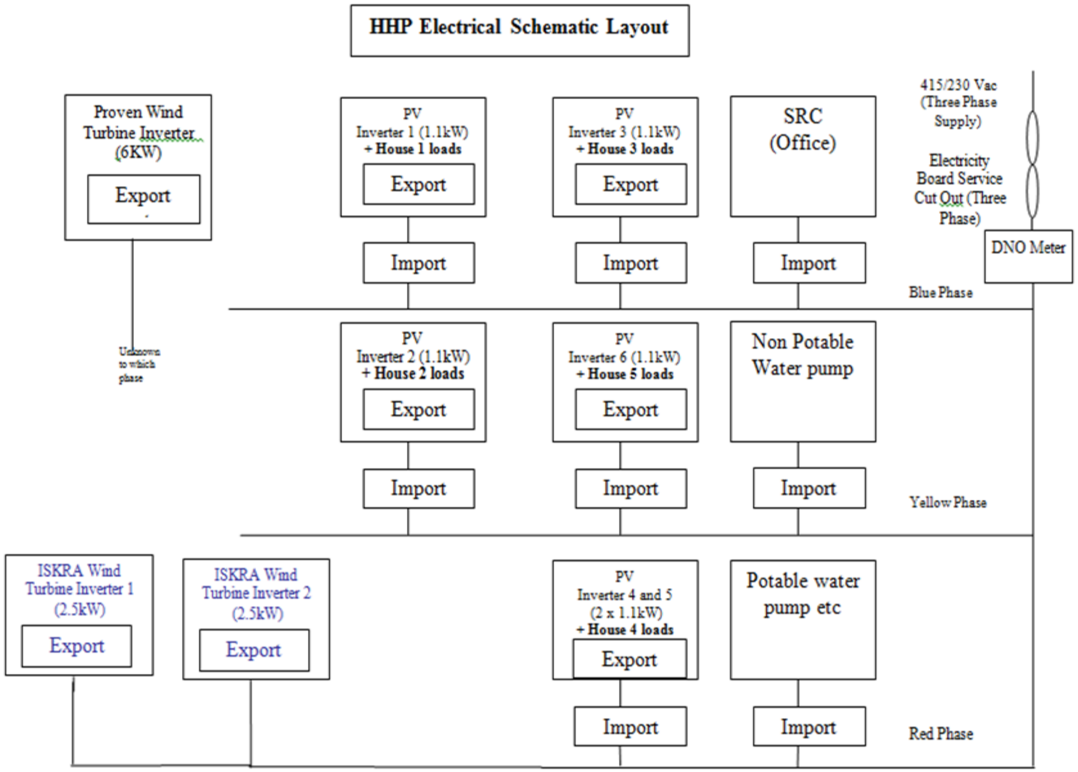
Appendix

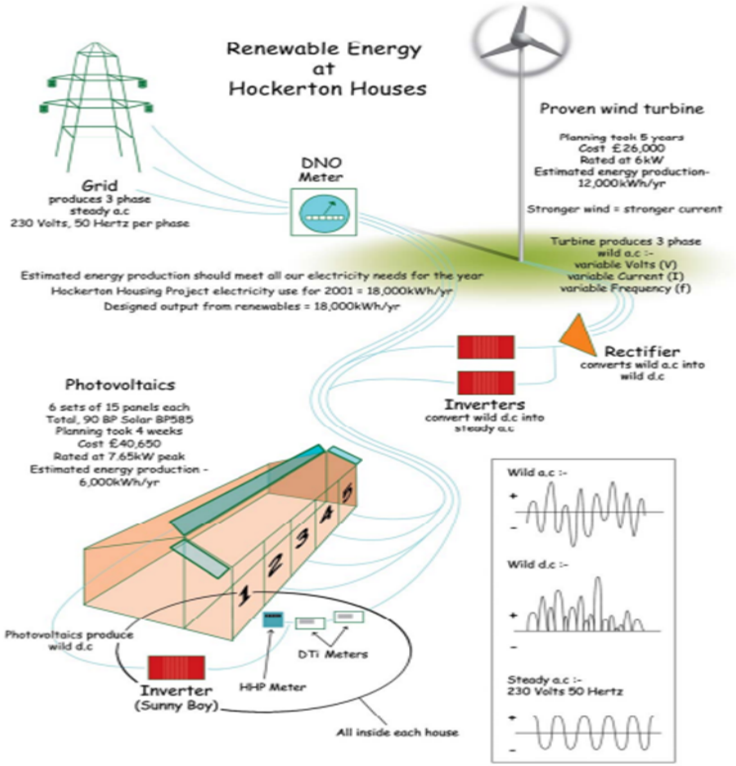
Appendix 4 Grid-linked microgeneration of the HHP development

From left to right: the sets of solar PV panels along the front parapet of the five south-facing dwellings, a set of solar PV panels down the side wall of the end-terrace dwelling, the PV inverter and main switch in a house porch area (Source: HHP, 2006c).

The three monitored houses (seven-bay center HHP3, six-bay mid-terrace HHP4, and six-bay end-terrace HHP5, PV panels, two wind turbines near to the office annex. Picture was taken from across the lake during one site visit in 2011.

Appendix

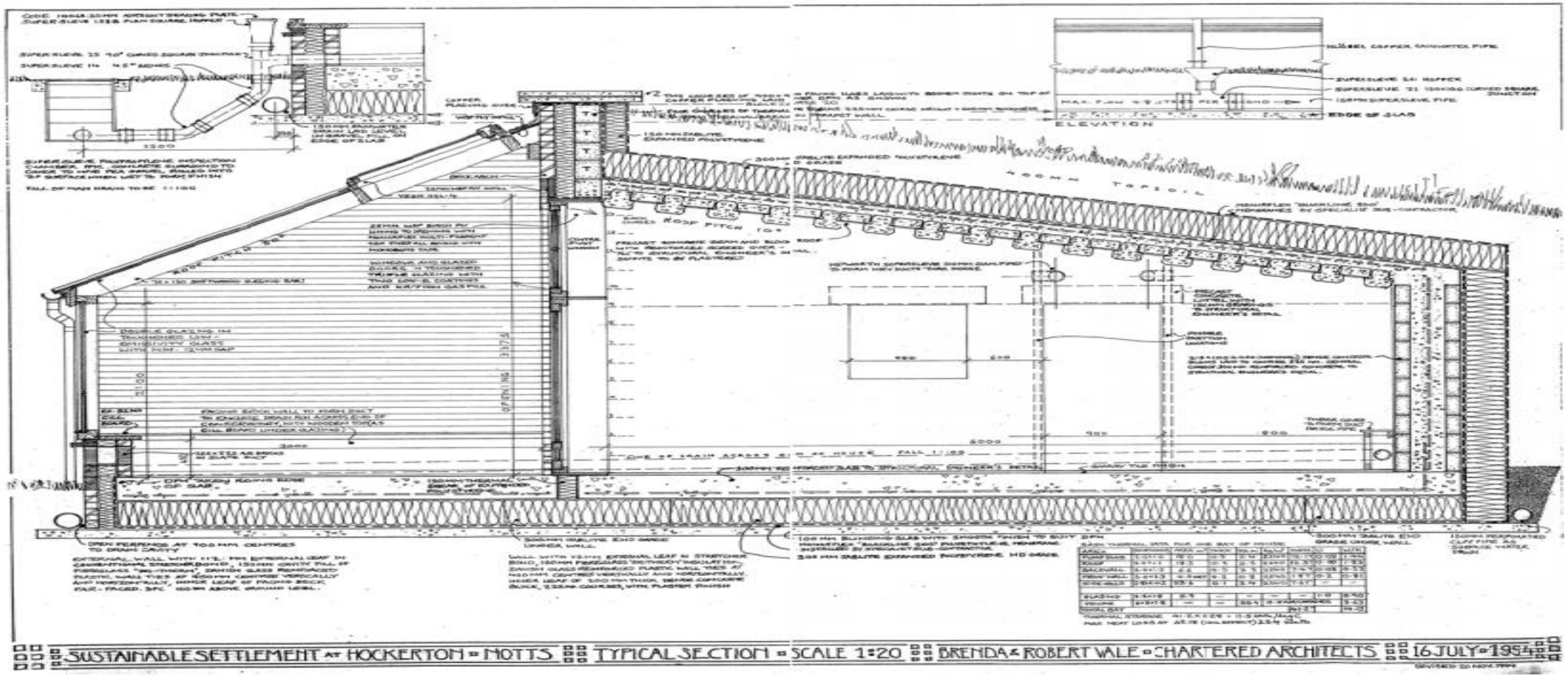




Left: the schematic layout of the electrical system of the Hockerton Housing Project (Note: for load balancing, the two inverters in HHP4 are lined to a separate AC phase together with the two wind power inverters of the second set of wind turbines and the potable water pump, etc.). Copyright© 2011 HHP/Simon Tilley. Right: demonstration of grid-linked microgeneration from the PV panels and wind turbines in Hockerton Housing Project. Copyright© 2004 HHP/Bill Bolton.

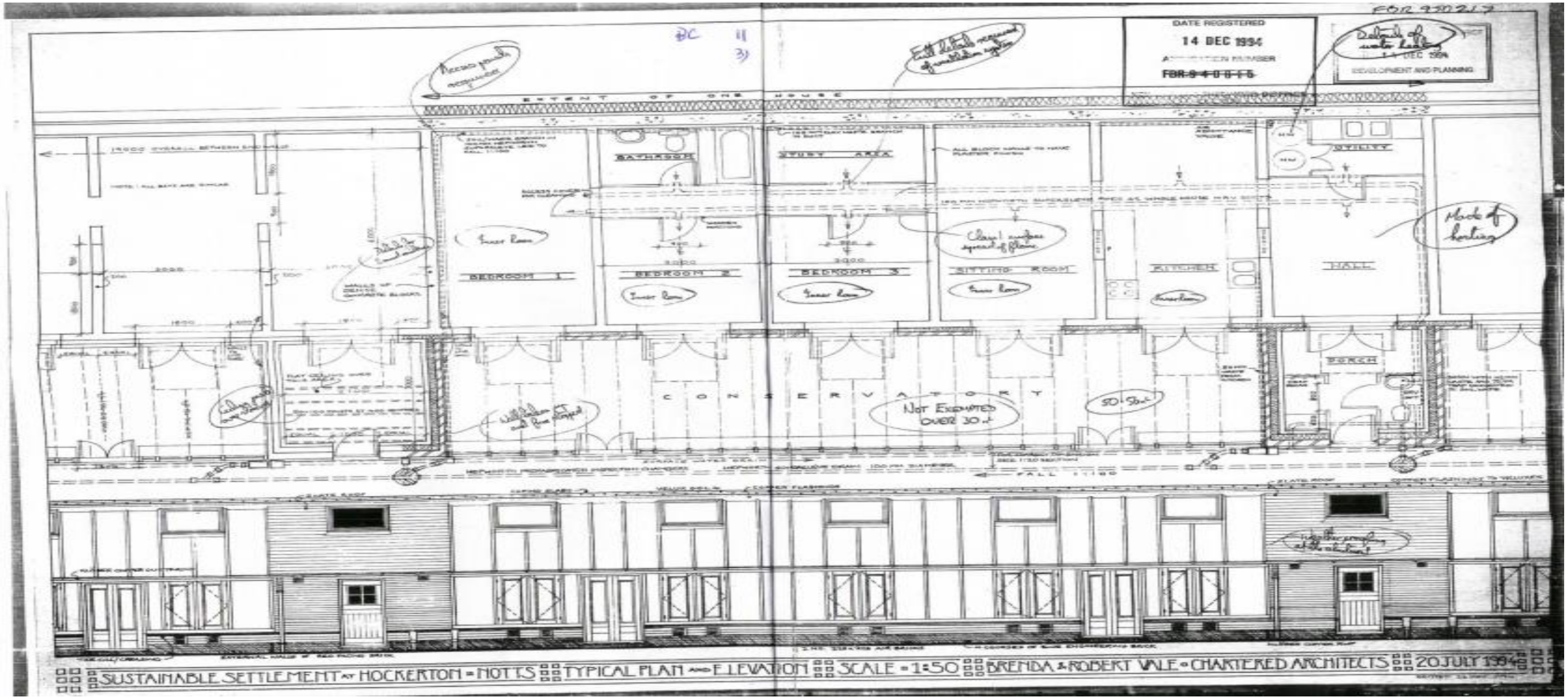
Appendix

Appendix 5 Section and plan drawings of HHP houses



The section drawing of one HHP House, showing the construction and layout infomation of the sun space and main house (Source: HHP, 2005).

Appendix

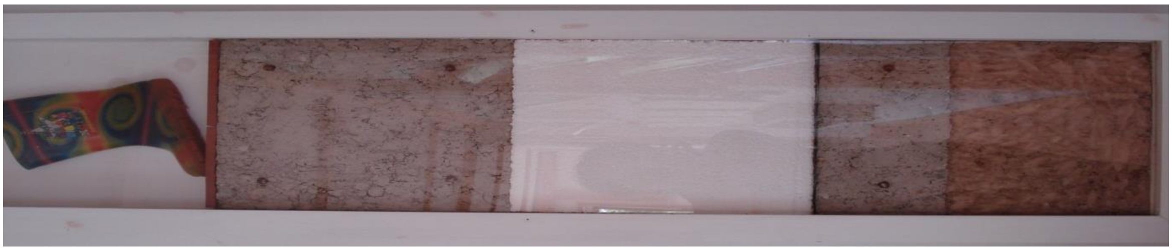


Plan drawing of a six-bay mid-terrace house with two houses on each side, showing the indoor layout, ventilation and sewage pipework (courtesy of the Building Control Department in Newark & Sherwood District Council, July 2011).

Appendix

Appendix 6 Sectional demonstration of the roof, floor, rear and end walls of HHP houses

Sectional demonstration of the concrete beam-and-block roof construction, from left to right: grass and plants, 400 mm excavated subsoil and topsoil, Geotecitile sheet (or Geofin membrane, having an outer water-pervious layer attached to 8.0 mm high flat top cones projecting from the inner waterproof layer to give a drainage space and relieve the hydrostatic pressure as a root barrier), Monaflex 250 waterproof membrane as the damp proof membrane (dpm), 250 mm polystyrene insulation, Monaflex blackline 500 dpm, 50 mm polystyrene insulation, 100 mm steel reinforced concrete, 100 mm dense concrete block, render, plaster skim, 3.2 m precast beams to span the bays. Picture scource: demonstration wall in the HHP office; information source: HHP (2005).



Sectional demonstration of the floor construction, from left to right: clay tiles, 300 mm steel reinforced concrete, 300 mm “Jablite” expanded polystyrene insulation blocks, Monaflex blackline 500 dpm, 100 mm reinforced concrete binding slab. Picture source: demonstration wall in the HHP office; information source: HHP (2005).

Sectional demonstration of the rear and side wall construction, from left to right: plaster skin, render, 100 mm dense concrete block, 300 mm steel reinforced concrete, 100 mm dense concrete block, 50 mm polystyrene insulation, Monaflex blackline 500 dpm, 250 mm polystyrene insulation, Monaflex 250 waterproof membrane as the damp proof membrane (dpm), Geotecitile sheet (or Geofin membrane, to give a drainage space and relieve the hydrostatic pressure), soil. Picture source: demonstration wall in the HHP office; information source: HHP (2005).

<u>Appendix</u>

Appendix 7 The dimension, mass, heat storage capacity of concrete and blocks for a 6-bay HHP house

1) Thermal mass calculations (Source: HHP, 2005)

	Horizontal Area (m^2)	Thickness(m)	Volume(m^3)	Density (kg/m^3)	Mass (tonne)	Sp. Heat (kWh/t.k)	Heat (kWh/k)
CONCRETE							
Roof (mix of concrete & block)	127	0.25	31.75				
Slab	127	0.30	38.1				
Wall (rear)	43.2	0.30	13.0				
Sub-total			82.9	2100	174	0.28	48.7
BLOCKS							
Wall (rear)	43.2	0.20	8.6				
Wall (front)	32	0.1	3.2				
Wall (inter)	99	0.20	19.8				
Sub-total			31.6	1900	60	0.28	16.8
TOTAL					**237**		**65.5**

Therefore for 1K temperature change throughout the mass of concrete, 65.5kWh will be released or absorbed

Total weight of concrete in a house above the base insulation is calculated in Appendix 1 =**237 tonne**

Weight of soil on roof = Roof area X depth of soil X density saturation
= $121m^2$ X 0.4m X $1200kg/m^2$ = **58 tonne**

Therefore Total Weight = 237 + 58 = **295tonne**

Mass/floor area = 295,000 Kg / 127 m^2 **= 2323 Kg/ m^2 = 2.3 tonne/ m^2**

2) Heat loss due to ventilation requirement for a four-people family in a six-bay Hockerton house (Source: HHP, 2006b). The heat loss due to ventilation is the maximum estimation under unlikely conditions.

Minimum fresh air for 4 people at 8 litre/sec.person:
= 4people* 8 litre/s.person * 3600s/h * 1/1000litre/m^3 = $115m^3/h$

Volume of house = 6bays*3m*6.3m*2.8m (average height) = $318m^3$

Number of airchanges = 115/318 = 0.36a.c/h

Allow heat exchanger efficiency of 60%[1], then 40% of the fresh air is required to be heated

Ventilation heat load = $0.33NVt_d$
= $0.33*0.36*318m^3*22K^2*40/100$ = 332W

[1]Manufacturers suggest a better efficiency of 70-80%. Also the ventilation units are not run continuously over a 24 hour cycle.
[2] A temperature difference of 22^0C is an extreme and likely to only occur for short periods!

3) Effective concrete surface area of the Hockerton house (Source: HHP, 2006b)

Concrete surface area of one bay	m^2
Floor	18
Ceiling	20
Walls (2 * 6 * 2.7)	32
Back wall	7
Front wall (3.7 * 3 * 0.45)	5
Total	**82**

Surface area of 6 bays (equivalent to typical HHP home) = 6 * $82m^2$ = $492m^2$

Specific surface area = $82m^2/18m^2$ = $4.6m^2$ surface/m^2 floor

Appendix

4) Heat loss due to building fabrics (Source: HHP, 2006b)

Item	Dimensions (m*m)	Area m^2	Thickness (m)	K (W/mK)	R (m^2K/W)	U (W/m^2K)	UA W/K	T_d (K)	Heatloss (W)	% heat loss of total
ROOF										
Concrete	6.3*19.2	121	0.33	1.3	0.25					
Insulation	6.5*19.2	125	0.3	0.034	8.2					
Surface					0.12					
					R_T=9.19	**0.11**	13.8	20	276	**14.3**
SLAB										
Concrete	6.3*19.2	121	0.3	1.3	0.23					
Insulation	6.5*19.2	125	0.3	0.035	8.82					
Surface					0.12					
					R_T=9.17	**0.11**	13.8	10	138	**7.2**
WALL, rear										
Concrete	2.3*19.2	43.2	0.25	1.3	0.19					
Blocks	2.3*19.2	43.2	0.2	1.0	0.2					
Insulation	2.4*19.2	46.1	0.3	0.035	8.82					
Surface					0.12					
					R_T=9.33	**0.11**	5.1	10	51	**2.7**
WALL, front										
Brick	3.38*1.4*6	28.4	0.112	0.84	0.13					
Insulation	3.38*1.4*6	28.4	0.15	0.034	4.41					
Block	3.38*1.4*6	28.4	0.20	1.0	0.20					
Surface	0.12*2				0.24					
					R_T=4.86	**0.21**	6	20	120	**6.2**
								Sub-Total (opaque)	585	**30.4**
GLAZING	3.38*1.85*5	30.4				**2.0**	60.8	20	1216	**63**
	3.38*1.8*1	6.1				**2.0**	12.2	10	122	**6.3**
								Sub-Total (glass)	1338	**69.6**
								TOTAL FABRIC	**1923**	

The dimension difference in the two tables results from the measurement criteria. To estimate the maximum heat loss values, indoor temperature is t_i set at 20 ºC, outside temperature $t_{o\ roof}$ at 0 ºC by ignoring the 400 mm soil on the roof, temperature in the porch area in front of the landing hall at 10 ºC (the reason for one glazing area having T_d at 10 ºC due to the buffer zone), temperature in the conservatory $t_{o\ conservatory}$ at 0 ºC (although it rarely drops to such a low temperature even in the coldest winter), and external surface temperature on wall and floor slab $t_{o\ wall\ and\ slab}$ at 10 ºC. Therefore, temperature differences: t_{droof} is 20 ºC, $t_{d\ wall\ and\ slab}$ is 10 ºC, and $t_{d\ conservatory}$ is 20 ºC. U-values in the table are maximum instantaneous estimations under unlikely conditions by assuming the earth-sheltered house is subject to weather. (Source: HHP, 2006b).

5) Heat retaining capability of the thermally heavy Hockerton house (Source: HHP, 2006b)

Heat storage = 65.5 kWh / K
Maximum rate of heat loss = Fabric losses + Ventilation losses = 1923 W + 332 W = 2.255 kW
Maximum heat loss / day = 2.255 kW x 24 h/day = 53 kWh / day
Endurance time of temperature drop by 1 K = 65.5 kWh/K / 53 kWh/day = 1.2 day / K
The result is based on maximum heat loss rate without heat gains from solar radiation and occupancy.

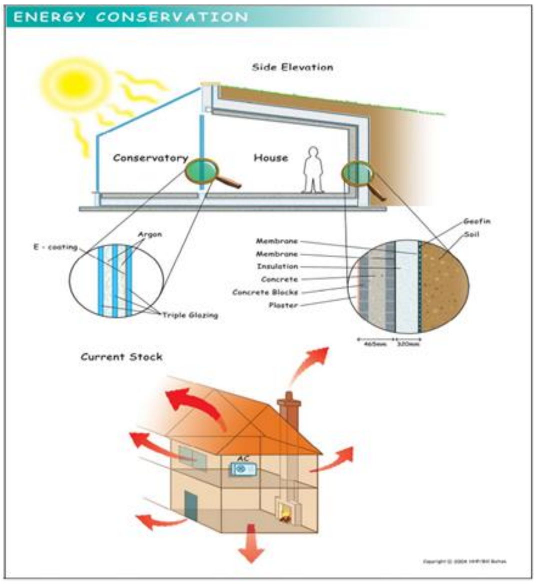
In imperceptibly still air with a wind velocity below 0.1 m/s, the convected heat transfer coefficient is around 3 W/m^2K. The rate of heat transfer between air and concrete is 3.0 W/m^2K x 492 m^2 = 1.5 kW/K.
Therefore, the time over which 1.0 K temperature variation occurs is 65.5 kWh/K / 1.5 kW/K = 1.8 days.

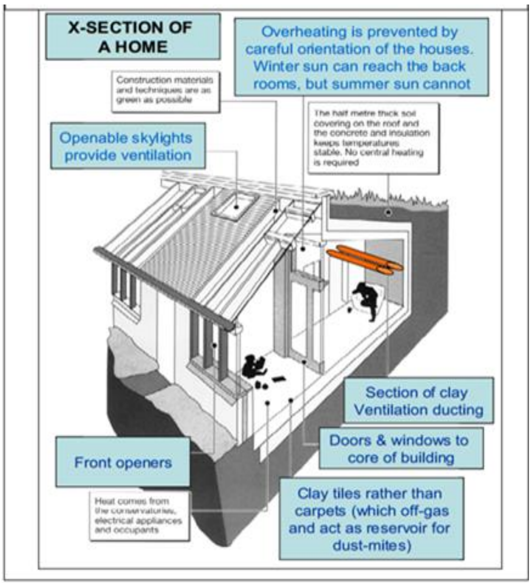
6) Solar gains in a six-bay Hockerton house (Source: HHP, 2006b)

Solar intensity * Glazing area (five sets excluding the porch area) * Frame factor * Transfer factor * gaining hour per day = 400 W/m^2 x 30.4 m^2 x 0.7 x 0.3 x 1.5 h/day = 3.83 kWh/day
To be converted to an equivalent gaining rate under steady state: 3803 Wh/day x 1/24 day/h = 160 W

Appendix

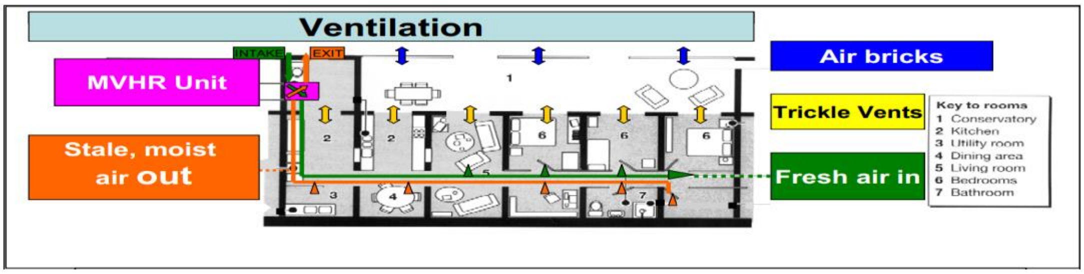
Appendix 8 Ventilation and energy conservation of HHP houses



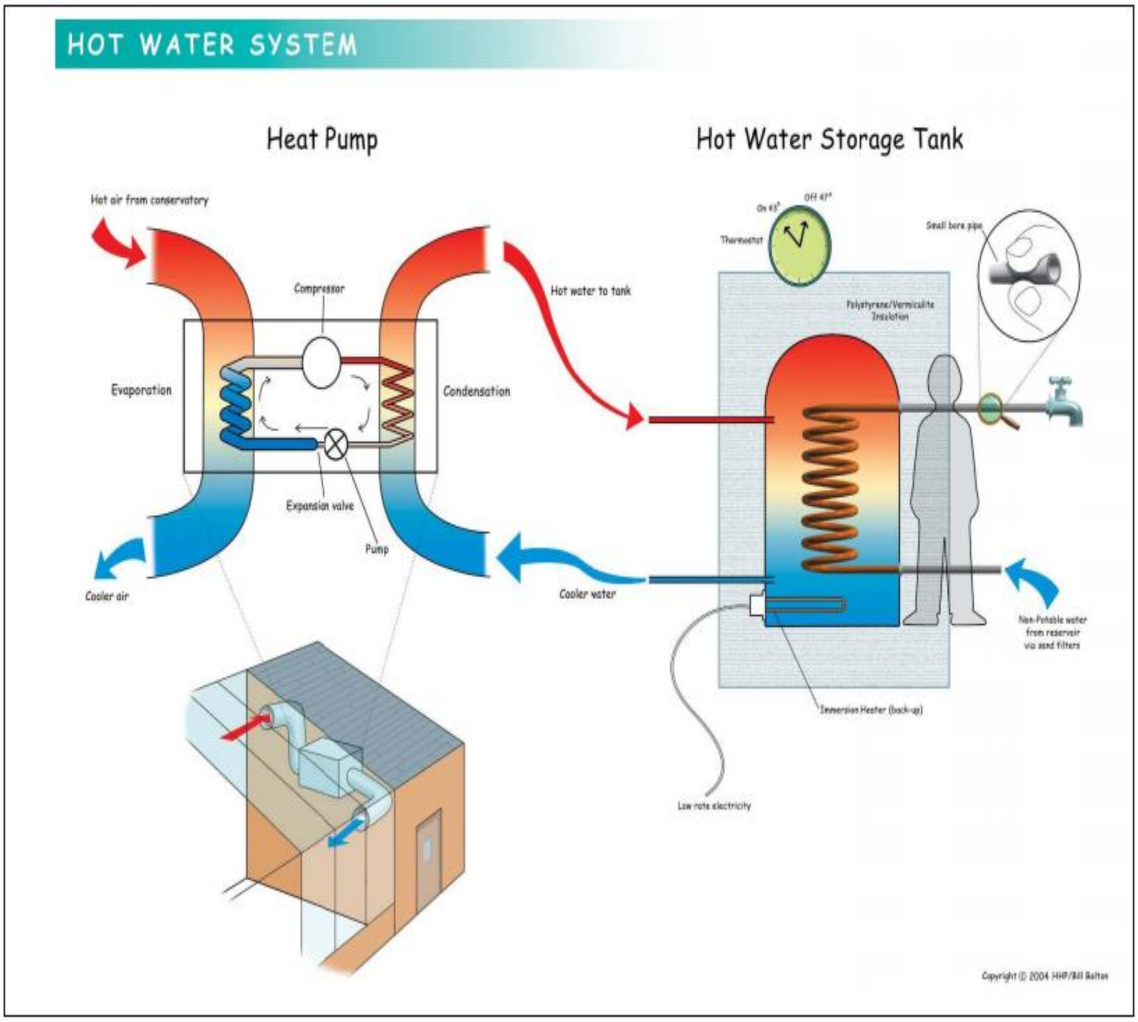


Left: the heat gains and loss of the HHP Houses compared to a conventional house. Right: the demonstration of the ventilation and energy conservation features of the HHP houses. Copyright© 2004 HHP/Bill Bolton.

Left: the natural ventilation in summers using the French windows, skylight window, and external windows in the sun space of the HHP Houses. Right: the inlet and outlet clay ductwork, 100 mm in diameter, of the mechanical ventilation and heat recovery (MVHR) system in one HHP house. Below: the demonstration of the ventilation system in HHP Houses. (Source: HHP, 2006c)



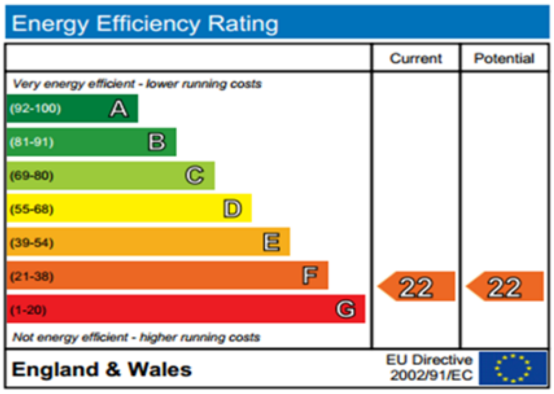
Appendix 9 Demonstration of the hot water system of HHP houses

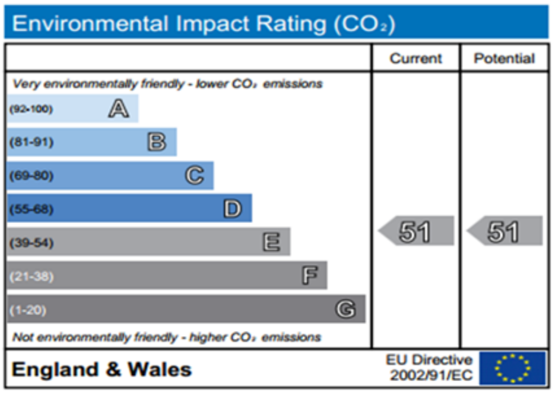


The shell-and-coil exchanger of the indirect hot water system. The Air-water heat pumps that were designed for the hot water system are not in use anymore. The immersion electric heaters are used in the 500 ml Hotsi® tanks at the moment for the hot water use of the monitored houses. Copyright© 2004 HHP/Bill Bolton.

Appendix

Appendix 10 Excerpt of the Energy Performance Certificate (EPC) produced for a HHP house in 2008





The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating the more energy efficient the home is and the lower the fuel bills will be.

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.

Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home

	Current	Potential
Energy use	377 kWh/m² per year	377 kWh/m² per year
Carbon dioxide emissions	7.9 tonnes per year	7.9 tonnes per year
Lighting	£88 per year	£88 per year
Heating	£1879 per year	£1879 per year
Hot water	£202 per year	£202 per year

Summary of this home's energy performance related features

The following is an assessment of the key individual elements that have an impact on this home's performance rating. Each element is assessed against the following scale: Very poor /Poor / Average / Good / Very good.

Elements	Description	Current performance Energy Efficiency	Current performance Environmental
Walls	Solid brick, with external insulation	Good	Good
Roof	Pitched, insulated (assumed)	Average	Average
Floor	Solid, limited insulation (assumed)	-	-
Windows	Fully double glazed	Average	Average
Main heating	Portable electric heaters assumed for most rooms	Very poor	Poor
Main heating controls	No thermostatic control of room temperature	Poor	Poor
Secondary heating	Room heaters, wood logs	-	-
Hot water	Electric immersion, off-peak	Poor	Poor
Lighting	Low energy lighting in 91% of fixed outlets	Very good	Very good
Current energy efficiency rating		F 22	
Current environmental impact (CO_2) rating			E 51

Appendix

Appendix 11 The NCH case study houses and the Quikbild® timber-frame built form

Quikbild

Manufacturers: Walter Llewellyn & Sons Ltd, Quikbild Homes Ltd

Alternative names: Llewellyn, Llewellyn Shells

Designers: R Stanley, L R Pope

Period built: 1965–80

Number built: 12,000

IDENTIFICATION CHARACTERISTICS

Bungalows and 2- or 3-storey semi-detached and terraced houses.
Medium pitch gable or mansard roof covered with tiles, or flat roof covered with bituminous felt.
External walls of brick throughout or to first floor level, with tile hanging, profiled aluminium or plastics sheets or horizontal timber boarding above.
Some dwellings have 2- or 3-storey feature panel of horizontal timber boarding or plastics weatherboarding between windows.
Some dwellings have horizontal timber boarding or plastics sheet below some ground floor windows.
Some dwellings have single storey flat roof entrance porch or pitched canopy over front door.

REFERENCES

BRE Report BR 284
CIBSA 1970
NBA Certificates February 1966, May 1967

NOTES FOR SURVEYORS

Cracks in brick external walls.
Minor looseness of wall ties.
Movement of window sills.
Internal surface condensation.
Breakdown of foam insulation in external wall cavities.
Corrosion of foil-backing to plasterboard linings.
Minor corrosion of bracing straps.
Inaccurate nailing of plywood sarking.

The system was also used for flats.

CONSTRUCTION

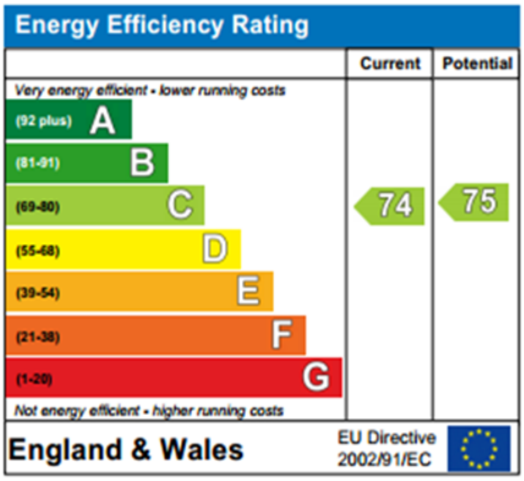
Substructure: Concrete strip footings. Brick underbuilding **[1]**. DPC.
External walls: Platform frame construction. Storey height timber frame panels based on 4' module **[2]** cross braced with metal strapping **[3]** and sheathed externally with bitumen-impregnated fibreboard **[4]** overlaid with bituminous felt **[5]** and directly clad with brick **[6]**. Lined with foil-backed plasterboard **[7]**. Mineral fibre insulation between frame studs **[8]**.
Separating wall: Timber frame cavity wall lined with 3 layers of plasterboard. Mineral fibre insulation between frame studs.
Partitions: Timber stud lined with plasterboard.
Ground floor: Concrete.
Upper floors: Plywood on timber joists.
Ceilings: Plasterboard.
Roof: Timber trusses, bituminous felt and tiles. Mineral fibre insulation at ceiling level.

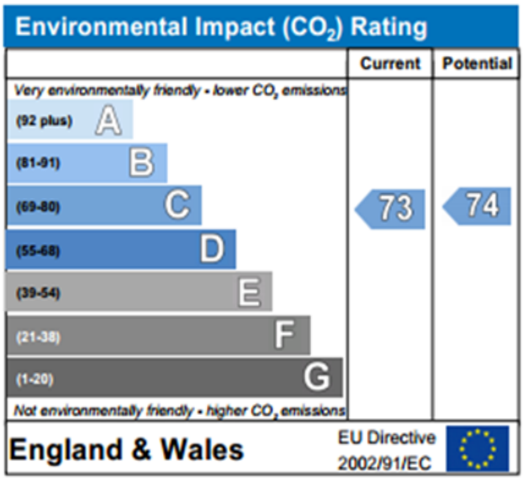
VARIANTS

Concrete underbuilding.
Foam insulation in external wall cavities.
Roof of plywood sarking on timber purlins.
Mansard roof.
Upper storey external walls separately clad with tile hanging, horizontal timber boarding or aluminium or plastics sheets on timber battens.
External sheathing of plywood or bitumen-impregnated fibreboard.
Upper storey ceilings of foil-backed plasterboard.
Ceilings of plywood.

The photos were taken by the researcher on 5 August 2011. The timber-frame building type of this council property is Quikbild (source: Harrison, et al. (2004), pp. 840-841. Permission to reproduce this figure has been granted by the Building Research Establishment (BRE) Bookshop.)

Appendix 12 Excerpt of the Energy Performance Certificate (EPC) produced for one post-retrofit NCH case study house





The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating the more energy efficient the home is and the lower the fuel bills are likely to be.

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.

Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home

	Current	Potential
Energy use	177 kWh/m² per year	174 kWh/m² per year
Carbon dioxide emissions	2.9 tonnes per year	2.8 tonnes per year
Lighting	£72 per year	£54 per year
Heating	£452 per year	£456 per year
Hot water	£145 per year	£145 per year

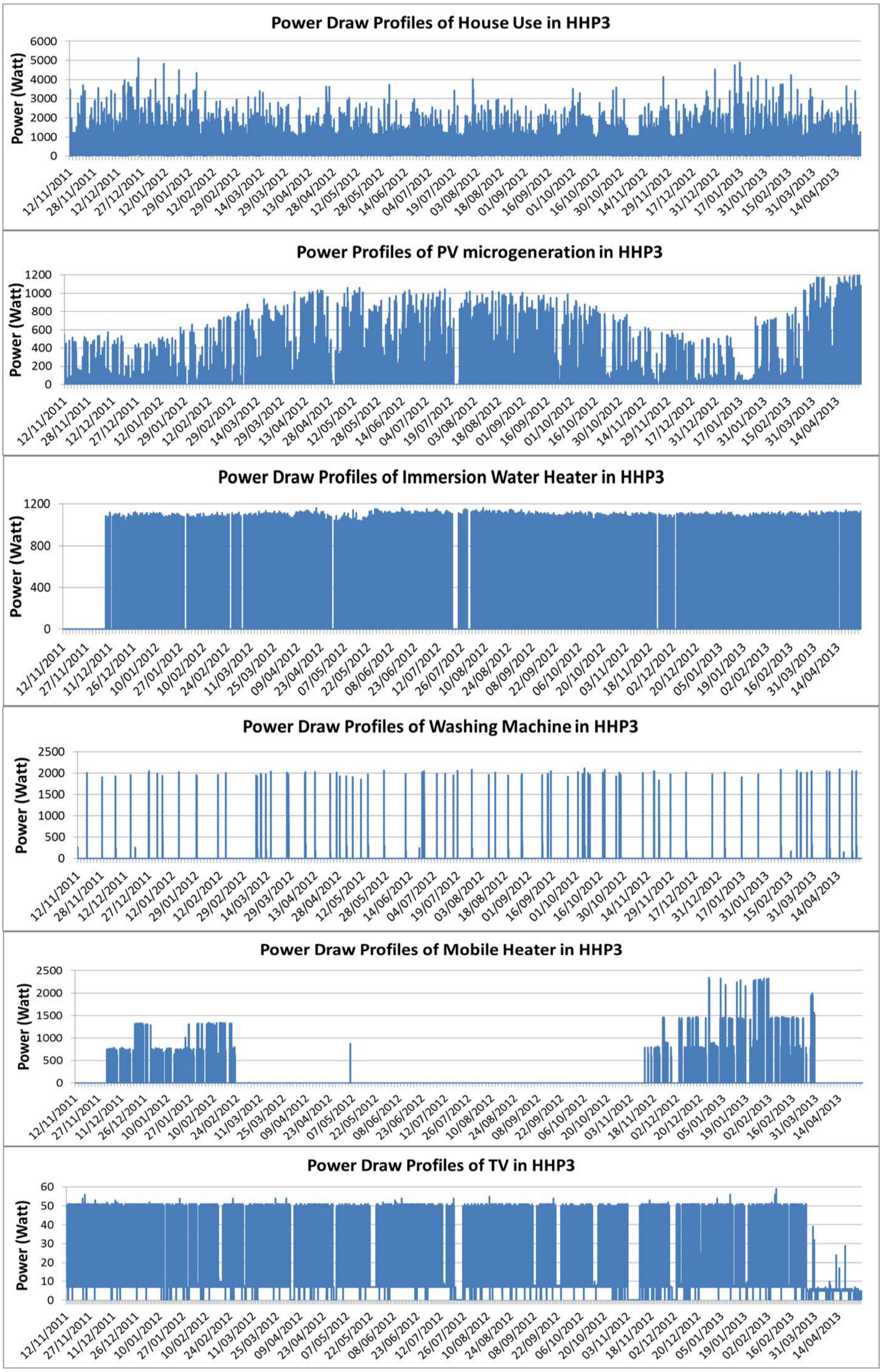
Summary of this home's energy performance related features

The table below gives an assessment of the key individual elements that have an impact on this home's energy and environmental performance. Each element is assessed by the national calculation methodology against the following scale: Very poor / Poor / Average / Good / Very good. The assessment does not take into consideration the physical condition of any element. 'Assumed' means that the insulation could not be inspected and an assumption has been made in the methodology based on age and type of construction.

Element	Description	Current performance	
		Energy Efficiency	Environmental
Walls	System built, as built, partial insulation (assumed)	Average	Average
Roof	Pitched, 250 mm loft insulation	Good	Good
Floor	Solid, no insulation (assumed)	-	-
Windows	Fully double glazed	Good	Good
Main heating	Boiler and radiators, mains gas	Good	Good
Main heating controls	Programmer, room thermostat and TRVs	Good	Good
Secondary heating	Room heaters, electric	-	-
Hot water	From main system	Good	Good
Lighting	Low energy lighting in 66% of fixed outlets	Good	Good
Current energy efficiency rating		**C 74**	
Current environmental impact (CO_2) rating			**C 73**

Appendix

Appendix 13 Power profiles of house use, PV microgeneration, and IAM-monitored appliances in HHP3 over the monitoring period 12/11/2011 to 06/05/2013



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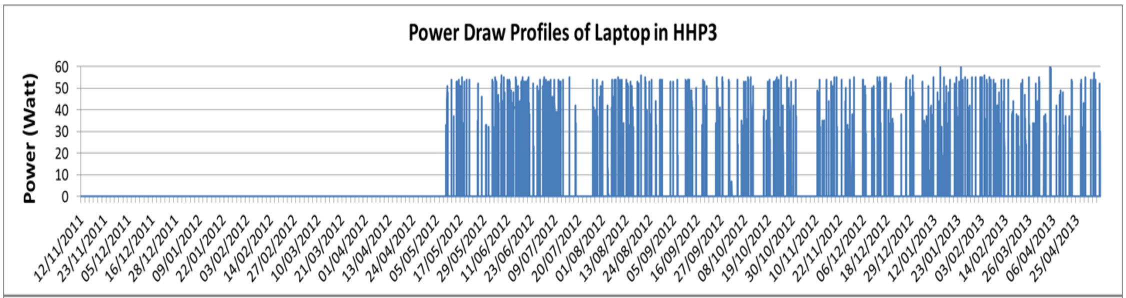
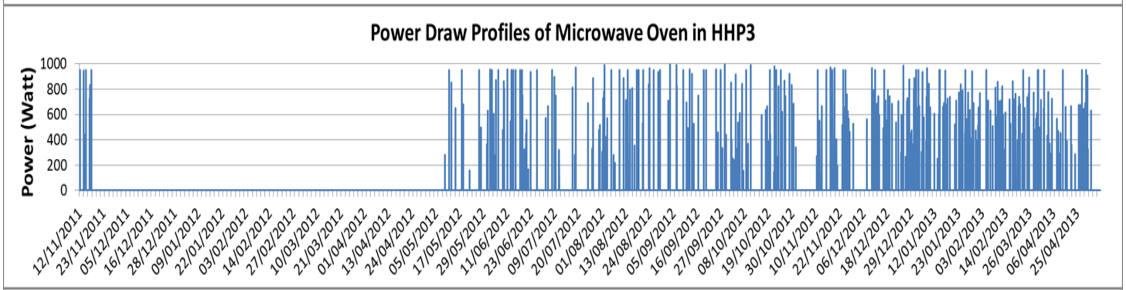
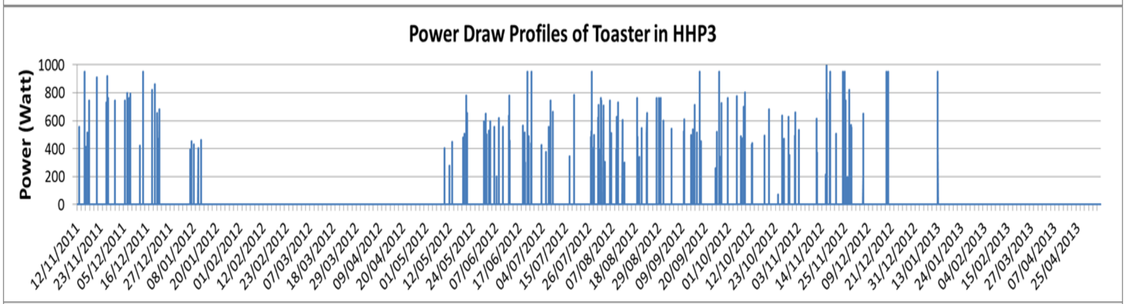
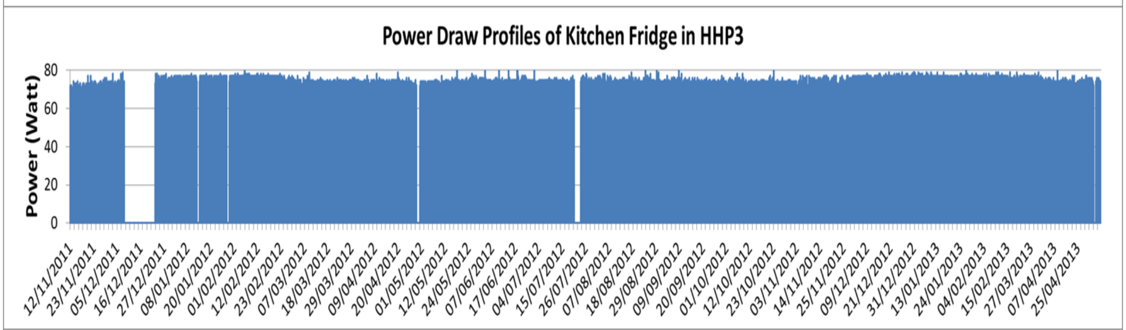
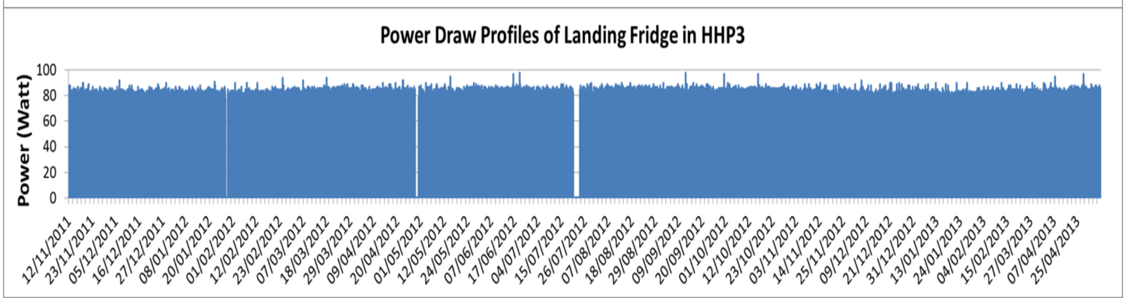
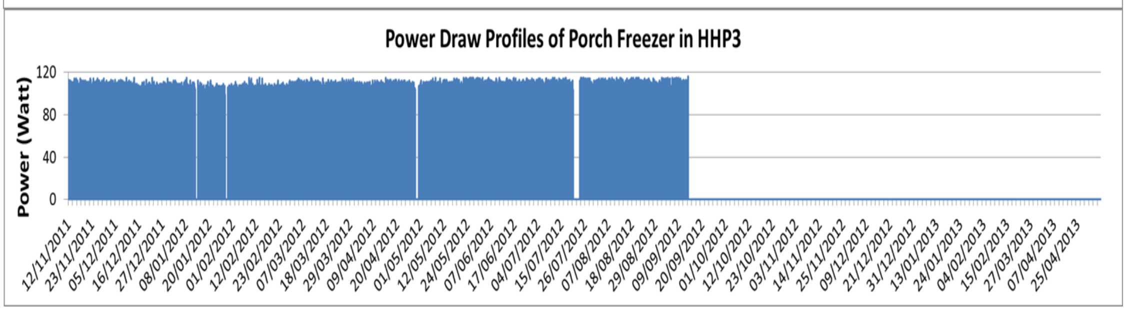

Power Draw Profiles of Laptop in HHP3
Power (Watt)


Power Draw Profiles of Microwave Oven in HHP3
Power (Watt)


Power Draw Profiles of Toaster in HHP3
Power (Watt)

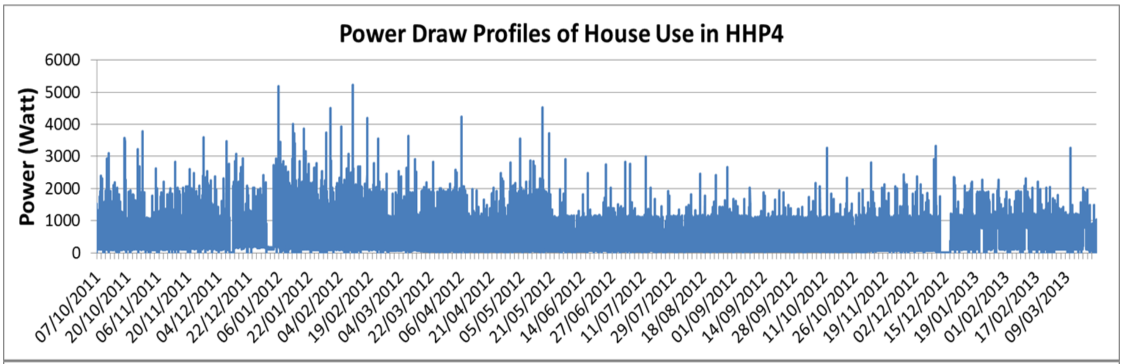

Power Draw Profiles of Kitchen Fridge in HHP3
Power (Watt)

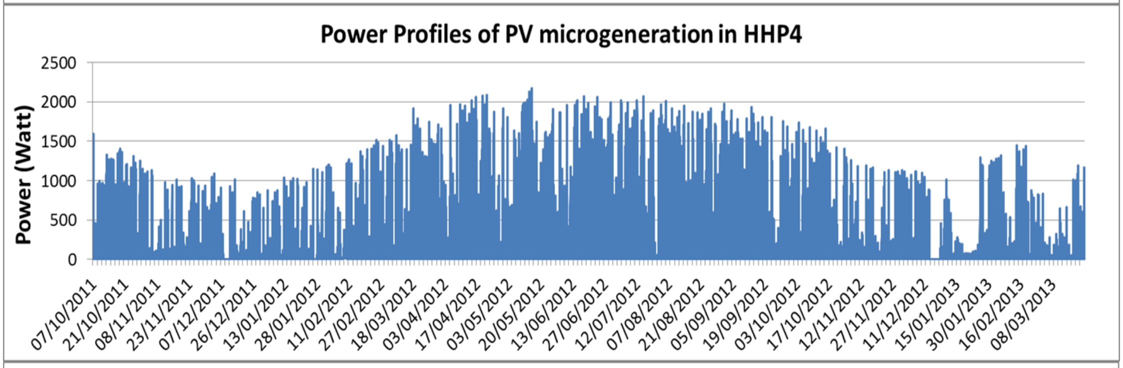

Power Draw Profiles of Landing Fridge in HHP3
Power (Watt)

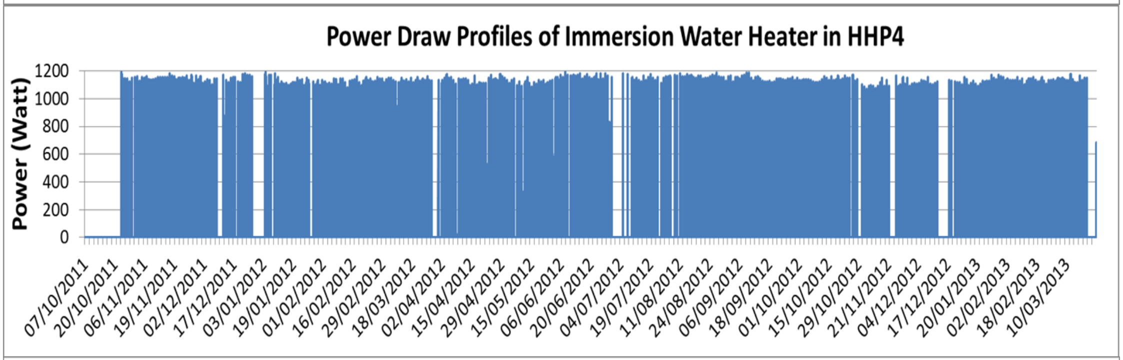

Power Draw Profiles of Porch Freezer in HHP3
Power (Watt)

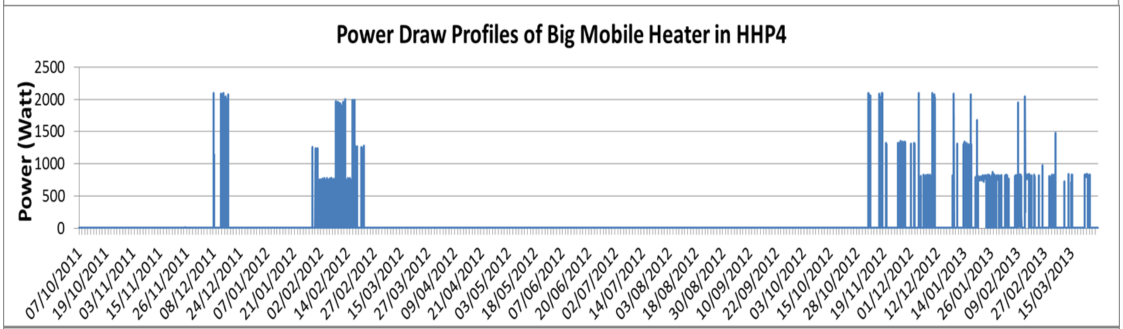
Appendix

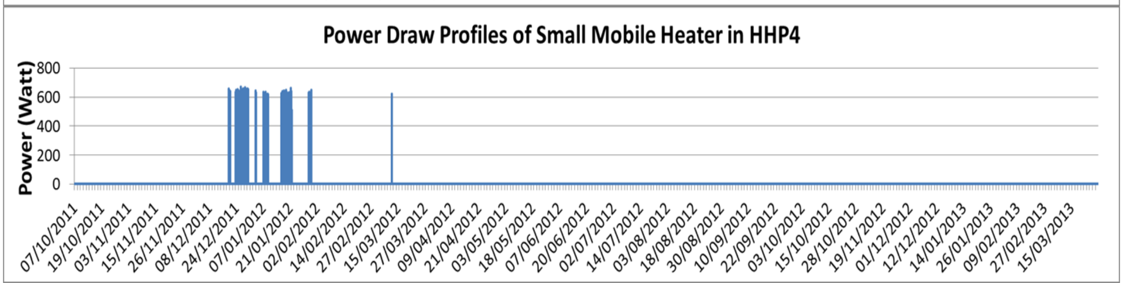
Appendix 14 Power profiles of house use, PV microgeneration, and IAM-monitored appliances in HHP4 over the monitoring period 07/10/2011 to 02/04/2013











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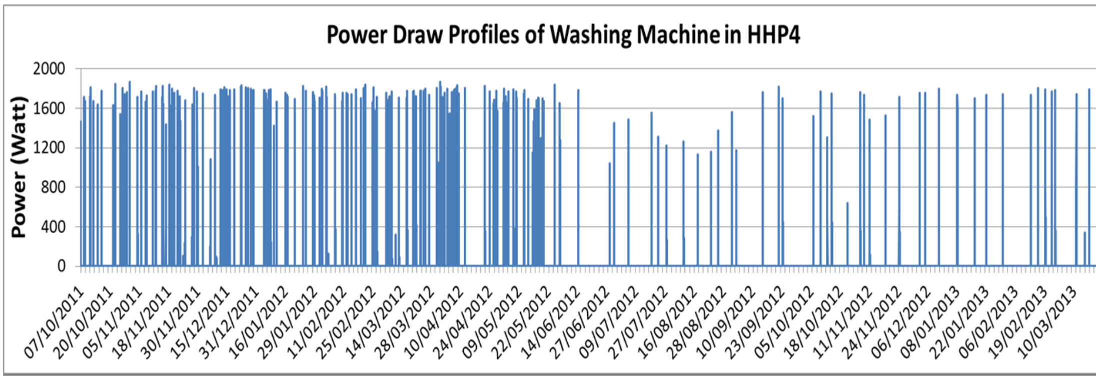
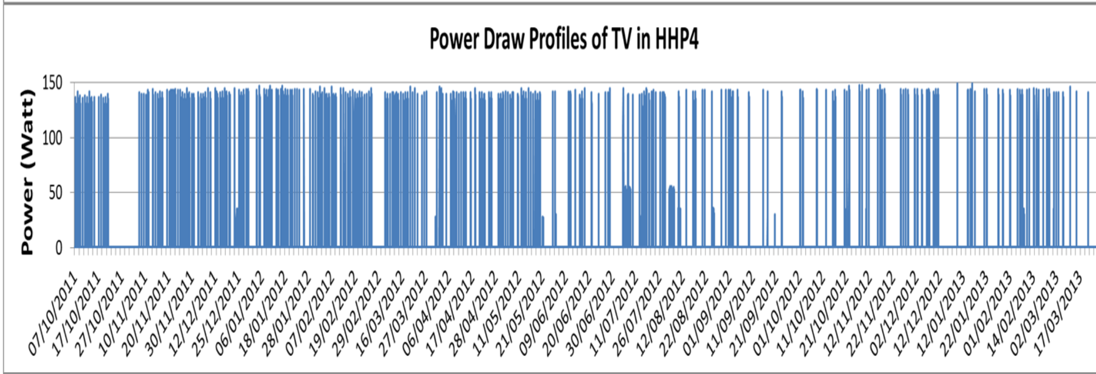
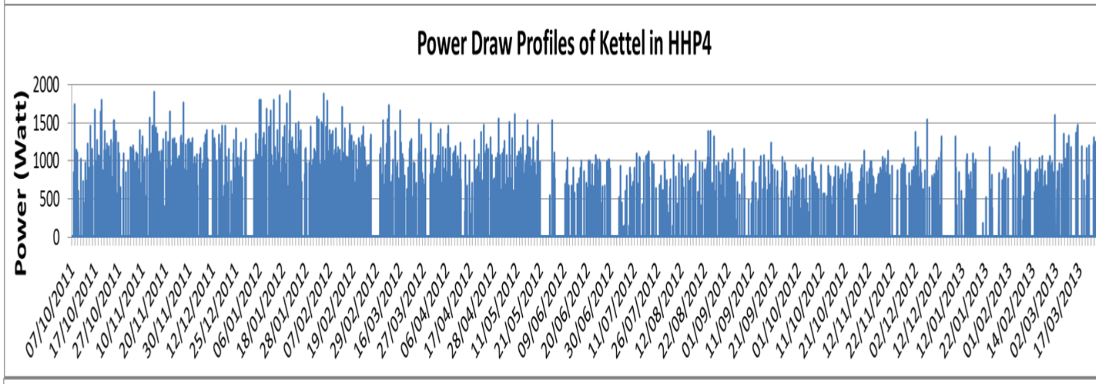
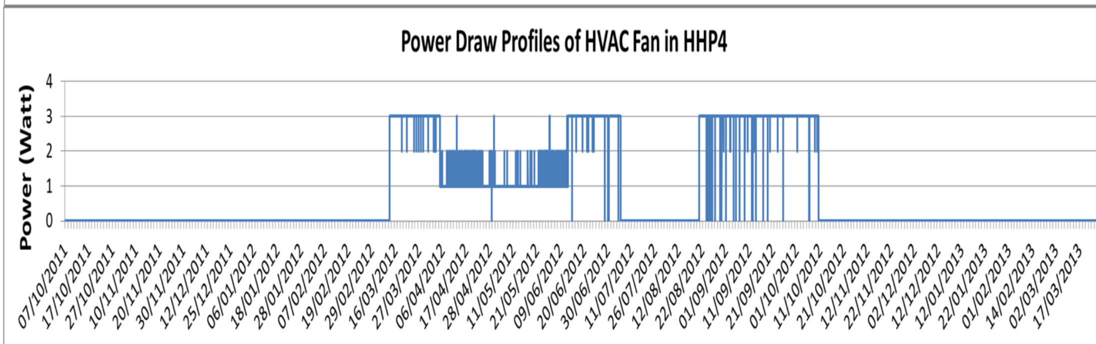
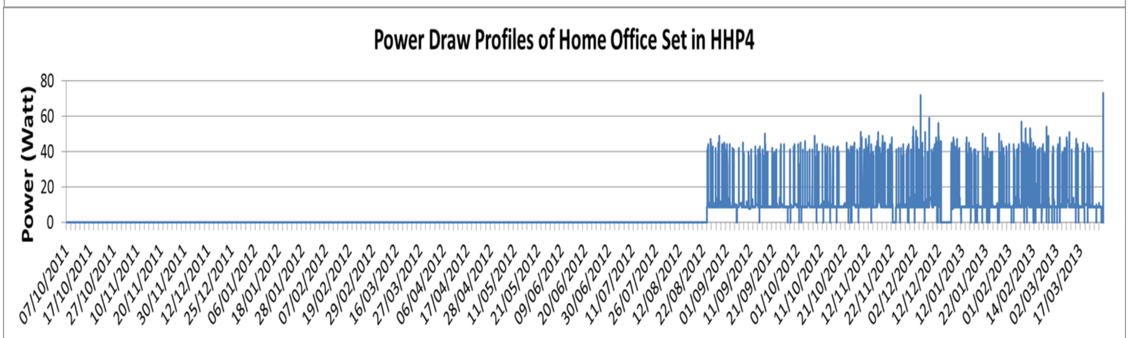

Power Draw Profiles of Washing Machine in HHP4
Power (Watt)
2000
1600
1200
800
400
0
07/10/2011 20/10/2011 05/11/2011 18/11/2011 30/11/2011 15/12/2011 31/12/2011 16/01/2012 29/01/2012 11/02/2012 25/02/2012 14/03/2012 28/03/2012 10/04/2012 24/04/2012 09/05/2012 22/05/2012 14/06/2012 27/06/2012 09/07/2012 27/07/2012 16/08/2012 28/08/2012 10/09/2012 23/09/2012 05/10/2012 18/10/2012 11/11/2012 24/11/2012 06/12/2012 08/01/2013 22/01/2013 06/02/2013 19/02/2013 10/03/2013

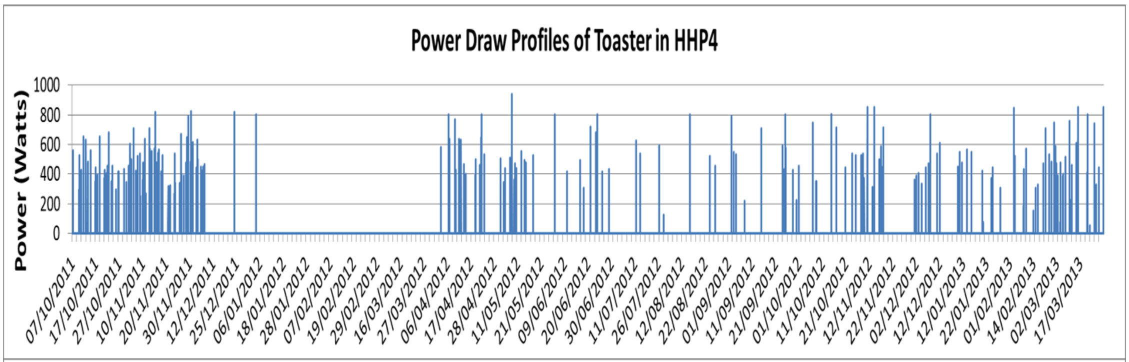

Power Draw Profiles of TV in HHP4
Power (Watt)
150
100
50
0
07/10/2011 17/10/2011 27/10/2011 10/11/2011 20/11/2011 30/11/2011 12/12/2011 25/12/2011 06/01/2012 18/01/2012 28/01/2012 07/02/2012 19/02/2012 29/02/2012 16/03/2012 27/03/2012 06/04/2012 17/04/2012 28/04/2012 11/05/2012 21/05/2012 09/06/2012 20/06/2012 30/06/2012 11/07/2012 26/07/2012 12/08/2012 22/08/2012 01/09/2012 11/09/2012 21/09/2012 01/10/2012 11/10/2012 21/10/2012 12/11/2012 22/11/2012 02/12/2012 12/12/2012 12/01/2013 22/01/2013 01/02/2013 14/02/2013 02/03/2013 17/03/2013

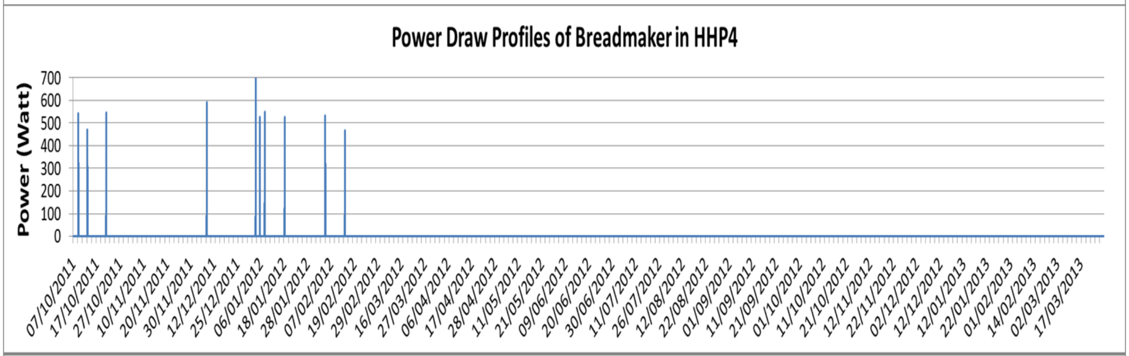

Power Draw Profiles of Kettel in HHP4
Power (Watt)
2000
1500
1000
500
0
07/10/2011 17/10/2011 27/10/2011 10/11/2011 20/11/2011 30/11/2011 12/12/2011 25/12/2011 06/01/2012 18/01/2012 28/01/2012 07/02/2012 19/02/2012 29/02/2012 16/03/2012 27/03/2012 06/04/2012 17/04/2012 28/04/2012 11/05/2012 21/05/2012 09/06/2012 20/06/2012 30/06/2012 11/07/2012 26/07/2012 12/08/2012 22/08/2012 01/09/2012 11/09/2012 21/09/2012 01/10/2012 11/10/2012 21/10/2012 12/11/2012 22/11/2012 02/12/2012 12/12/2012 12/01/2013 22/01/2013 01/02/2013 14/02/2013 02/03/2013 17/03/2013

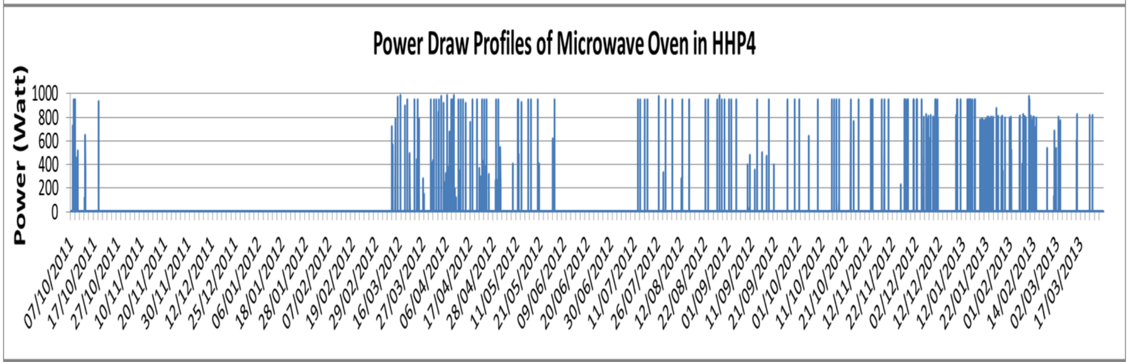

Power Draw Profiles of HVAC Fan in HHP4
Power (Watt)
4
3
2
1
0
07/10/2011 17/10/2011 27/10/2011 10/11/2011 20/11/2011 30/11/2011 12/12/2011 25/12/2011 06/01/2012 18/01/2012 28/01/2012 07/02/2012 19/02/2012 29/02/2012 16/03/2012 27/03/2012 06/04/2012 17/04/2012 28/04/2012 11/05/2012 21/05/2012 09/06/2012 20/06/2012 30/06/2012 11/07/2012 26/07/2012 12/08/2012 22/08/2012 01/09/2012 11/09/2012 21/09/2012 01/10/2012 11/10/2012 21/10/2012 12/11/2012 22/11/2012 02/12/2012 12/12/2012 12/01/2013 22/01/2013 01/02/2013 14/02/2013 02/03/2013 17/03/2013

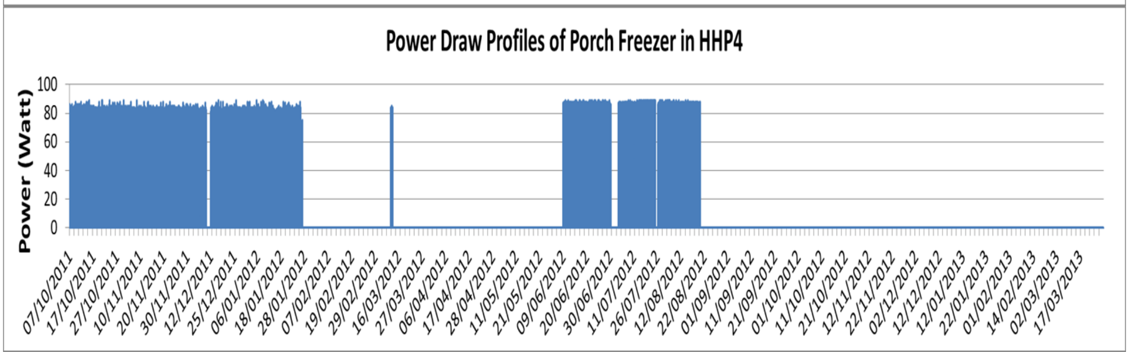

Power Draw Profiles of Home Office Set in HHP4
Power (Watt)
80
60
40
20
0
07/10/2011 17/10/2011 27/10/2011 10/11/2011 20/11/2011 30/11/2011 12/12/2011 25/12/2011 06/01/2012 18/01/2012 28/01/2012 07/02/2012 19/02/2012 29/02/2012 16/03/2012 27/03/2012 06/04/2012 17/04/2012 28/04/2012 11/05/2012 21/05/2012 09/06/2012 20/06/2012 30/06/2012 11/07/2012 26/07/2012 12/08/2012 22/08/2012 01/09/2012 11/09/2012 21/09/2012 01/10/2012 11/10/2012 21/10/2012 12/11/2012 22/11/2012 02/12/2012 12/12/2012 12/01/2013 22/01/2013 01/02/2013 14/02/2013 02/03/2013 17/03/2013

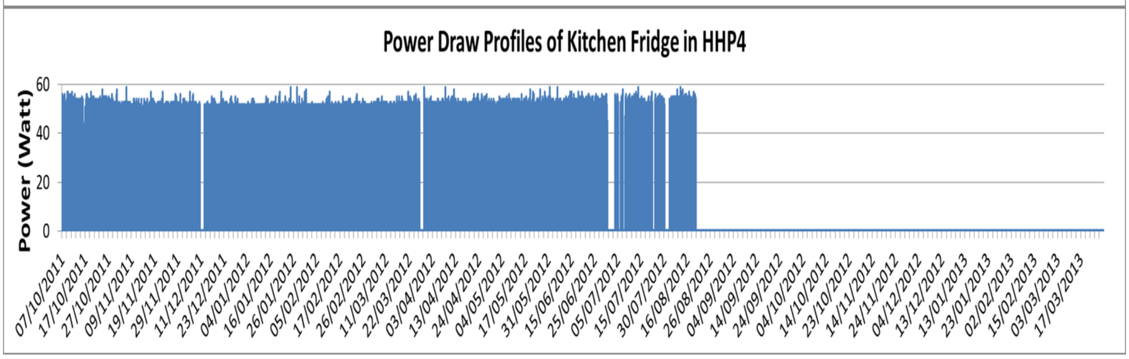
Appendix


Power Draw Profiles of Toaster in HHP4
Power (Watts)
1000
800
600
400
200
0

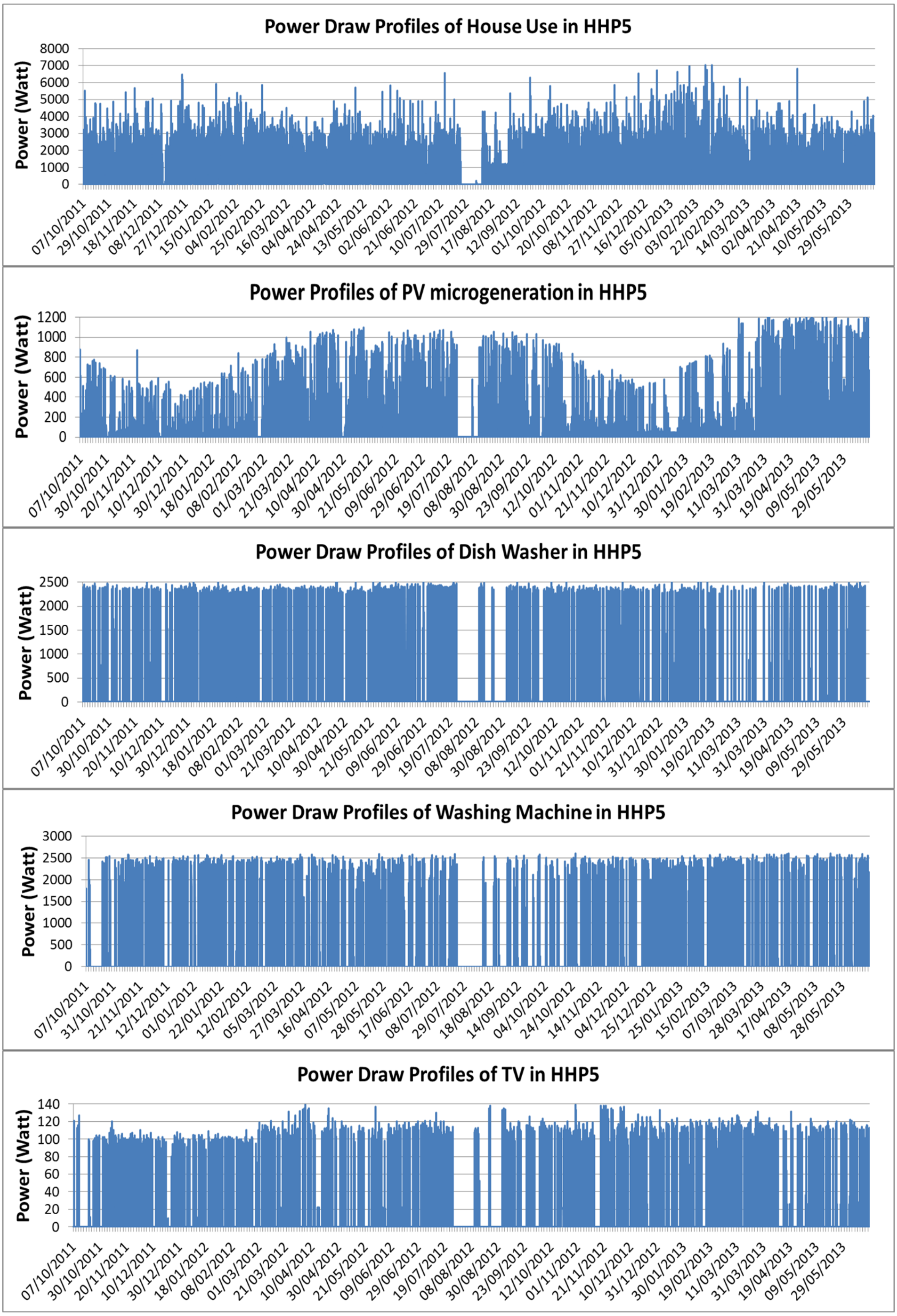

Power Draw Profiles of Breadmaker in HHP4
Power (Watt)
700
600
500
400
300
200
100
0


Power Draw Profiles of Microwave Oven in HHP4
Power (Watt)
1000
800
600
400
200
0


Power Draw Profiles of Porch Freezer in HHP4
Power (Watt)
100
80
60
40
20
0


Power Draw Profiles of Kitchen Fridge in HHP4
Power (Watt)
60
40
20
0

Appendix 15 Power profiles of house use, PV microgeneration, and IAM-monitored appliances in HHP5 over the monitoring period 07/10/2011 to 17/06/2013



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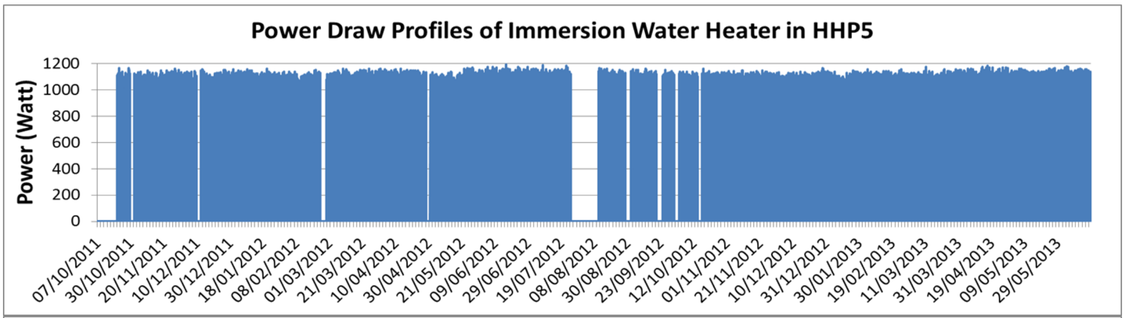
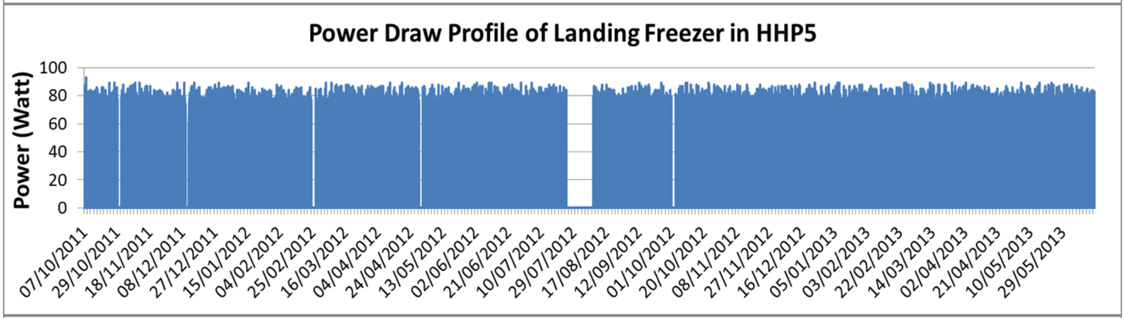
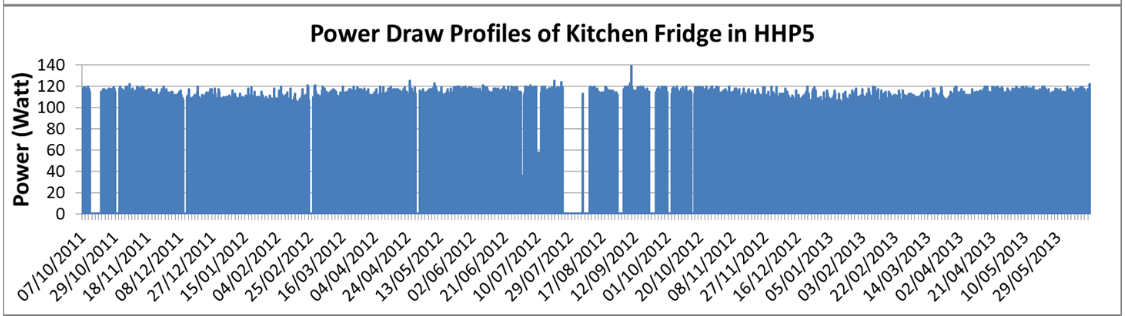
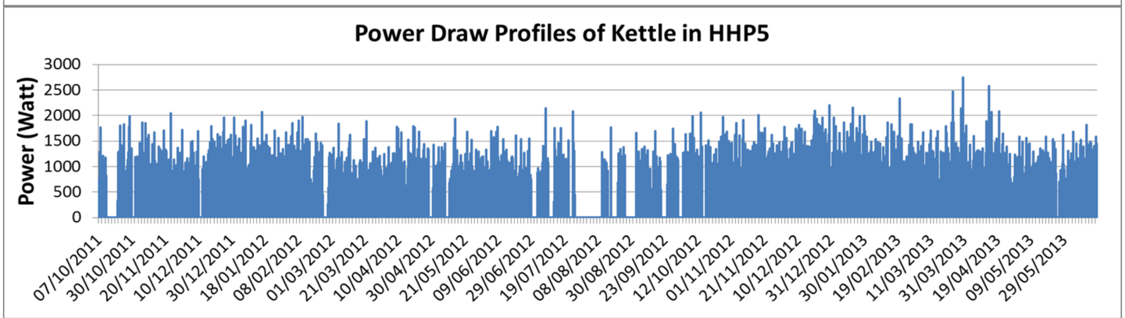
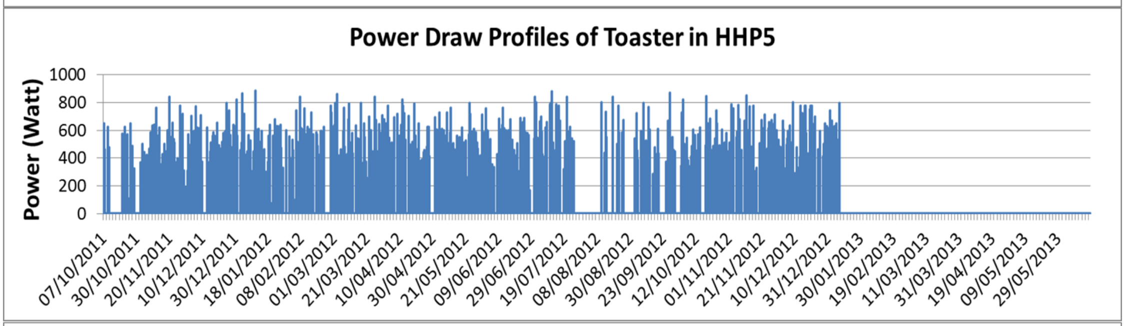
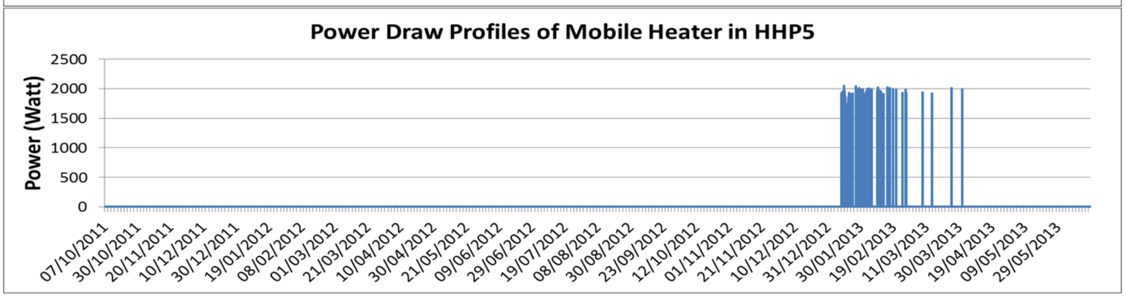

Power Draw Profiles of Immersion Water Heater in HHP5
Power (Watt)


Power Draw Profile of Landing Freezer in HHP5
Power (Watt)


Power Draw Profiles of Kitchen Fridge in HHP5
Power (Watt)

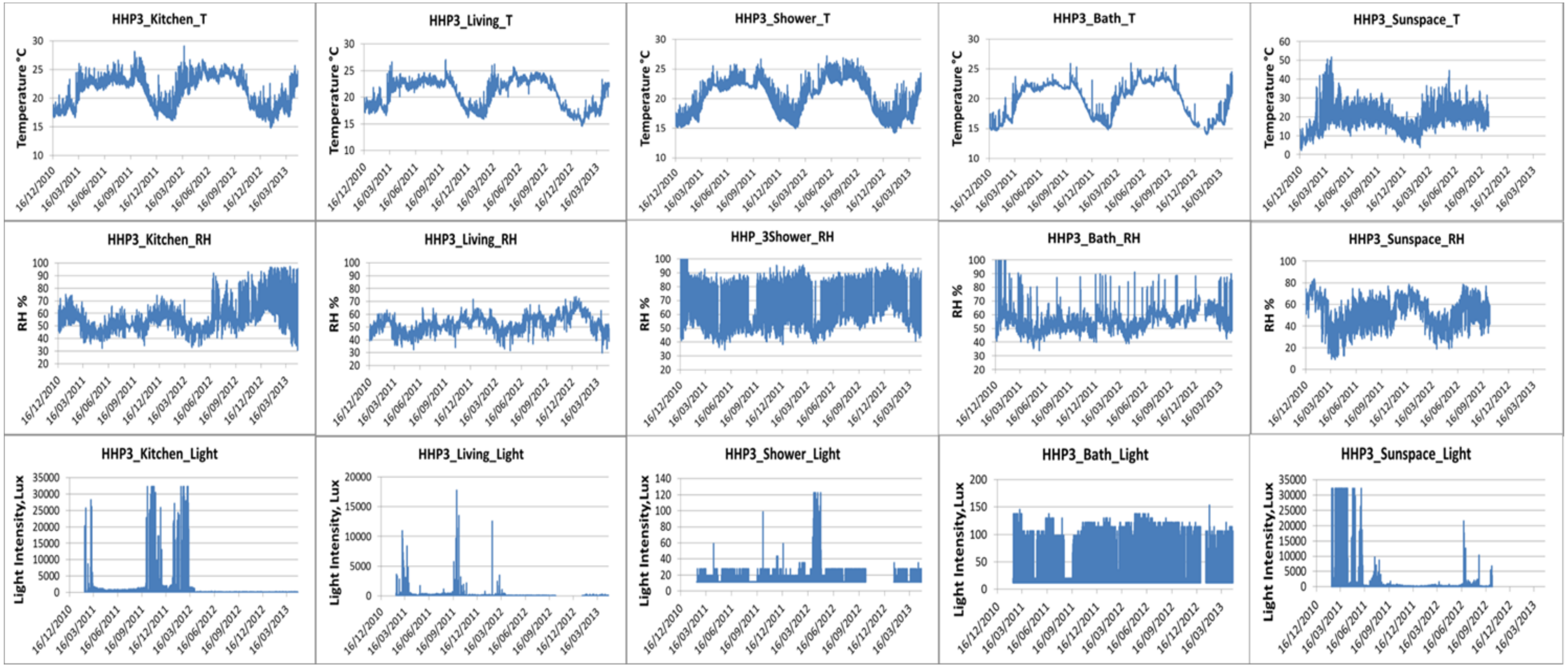

Power Draw Profiles of Kettle in HHP5
Power (Watt)


Power Draw Profiles of Toaster in HHP5
Power (Watt)


Power Draw Profiles of Mobile Heater in HHP5
Power (Watt)

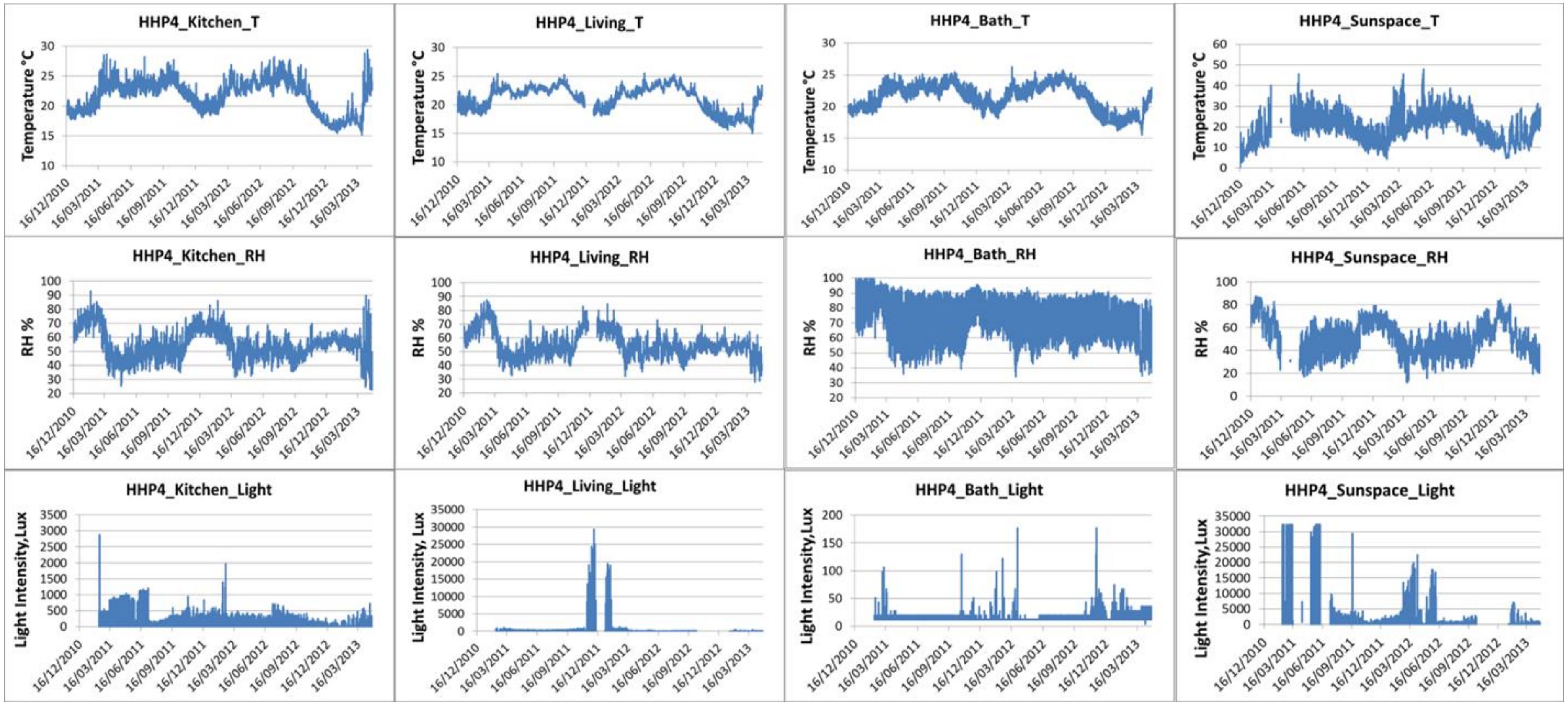
Appendix

Appendix 16 Indoor hygrothermal and light intensity measurements in HHP3 over the monitoring period 16/12/2010 to 27/04/2013



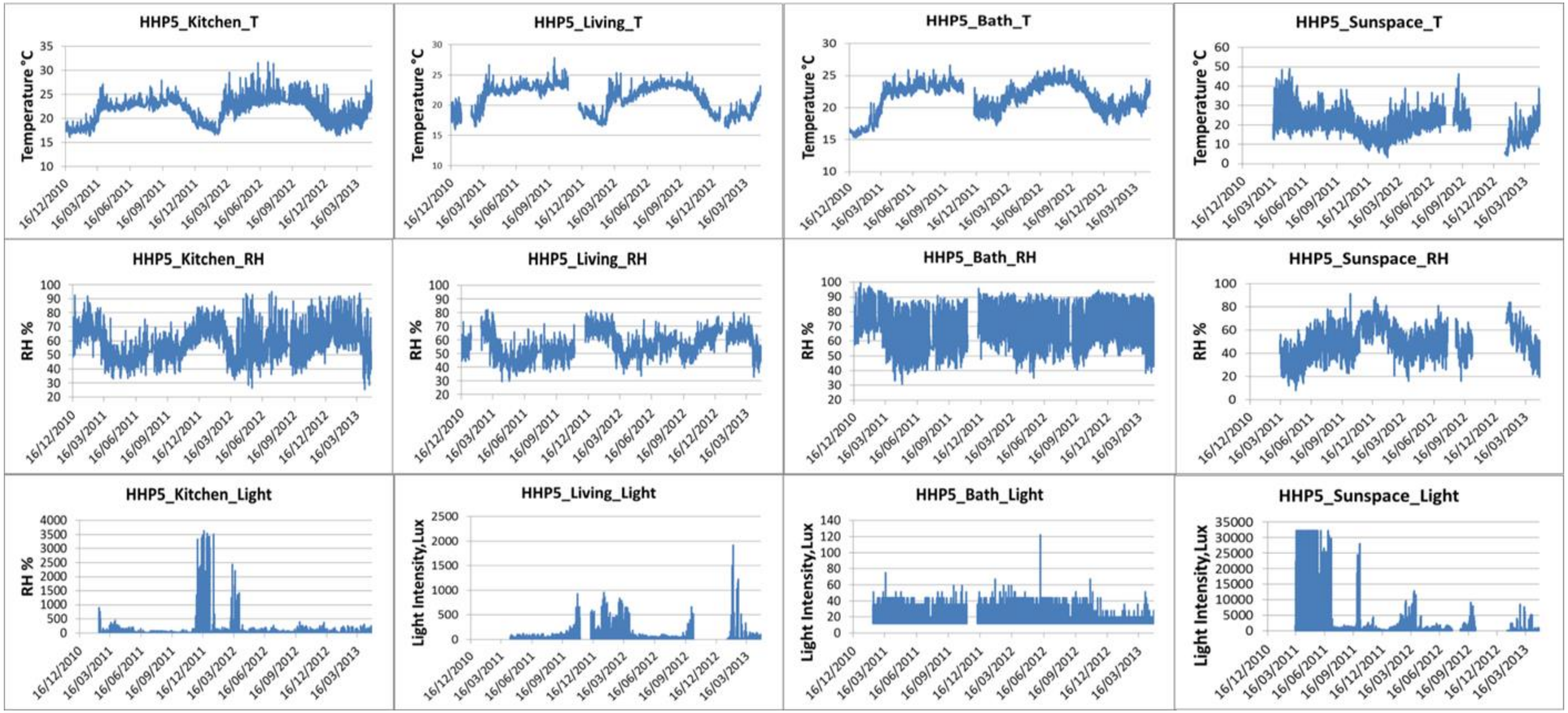
Appendix

Appendix 17 Indoor hygrothermal and light intensity measurements in HHP4 over the monitoring period 16/12/2010 to 27/04/2013



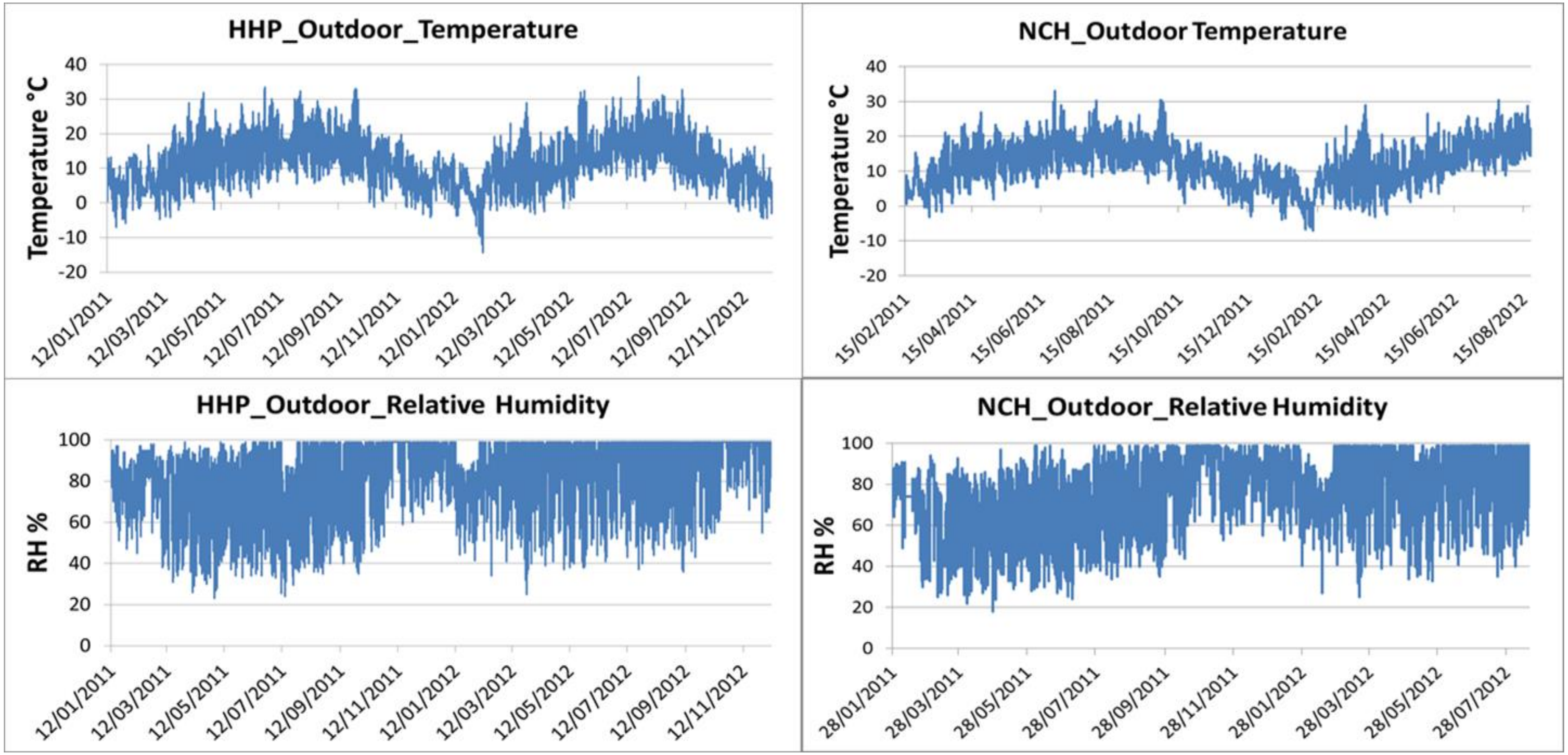
Appendix

Appendix 18 Indoor hygrothermal and light intensity measurements in HHP5 over the monitoring period 16/12/2010 to 27/04/2013



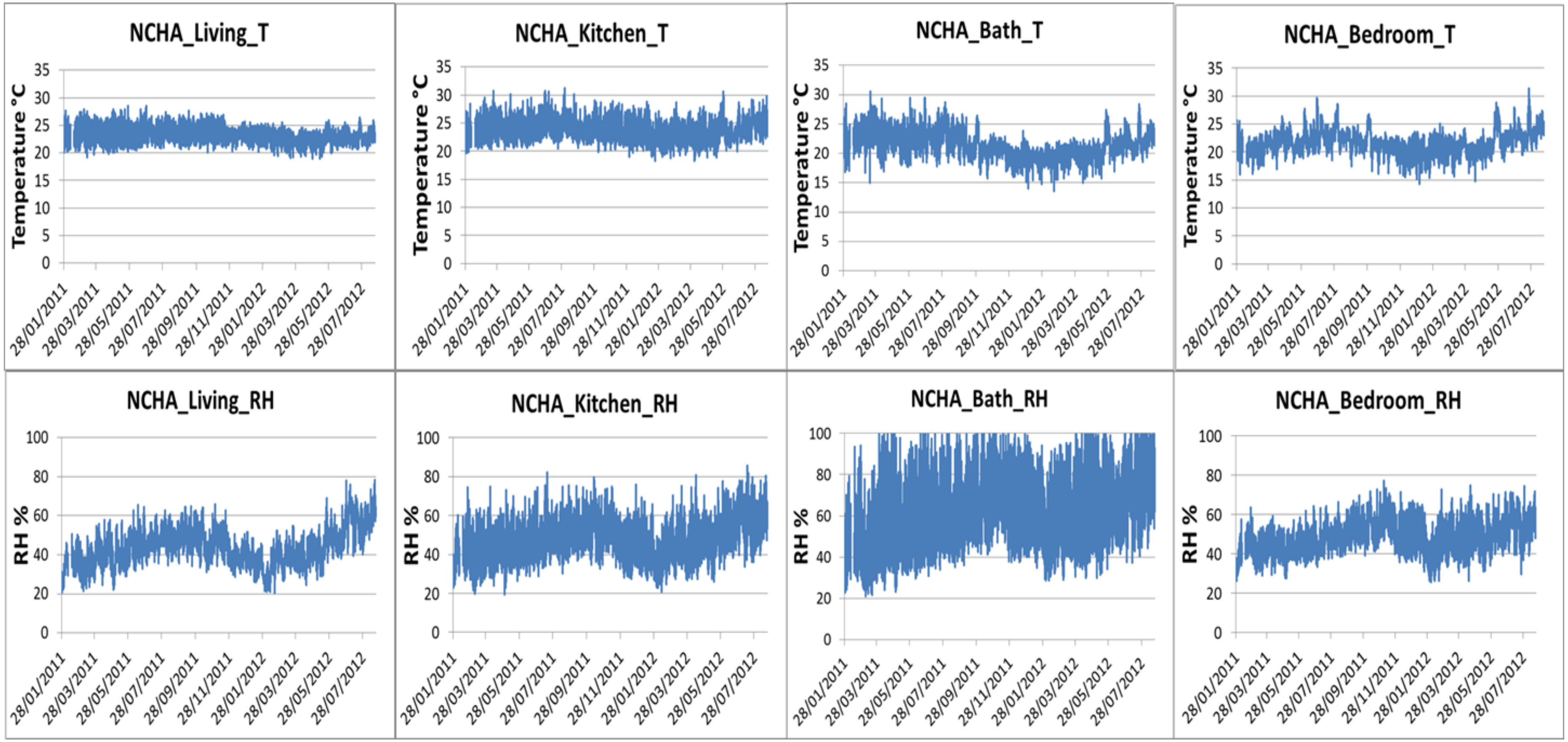
Appendix

Appendix 19 Outdoor hygrothermal measurements of the HHP case study over the monitoring period 12/01/2011 to 11/12/2012 and the NCH case study over the monitoring period 15/02/2011 to 21/08/2012



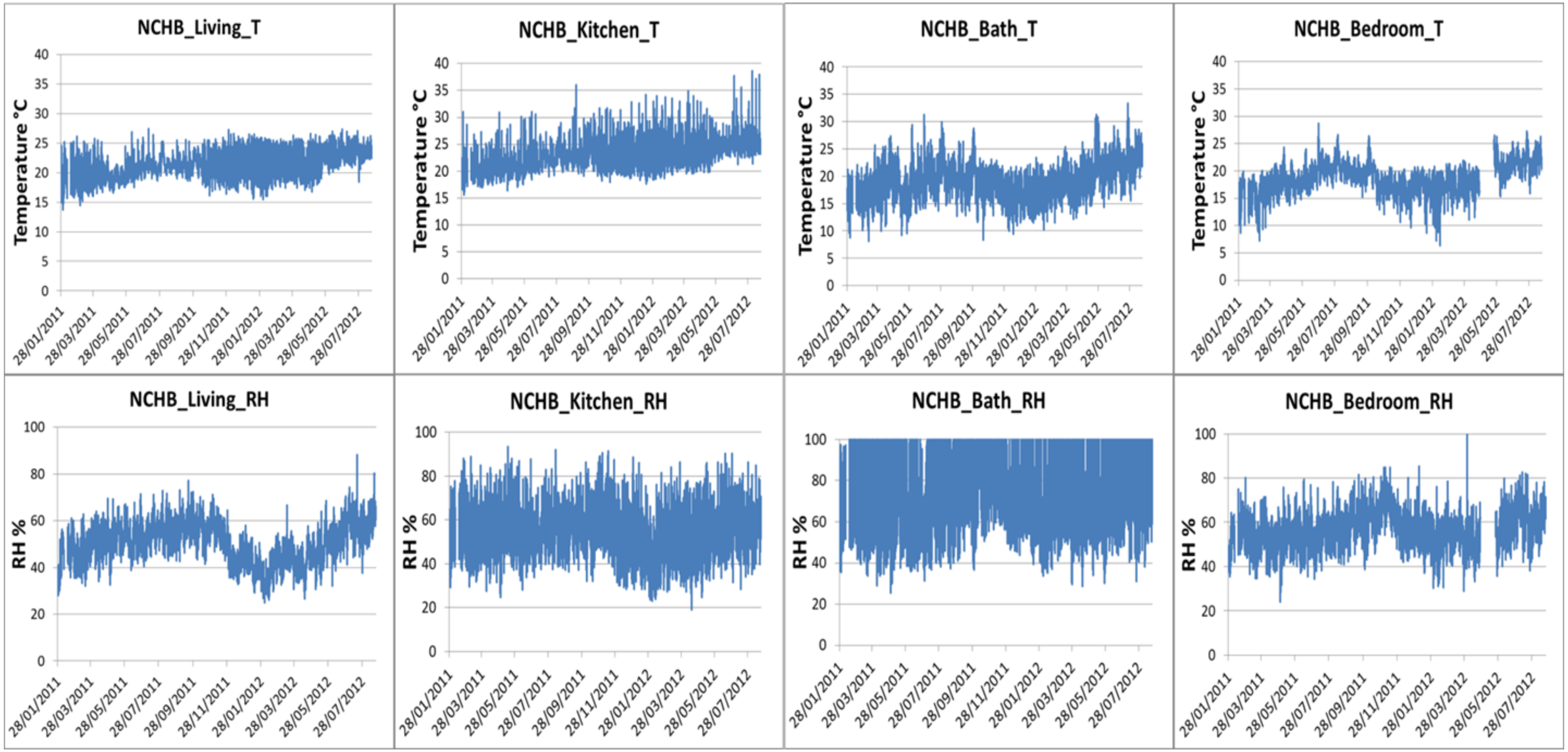
Appendix

Appendix 20 Indoor hygrothermal measurements in NCHA over the monitoring period 28/01/2011 to 21/08/2012



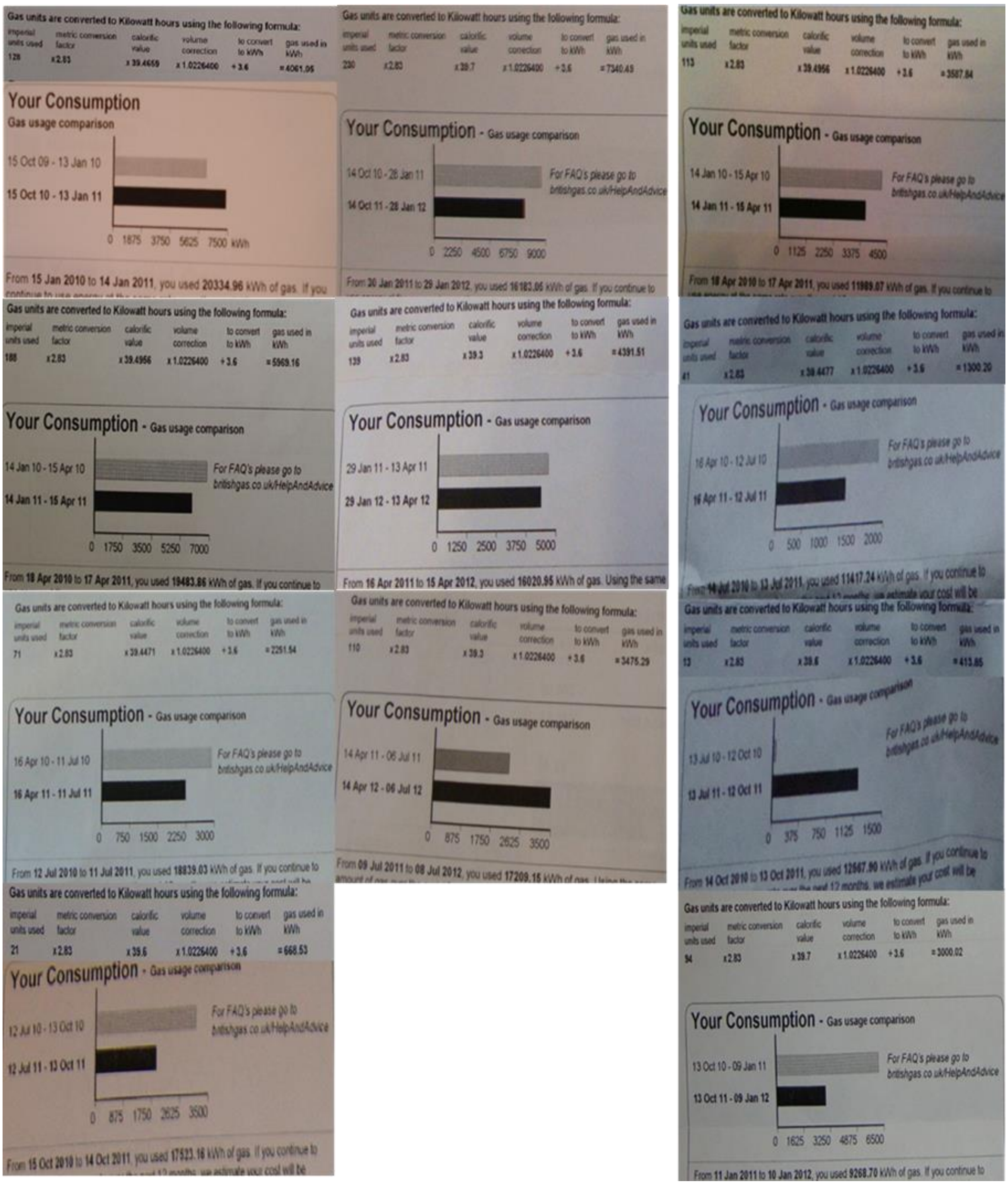
<u>Appendix</u>

Appendix 21 Indoor hygrothermal measurements in NCHB over the monitoring period 28/01/2011 to 21/08/2012



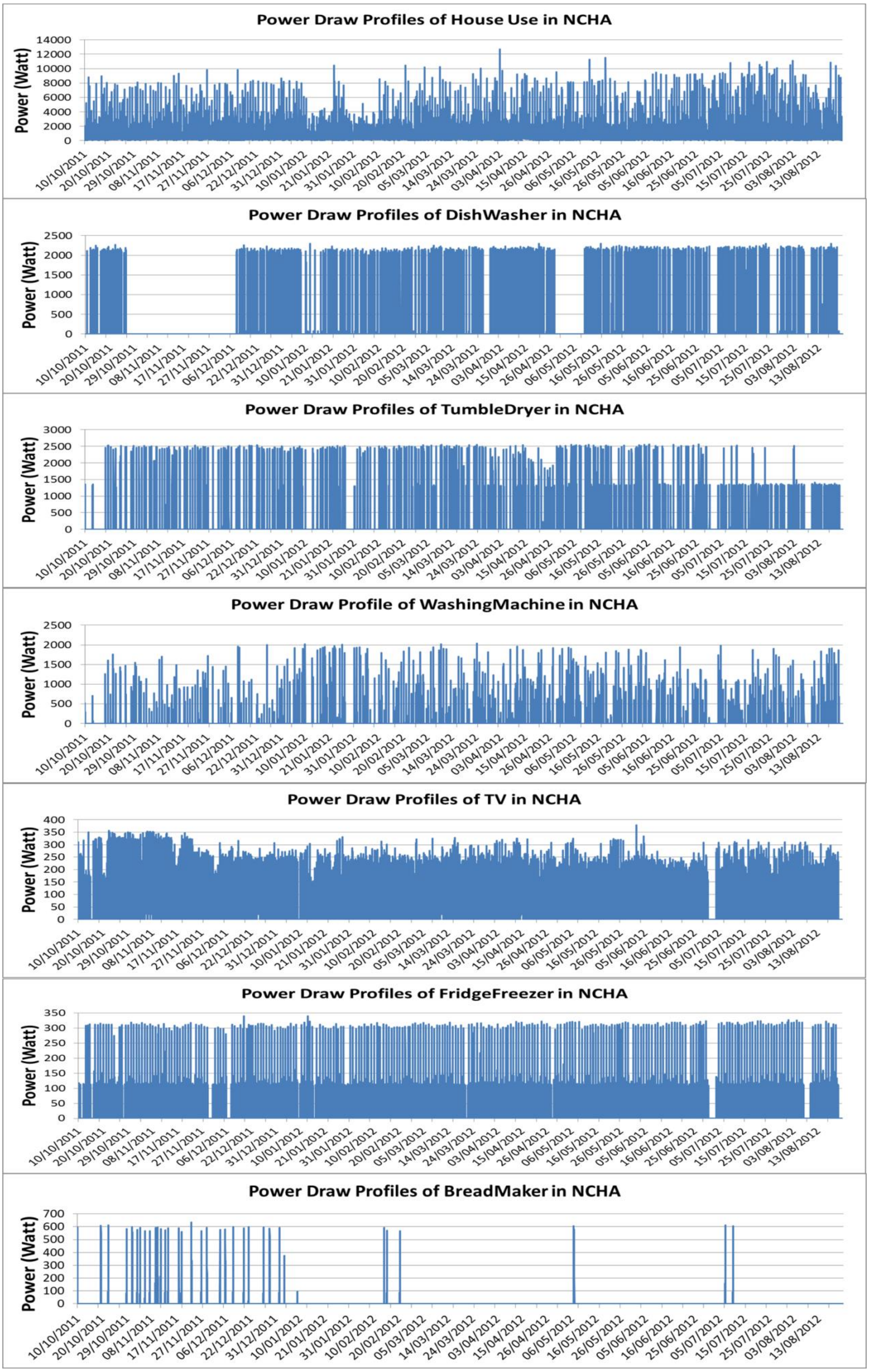
Appendix

Appendix 22 Excerpts of gas bills collected from the two NCH homes

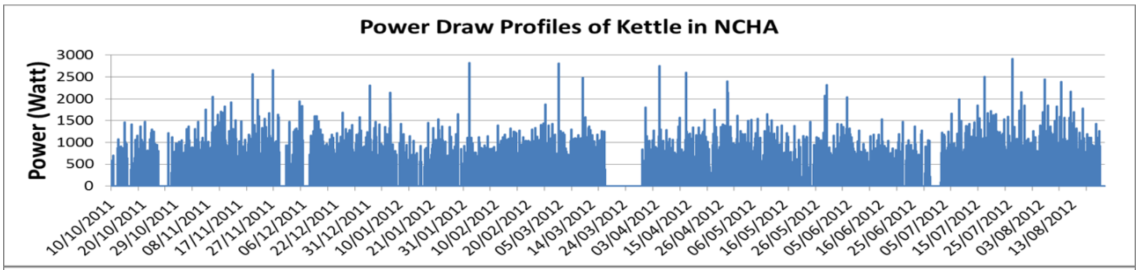


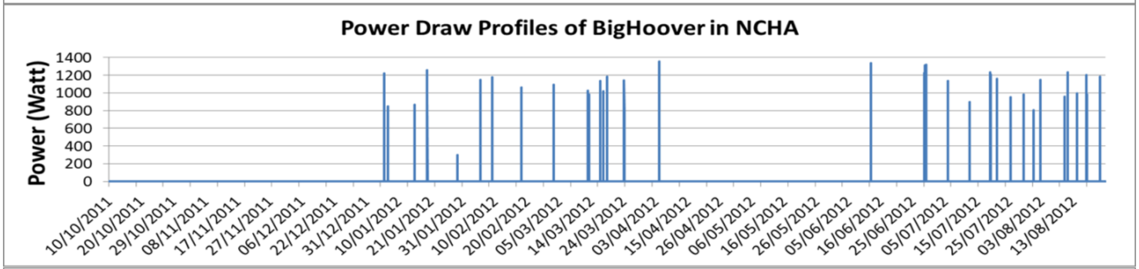
The gas bill excerpts are sourced from the two case study homes that are serviced by the same utility supplier, British Gas. The graph in each excerpt superimposes the quarterly gas use with the use over the same quarter of the previous year in the bar chart that takes kWh as the gas use unit. The conversion formula and values are quoted above the chart within which the calorific values vary. The bills of certain quarters were based on actual readings. When estimated figures were used for certain bills, the cross-comparison with the manually logged gas use proves that the estimation of the utility suppliers was reasonably close to the actual use.

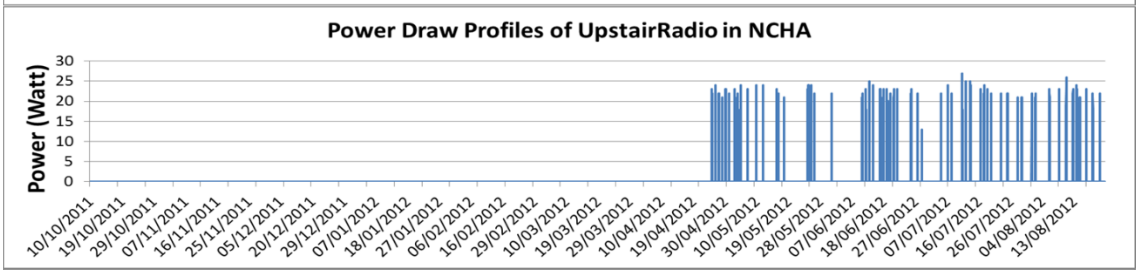
Appendix 23 Power profiles of house use and IAM-monitored appliances in NCHA over the monitoring period 10/10/2011 to 23/08/2012

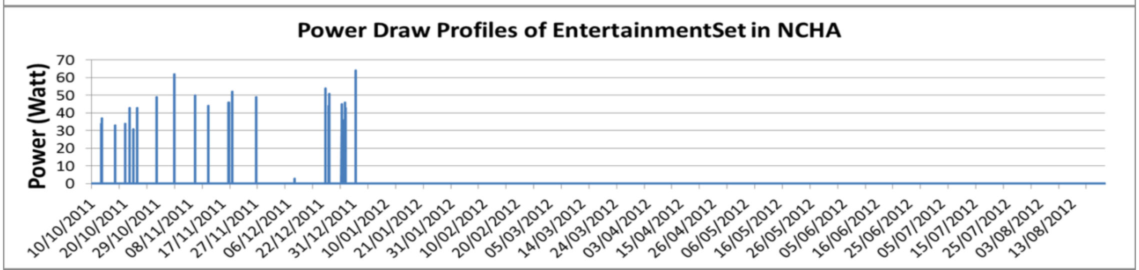


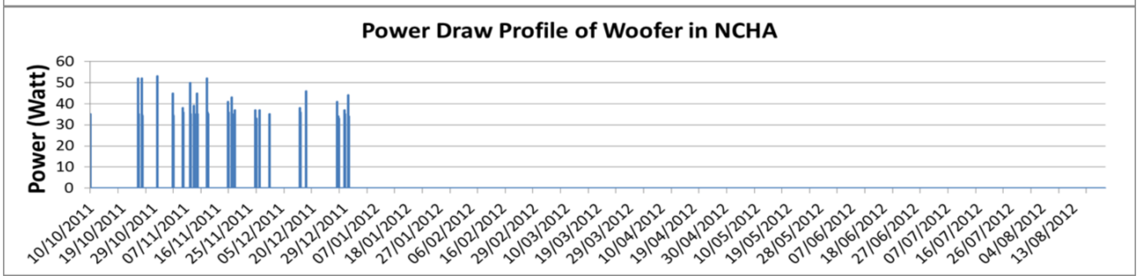
Appendix

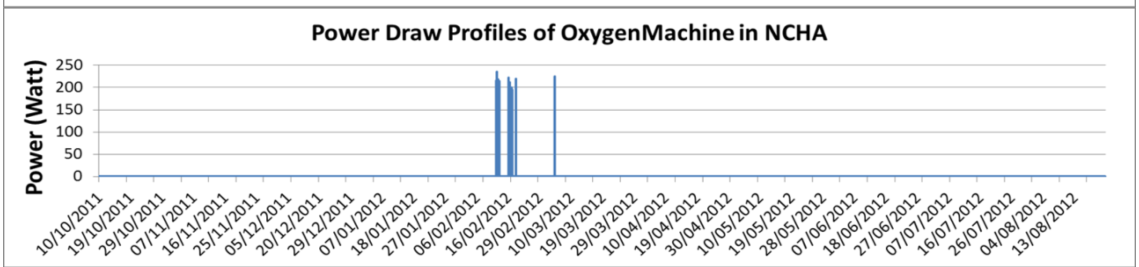

Power Draw Profiles of Kettle in NCHA
Power (Watt)

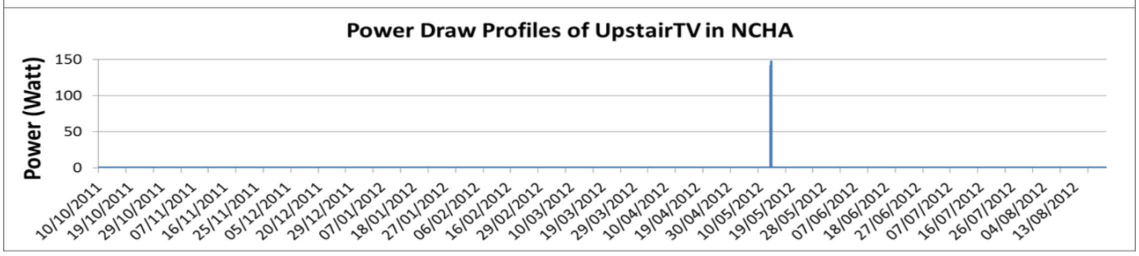

Power Draw Profiles of BigHoover in NCHA
Power (Watt)


Power Draw Profiles of UpstairRadio in NCHA
Power (Watt)

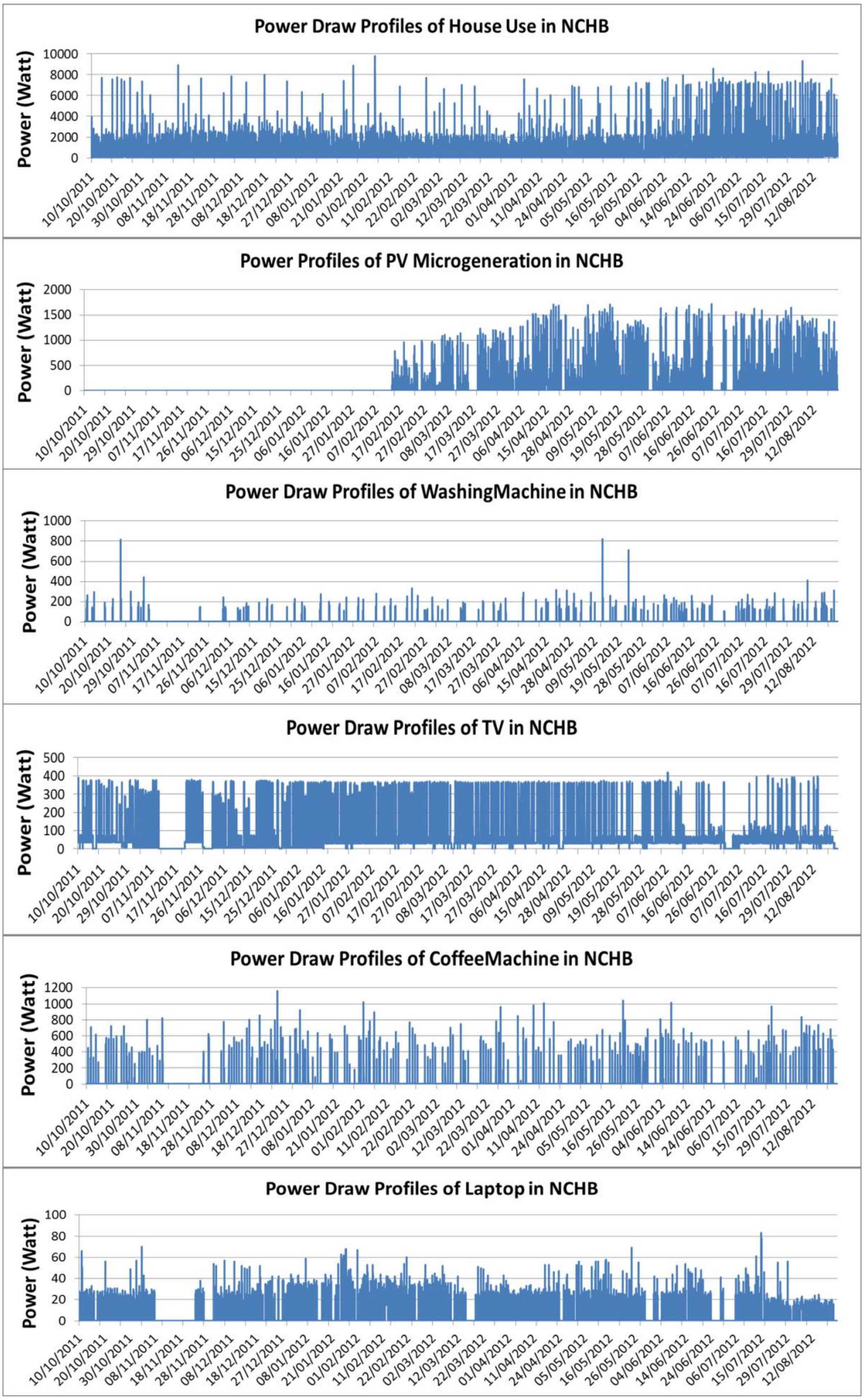

Power Draw Profiles of EntertainmentSet in NCHA
Power (Watt)


Power Draw Profile of Woofer in NCHA
Power (Watt)

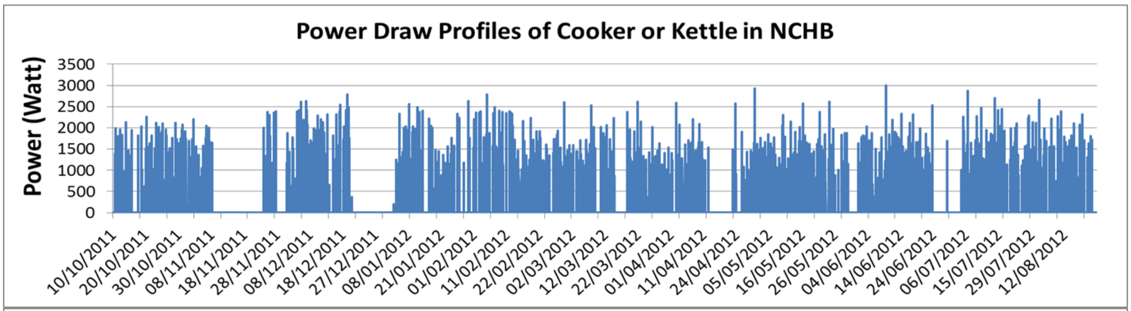

Power Draw Profiles of OxygenMachine in NCHA
Power (Watt)

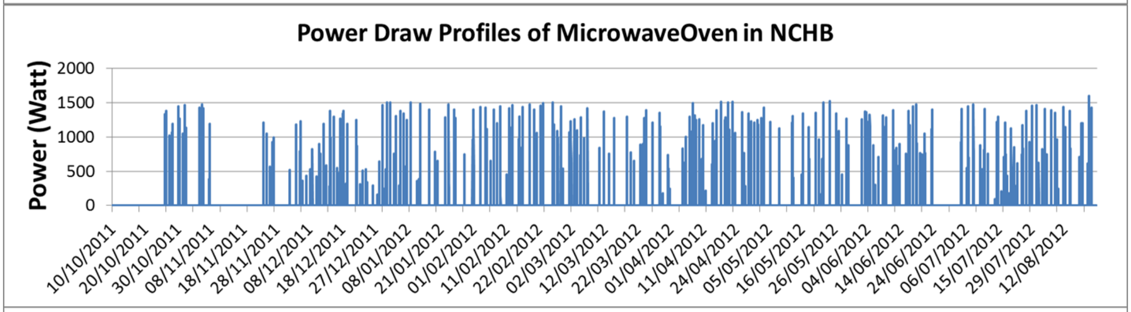

Power Draw Profiles of UpstairTV in NCHA
Power (Watt)

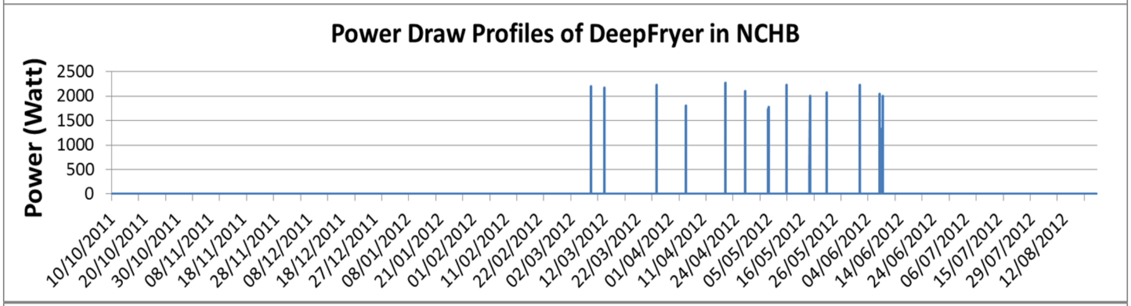
Appendix 24 Power profiles of house use, PV microgeneration and IAM-monitored appliances in NCHB over the monitoring period 10/10/2011 to 23/08/2012

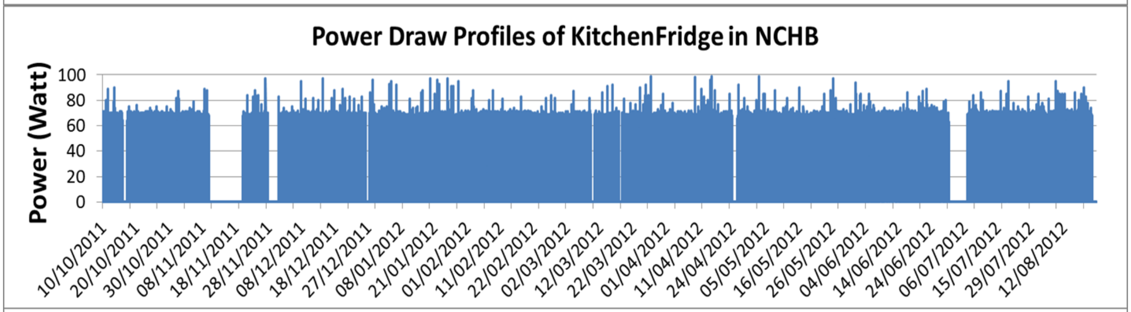


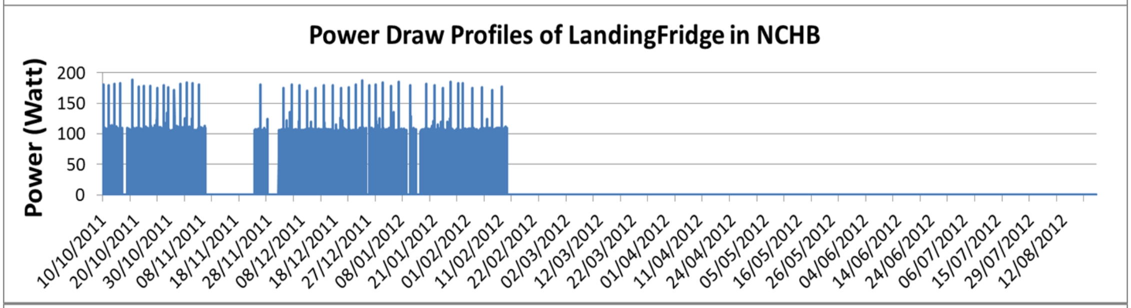
Appendix

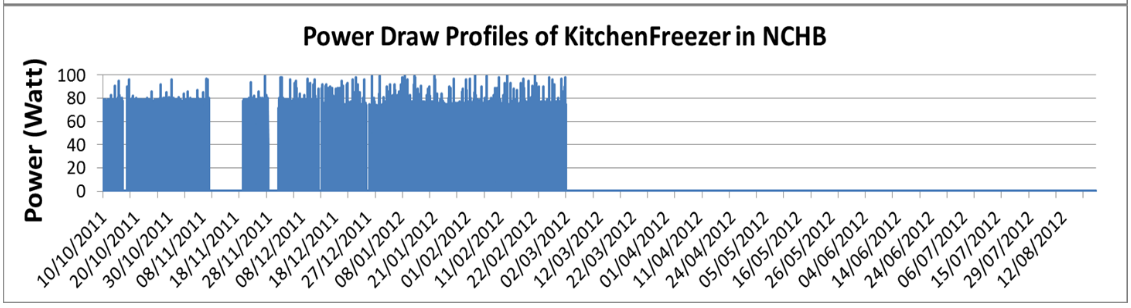

Power Draw Profiles of Cooker or Kettle in NCHB
Power (Watt)
3500
3000
2500
2000
1500
1000
500
0
10/10/2011 20/10/2011 30/10/2011 08/11/2011 18/11/2011 28/11/2011 08/12/2011 18/12/2011 27/12/2011 08/01/2012 21/01/2012 01/02/2012 11/02/2012 22/02/2012 02/03/2012 12/03/2012 22/03/2012 01/04/2012 11/04/2012 24/04/2012 05/05/2012 16/05/2012 26/05/2012 04/06/2012 14/06/2012 24/06/2012 06/07/2012 15/07/2012 29/07/2012 12/08/2012


Power Draw Profiles of MicrowaveOven in NCHB
Power (Watt)
2000
1500
1000
500
0
10/10/2011 20/10/2011 30/10/2011 08/11/2011 18/11/2011 28/11/2011 08/12/2011 18/12/2011 27/12/2011 08/01/2012 21/01/2012 01/02/2012 11/02/2012 22/02/2012 02/03/2012 12/03/2012 22/03/2012 01/04/2012 11/04/2012 24/04/2012 05/05/2012 16/05/2012 26/05/2012 04/06/2012 14/06/2012 24/06/2012 06/07/2012 15/07/2012 29/07/2012 12/08/2012


Power Draw Profiles of DeepFryer in NCHB
Power (Watt)
2500
2000
1500
1000
500
0
10/10/2011 20/10/2011 30/10/2011 08/11/2011 18/11/2011 28/11/2011 08/12/2011 18/12/2011 27/12/2011 08/01/2012 21/01/2012 01/02/2012 11/02/2012 22/02/2012 02/03/2012 12/03/2012 22/03/2012 01/04/2012 11/04/2012 24/04/2012 05/05/2012 16/05/2012 26/05/2012 04/06/2012 14/06/2012 24/06/2012 06/07/2012 15/07/2012 29/07/2012 12/08/2012


Power Draw Profiles of KitchenFridge in NCHB
Power (Watt)
100
80
60
40
20
0
10/10/2011 20/10/2011 30/10/2011 08/11/2011 18/11/2011 28/11/2011 08/12/2011 18/12/2011 27/12/2011 08/01/2012 21/01/2012 01/02/2012 11/02/2012 22/02/2012 02/03/2012 12/03/2012 22/03/2012 01/04/2012 11/04/2012 24/04/2012 05/05/2012 16/05/2012 26/05/2012 04/06/2012 14/06/2012 24/06/2012 06/07/2012 15/07/2012 29/07/2012 12/08/2012


Power Draw Profiles of LandingFridge in NCHB
Power (Watt)
200
150
100
50
0
10/10/2011 20/10/2011 30/10/2011 08/11/2011 18/11/2011 28/11/2011 08/12/2011 18/12/2011 27/12/2011 08/01/2012 21/01/2012 01/02/2012 11/02/2012 22/02/2012 02/03/2012 12/03/2012 22/03/2012 01/04/2012 11/04/2012 24/04/2012 05/05/2012 16/05/2012 26/05/2012 04/06/2012 14/06/2012 24/06/2012 06/07/2012 15/07/2012 29/07/2012 12/08/2012


Power Draw Profiles of KitchenFreezer in NCHB
Power (Watt)
100
80
60
40
20
0
10/10/2011 20/10/2011 30/10/2011 08/11/2011 18/11/2011 28/11/2011 08/12/2011 18/12/2011 27/12/2011 08/01/2012 21/01/2012 01/02/2012 11/02/2012 22/02/2012 02/03/2012 12/03/2012 22/03/2012 01/04/2012 11/04/2012 24/04/2012 05/05/2012 16/05/2012 26/05/2012 04/06/2012 14/06/2012 24/06/2012 06/07/2012 15/07/2012 29/07/2012 12/08/2012