MEASURING THE IMPACT OF OCCUPANT BEHAVIOUR ON ENERGY USAGE IN EXISTING HOMES

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Abstract

Thermal, visual, and acoustic comfort and air quality in buildings have a significant effect on occupant performance, productivity and satisfaction. Most importantly, earlier research has found that maintaining thermal comfort can make heavy demands on building energy usage in dwellings. Those trends are leading to even greater increases in energy demand and CO2 emissions that create a vicious cycle.

In the real world, human indoor thermal comfort is influenced by complexities of past comfort history, technical practices and culture. There is a need to review of existing research and achievements. It provides great benefits to identify future research directions. For this reason, this research presents the results of an extensive literature review on previous studies on different topics of indoor comfort and human behavioural response in the built environment.

This study is focused on monitoring and measuring energy consumption and physical environment in dwellings to test various methods that can capture how occupants control their indoor built environment at what cost of energy. Eight dwellings have been selected and the occupants have participated this study. Their thermal comfort, energy consumption, indoor and local outdoor physical conditions have been monitored by mixed methodologies at detailed level. Due to the level of disaggregated information, the number of dwellings was limited and the data can only represent the participating occupants, but the validation of monitoring methodologies has provided valuable overview regarding a range of methods instrumentations for measuring various parameters that could be used different levels of detailed domestic energy consumption and thermal environment information.

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CHAPTER 1: INTRODUCTION

1.1 Energy consumption in the domestic sector

This research takes as its starting point the potential energy savings that could be made in dwellings in day-to-day life and attempts to develop a methodology to measure the variation in energy usage caused by different occupant behaviour and preferences. Proportionally, one of the highest energy saving could be achieved from maintaining thermal comfort at our homes during the heating season, which led to one of the objectives of this research: to find a means of quantifying energy consumption and thermal comfort related indoor physical variables. Appropriate measurement method could help to determine the potential of energy savings in domestic building sector, which is commonly difficult to estimate due to its complexity. Comparing with commercial buildings, general public may not see domestic buildings consume as much as energy, however, the potential benefits could be significant once multiplied by the number of homes and the amount of time that people spend at their homes. Thus, reducing energy consumption in the domestic sector may have a crucial role in reducing carbon emissions, which is a major aspect of climate change mitigation.

To be more precise regarding the carbon emission, around 30 per cent of the UK's total CO_2 output is accounted for by domestic energy, a figure that could be reduced by up to 10 per cent through simple energy saving steps and tips(Sundramoorthy and Cooper, 2011). In addition, persuading households to become more energy efficient is vital if CO_2 emissions are to be reduced; research shows that behavioural interventions have the potential to reduce the energy consumption of a household by 15 per cent(Darby, 2006).

Climate change is one of the most significant environmental issues facing human beings today. Ever-increasing fossil fuel-based energy consumption is contributing to this issue at a higher level(Boardman, 2007). Figures from the Department of Energy and Climate Change show that the UK building sector consumes 40 per cent of energy and that domestic buildings are one of the most important aspects to consider when attempting to reduce energy consumption(DECC 2011).

In the UK, domestic building energy consumption has increased substantially since 1945. In the 2011 energy consumption statistical report, the domestic sector accounted for 32 per cent of total UK final energy consumption(DECC 2011). Comparing with the statistics at 1970, 1990 and 2009, respectively, domestic sector accounts for 22 per cent, 26 per cent and 28 per cent, a trend of can be clearly seen(DECC 2011).

In response to incremental energy consumption, the efficiency of domestic buildings has been continuously enhanced and. In past decades, buildings with better thermal properties and improved heating systems lowered domestic energy usage in theoretical calculations. However, significant differences in energy consumption, such as by space heating, have been found in even identical building types through long-term monitoring(Haas 1996; Emery and Kippenhan, 2004, Hens et al. 2010). Haas(1996) showed that the actual energy consumption of different families could double. Emery and Kippenhan(2004) found that the difference between heating consumption varied from 29 per cent to 32 per cent amongst households of a similar socio-economic status. It is possible that these differences might be caused by users' patterns of behaviour and setting the heating output level(Hens et al., 2010). These significant differences show that the potential to greatly reduce energy consumption exists when occupants optimise the potential of their home.

The UK government has introduced regulations to improve the energy efficiency within the domestic building sector. The 1965 Building Regulations introduced the first limits on the amount of energy lost through certain elements of the fabric of new houses. This was expressed as a U-value, giving the amount of heat lost per square metre, for each degree Kelvin of temperature difference between inside and outside. The energy policy of the United Kingdom, as set out in the 2003 Energy White Paper(DEFRA, 2003), specified directions for more energy efficient building construction. Energy efficiency requirements within the Building Regulations were hence significantly tightened in 2006.

With the long term aim of cutting overall emissions by 60 per cent by 2050, and by 80 per cent by 2100, the intention of the 2006 changes was to cut energy use in new housing by 20 per cent compared to similar buildings constructed according to the 2002 standards. The changes to the regulations were first brought about by the desire to reduce emissions. In the 2006 regulations, the U-value was replaced as the primary measure of energy efficiency by the Dwelling Carbon Dioxide Emission Rate(DER), this provides an estimate of carbon dioxide emissions per m^2 of floor area. This is calculated using the Government's Standard Assessment Procedure for the Energy Rating of Dwellings(SAP 2005).

In addition to the levels of insulation provided by the structure of the building, the DER also considers the airtightness of the building, the efficiency of space and water heating, the efficiency of lighting, and any savings derived from solar power or other energy generation technologies employed, as well as a range of other factors. This was when it first became compulsory to upgrade energy efficiency in existing houses when extensions or certain other works are carried out.

The Climate Change Act, 2008, imposes a legal requirement on the UK to reduce greenhouse gas emissions by 80 per cent compared with 1990 levels, with a reduction of at least 34 per cent by 2020. The government now sets carbon budgets spanning five-year periods. The government has stated that all new buildings will eventually be “zero carbon” and has also published a timetable to deliver this(Building a Greener Future: Policy Statement, CLG 2007 for dwellings, and the 2008 Budget for non-domestic buildings):

- 2010 – New dwellings and non-domestic buildings reduce emissions by 25 per cent compared to a 2006 building. This corresponds to Code 3 in the Code for Sustainable Homes(CSH).
- 2013 – New dwellings and non-domestic buildings reduce emissions by 44 per cent compared to a 2006 building. This corresponds to Code 4 in CSH.
- 2016 – New dwellings to be zero carbon, including unregulated emissions. This corresponds to Code 6 in CSH.
- 2018 – New non-domestic public buildings to be zero carbon.
- 2019 – All new non-domestic buildings to be zero carbon.

These regulations have been pushing developments, such as new designs for sustainable homes, with substantially improved thermal performance and eco refurbishment throughout to extend the life of the house. Theoretically, these sustainable homes should need less energy to heat. Interest in and research into energy consumption in buildings are usually focused on the systematic evaluation of the building envelope and HVAC system. However, improved building thermal performance and heating systems do not always lead to lower energy consumption(Hass 1996). Rather, this is generally perceived to be caused by occupant behaviour, the local climate and the properties of the building. This research investigates the effect of occupant behaviour on energy consumption in domestic buildings, especially in new-build and recently eco-refurbished sustainable homes, since these follow future trends and are considered to be key to reducing energy consumption in the domestic building sector.

1.2 Background

1.2.1 Role of sustainable home development in Wales

In Wales, DEFRA(2006) states that the domestic sector is responsible for 11 per cent of total CO_2 emissions, which increased by 16 per cent between 1990 and 2004. As one of the measure to take to reduce domestic CO_2 emission In Wales, in 2007, the Code for Sustainable Homes(CSH) was introduced to build new homes with lower running costs and a reduced carbon footprint. A few "Code level" homes with improved thermal efficiency in walls and windows and roofs that use the latest materials have since been constructed. The fabric is carefully designed to minimise thermal bridging and heat loss and uses a high-efficiency condensing boiler and low carbon technologies such as solar panels and PV.

Wales faces more challenges than other parts of the UK in making its housing stock energy more efficient. 36 per cent of the domestic residences in Wales was built before 1919(Welsh Assembly Government 2006); these are typically difficult to insulate and heat. In 2013, it was estimated that 29% of all households in Wales were experiencing fuel poverty, which is much higher than rest of the UK(DECC, 2013). This figure has increased substantially over the survey taken in 2004 and 2011, raised from 15% to 26%. In addition, a comparatively large proportion of Welsh homes are not connected to mains gas, meaning that they rely on electricity or bottled oil or gas for space heating. In addition to building "code level" new homes, existing homes can be refurbished to make them more energy efficient, at a reasonable cost to achieve long-term energy gains rather than demolition. Showcase projects have attempted to test if it is possible that energy use can be reduced by 60 per cent by such improvements(SDC, 2006).

The energy consumption for space of both the new and existing British homes is closely double the amount of the Nordic countries(Lapillonne and Pollier 2007; Olivier 2001). In addition, 25 million out of 25.8 million of the properties standing today will still be around by 2050, by then the rate of heat loss in these homes has to have dropped by at least half, which probably makes existing domestic housing stock the biggest challenge(Boardman, 2007).

1.2.2 Impact of occupant behaviour on energy consumption

The way in which occupants operate their buildings has profound implications for the quality of both the natural and built environments(Kempton, 1987; Humphreys, 1994; Haas, 1996; Brager, 2004; Bourgeois, 2005; Haldi, 2008). It is commonly estimated that people in economically developed countries spend at least 80 per cent of their time indoors, which suggests that much of the energy consumption of the home depends on occupant behaviour(Brager, 2004). Due to population increase and falling household size, there could be 23 per cent more households in the UK by 2050, and, under a business as usual scenario, a 23 per cent increase in energy consumption. Electricity use by lights and appliances continues to rise(Boardman, 2007). In an effort to maintain the quality of the indoor environment, occupants mechanically condition their home to provide a "comfortable" environment.

Interest and research into occupant behaviour and energy consumption first began in the mid-1970s in response to the oil crisis and has recently regained attention due to increasing concerns over human impact on the global climate. A number of international studies have been conducted to collect data on the behaviour of building users with regards to building control systems and appliances, for example how people operate fans, radiators, windows, shades and lights to create desirable indoor environmental conditions((Kempton, 1987; Humphreys, 1994; Yun and Steemers, 2008; Haldi, 2008).

1.3 Problem Definition

The fundamental problem is that often energy consumption fails to fall by the predicted amount, following an energy upgrade and it is not entirely clear how much this is because of the behaviour of the occupants or what that behaviour is. So, we need to develop new ways of monitoring and measuring the impact of occupant behaviour on energy consumption in dwellings.

The main objective of sustainable homes and new energy regulations is to reduce energy consumption by domestic buildings. The Affordable Housing Development in Liverpool, Urban Splash in inner Salford, Parity Projects in South London and the ZED Factory have all shown that new "Code level" homes and refurbished old households have actually reduced their energy consumption(CASE, 2008). However, not all households showed the expected energy improvements(CASE, 2008). Further research is therefore needed into the relationship between improved sustainable homes and reductions in energy consumption. In other words, further research is needed into the relationship between energy reduction and unexpected consumption.

National planning policy now requires that new developments of five or more dwellings meet Level 3 of the Code for Sustainable Homes and reduce carbon emissions by 31 per cent above current Building Regulations requirements(Welsh Assembly Government, 2009). The diagram below illustrates the steps in the approach to the design of sustainable energy management that should be used within new-build projects and refurbishments.

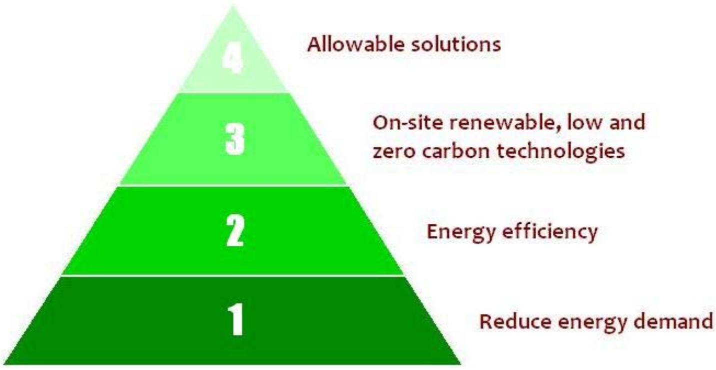


Figure 1.1: Sustainable energy management hierarchy

The purpose of the energy hierarchy is to provide a clear pathway to detail the design of a building with a sustainable energy performance in mind. This hierarchy is being embedded into policy and practice on Low and Zero Carbon buildings, Building Regulations, and is part of planning policy.

The energy hierarchy aims to reduce the demand for energy by reducing the quantity of energy required for heating, lighting and cooling via fabric efficiency and passive design. The second most important aspect involves the use of energy to efficiently provide occupants with comfort and safety via appliances and controls, such as high efficiency condensing boilers, low-energy lighting and energy-efficient white goods. Furthermore, on-site renewable, low and zero carbon technologies will be used to minimise energy consumption. Air or ground source heat pumps are most popular in “Code level” homes. Other technology includes combined heat and power, biomass boilers, solar water heating and solar photovoltaic panels to offset carbon emissions. The remainder of the energy hierarchy involves determining what solutions might be used and at what cost.

Based on this hierarchy, reducing the amount of energy required, consuming it at maximum efficiency and then fully utilising the potential of renewable technologies are still the mainstream approaches and are currently more achievable(CASE, 2008). However, witnesses from housing associations and occupant communities have pointed out that in some of their sustainable home projects net energy consumption does not meet the target for energy reduction, whilst some occupants have claimed that the new homes actually need more energy to run(Wales Consumer Council, 2007; Pembrokeshire Coast National Park, 2007). An interim assessment suggests that at least a third of the carbon savings in the residential sector will have to come from day-to-day behavioural changes(Hillman and Fawcett 2005), as opposed to the effective use of new technology or fuel-switching. People are an important resource to consider, they are the only agents who can invent, adopt, ignore, reject, adapt or subvert technologies.

All those previous investigations lead to a possible hypothesis that occupant behaviour probably provides the greatest opportunity to reduce energy demand and to consume energy efficiently in home. Occupant behaviour also represents the most immediate response link to the built environment, for instance, if occupants feel uncomfortable, they take corrective action to meet their comfort expectations. In terms of impact, occupant behaviour in relation to achieving indoor comfort is responsible for energy wastage, overusing automated comfort systems and direct/indirect carbon emissions and accounts for a large proportion of energy use in the targeted improvements. Thus, it is essential to investigate the impact of occupant behaviour on energy consumption, as it could be one of the key solutions to ensuring that the maximum benefit is derived from constructing new buildings and retrofitting sustainable homes.

1.4 Aim of the study

The aim of this study is to investigate methods of quantifying impact of occupant behaviour on domestic energy consumption, thermal comfort and indoor environmental conditions.

1.4.1 Objectives of the thesis

This research is based on the development of different strategies and devices for monitoring energy and environmental conditions in dwellings and tested through fieldwork involving the monitoring of physical conditions, energy usage and occupant behaviour within three Code Level 4 sustainable homes and one eco-refurbished terrace house. By working closely with occupants, the resulting analysis addresses uncertain causes of energy consumption variation, as these are impacted by different patterns of occupant behaviour and aims to understand their day-to-day comfort practices. The specific objectives are:

1. To review and summarise current knowledge of the impact of behaviour on energy usage in the literature;
2. To devise empirical studies to investigate people's behaviour in buildings and the resulting impacts on energy consumption and the environment;
3. To monitor behaviour in actual buildings and to record its impact on energy consumption and the environment.

1.5 Hypotheses and Research Questions

The importance of the role of domestic buildings in low carbon developments has been increasingly acknowledged in recent years; reducing carbon emissions in the domestic sector is crucial to achieving the UK's future targets. This research therefore examines the possibility of creating a constructive means of understanding occupant behaviour and its implications with regards to domestic energy usage and the indoor environment in South Wales during cold winters. Moreover, this research aims to help housing associations and energy advisers improve the thermal performance and energy efficiency of both existing housing stock and future designs. This should be a time-saving and convenient means of promoting sustainable development in Wales.

In accordance with the background of this study, the following hypotheses were proposed:

- Occupant behaviour can account for significant variation in energy consumption.
- Indoor comfort requirements are dynamic. Occupants can perceive the home to be adequately comfortable under different physical conditions, such air temperature and relative humidity.

In order to achieve better understanding of these hypotheses, this study also aims to answer the following research questions:

1. What methods may be used to measure occupant behaviour conveniently and ethically?
2. How can we measure the impacts of occupant behaviour on energy consumption?
3. How much will energy consumption change after people move from a less energy efficient home to a more energy efficient home?

4. What behaviour has the greatest impact on energy consumption?

5. What are the differences between the perceived comfort level and actual physical parameters?

1.6 Scope and Limitations of the Research

This research focuses on the impact of occupant behaviour on indoor environment, including thermal comfort and domestic energy reduction, across a selection of sustainable homes in south Wales. This allows for a better understanding of the impact of occupant behaviour on energy consumption and thermal comfort in domestic buildings. This study therefore examines the influence of the impact of behaviour on thermal comfort and energy performance.

Field measurements to investigate energy consumption and an indoor thermal comfort survey were conducted at the same time. Due to time constraints, cost and equipment limitations, only two pairs of building energy performance field measurements were taken simultaneously. This limited the range of different sustainable housing types but provided a more in-depth detail from pairs of identical houses.

The analyses were conducted in three parts, and limitations are listed according to the individual investigations as follows:

- Physical parameter measurement, include space heating adjustment, domestic hot water demand, windows and doors operation, electrical appliance and lighting demand, occupancy and wearable activity meter.

- Social science survey, contains questionnaire, self-administrated diary and interview.

- Integration of data from above two.

1.7 Structure of the thesis

In order to answer the research questions and to achieve the research objectives, the following tasks were identified and carried out, as shown in Figure 1.2.

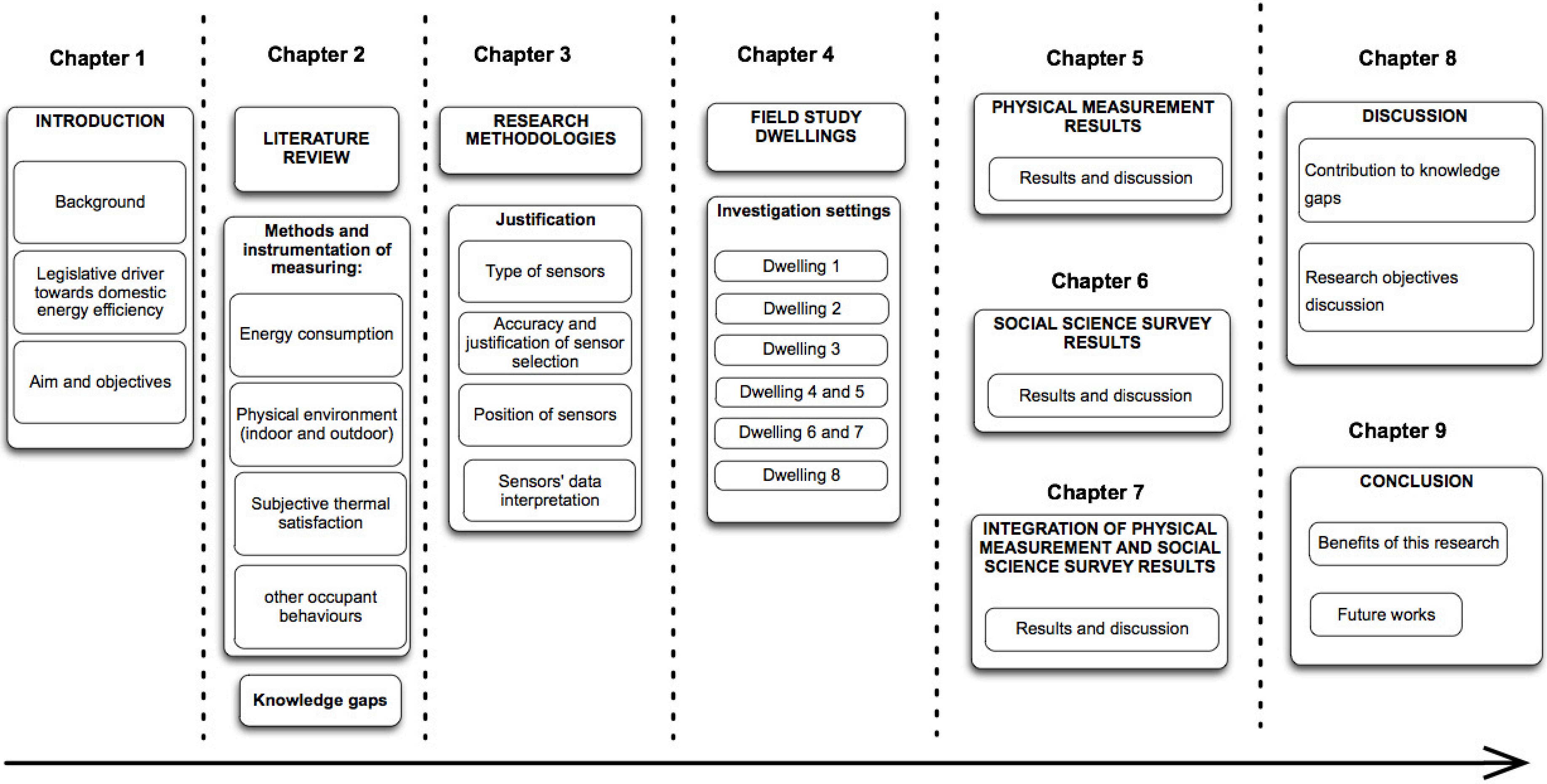


Figure 1.2: Structure of the thesis

Chapter 1 introduces the research and defines the problems and background. It also sets out the aims, objectives and significance of the study as well as its scope and limitations. The research methodology and structure of the thesis are also briefly outlined.

Chapter 2 discusses the theoretical background and reviews the literature in the field of method and instrumentation of monitoring; including a review of previous research designed to monitor and analyse domestic energy consumption, physical indoor environment, subjective thermal satisfaction and other occupant behaviours. It also summarises the gaps between knowledge base towards better monitoring methods and technologies.

Chapter 3 describes the practical research methodology. The research methodology focuses on justification of sensors regarding their type, accuracy, position and data interpretation. All the instruments and methods of physical environmental parameter and subjective thermal satisfaction monitoring are explained further in this chapter.

Chapter 4 describes the field study dwellings, include specific methodologies and instrument installed in each property and their purposes.

Chapter 5 and 6 present result from measurement of indoor environment, external climate conditions, occupant behavioural variables, subjective comfort and energy consumption. All the results above and findings for further data analysis and cross comparison in case studies are also discussed in **Chapter 7**.

Chapter 8 connects the findings and knowledge gaps and attempts to answer research questions by discussing research objectives. Data from the case studies are extracted and evaluated to discuss findings that correspond to the literature review and an attempt is made to address the research objectives.

In Chapter 9, conclusions are drawn from this study, successes, failings and further research on the subject of measuring occupant behaviour on energy usage in domestic dwellings.

1.8 Summary

Occupant behaviour and energy efficiency in residential buildings merits attention because of its assumed role in creating a performance gap between predicted and actual energy performance of dwellings. Dwelling have a crucial position in global sustainable development and tackling global warming, not only because of its huge current energy use, but also because of the greater potential of increasing energy demand in the future. Serious consideration must be given to exactly how energy is used by occupants in dwellings and where significant savings and indoor comfort could be achieved. Relevant authorities who design, construct, manage and maintain properties therefore have a significant responsibility to reduce the demand for energy use in buildings and to supply people with a better living environment with a greater respect for energy efficiency.

As previously stated, it is claimed that energy consumption might be significantly reduced by changing occupant behaviour and preferences. This research focuses on domestic buildings that are located in South Wales. Research questions are studied and answered through literature review, field study and on-site measurements in order to achieve the main aims of this research.

The conclusions and findings of this research are intended to help others who wants to explore the actual building performance especially the energy usage of domestic buildings in order to better meet energy regulations and carbon reduction targets and to provide adequate indoor thermal conditions to meet occupants' need.

Chapter 2 Literature review: methodologies and instrumentations for occupant behaviour monitoring

2.1 Introduction

This chapter aims to review the existing instrumentations and methodologies with regards to the measurement of energy related occupant behaviour that have been studied in previous research work, mostly focused in dwellings but also includes some non-domestic buildings. The following objectives were followed:

- Review previous studies that focused on parameters of energy-related behaviour, namely, space heating, ventilation and window operation, domestic hot water, electric appliances and lighting.
- Review current high resolution monitoring methods of gas and electricity meters, domestic hot water flow, indoor air temperature, relative humidity, CO2 concentration level, room occupancy and wearable activity tracker.
- Summarise knowledge gaps and make selection of which would be tested in the field study

Having reviewed how these parameter related to energy consumption and how monitoring method and instrumentations can be used to measure them, provides good understanding of their strength and limitation towards making choice in the field monitoring of this study.

At the end of this chapter, these methods and instrumentations will be gathered and summarised in a table together with selected knowledge gaps and corresponding field study plans that attempt to address them.

In western countries, in order to reduce the energy consumption in buildings, effort has been put in research on and development of more energy efficient technologies and buildings, especially during the last decades. Effort has also been placed on encouraging households to purchase more energy efficient technologies. The physical aspects related to the energy consumption of buildings, such as the building envelope, building installations and climate, are well understood. However, in practice, there is often a significant discrepancy between the designed and the real total energy use in buildings.

Interest in behaviour change reflects a growing recognition that technology solutions alone will not achieve energy conservation goals. While organizations often emphasize investments in physical upgrades and new technologies, the full potential of these technologies often cannot be achieved without accompanying behavioural and institutional change(Lutzenhiser, 1993; Earhardt-Martinez and Laitner, 2010). Even when technology upgrades, such as occupancy sensors on lights, can reduce exclusive reliance on the need for behaviour change for certain end uses, budgets may constrain integration of technology upgrades into existing buildings, making human behaviour the only means of conserving resources in some facilities. Furthermore, the practice of trying to design out the human element often has unforeseen consequences, such as creativity by building occupants to defeat or modify intended functionality(e.g., light sensors, thermostats). Occupant behaviour can strongly influence building energy use. As shown by NREL in a study of zero energy homes1 in the San Diego area, variation in utility consumption and cost across homes was considerable(a factor of 50) for homes with photovoltaics, with the primary difference being homeowner choices about energy-intensive equipment and amenities(Farhar and Coburn, 2006). Some homes with zero-energy capability actually consumed more electricity than conventional designs.

A focus on behavioural interventions can be useful in defining and executing the transferable actions and lessons learned to help fully realize the "behavioural wedge" of a broader set of strategies that can help reduce energy use and stabilize greenhouse gas emissions. Considerable analysis in the past several years suggests that the behavioural wedge, which can include actions such as reducing plug loads or minimizing trips, and efficiency actions such as equipment replacement, can reduce energy consumption in the range of 10–30%(Gardner and Stern, 2008; Dietz et al., 2009). Longer-term, understanding of behaviour can help to reduce potential divergences between modelled and actual building energy performance, which is frequently observed in practice(Heschong, 2012).

Monitoring studies for identical dwellings having the same type of installations have shown great variation in energy use. See for example Figure 2-1, which shows the variation in heating energy for identical dwellings having the same installations. The three curves in Figure 2.1 represent the heating energy use for three different types of dwellings installation at three locations in the Netherlands(Abushakra, 2004). For example, the single family buildings represented by the red curve display approximately a fourfold difference in heating energy use. The other curves show an even greater variation in heating energy use. This variation in energy use is in this case in a large extent related to the behaviour of the occupants of the dwellings, since identical buildings and installations having the same energy efficiency have been considered in this study. Similar findings of the effect of occupant behaviour have been reported by other studies(Ajzen, 1991; de Almeida, 2008).

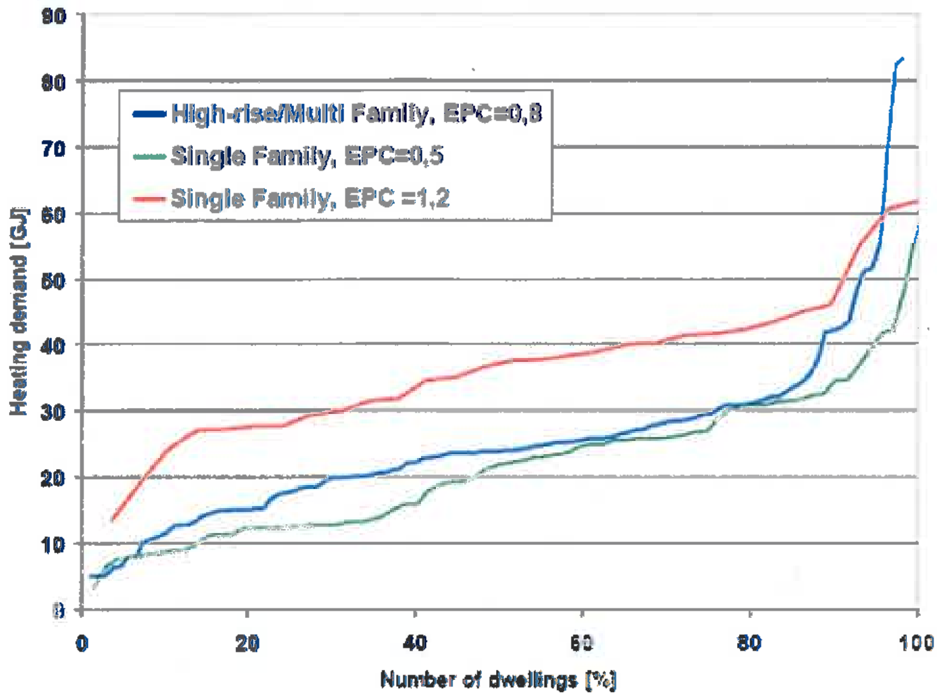


Figure 2.1: Variation in energy use in identical dwellings for three different projects(Abushakra, 2004)

de Almeida(2008) reports on a study of 1000 quite similar residential buildings in a suburb of Copenhagen, which in spite of their similarity show huge variation in energy consumption. The comparison of heating energy use for identical houses showed that households using the greatest heating energy used three times more heating energy than the households using the least energy for heating. For electricity use, an even larger variation was found; households using the greatest electricity used five times as much as the households using the least electricity.

Energy use in modern dwellings may show an increased sensitivity to occupant behaviour. For example, for very well insulated dwellings the relative increase of heating energy use is quite sensitive to the set point temperature chosen by the occupant(figure 2.2)

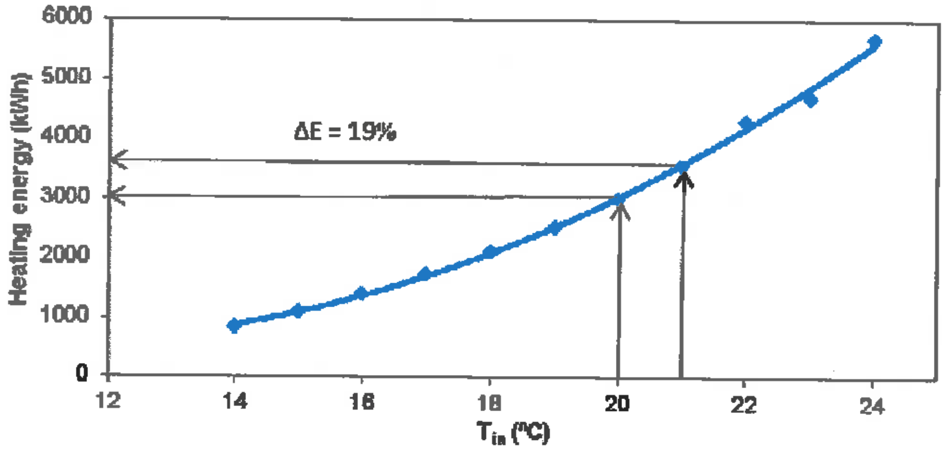


Figure 2.2: Increased sensitivity of heating energy for set point behaviour(Andersen, 2009)

The increase of heating energy of a very well insulated dwelling as a function of the set point temperature is displayed in Figure 2.2. Increasing the set point with one degree, from 20°C to 21°C, results in a 19% increase of the heating energy.

For modern dwellings with increased air tightness, the occupant behaviour can have a larger effect on the air change rate and consequently the energy consumption of the dwelling. As the requirements for energy use in buildings are tightened in national and international regulations, knowledge of physical aspects of energy efficiency is being implemented in new residential and office buildings. In order to fulfil the high expectations for energy savings in buildings in the future, better understanding of how energy-related occupant behaviour influences building energy consumption is required. The above examples of the effect of occupant behaviour on energy use and the sensitivity to occupant behaviour illustrate the importance of acquiring more knowledge on energy-related occupant behaviour for understanding and realistically predicting the total energy use in present and future residential buildings and for adapting future building technology to occupant behaviour.

2.2 Parameters influencing energy-related occupant behaviour

Energy consumption in dwellings is influenced by the behaviours of occupants in various ways. In this study, occupant behaviour mainly refers to energy-related and physically-environment related actions and reactions of an occupant in response to changes of external or internal stimulations, and actions and reactions of an occupant to adapt to ambient environmental conditions, such as air temperature, humidity, air quality, sunlight, home and other activities. Such behaviour influences energy consumption and indoor environment in various ways.

The influence of occupant behaviour on the energy consumption in dwellings has been investigated in various domains such as the building sciences, social sciences and economics. Natural science publications focus more on statistical relations between occupant behaviour and mostly physical parameters influencing this behaviour, such as outdoor air temperature, indoor air temperature and solar radiation(Anderson et al., 2011). As shown in figure 2.3, building science pays more attention of the upper link between quantitative descriptions of occupant behaviour influenced by physical parameters.

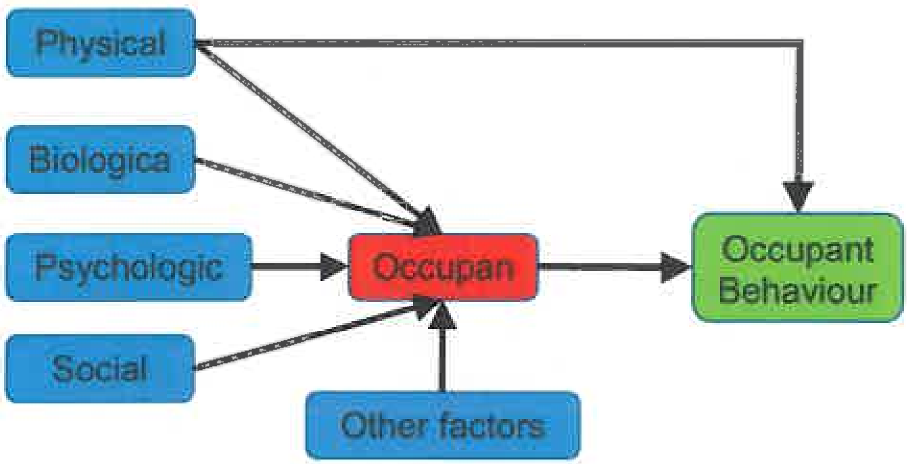


Figure 2.3: parameters influence energy-related occupant behaviours

However, there is no well-defined relation between physical parameters and occupant behaviour such as outdoor temperature and window opening. In reality, an occupant decides to open or close a window and the decision is based on a number of influencing parameters that can be categorized as physical, biological, and psychological, as well as social(the interaction between occupants, the norms of their culture, economics, etc.) to name a few. The lower part of Figure 2.3 illustrates parameters influencing occupant and behaviour.

This complex relationship between occupants and their environment is elaborated further in Figure 2.4. Much is still unknown about the motivation of the building control related occupant behaviour. Occupant behaviour is influenced by quite a large number of causes, both external to the occupant itself(e.g., air temperature, wind speed), and internal(e.g., personal background, attitudes, preferences) and building properties(e.g., ownership, available heating devices).

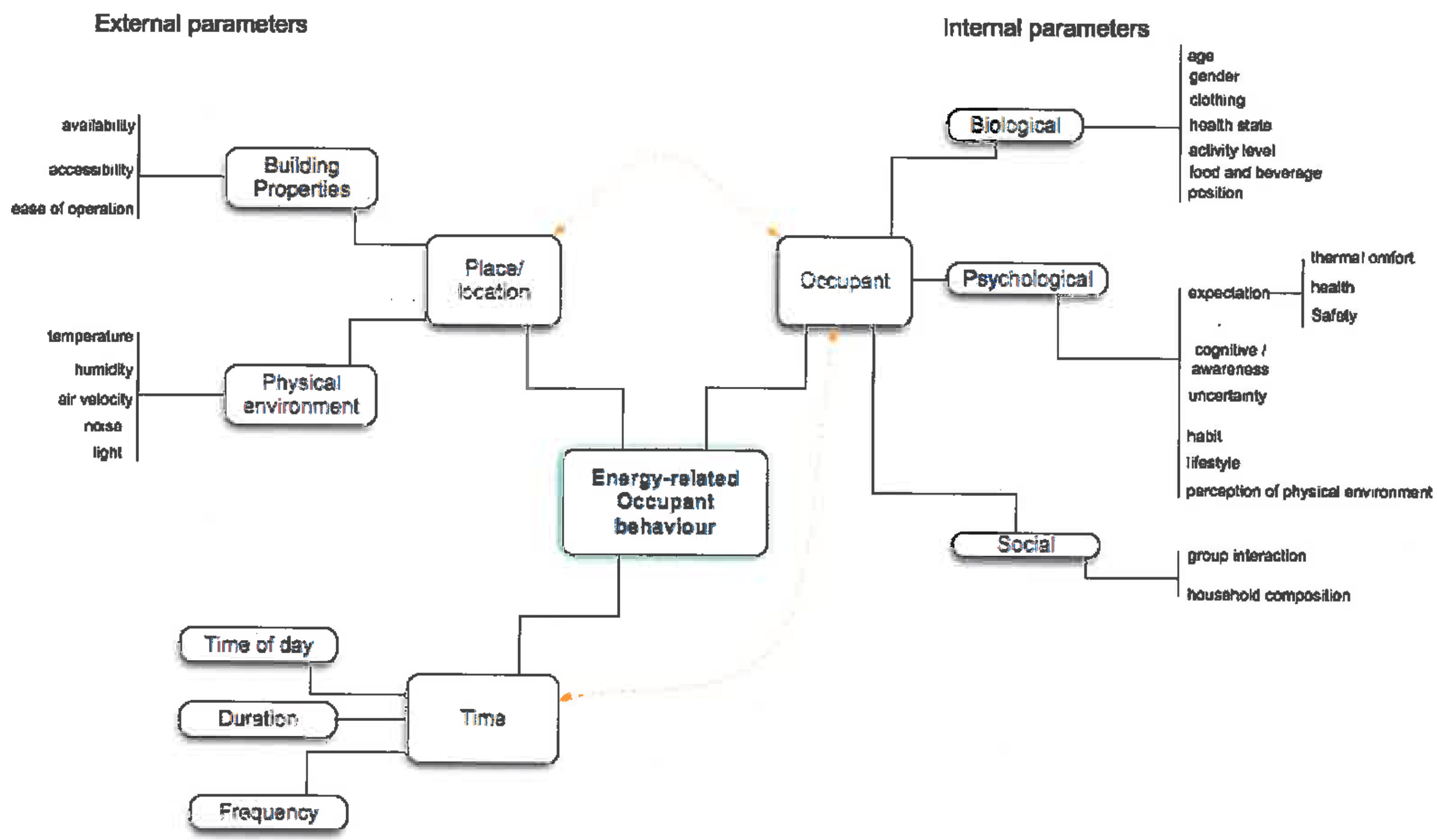


Figure 2.4: expanded parameters of energy-related occupant behaviour

2.3 Internal parameters

The first three types of parameters of occupant behaviour are biological, psychological and social parameters of the occupant. These parameters are being studied and investigated in the domain of social sciences, economics and biology. Strong interaction has been found between biological and psychological aspects, thus, a parameter like health can be considered as jointly unit of three types listed above. Other parameters like food and beverage habits are heavily influenced by cultural aspects and individual preferences. Some thermoregulation behaviours represent the interaction between biological and psychological parameters such as heating, cooling, ventilating and window opening. Some examples are listing for each parameter as followings:

Biological parameters: Examples of biological parameters are age, gender, health condition, activity level, hunger, and thirst. These factors together determine the physiological condition of the occupant. They have been the primary focus of early research on thermal comfort.

Psychological parameters: Occupants tend to satisfy their needs concerning thermal, visual, and acoustic comfort requirements, driven by physiological needs, along with health and safety, to name a few. Furthermore, occupants may have certain expectations of e.g. the indoor environmental quality(such as temperature). Other examples of psychological parameters are awareness(e.g. financial and environmental concerns), cognitive resources(e.g. knowledge), habits, lifestyle, perceptions, emotions, and self-efficacy(e.g. environmental control).

- Behavioural thermoregulation: Apart from autonomous biological processes, there is a variety of deliberate regulation options which are listed below. Adequate behavioural thermoregulation can be considered result of learning processes, experiences, and/or culturally-driven factors.

- Clothing: relevant in hot as well as in cold climate conditions, adequate clothing fosters reducing convection;

- Use of external sources for convection or thermal heat;

- Looking for places which, which are more convenient, e.g. shade, areas with more or less natural convection;

- Acclimatization: the process by which an individual becomes physiologically, behavioural, and psychologically adjusted to the temperature of the environment. This is of importance regarding the degree by which the individual tolerates actual sensitized temperatures especially when it comes to extreme and unfamiliar climates;

Social parameters: Social parameters refer to the interaction between humans and includes the culture that identifies specific groups of people. For example for residential buildings, this depends on household composition, which is linked to the primary decision maker in the household, i.e. which household member determines the thermostat set point or the opening/closing of windows?

2.4 External parameters

The external parameters depicted at the left-hand side of Figure 2.4(building and building equipment properties, physical environment, and time), are being investigated in the field of natural(or building) science.

Physical environment: Examples of physical environment aspects that drive energy-related occupant behaviour are temperature, humidity, air velocity, noise, illumination, and indoor air quality. Again, these variables have typically been used to predict physiological responses to a given environment.

Building and building equipment properties: Examples of building and building equipment properties are the insulation level of buildings, orientation of façades, heating system type, and thermostat type(e.g. manual or programmable), to name a few.

Time: Examples of this type of parameters that affect energy-relates occupant behaviour are season of the year, week or weekend day, time of the day.

2.5 Occupant behaviours

The energy-related occupant behaviour in Figure 2.4 refers to actions and activities related to the categories heating, ventilation and window operation, domestic hot water, electric appliances / lighting, and cooking. These categories are briefly introduced underneath and are discussed in greater detail in the subsequent sections of this chapter.

Heating: The activities of occupants have become more important within energy efficient buildings. Studies have shown that user behaviour and lifestyle can affect energy consumption by up to a factor of three. Occupant behaviour related to heating concerns temperature set point, number of heated rooms, heating duration, gender, age, expectations, knowledge of control function and meteorological conditions.

Ventilation and window operation: Investigations on window opening behaviour and natural ventilation have mainly been carried out with two aims: to find whether or not occupants are provided with adequate fresh air and to find the influence on energy consumption. The former category of studies has usually been carried out in dwellings and has a health or a comfort perspective, while the latter category has mostly been studied in offices with a comfort and energy performance perspective. Occupant behaviour concerns mechanical ventilation operation, natural ventilation inlet operation, window opening or closing.

Domestic hot water: Occupant behaviour can significantly influence the use of hot water in residential buildings. Examples of energy-related occupant behaviour related to domestic hot water use are the frequency of taking a shower, duration and intensity of showers; frequency of taking a bath; frequency of sink use; frequency and temperature of washing machines and dishwashers, and efficiency of water usage.

Electric appliances / lighting: The use of electric appliances and lighting in residences is strongly influenced by occupant behaviour. When the energy consumptions for appliances and lighting are considered, large variations are found, which partly relates back to socioeconomic parameters such as income, persons per household, age, education etc. The number of appliances and their energy efficiency, as well as the usage frequency and duration determine the energy use.

Cooking: Many different appliances can be used for cooking purposes, such as microwave ovens, ovens, stoves, pressure cookers, kettles, etc. The type of equipment used and their corresponding energy consumption as well as the number of meals prepared will determine energy use for cooking.

Among the behaviours listed above, this study focuses on space heating, window operating and electric appliance/lighting, of whose parameters that have been studied are reviewed in the next section.

2.6 Parameters of energy-related behaviour
2.6.1 Space Heating

The activities of occupants have become more important within buildings when considering space heating energy use in buildings. Low-energy, passive house, and zero buildings, are designed to minimize the heating load to supply only the required heat when occupants are present that cannot otherwise be gained through passive solar and internal heat gains. Studies have found that improving the efficiency of the building envelope and building systems significantly reduces overall energy consumption, thus increasing the importance of the role or actions of the occupant(Haasw et al, 1998; Satin et al, 2009).

Studies have shown that user behaviour and lifestyle can affect space heating energy consumption(Andersen, 2009; Larsen et al, 2010). Regarding the measurable parameter, one the most interesting psychological parameter is thermostat set-point temperature as a result of personal preference towards indoor temperature. This parameter often extends the heating schedule and individual thermostatic radiator valve(TRV) control. How the set-point temperature is determined, the correlating factors for temperature, and the overall operation of the heating system must be understood to define the parameters for energy-related behaviour for heating.

In a study conducted by Kvistgaard and Collet(1990), night-time thermostat set-point temperatures and number of heated room are shown to have a significant impact on room heating energy consumption due to the large variance of preferred sleeping temperatures. Thermostat set-point temperature and individual radiator were observed at fixed interval. It was observed that occupants have a large variance of thermostat set-point temperature for night before they sleep. Additionally, the individual radiator status was observed for estimated number of heated bedrooms, which was found to have a large influence on heating energy consumption.

Dörn(2011) used temperature logger to record individual room temperature and also found that number of heated room has effect in single-family houses. The estimated total energy use was studied and indicated that estimations were higher than actual consumption on monthly gas meter reading due to different heating habits for different rooms. The questionnaire studies of Weihl and Gladhart(1990) found that individual households have constant heating set-point temperatures that vary from each other, and questionnaire results of Baoping et al(2009) that indicate that there is large variance in the frequency a user decides to control their environment.

Emery and Kippenhan(2004) carried out a long-term monitoring study of two homes' space heating consumption and the effect of occupant behaviours. Their houses have identical room layout and heating system. One of the house consumed up to 32% less energy for space heating by maintaining a very low indoor temperature and only rise thermostat set-point when more heat is desired while occupants in the other house rarely change the thermostat temperature setting. Emery and Kippenhann used interview to find out occupants' habit of space heating control and temperature logger to record actual indoor readings.

Psychological parameter like understand of space heating control can also affect energy consumption of space heating. Several studies that have determined that many users do not understand how to use thermostats and thermostatic radiator valve controls properly(Karjalainen, 2007; Rathouse and Young, 2004; Peeter et al., 2008). Peeter et al(2008) found that overheating occurred as a result of misunderstanding the operation of TRV's. Questionnaire results in this study also suggests a large number of occupants who have poor understanding of heating controls, leading to improper use, working against advances in energy efficiencies. Andersen(2009)'s questionnaire and observation based study concludes that users' TRV control decisions are habit-based and misconceptions are widespread. The observed frequency by which occupants control heating coupled with the depth of understanding how the heating functions suggests a correlation with the energy used for heating. Interestingly, mixed method of diary and observation studies show that occupant's discomfort tolerance level is higher when they are aware of more space heating adjustment options available even they don't use(Paciuk, 1990; Leaman, 1995). Keul et al.(2011) have found that training occupants about the new technologies and correction of incorrect heating use soon after moving-in are very important for maintaining high satisfaction with living quality in low energy houses.

Satisfaction of indoor thermal environment is one of most popular parameter in the field of space heating research. Keul et al(2011) also asked occupants to keep a diary of their satisfaction level about internal air temperature and relative humidity every three hours for 14 days. Result shows that resident with data loggers have the higher satisfaction than those who have no devices at all, whereas residents with real time display of temperature and humidity information are least satisfied. Keul et al(2011) measured and recorded indoor air temperature, relative humidity and CO2 concentration along with interviews and thermal comfort satisfaction questionnaires in complex apartments, where an empty apartment was logged as a reference point. It was found that the perception of better satisfaction was higher with higher humidity, despite the fact that measurements recorded higher CO2 concentrations with higher humidity levels and the overall satisfaction was very high. The location of the data logger was not mentioned in this study especially the CO2 concentration logger whose measuring location can affect its accuracy and correct representation of a room.

Physical parameter such like air temperature can affect clothing choice occupant choose to wear which indirectly lead to different space heating control pattern. Morgan and de Dear(2003) state that outdoor exposure from the previous day influences clothing selection upon waking, weather conditions from the previous day also influence the current day's adjustments made to heating; either set-point temperature or degree of radiator TRV opening.

Time of day is related to both clothing and outdoor conditions. This indirectly influences the selected residential set- point temperature as higher clothing values are generally correlated with lower set-point temperatures(Morgan and de Dear, 2003). On heating systems without thermostatic controls, it is also possible for occupants to either activate the heating system or increase heating in the evenings when the outdoor temperature is cooler. In this study, external weather data was logged by a compact weather station and internal adjustment data such as set-point temperature and TRV were collected by observation visit. External climatic condition was also stated as an influential factor on indoor set-point temperature by comparison of local weather data and questionnaire results of thermostat setting preference(Haas et al., 1998). Other study used even hourly questionnaire to collect clothing adjustment along with recording of indoor conditions for a short period of 7 days(Baker and Standeven, 1994). In a more recent field survey, Haldi(2008) ask participant to complete short electronic questionnaire software whose window appears at regular participant-defined interval for three month.

DeCarli(2007) also found a pattern where occupants decided their daily clothing level based on the exterior weather conditions at 6 a.m. and made little alterations to the clothing level afterwards. However, exterior weather conditions were not the only influential parameter. As occupants spend more than 90% of the time indoors, climate parameters as defined by Fanger determine their subjective wellbeing. Many studies have been conducted about clothing levels in relation to various activities such as work, shopping, and leisure at home(Bakers and Standeven, 1996; Morgan and de Dear, 2003; Keul, 2010). Among these studies, Keul(2010) finds that people actively change their clothing at home corresponding with Andersen's residential questionnaire results finding that clothing adjustment was the main adaptive action(Anderson, 2009). The laboratory tests by Fanger, which used the same clothing ensemble for all experimental groups(Plinder and Kalkman, 2011) is disproven in the opinion of Keul(2010) as social, cultural, and historic aspects must also be considered.

Ownership of housing as a psychological parameter can affect heating use. The results questionnaire surveys in Austria of 933 and 636 participants showed that solar radiation, type of housing ownership, and perception of indoor environmental values were factors affecting heating use(Braun, 2010), and Kvistgaard and Collet(1990) also acknowledge the importance of home ownership on domestic energy use, indicating that more energy is used when energy costs are shared collectively in the rent.

As stated in study of Anderson(2009), the physical aspects of the building play a greater role than occupant behaviour in an approximate ratio of ten to one. In lowest energy buildings, where all building systems have been maximized for energy efficiency, the role of the occupant plays a larger role in determining whether or not the lowest energy targets are achieved. The comparative energy behaviour variance can be up to a factor of three(Anderson, 2009).

Biological parameters such like gender and age have been found to be influential on space heating energy consumption. In Fanger's(1970) experiments using two test groups of university students in Denmark and the USA and a test group of older, retirement-aged people, it was found that men preferred a warmer environment, but the findings were not statistically significant(5%). Fanger compared various literature studies and found that women are more sensitive to changes in temperature, but the results were inconclusive with some studies concluding that women preferred higher temperatures, while other studies showed that men preferred higher temperatures. Questionnaire study conducted by Kvistgaard and Collet(1990) also shows that heating energy consumption increases with age of occupant.

Karjalainen(2007) found that women were more dissatisfied with room temperatures than men, and preferred higher set-point temperatures. In the same study, it was also found that men controlled the set-point temperatures more often than women did. The effect of gender was also questioned by Andersen(2009); whose questionnaire results illustrated a trend that women desired higher set-point temperatures than men. In these studies, biological parameters were measured by questionnaire that distributed to participant during the heating season, with oblivious advantage of big coverage of participants.

Amongst the important psychological parameters, was the occupants' thermal comfort expectations. Hass and Biermayr(1998) and Biermayr et al(2005) respectively mentioned an "economic rebound effect" whereby occupant expectations and heating energy use increases with higher comfort levels achieved by thermal renovations, resulting in achieving only a partial potential of cost and energy savings.Reilly and Shankle(1988) state that it is common for a combination of heating systems to be used in buildings, and that there is a large variety of types used in different ways by homeowners. Braun(2010) examines heating system types in German homes, finds a positive correlation between education and gas consumption for space heating. However, decisions related to socioeconomic factors are secondary to location(urban/rural, East/West Germany) with preference for solid fuels in rural areas, thermal quality of the building envelope, and storage space for solid fuels. Building quality, heating system type, and climate together can influence set-point temperature and thermal comfort satisfaction by occupants(Haas et al., 1998). These psychological parameters such like cost, education level, expectations were measured by questionnaire method with large quantity of samples.

Regarding the most influential parameter, Larsen et al.(2010).proposed that the most influential parameters for conventional residential buildings were found to be outdoor climate namely, temperature, outdoor air humidity, and wind speed. Wei et al(2013) systematically reviewed 38 papers with 27 influential parameters related to the space heating behaviour and found that among these parameters, outdoor climate, occupant age, house/room type, house insulation, time of day, type of heating control and occupancy have the much higher influence than others.

As low energy houses have higher air tightness and thermal insulation, and use balanced mechanical ventilation with heat recovery, occupant behaviour becomes less dependent upon environmental and building/building system factors. Internal factors such as clothing and activity levels, perceived indoor environmental quality(IEQ), and established habits, especially window opening and ventilation, have greater effect on the overall heating energy consumption and will be discussed in the next section. Table 2.1 briefly listed the measurement methods and parameters based on previous studies, of which does not give detailed description nor specifications of sensors that were used.

Table 2.1: Parameters for space heating related behaviour and measurement method

Parameter type	Parameter	Method of measuring parameter	Effect	Effect measurement method
Physical	Number of room are heated	Temperature data logger	Space heating energy consumption	Temperature data logger
	Internal temperature	Indoor temperature sensor and display	Thermal satisfaction	Thermal comfort survey
	Household size	Visit	Space heating energy consumption	Questionnaire survey
	External weather at morning	External temperature sensor Weather station	Daily clothing level choice Thermostat set-point temperature	Questionnaire survey Temperature sensor Questionnaire survey
Biological	Gender, age	Questionnaire survey	Heating preference	Gas meter reading
	Clothing level/ preference	Observation, Questionnaire	Thermal satisfaction, Heating energy consumption	Questionnaire survey
Time	Time of day	Plan data collection time in advance	Thermostat set-point temperature clothing level choice	Questionnaire survey Interview survey Observation
Social	Number of occupants	Questionnaire survey	Space heating energy consumption	Gas meter reading
Psychological	Thermal expectation	Questionnaire survey	Thermal satisfaction	Thermal comfort questionnaire Hydrothermal information display Self-reported diary
	Understanding of heating control	Questionnaire survey Interview	Control of thermostat Thermostatic radiator valve	Interview
	Interaction with heating controls	Questionnaire survey Observation	Thermostat set-point temperature Space heating energy consumption	Interview Meter readings Compare identical buildings
	Memory of temperature from previous day	Interview	Clothing selection	Observation
	Ownership	Questionnaire survey	Space heating energy consumption Thermal satisfaction	Temperature sensor Thermal comfort questionnaire
	Occupancy	Observation and interview	Heating duration	Observe heating system timer setting

2.6.2 Ventilation and window operation

One physical parameter having a high influence both on the energy consumption and on indoor environmental quality is the air change rate. Since the thermal load for ventilation is related to the air change rate, a close examination of this indicator is important to consider when investigating the effects of the occupant behaviour.

The air change rate is affected by the occupants' behaviour, indoor environment and weather, but how dependent is the air change rate on the behaviour of the occupants?

As early as Bedford et al.(1943) conducted 358 measurements of the air change rate in six properties in London using the decay of coal-gas(containing about 50% of hydrogen) liberated into the air. They noted that any reasonable amount of ventilation could be obtained if liberal window openings were provided. Since then, houses have been tightened and sealed, increasing the relative effect of window opening on the air change rate. Coal-gas as a tracer was not recommended in the later study and they did 358 spot measures of the decay along with observation of window status. Kvistgaard et al.(1985) measured air change rates in 16 family houses for 7 month with lower toxic sulfur hexafluoride(SF6) as tracer gas, they found that the window opening behaviour had the largest effect on air change rates, causing increases ranging from a few tenths of an air change per hour to approximately two air changes per hour. SF6 as tracer gas was also used by Wallace et al.(2002) for 1 single family house for one year, they found that the window opening behaviour had the largest effect on air change rates, causing increases ranging from a few tenths of an air change per hour to approximately two air changes per hour. In another paper describing the same measurements Howard-Reed et al.(2002) stated that opening of a single window increased the air change rate by an amount roughly proportional to the width of the opening. In these two long-term studies, the window operating behaviour data was observed by the researchers during fixed period.

Given the complexity of setting up of releasing tracer gas, Price and Sherman used questionnaire and spot measured air change rate of 1515 houses for greater coverage. Questionnaire and spot measurement were taken in both winter and summer. They found that it is evident in the winter months occupants opened windows to a smaller degree than in summer. For better long term measurement method, Bekö et al.(2010) attempted to measure air change rates based on the build-up level of CO_2 emitted by occupants. CO_2 concentration level was continuously measured for 3-5 days in 500 bedroom of Danish dwellings. The results showed that a large proportion of Danish occupants use windows to adjust the supply of fresh air to the dwelling. Since the lowest temperatures occur during night time in winter, the effects of this behaviour on the energy consumption might be substantial.

Observation of the window status has been one of popular method since it doesn't require any special setting up or equipment. As early as the study Dubrul(1988) on occupant behaviour focused on a combination of questionnaires and observations to determine which action is taken by occupants to ventilate their homes and to evaluate the reasons for their actions. The study has shown that the type of dwelling(house or apartment) influences the length of time windows are open and also has an effect on the degree of window opening. In this investigation, as shown in figure 2.6, it appeared that windows in living rooms and kitchens were open on average for shorter periods, whereas windows in bedrooms were open for longer periods in houses compared to apartments. Dubrul also observed three levels of window opening were examined(closed, slightly open, and wide open) and large variations among the degree of window opening were found.

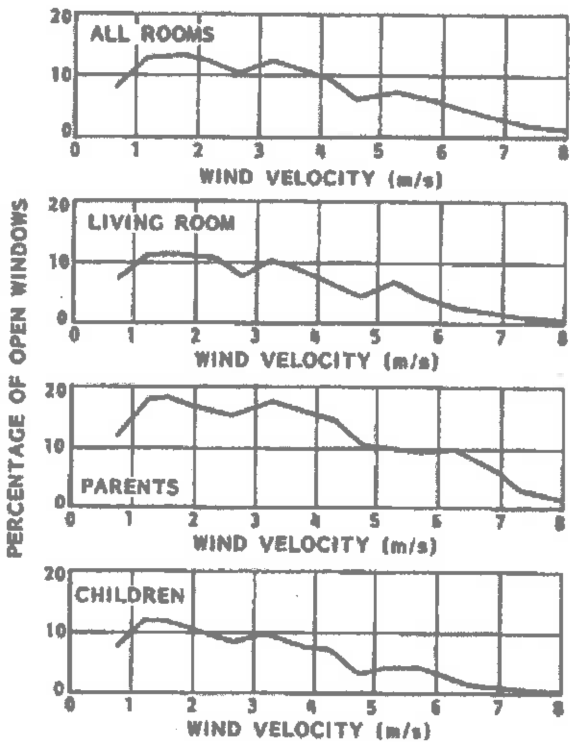


Figure 2.6: Percentage of open windows as a function of wind speed(Dubrul,1988).

This finding is consistent with a study for 24 identical flats in Germany(Erhorn,1988). Even in the extreme winter weather, bedrooms are ventilated more frequently than all rooms on average: during the entire measuring period the window opening time in bedrooms exceeded the average for all rooms by approximately 50%. The room orientation is also important.

Time of day is also found to be an effective parameter. Result from Duburl's(1988) observation of dwellings have shown different daily patterns for the different types of rooms(figure 2.5). Typically in the study, the maximum number of open windows occurs during the morning, but during early afternoon(when cooking) the number of open windows is still relatively high but gradually decreases during the afternoon until the return of working inhabitants to the home at about 5 pm(Duburl, 1988). The time of day was also found to be influential to determine window transition probabilities, e.g. closed to open and open to closed(Johnson and Long, 2005).

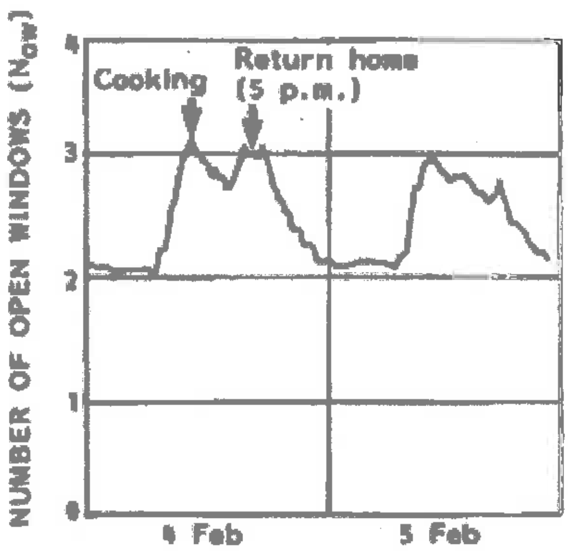


Figure 2.5: Daily profile of window opening,(Duburl,1988).

Psychological parameters like perceived illumination and thermal comfort were found to be influential on window operation behaviour, driven by the physical parameters like solar radiation, outdoor temperature and wind speed. In the study of Anderson et al.(2009), they found the interaction between the occupant's gender and perceived illumination had a statistical impact on the window opening behaviour from the result of combination of questionnaires and observations to determine which action is taken by occupants to ventilate their homes and to evaluate their reasons for these actions. They found that when the sun was shining, south facing living rooms and bedrooms were more likely to be ventilated for longer periods than similar rooms orientated in other directions. It seems most likely that it is the effect of solar radiation and temperature, rather than the orientation itself that affected the occupants' window opening behaviour.

Not surprisingly, the outdoor temperature had a considerable impact on the window opening behaviour. An early study of J.B. Dick and D.A. Thomas(1951) found that the outdoor temperature was the single most important explanatory variable when observing the number of open windows in 15 houses. Brundrett(1977) found the monitored temperature(mean monthly temperature and average temperature swing) to be an important explanatory variable for the occupant's opening of windows.

Warren and Parkins(1987) furthered their agreement by applying multiple correlation analysis of their field observation that outdoor air temperature contribute 76% of variance, wind speed with 4% and 8% from solar radiation. The results of Andersen(2009)are consistent with these findings. The statistical analysis related to the questionnaire survey carried out in 2006 and 2007 in Danish dwellings has shown that window opening behaviour is strongly linked to the outdoor temperature.

Observation of window open/close behaviour has its limitation since it requires manual effort of scheduled inspection or continuous check for a fixed period. Automated method such as magnetic switch have be employed in recent studies. More recently, field investigations of Yun and Steemers(2008) have indicated that the variation in energy consumption of two natural ventilated office buildings were mainly due to the behaviour of the occupants. Each building mainly houses offices for one to two occupants. Central pivot widows and night ventilation were offering each of their ventilation separately. Windows in each room have been designed carefully which enable occupants to open in two ways(tilt and turn). They provided occupants with options of wide and small opening. Besides these opinions, these offices are free of security issues and not exposed to heavy, wind-blown rain. Under these conditions, these two building provided most generous convenience to people to adjust their windows for their own indoor comfort. In their field study, indoor temperatures and the state of the windows were collected from data loggers installed in each office and windows. External temperatures obtained from the nearest weather station. In her findings, there is a statistically and substantively significant correlation between the window-opening patterns and indoor air temperatures. It seems that people recognised the window as a comfort controller and this played an important role in their response to the window opening. Their finding is consistent with the observation result by Rijal et al(2007).

The influence of physical parameter wind speed was investigated in the aforementioned studies(Dubrul, 1988 and Erhorn, 1988) and the results show a significant decrease in the prevalence of open windows at high wind speed. Dubrul's observation results shows that nearly all windows were closed at wind speeds above 8 m/s.

The questionnaire investigation of Guerra-Santin and Itard(2010) of households in the Netherlands in autumn 2008 showing biological parameter such as gender and age can be influential on window operating behaviour. They found that the behaviour of elderly people significantly differed from that of younger people. Other parameters, for example, habits and lifestyle, are also found to affect window operating. Questionnaire interview of 1515 houses highlighten a clear correlation between smoking behaviour and the airing and ventilation of living rooms. Moreover, the longer the dwelling is occupied the more the windows, especially the bedroom windows were kept open, and in this way the Dubrul(1988) concluded that the presence of the occupants in the home and use of the windows were related. No other of the surveyed studies took into account the occupant lifestyle as explanatory variable of the model.

Having considered CO2 level as a tracer of measuring air flow rate, it can also be used to indicate IAQ. Elevated CO2 levels affect occupant comfort and IAQ and in dwelling without powerful mechanical ventilation system, poor IAQ may lead to window operating behaviour. Brundrett(1979) found that windows in flats without mechanical ventilation systems are open about four times longer than in flats with mechanical ventilation. With elevated CO2 levels, occupants may complain of perceived poor air quality and may face health problems such as headaches, fatigue, and eye and throat irritation(Wyon & Wargocki, 2006). Occupants continuously exhale CO2 formed in the body during metabolic processes and, where fuel is not being burnt, these emissions comprise the greatest contribution to indoor concentrations(Wanner, 1993). Typical indoor CO2 concentrations range between 700 and 2000 ppm(approximately 3657 mg-3) but can exceed 3000 ppm(Arashidani et al., 1996).

As stated in the new European standard EN 13779:2007, it is recommended to achieve a comfortable and healthy indoor environment in all seasons with acceptable installation and running costs and this is now a national standard in all countries. The new standard classifies the indoor air quality from IDA 4(low IAQ) up to IDA 1(high IAQ) with typical ranges of CO2 levels listed in table 2.5. As a traditional but limited method for determining the IAQ, CO2 level is a good indicator of effective ventilation, but not of absolute air quality. The results of the logistic regression model based on long-term monitoring of windows operating behaviour and environmental variables in 15 dwellings confirm that outdoor temperature, indoor temperature, solar radiation, and indoor CO2 concentration were the most influential variables to determining window opening/closing probability(Dubrul,1988).

Table 2.2: IAQ and Indoor CO2 level(European Committee For Standardization, 2007)

Category	Description	CO_2 –level(ppm) Typical range
IDA 1	High IAQ	< 400
IDA 2	Medium IAQ	400 – 600
IDA 3	Moderate IAQ	600- 1000
IDA 4	Low IAQ	> 1000

In summary, the previously identified parameters for energy-related behaviour with respect to ventilation and window operation in residential buildings are grouped and listed in table 2.3.

Table 2.3: Parameters for ventilation and window operation behaviour

Parameter type	Parameter	Method of measuring parameter	Effect	Effect measurement method
Physical	Air change rate	Decay of tracer gas	Window opening behaviour Degree of window opening Indoor temperature	Observation Temperature data logger
	External wind speed	Wind speed sensor	Window operation	Outdoor exposure from previous day
	Mechanical ventilation	Observation	Air change rate window opening frequency	Questionnaire survey Decay of tracer gas
	Outdoor temperature	Observation	Number of window opened	Interview survey
	Indoor temperature	Temperature logger	Window operation Space heating energy	Observation Gas meter reading
Psychological	Smoking behaviour	Questionnaire	Living room ventilation rate	CO2 measurement
	Perceived thermal comfort	Questionnaire	Window operation	
	Perceived illumination	Handheld Lux meter	Window opening preference	Interview
	Window opening	Questionnaire survey General meter readings	Energy consumption Indoor air temperature Air change rate	Questionnaire survey Temperature data logger Handheld air speed spot measure
	Occupancy of a room	Questionnaire	Air change rate	Decay of tracer gas
Time	Time of day Season	Observation Questionnaire	Window status transition probability	Interview Questionnaire
Biological	Occupancy	Questionnaire	Air change rate	Decay of tracer gas
	Clothing level	Questionnaire survey	Window opening behaviour	Observation
Building properties	Function of room	Questionnaire survey	Window opening time	Questionnaire survey
	Mechanical ventilation	Questionnaire survey	window opening frequency	Observation

2.6.3 Domestic hot water

Occupant behaviour can significantly influence the use of hot water in residential buildings and energy that consumed to maintain its suppply. Showering frequency, duration and intensity of showering, bathing frequency, sink use frequency, washing machine and dishwasher use frequency and running temperatures, and appliances' water use efficiency are examples of domestic hot water energy-related occupant behaviour.

Various studies found that domestic hot water use patterns vary on different time scales: time of day, time of the week, month, and year(Buchberger and Wu,1995; Buchberger and Wells,1996; Blokker,2010, Blokker et al.,2010) . In all these field studies, the water flow was monitored by logging its pulse output which represents the volume of hot water pass through the sub water flow meter..

Function of room as building property parameter was found to affect the domestic hot water consumption. Kempton(1987) reported the findings of study based on sub water meter data from seven dwellings show based on sub water meter data from seven dwellings. Flow meters have been added to hot water pipe of kitchen and bathroom that bathing accounts for the largest use, while the kitchen accounts for the second largest use. The variation in energy use per person is primarily attributed to behavioural differences among the occupants. In this study, the variation in individual water use behaviour is greater than the variation in the total domestic hot water use in all houses. Due to complexity, this study did not separate hot water end use in each space, for example, kitchen sink tap and washing machine.

In the field study conducted by Vine et al(1987), where a further disaggregation was made to hot water end use by adding more sub flow meters. They reported the largest daily hot water use was for bathing and showering(43%) and the second largest use was by washing machines(30%).

Various parameters have been measured by questionaire and analysed in this study, such as age(biological), number of children(social), education, ownership satisfaction with hot water temperature, and hot water conservation attitude(psychoglocial). In this study, education was found to be the only significant variable explaining hot water use. The higher the education level, the more hot water was used. Since education is usually correlated with income, it is likely that these households owned more water-using appliances. A positive correlation between income and domestic hot water use was also found(Aydinalp et al.,2004). However, it was found that people having a higher education, higher income, and a higher status job were more likely to apply water saving strategies(Berk,1993). The lower the education level and job status, the more water is used for showering according to Foekema(2008). Contrary to the study of Foekema(2008), Aydinalp et al(2004) found a positive correlation between income and domestic hot water use. According to study of Volkshuisvesting et al.(2009), the frequency of using a bath depends upon income. Households that frequently use their bath are mainly families with children and a relatively high income. The frequency of using the bath also depends on household composition and household size, households that frequently use their bath are mainly families with children. Ownership as psychological parameter was found to be influential. The field hot water monitoring by Aydinalp et al(2004) suggests that renter-occupied dwellings consume less domestic hot water than owner-occupied dwellings. However, Barr and Ford(2005) suggests that homeowners are more likely to save energy than renters.

While questionnaire method provide overview of hot water related behaviour, self reported diary could offer more details. A Dutch study(Volkshuisvesting et al.,2009) showed that shower duration is strongly related to age, see Figure 2.7. The shower duration data was collected by self-reported diary kept by participants. Results shows that the shower duration is relatively long for people around 20 years old and for people older than 65 years. Shower frequency is also strongly related to age. The reported shower frequencies are shown in Figure 2.8. The shower frequency is highest for ages between 20 and 45 years; the corresponding average shower frequency is six to seven times per week. Lower frequencies are found for younger and older people.

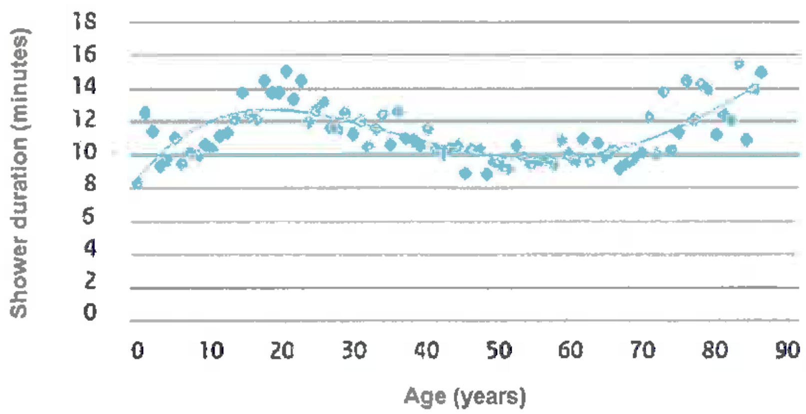


Figure 2.7: Shower duration in minutes as a function of the age of occupants in years in the Netherlands(Volkshuisvesting et al.,2009).

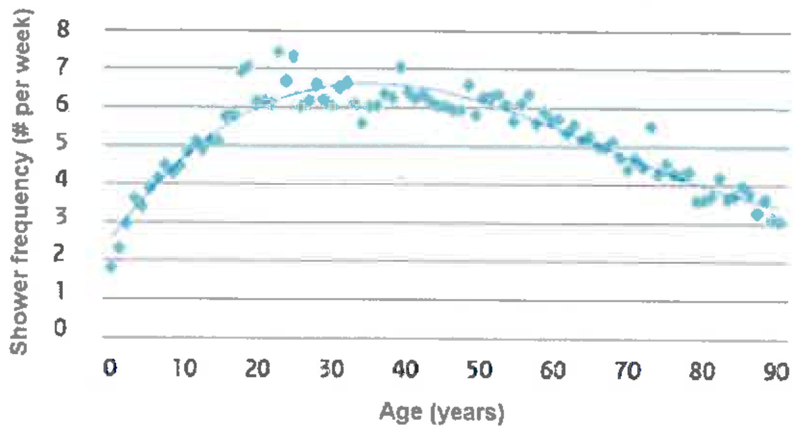


Figure 2.8: Shower frequency per week as a function of the age of occupants in years in the Netherlands(Volkshuisvesting et al.,2009).

Intensity of water use events can be influenced by specific properties of the applied equipment(water saving devices). For example, the use of low-flow showerheads can reduce energy use for domestic hot water. However, off-setting behaviour such as an increase in shower length after installing a low-flow showerhead may undo the positive effects of water saving technologies(Campbell et al,2004).

Table 2. 4 summarised the method of measurement of domestic hot water consumption related behaviour in the previous studies.

Table 2.4: Parameters for domestic hot water

Parameter type	Parameter	Method of measuring parameter	Effect	Effect measurement method
Biological	Age, gender, health, income, origin	Questionnaire	Shower duration Frequency bath/shower	Water flow meter Self-reported diary
Social	Household composition Number children	Interview and questionnaire	Frequency of bath/shower	Water flow meter
Building properties	Water saving devices Function of room	Questionnaire	Shower duration Intensity shower	Water flow meter Questionnaire survey
Time	Time of day	Interview and Questionnaire	Shower duration	Water flow meter
Psychological	Education Ownership Satisfaction with hot water temperature Hot water saving attitude	Interview and Questionnaire	Shower duration	Water flow meter

2.6.4 Electric appliances and lightings

Electric appliance monitoring is essential for understanding the sources of consumption inside a building. As electricity in buildings typically flows along a tree-shaped distribution network, Jiang et al.(2009) employed a sparse set of carefully placed wireless metering sensors at several load sensing points to approximately disaggregate the electric appliance load tree. Patel et al.(2009) demonstrated a technique to detect and classify electric loads using a single plug-in sensor, by monitoring noises on power lines. Similar to this work, Taysi et al(2010) performs device-level power consumption identification primarily based on acoustic signatures of household appliances using audio sensors.

When the energy consumptions for appliances and lighting are considered, large variations are found, partially relating to socioeconomic parameters such as income, persons per household, age, and education, etc. 30-40% of the variation in electricity consumption can be explained by these parameters(Gram-Hanssen, 2005). In this study, to get an idea of how electricity is used per household, an analysis of end use was made in 100 different households.The results are displayed in Figure 2.10. The group for "other" consumptions also includes electricity for cooking, which typically amounts to 10% of total electricity consumption(Gram-Hanssen,2005).

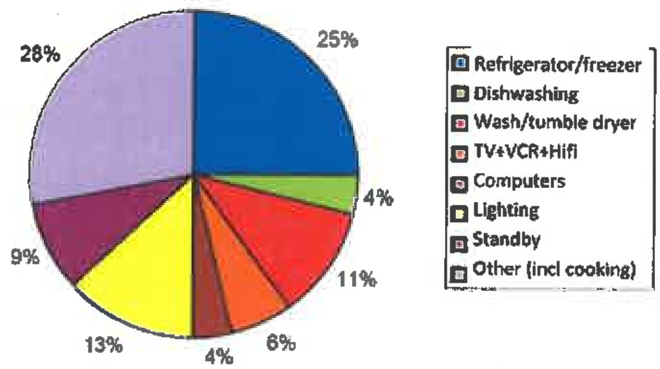


Figure 2.10: Distribution of household electricity consumption based on measurements in 100 dwellings,(Gram-Hanssen,2005)

Different electrical appliances have different routines of operation and measurable parameters. Lighting practices(number and type of lamps and operation) are strongly influenced by cultural norms of comfort and interior decoration style(Wilhite, 1996) and also habits from childhood seem to influence electricity use routines(Gram-Hanssen, 2008). Interviews in the latter study showed that occupants reflected much more about lighting energy use than on all other aspects of electricity consumption, which was not very rational as it typically accounted for less than 15% of total electricity use. The use of electric lighting in the domestic sector also depends on the level of natural light coming in from outdoors coupled with the activity of the household residents. Monitoring result from presence sensor shows that the number of people who are at home and awake(active occupancy) is the other key factor for domestic lighting use.

Jensen(2012) also monitored the total electricity consumption and compared with the number of occupant which is shown in figure 2.11. The electricity consumption per person decreases as total number of occupant increases.

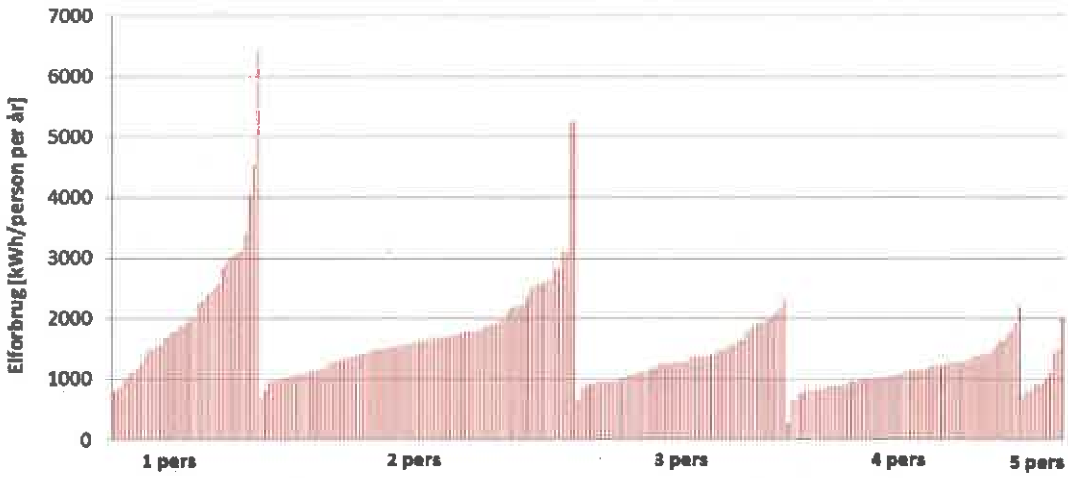


Figure 2.11: Electricity consumption in kWh/person per year as a function of the number of persons per household in a larger area with dwellings in Århus, Denmark,(Jensen, 2002).

The decreasing consumption per person can be explained by the basic electricity consumption which is common for all households despite household size. Included is electricity use by the refrigerator, freezer, and partly by cooking, and lighting. Another study showed that the energy use for artificial lighting was also strongly dependent on household size(Bladh and Krantz, 2008).

Table 2.5: Electricity consumption by lighting; annual average for different household sizes. The data are seasonally and geographically standardized,(Bladh and Krantz, 2008).

Household size, Nunmber. of occupants	Number of homes	Lighting energy, kWh	Lighting energy per person, kWh
1	20	405	405
2	27	586	293
3	7	735	245
4	11	941	235
>=5	4	1113	223

Acker et al. 2012 deployed smart strip sensors and occupancy sensor in a two-year project to characterize space level plug load profiles. Average potential savings of 0.6 kW h/ft2/year were found by smart plug sensor with occupancy sensors. The Green Proving Ground program [105] monitored more than 295 devices across eight office buildings for four weeks. Results indicated that the use of cheap scheduled timer controls yielded reductions of 43% from baseline, whereas combining load sensing and control offered only 23% savings, and is best suitable for individual workstations where occupants have various appliances and unpredictable schedules.

Other method have been used to monitor occupant behaviour related electric appliance usage. Viridiscope(2012) uses an array of indirect sensors such as magnetic, light and acoustic to disaggregate total electricity load. Moreover, a proximity sensor is used by Kim et al.(2008) to monitor electric appliance usage by individuals. The basic idea is that an occupant carries an active RFID tag, used for detecting proximity between a user and each device. In later study, Kim et al.(2010) combined circuit-level energy monitoring with statistical Granger causality analysis to automatically understand the causal relationship between occupants and their energy use.

Comparing to the various functions of difference appliances, lighting perhaps is simpler as it is to provide artificial light when occupant requires. In office and school buildings, occupants switch on artificial lighting upon arrival and while present in a room as a function of the natural illumination, and rarely switched off artificial lighting until departing a room if the room was completely empty(Hunt, 1979). Figure 2.12 shows the probability of switching on artificial lighting as a function of work plane illuminance. Similar results have been found by other authors(Reinhart, 2004). In both studies, the illumnance level was monitored by portable sensor and lighting control behaviour was observed.

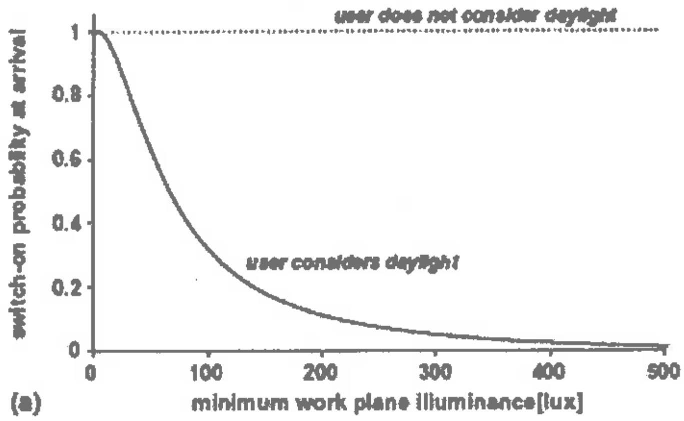


Figure 2.12: Measured switch-on probability function upon arrival in office buildings. Hunt's original function(solid line) describes the average switching behaviour of a group of users,(Hunt, 1979).

Similar results have also been found by Pigg et al.(1995) through similar observation method and in expand on the same office building Mahdavi and Pröglhöf(2009) obtained similar results through measurements in three different office buildings during working hours. with digital cameras recorders which filmed the occupancy and lighting control footage. They noticed that on average, occupants spend more than 50% of the time away from their work station. Lights and office equipment remain operational all day. Figure 2.13 shows the probability of switching the lights on upon arrival in two of the offices as a function of the prevailing task illuminance level, while Figure 2.14 shows the probability of switching the lights off as a function of the duration of absence in minutes.

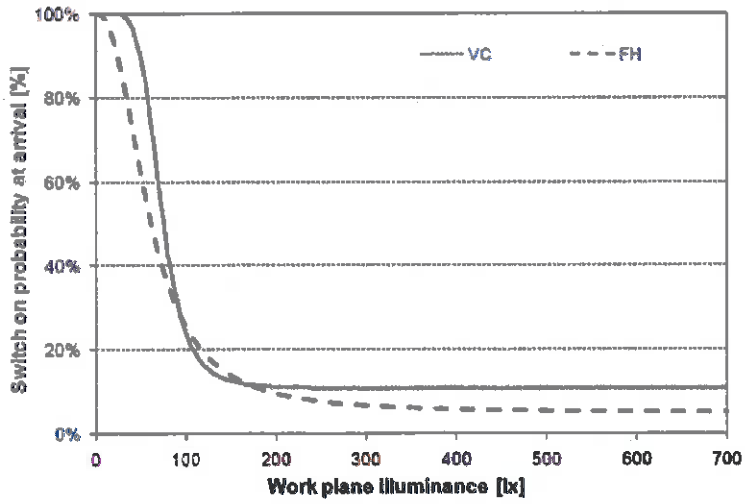


Figure 2.13: Probability of switching the lights on upon arrival in the office in VC and FH as a function of the prevailing task luminance level,(Pigg et al.,1995).

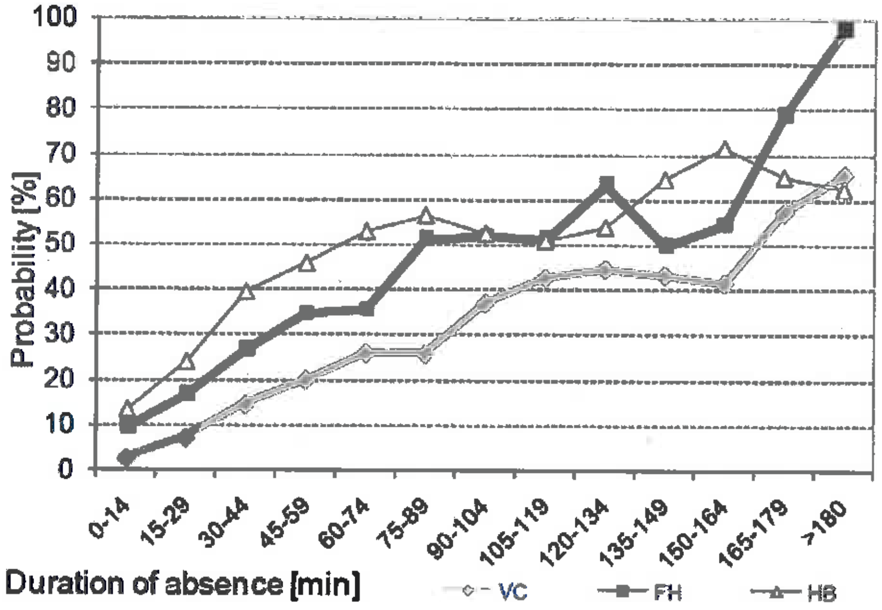


Figure 2.14: Probability of switching the lights off as a function of the duration of absence(in minutes) from the three offices in VC, FH, and HB,(Mahdavi and Pröglhöf, 2009)

Similar results could be expected to be valid for residences, although the relationships might be quite different. Moreover, the number of people who are at home and awake(active occupancy) is the other key factor for domestic lighting use. This expectation is supported by results obtained from a lighting demand survey by Stokes et al(2004), who took samples of 24 hours lighting electricity profile through temporarily current transducer on the lighting circuit from 100 homes in the UK.

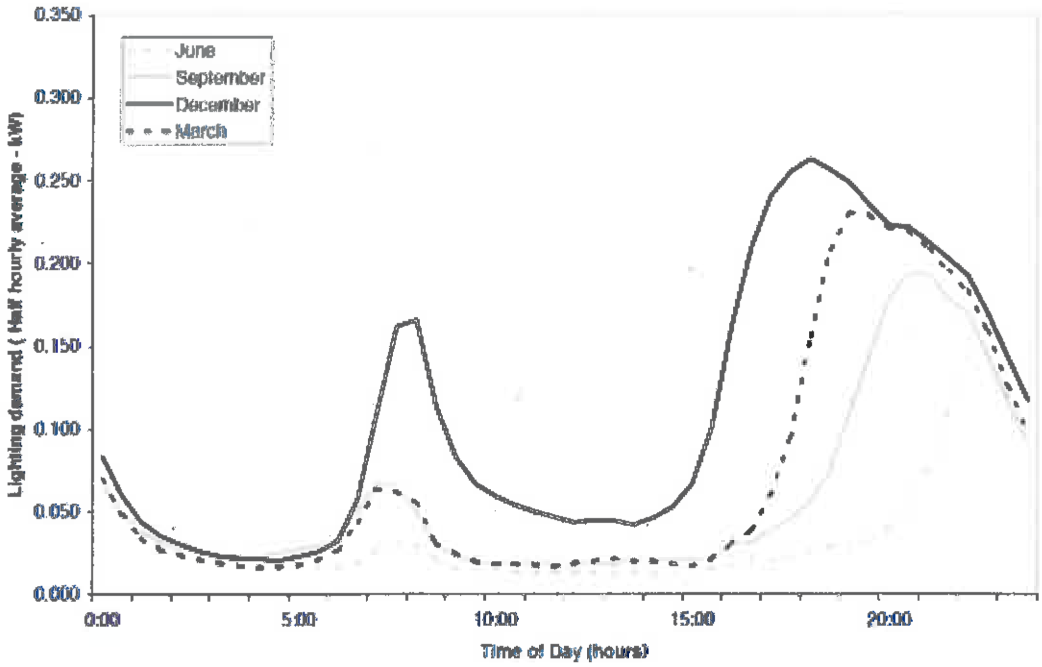


Figure 2.15: Daily lighting profile(monthly averages, weekdays) at different times of the year averaged over 100 homes showing demand in June(dashed grey line), September(solid grey line), December(solid black line) and March(dashed black line),(Stokes et al, 2004).

The use of electric appliances and lighting in residences is strongly influenced by occupant behaviour. In the literature, investigations of energy-related behaviour and its parameters are very rarely separated between appliances and lighting, but information from studies in office buildings can be used to some extent. Table 2.6 summarised the parameters and methods appeared above.

Table 2.16: Parameters for electric appliances and artificial lighting measurement

Parameter type	Parameter	Method of measuring parameter	Effect	Effect measurement method
Biological	Age gender activity level Occupancy	Questionnaire Presence sensor	Electrical appliance operation Lighting control	Smart plug Video camera
Social	Household composition Education Habit	Interview and questionnaire	Electricity consumption	Sub electricity meter for individual circuit Device energy meter for high power-rated appliances
Building properties	Device level power consumption	Audio sensor Proximity sensor Indirect sensor array	Electricity consumption	Electricity meter with pulse output RFID tag to detect distance between user and appliance
Time	Time of day Season	Interview and Questionnaire	Lighting control	Current transducer Sub electricity meter
Psychological	Education Ownership Satisfaction with illuminance level	Interview and Questionnaire	Lighting control	Handheld lux meter

2.7 High resolution monitoring method

Majority of the previous studies reviewed earlier do not describe the instrument or measurement method in great details, therefore, key sensors and technologies have been picked and reviewed in this section. Most existing literature regarding the high resolution monitoring focus on single technology, method and instrument, but not so much on the occupant behaviour aspect. As a result, it was difficult to merge and review them into previous sections under appropriate behaviour category.

2.7.1 AMR and NIALM for utility meter monitoring

The idea of automated meter reading(AMR) was first developed in 1962 at AT&T in cooperation with a group of utilities and Westinghouse. The modern era of AMR took off in 1985, when several major full-scale projects were implemented by utility companies(Tamarkin, 1992). With the rapid growth of AMR technology also developed interest in developing an automatic metering infrastructure(AMI), which refers to the integration of AMR capable meters to provide an overview of the entire gas distribution, and non-intrusive appliance load monitoring. Presently, gas utilities are adopting AMR solutions to decrease costs, eliminates missed meter reads because of bad weather or difficulty accessing meters, reduce estimated bills and provide better service to their customers. These AMR solutions have been implemented as retrofit solutions, and several designs for a retrofitted meter modules have been proposed in the patent literature(Fischer, 2002; Payne and Lien, 2011; Cuneralto and DeVries, 2008) . These meter modules can record daily or even hourly aggregate usage data, however, they do not have provisions for NIALM, nor do they provide a high-resolution metering capability.

Sub-metering of appliances even at relatively small, statistically representative samples of houses is expensive and problematic(Marceau and Zmeureanu, 2000). Sub-metering of individual appliances for different utilities have been reported in several papers(Agogino et al, 2002; Wilson and Atkeson, 2005; Kim et al., 2009). It requires sensors that are flexible and robust enough to fit a variety of pre-existing gas appliance models. It also inherently involves multiple sensors, which increases both the technical complexity(e.g., network communications) and the complexity of deployment. For natural gas, this method poses the risk of fire or explosion.

The first practical application of NIALM for electric utilities was introduced by Hart in 1985 to monitor the power consumption of individual electrical appliances in residential homes(Hart, 1989; Hart, 1992). This was achieved by sophisticated analysis of current and voltage waveforms of the total load to infer the energy consumption of appliances turning on and off. Harts' algorithms were only viable for large electrical appliances with steady power consumption but were later extended to include a higher number of electrical appliances and to resolve specific loads for electrical systems(Leeb et al., 1995, Farinaccio and Zmeureanu, 1999, Laughman et al., 2003). Since then, significant advances have been made in monitoring electric load non-intrusively. Although some problems such as event overlap present challenges, NIALM for electricity is a mature field at present.

2.7.2 Gas meter

Natural gas is the most popular of choice for space heating and domestic water in the UK, residential customers receive gas via a dedicated piping infrastructure provided by a local utility. The supply lines are connected to mechanical gas meters that utilize an internal positive-displacement flow mechanism and a mechanical index to record the total volume of gas consumed. The vast majority of gas meters are read manually at quarterly intervals to determine gas usage for customer billing.

The smart grid is a rapidly developing concept intended to improve the delivery of electricity, gas and water utilities. Smart meters installed at the utility endpoints to monitor usage are an important component of the smart grid. The current state of the art in smart meters includes wireless meter reading, two-way communication and security features(Gungor et al. 2012; Rouf et al, 2012). More advanced features for smart meters are still being developed.

The ideal of Non-Intrusive Appliance Load Monitoring(NIALM) was first proposed for electricity by Hart(1989) and(1992), but his algorithms were only viable for electrical appliances with large loads and constant power consumption profiles. NIALM algorithms were later improved to handle more electrical appliances and resolve more specific loads for electrical systems by Laughman et al.(2003), Farinaccio and Zmeureanu(1999) and Leeb et al.(1995). Significant advances have since been made in monitoring electrical loads non-intrusively by Lei et al.(2011) and Zeifman and Roth(2011)

The first application of NIALM for gas meters was presented by Yamagami and Nakamura in 1996 using Hart's steady-state method for Japanese households(Yamagami, 1996). They utilized meters installed with data loggers and developed a method which they applied to homes so that they could develop demand models for the various gas appliances as a function of household configuration and occupant. Conventional sub-metering was used to validate the models. The algorithms could not consistently identify variable rate gas appliances and reported an overall accuracy rate of 95%. They suggested that further development would be required to adapt the procedure for the American market. More recently, Chon *et al.*(2010) have also presented different approach utilizing the acoustic signature of gas meter pressure regulators to perform NIALM. Further details of latest gas monitoring method are review in the next section.

Developing NIALM techniques for gas meters has presented unique challenges. Yamagami and Nakamura(1996) concluded that their system could not consistently identify variable rate gas appliances and had an overall error rate of 5%. Their algorithms were also implemented on specialized high-resolution residential gas meters used in Japan. Cohn et al.(2010) reported that they were not able to accurately measure low flow rates, and experienced issues with background noise and difficulties distinguishing between concurrent appliance usage.

It is costly and labor-intensive to replace an existing, mechanically plumbed gas meter, e.g., with a modern ultrasonic gas flow meter. An interruption of gas service and a post-install inspection of the gas supply system are also required. A less costly approach is to retrofit existing meters with a meter output module, as shown in **Figure 2.17** that can be installed in a few minutes time to an existing meter without having to disconnect or interrupt service. Several different designs for a retrofit module are currently in use(Fischer, 2002; Payne and Lien, 2011; Cumeralto and Devaries, 2008). Most provide wireless automated meter reading(AMR) capabilities to record daily or hourly usage information. However, none of these modules provide a high-resolution metering capability and none have provisions for NIALM.

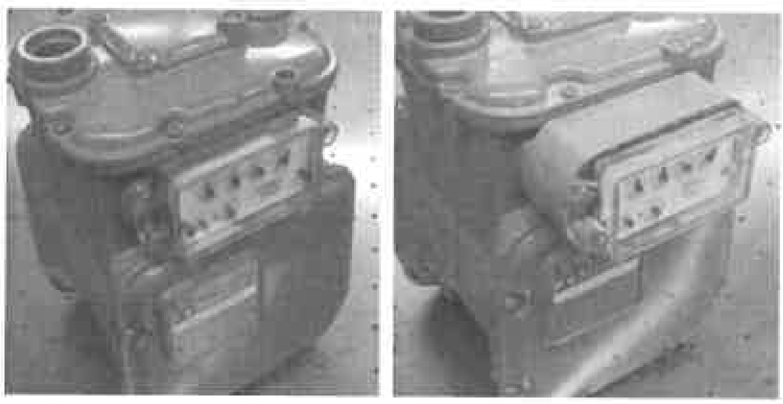


Figure 2.17: Retrofit assembly & attachment to meter.

The vast majority of gas meters in domestic applications, including the UK are the diaphragm displacement meters(Cascetta and Vigo, 1994), although rotary displacement meters are also significantly in use. Both meters are purely mechanical, and are typically read manually at monthly intervals for billing purposes. Diaphragm meters measure gas flow directly from positive displacement(which drives a mechanical counting index indicative of volumetric flow) caused by filling and emptying of one or more measurement chambers. While, rotary displacement meter measures volumetric flow from gas displacement which occurs due to two impellers rotating at opposite direction to each other within the meter's internal housing. These devices may suffer high pressure losses(due to wear of their moving parts), and are unable to provide instantaneous flow-rate values(Hazlehurst, 2009).

With ultrasonic gas meters excessive pressure drops are rare and also offers non- invasive flow measurements using 'clamp-on' units, otherwise they are minimally invasive(Lynnworth and Liu, 2006). Ultrasonic gas meters usually consist of an emitter and a receiver pair which measures the transit-times(which is proportional to gas flow) of ultrasonic pulses between transmission and reception. Non-invasive ultrasonic flow metering is widespread, although metering can be affected by changes in pipeline wall roughness for fluids such as natural gas(Calogirou et al., 2001). Current state -of-the art smart meters have wireless automated meter reading(AMR), two-way communication and security capacity(Rouf et al., 2012). However, replacing existing mechanically based gas meters with ultrasonic types can be labour intensive, costly and cause disruption of gas service(Tewolde et al., 2013). A more convenient and less expensive approach is to non-invasively retrofit existing meters with modules to facilitate AMR capabilities. Several different AMR retrofit modules are already in use(Fischer, 2002),(Payne and Lien, 2011). A summary of the studies, the types of energy related behaviour investigated and the measurement frequency of the usage data is provided in Table 2.15.

Table 2.15: Summary of gas monitoring studies.

Authors	**Gas related behaviour**	**Measurement frequency: Gas**
Ueno et al.(2006)	Space heating, hot water heater	1 h
Tsuji et al.(2000)	Total household usage	30 min
Wood and Newborough(2003)	Hot water heater, stove/oven	1 min
Menkedick(1993)	Total household usage, space heating, water heater	1 h
Pigg et al.(2010)	Hot water usage	1 s
Warren(1993)	Total household usage, space heating, hot water heater	5 min

Authors	Gas related behaviour	Measurement frequency: Gas
Ferreira(2009)	Total household usage	30 min
Hendron and Burch(2008)	Hot water usage	6–12 min
Hendron and Engebrecht(2009)	Hot water usage	1 h

Gas usage data includes both long-term and short-term profiles. Long-term gas usage patterns were used to understand the daily usage rates of appliances and classify their seasonal patterns(Ueno et al.,2006; Tsuji et al., 2000; Ferreira, 2009; Hendron and Burch, 2008). The investigators made use of coarse usage data with measurement frequencies of an hour or more. This information reveals the general usage patterns of major appliances. For example, water heaters and furnaces have longer periods between cycles while a clothes dryer cycles more frequently(Hendron and Burch, 2008). Short-term studies were also performed, which provided higher-frequency appliance usage data. Examples include furnace operation data from a residential home that was taken every 5 min(Warren, 1993) and hot water heater usage data taken every second(Pigg et al, 2010).

2.7.2 Electricity meter

Electricity monitoring is essential for understanding the sources of consumption inside a building, and to take appropriate measures to save energy. To perform energy monitoring, dedicated hardware needs to be deployed in the main electric distribution board, in specific sub-circuits or even on wall sockets to measure the consumption of individual electric appliances. Originally, energy monitoring was based only on the traditional electric meter installed by the utility to measure the overall consumption. At this time, energy audits relied on log-books and calendars. Typically, electricity meters are deployed for monitoring power consumption in buildings. An electricity energy meter usually measures voltage and current flowing through an electrical system in a non-invasive manner for power monitoring. Meter readings may be taken manually at periodic intervals, usually once a week or more typically once a month, doing this at a higher frequency is not practical.

Many electricity meters produce pulse outputs which correspond to a certain amount of electricity passing through them. Pulse outputs may be dry contact in nature, meaning that the output is essentially a switch. Some manufacturers often state the nature of the pulse output: dry or wet contacts, as such information is necessary to determine the extra circuitry needed before the data logger. For instance, meters with mercury wetted contacts require some circuitry to electrically 'de-bounce' the signal, since more than one signal could otherwise be picked up, per pulse due to vibration of the switch contacts. A basic logic gate circuitry or a solid state output can be applied to address this. Specification and explanation of terms for pulse outputs are given in(BSI, 1999) and(BSI, 2002) respectively. Where a pulse output meter is fitted, it can be easy and straightforward to add a data logger with no further disturbance.

Current transformers(CTs) are also useful for monitoring building electricity usage. The most commonly utilised ones are the solid core and split core types(O'Driscoll and O'Donnell, 2013). Both are based on the principle of Faraday's law of induction to measure current flowing through an electrical circuit. The split core types tends to be less accurate than the solid core variations however, spilt core CT's can be installed more easily(Koon, 2002), and may be ideally suitable for remote monitoring applications without any disruption to a power system. CTs can be used in the case of either single or multiphase power consumption monitoring. The live or neutral cable(not both) usually goes through a CT's opening for both cases. Some CTs may be in the form of low-cost transducers, with their outputs often requiring signal conditioning, while others such as 'Clamp Meters' have inbuilt signal conditioning circuits, and are commonly applied for spot measurements rather than any long term monitoring. Multiphase units with pulse output which is compatible with conventional data loggers are also available. Several CT based 'plug in' power meters are available; a good example is the 'Watt Up' power meter(mostly marketed in US and Canada), which is capable of monitoring power factor. In Europe, smart 'plug in' units have also been introduced in to the market. For instance, Watteco units(with data logging capacity)(Bertrand, 2001), can distinguish between electrical loads plugged in, by detecting the unique electrical signature of each appliance, using proprietary signal processing techniques.

CT based energy monitors appeared measuring the total consumption of the building in real-time. Popular commercial products include British Gas Energy Monitor from British GAS and OWL Pro from 2SaveEnergy. Figure 2.18 shows the installation for measuring the total building's consumption.

Figure 2.18: Wireless current transducer and electricity monitor, source: author

Even as recent as ten years ago, more sensitive meters were manufactured to perform sub-metering in specific branches or circuits of the building. Nowadays, equipment for device-level monitoring is available by using smart plugs that stand in between the wall socket and electric appliances to measure their consumption and control their operation.

In academia, various smart plugs have been developed to facilitate research in energy auditing. These devices offer actuation capabilities and may form wireless networks to propagate energy measurements to a base station. Examples include ACme sensor mote, used in many research works(Jiang et al.,2009; Kazandijieva et al., 2009; Kazandijieva et al., 2010;). Lifton et al.(2007) measured device level electricity usage with MIT Plug, which is a functional power strip with sensing, networking and computing abilities, Synergy Energy Meter(SEM) from University of California, San Diego(Weng et al. 2011) and REAM(O'Connell et al.,2011). In these electricity monitors, the IEEE802.15.4 standard is used for wireless communication between the nodes of the network.

Nowadays, hardware products for energy metering are more stable and reliable, though their price is still high. This is the main reason load disaggregation techniques have been proposed. Some limitations of existing hardware are that it cannot sense the ambient environment(e.g. occupancy, temperature, noise), control of devices is limited to switching them on/off and also it fails to integrate smoothly with the rest electric appliances of the building(e.g. lighting, HVAC). Extra caution must be taken as these energy monitoring products, operating based on low- power wireless communication, might cause possible interference due to congestion in the local wireless network(s) of the building, e.g. Wi-Fi.(Yang et al.,2011).

The simplest and least expensive NIALM techniques typically measure changes in real and reactive power levels, requiring only low frequency sampling(Hart, 1992; Marchiori and Han, 2009). More complex techniques rely on harmonic analysis to distinguish loads, requiring costlier hardware and sophisticated software(Laughman et al., 2003).

Hart(1992) developed a NIALM algorithm that determines the energy consumption of individual appliances based on state transitions, i.e. turning on/off. However, in case when load operates in multiple or variable states, NILM is difficult(Ruzzelli, 2010). Laughman et al.(2003) improved NIALM by using event detection, to help disambiguate appliances with similar real/reactive power signatures. In the study of Marceau et al,(2000), the load disaggregation algorithm differentiates edge cases with a classification of appliances according to their frequency of use to balance decision making. This approach had a limitation to a selected number of appliances with distinguishable differences in frequency of use.

A fundamental limitation preventing wide acceptance of NIALM is its difficulty to calibrate an appliance recognition system ad hoc to each building typology. Ruzzelli(2010) tried to reduce this difficulty by using a single sensor clipped to main electric unit, guiding the user to profile electric appliances in order to generate a database of unique signatures. By using this signature database, it is possible to develop an artificial neural network system to recognize appliance activity.

A summary of the most important case studies dealing with electricity metering including the methodology used, is summarised in Table 2.16

Table 2.16: Methodologies and key findings of related work in energy audits in buildings.

Authors	Year	Monitored buildings	Methodology of measurement electricity usage
Kazandjieva et al.	2012	University campus	Plug level electricity consumption sensor
Dawson-Haggerty et al.	2012	School and office	500 wireless Zigbee smart plugs in 9000ft2 office space
Kazandjieva et al.	2010	University campus	Use of device inventory and smart plugs to measure power consumption
Kawamoto et al.	2004	Office	Surveys and field measurements of usage in business hours and turn-off rates at night
Webber et al.	2006	Health centres and offices	After-hour power state of ENERGY STAR-rated office equipment
Schoofs et al.	2011	University and residential	Side-band detection of network equipment operating state through LAN
Webber et al.	2001	Multiple building types	Walk-through night-time audit PM settings and turn-off rates
Kawamoto et al.	2002	Residential, commercial and industrial	Annual unit energy consumption estimate based on stock power requirements usage and saturation of PM

2.7.3 Domestic hot water flow

The mechanical nature of water metering equipment has made it difficult for nonintrusive monitoring techniques to be implemented. As a result, there has been much less activity in this area. Water metering using different approaches to disaggregate total usage have been presented by Fogarty and Hudson.(2006), Kim et al.(2008) and Larson et al.(2010). Generally, there are several options the hot water flow of the dwellings:

a) Use of one flow meter at boiler/hot water tank outlet: This option requires one flow meter. However, this does not allow separate monitoring of hot water used for say washing up, bath, etc.

b) Use of flow meters at boiler/hot water tank and at points of use: This option enables the monitoring of both the total flow and the flow at each point of use(kitchen, bathroom, etc...), giving a better understanding of the use of DHW in the dwelling. However the cost of flow meters is quite high as a non-intrusive ultrasonic flow meter which can be clamped to the water pipe costs around £2,000.

c) Use of temperature sensors to detect hot water usage at each appliance: Temperature sensors can give a good indication when hot water is used. The Market Transformation Programme(2007) used temperature sensors attached to the hot water pipes leading to each appliance to detect when and from which appliance hot water was used. A rise in Temperature within the pipe indicates that hot water is used, and a slow decrease in water temperature thereafter indicates hot water use has ceased. The use of temperature sensors is a less expensive and but not less accurate. The major drawback is that if there is hot water remains in the pipe, surface temperature of pipe does not drop instantly which could cause false readings between close hot water events.

d) Use of a combination of flow meter and temperature sensors: Adding a flow meter at the outlet from the boiler/hot water tank to option c, would give a better understanding of the flow rates of the hot water used. Although an in-line flow meter provides more accurate readings, a clamp-on flow meter is less intrusive.

Proper understanding of water and hot water based heating system use patterns can provide compelling insights on space use(Beal et al. 2013), from which occupancy can be inferred. As with electricity and gas meters, water meters can be read manually with the same restrictions. Most water metering systems requires pluming work for set up, and typically produce outputs compatible with convectional data logging devices. For instance, a low-cost system marketed in the UK for £79 can easily be mounted on the pipework(Anon, 2005a), but would require brief disruption of water supply during installation, hence it is seen as minimally invasive.

Ultrasonic meters can be applied for flow measurements, where flow intrusion is not an option. Prices of these devices are gradually falling due to advancement in digital technologies, for example Texas Instruments 'industry standard' TMS320 series. Two basic formats of ultrasonic meters are available – Doppler(usually applied for contaminated liquids) and transit-time(for clean liquids). Clamp on units are readily available, and do not require cutting of pipes for installation. Figure 2.19 shows a typical ultrasonic clamp-on unit arrangement.

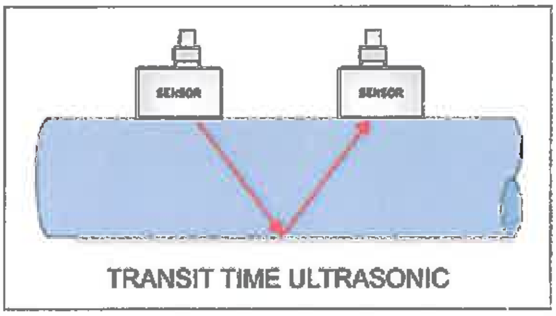


Figure 2.19: Ultrasound transducer clamping arrangement, Courtesy: Procon Systems Inc.(www.proconsystems.com)

Central heating water may be classed as a 'clean liquid'. Transit-time ultrasonic flow meters usually makes use of two transducers(forming a transmitter and a receiver pair), and measures the time it takes for an ultrasonic pulse transmitted from one transducer to go through a pipe's cross section, and be received by another transducer. This time of travel is proportional to flow rate(Figure 2.20). Deployment of these meters may be limited by pipe sizes(for example diameters of 6 – 20mm and 20 – 200mm requiring different sets of sensors) - requiring separate sensor heads, which often comes at a significant cost penalty. Besides, flow meters would require calibration once new heads are fitted.

A detailed summary of the operational guidelines for ultrasonic flow metering can be found in Sanderson and Yeung(2002), while current state-of-the-art of this technology is given in Lynnworth and Liu(2006). Ultrasonic meters may offer two channels of flow metering and two channels for temperature metering, combined with a datalogger, to instrument, for example, send and return pipelines for a central heating boiler.

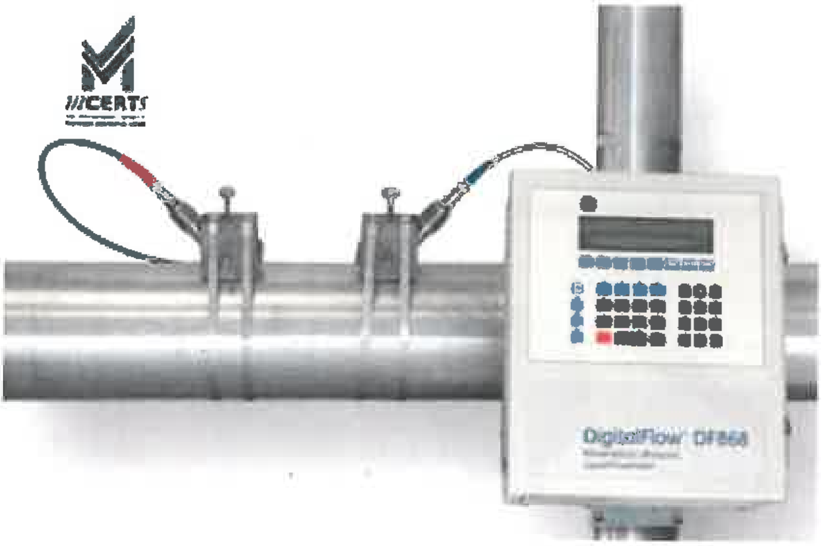


Figure 2.20: Ultrasonic flowmeter, Courtesy: rshydro(www.rshydro.co.uk)

Doppler flowmeters are commonly applied for metering dirty or contaminated liquids(which require fluids with a minimum concentration of 100 ppm of solids or bubbles having minimum size of 100 microns), such as Agricultural water, Drilling mud, etc. They may also be useful for metering useful greywater or waste water output from dwellings to assess opportunities for heat recovery, or to monitor water input for industrial uses(e.g. river water extraction).

2.7.4 Temperature and humidity measurement

Temperature

Most commonly used temperature measurement instrument is thermocouples, which are semiconductors which exhibit changes in electrical resistance when exposed to temperature changes. The accuracy may be 0.1 °C if reasonable precautions are taken. The two basic types of thermistor are the negative temperature coefficient(NTC), and the positive temperature coefficient(PTC). The former is best suited for precision temperature measurement and the latter for switching applications(Jain, 1989). They are manufactured from oxides of transition metals such as manganese, cobalt, copper and nickel. Thermocouples are devices made from two dissimilar metals welded together such that a small open-circuit voltage(normally in millivolts) is produced through a phenomenon known as the Seebeck effect. This voltage magnitude depends on the material and the temperature difference between the junctions. Both technologies can be utilised for ambient temperature monitoring, although choice is dependent upon the desired accuracy, and temperature range of the measurement. Thermocouples can operate over a wide range of temperatures compared to thermistors. Generally speaking, thermocouple measurements will be more precise(Anon, 2005b), providing that the measurement- circuit temperature is accurately known. Conversely, accuracy of thermistors may be slightly greater, with slightly reduced precision. Figure 2.21 shows typical thermocouple and thermistor sensors.

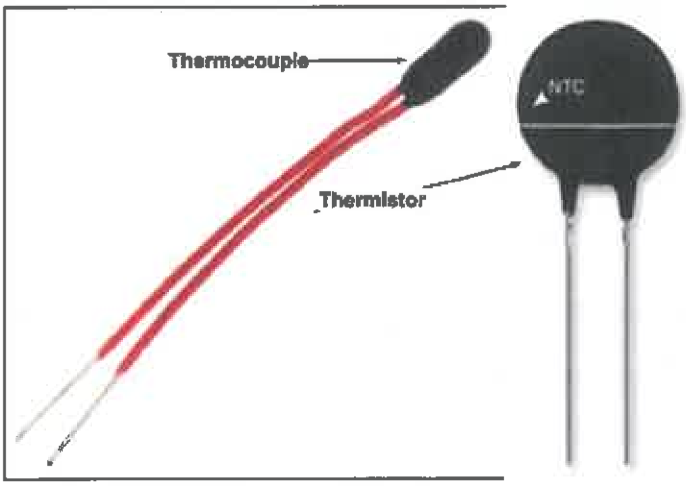


Figure 2.21: Typical thermocouple and thermistors sensors, source: author

A Resistance Temperature Detector(RTD) operates through the principle of electrical resistance changes in pure metal elements(Hashemian, 2005). The element's resistance increases with temperature in a known and repeatable manner. Due to its low cost, and ability to measure point heat sources in a manner similar to a Thermistor, the RTD is slowly becoming more popular. Sensing circuitry is slightly harder to build due to a low sensitivity(though accuracy and precision are equivalent) compared with thermistors. This may also affect the use of the devices in areas with high levels of electromagnetic interference.

Relative humidity

This section concentrates on the principal technologies for automatic monitoring of relative humidity(RH) in buildings. Reference devices, such as the gravity train hygrometer, or gravimetric hygrometer, are not considered here. These sensors are mostly used to control indoor RH levels especially in residential buildings, where they form an intricate part of extraction systems used to ventilate spaces when humidity levels are high(IEA, 1997). Semiconductor based RH sensors tend to show greater accuracy and reliability, and their prices are also affordable(Roveti, 2005). Capacitive RH sensors utilise thin film polymer or metal oxide that change capacitance with changes in humidity levels, and use an appropriate signal conditioning circuitry to measure humidity(Figure 2.22). The sensing surface is normally coated with a porous metallic oxide to avoid contamination or exposure to condensation. Self-logging version such as the HOBO relative humidity U-series loggers are readily available(Onset-Corperation).

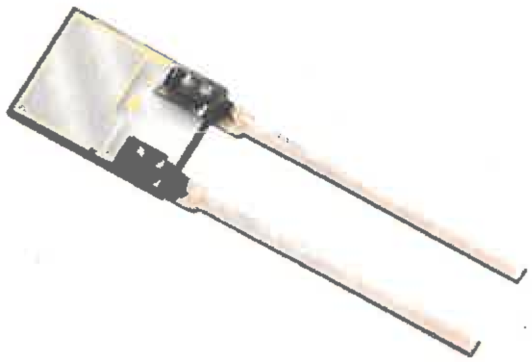


Figure 2.22: Capacitive humidity sensing element Courtesy: Vaisala(www.vaisala.com)

Resistive humidity sensors measure the change in electrical impedance of a hygroscopic medium such as a conductive polymer, salt, or treated substrate. Resistive sensors are interchangeable(sensors are generally field replaceable), usable for remote locations, and cost-effective. Resistive RH sensors may suffer drift in condensing environment if water soluble coating is used for the sensing element, and does not show the same good long-term stability when compared to capacitive ones.

A thermal conductivity RH sensor comprises of two matched NTC thermistor elements in a bridge circuit. One of the thermistor is hermetically encapsulated in dry nitrogen while the other is exposed to the observed environment. Thermal conductivity(or absolute humidity) sensors measure absolute humidity levels by quantifying the difference between the thermal conductivity of dry air and that of air containing water vapour. The difference in heat dissipated between both thermistors results in a resistance change that is proportional to absolute humidity levels. For high temperature applications usually above 930C, thermal conductivity RH sensors are utilised, and would normally outperform both capacitive and resistive types(Roveti, 2005).

2.7.5 CO2 concentration measurement

The majority of CO2 sensors used in building monitoring utilise non-dispersive infrared(NDIR) technology, which is based on the infrared broadband absorption characteristic of CO2 gas. A light source transmits light(non-dispersive infrared) through a selective infrared filter into a measuring cell, where an interaction between CO2 molecules and light occurs. This leads to a rise in temperature proportional to the CO2 concentration which is commonly measured electronically using photo- acoustic or photometric methods(Won and Yang, 2005). In the photo-acoustic method, a small microphone is used to monitor vibration of CO2 molecules caused by their interaction with light. CO2 concentrations are then determined from vibration levels using on-board processing in the sensor. The photometric method measures the temperature of CO2 molecules to determine concentration levels. Portable indoor units such as Telaire Ventostat T8200DB CO2 sensor manufactured by GE sensing, which costs about £250/unit are widely utilised for ventilation control in commercial buildings(GE-Sensing). NDIR sensors can last up to 5 years, although they have the potential to drift significantly. Poor CO2 sensor performance has been reported in some commercial buildings. In a recent study, the performance of 44 CO2 sensors were investigated and results showed that measurements varied widely, sometimes in hundreds of parts per million, prompting recommendation from the author on the need to use more accurate CO2 sensors, and calibration procedures(Fisk, 2008). Sensor accuracy can also be affected by vibrations and air pressure changes(Schell, 2001). CO2 sensors are also not sensitive to other air contaminants, and this may be a major limitation for CO2 based IAQ monitoring.

2.7.6 Building occupancy monitoring

Occupancy sensors act as switching devices that respond to occupants' presence/absence within their field-of-view. Several building occupancy instrumentations are available, although two technologies dominate; PIR and ultrasonic sensors. PIR sensors are commonly used for building occupancy sensing especially in lighting control applications(Delaney et al., 2009). The main sensor components in a PIR sensor are a pyroelectric detector and a lens. They are most sensitive to moving objects that emit heat energy at around 10µm(Moghavvemi and Seng, 2004). When a PIR sensor detects temperature changes within its field of view, the pyroelectric material undergoes a change in polarisation which produces a voltage signal. Its sensitivity decreases when distance between the sensor and a moving warm object increases(Kaushik and Celler, 2007). PIR sensors tend to work well where the entire observed space is within their direct line-of-sight, although they fail to detect stationary occupant(Benezeth et al., 2011). Consequently, they may switch off services in occupied spaces causing inconvenience to occupants. PIR sensors are available as an off-the-shelf product, with the cheapest one sold for £7.

An ultrasonic sensor uses high frequency sound(between 25 and 40 kHz) for motion detection. The major components for this sensor are an emitter and receiver assembly. They monitor frequency changes caused by moving objects(such as a person) through a phenomenon known as Doppler Effect. Unlike the PIR sensor, an ultrasonic sensor does not require a line-of-sight which makes it more suitable for occupancy monitoring in partitioned spaces. An ultrasonic sensor is more sensitive to minor motions, such as hand movements, when compared to a PIR sensor. Although, such improved sensitivity can lead to false switching(Floyd et al., 1995). This sensor is generally more expensive than a PIR sensor, with a single unit costing more than £13.

A typical microwave sensor has similar principle of operation as the ultrasonic sensor; the differentiating feature is the emitted signal, since it generates an electromagnetic signal at a frequency of 1-10GHz, and measures the frequency change of a reflected signal for occupancy detection(Runquist et al., 1996). The performance of this sensor is not affected by obstacles within its field-of-view in an observed space, although it can be prone to false switching, if adjacent spaces are occupied.

Video camera or networks of cameras are also used for building occupancy monitoring. Images can be observed by human operators or by the use of specialized computer software(Wusheng et al., 2008). While this method of sensing produces good accuracy, privacy may be a serious concern especially when occupancy counts are generated from images using human observers. However, analytical algorithms used for processing occupancy counts from images are still in the early stages of development(Benezeth et al., 2011).

Another method for building occupancy sensing is the use of biometric sensors which take measurements of human physiognomy for identification(Frischholz and Dieckmann, 2000, Dugelay et al., 2002), and produce an electrical signal. These sensors use algorithms to process images from occupants' physical characteristics, such as finger prints, eye-scan etc. These sensors contain an analogue to digital converter enabling it to digitise images, and store the digital information in memory so that it can verify the user next time he or she needs to authenticate their identity. Biometric sensors are mostly deployed for access control in buildings. High sensor cost is a major limitation for its widespread uptake.

Electromagnetic based sensors such as infrared sensors have potential use for occupancy sensing. The axiomatic people counter is a good example of this(Axiomatic-technology-limited). These are normally mounted at exit points to monitor occupant traffic. They use an infrared beam, with a transmitter and receiver pair mounted such that an infra-red beam is interrupted when occupants pass through the door. The sensor has good accuracy for establishing occupant presence but may be unsuitable for counting numbers of occupants, since the sensor is unable to detect multiple people crossing the infrared beam. Starting price for a beam counter is £276.00 for a basic model, up to £844.80 for one with Ethernet connectivity and automated reporting(Axiomatic-technology-limited). It is rarely used in building services control applications. However, it does have widespread usage in industries for machine operations safety.

An acoustic sensor such as a microphone can also be deployed for sensing occupants' activities(Fogarty and Hudson, 2006), and is simple and cheap. However, noise from sources other than occupants can result in false triggering. Performance limitations associated with single occupancy sensing technologies may have prompted manufacturers to combine different technologies. Some commercially available products combine PIR and sound, or ultrasonic with microwave, thereby reducing the likelihood of false switching. Hybrid sensors tend to offer improved sensitivity, accuracy and flexibility, but often come at a higher cost. These sensors can be effective in partitioned offices, although their performance has not been documented(Maniccia and Wolsey, 1998).

2.7.8 Wearable activity trackers

A limited number of studies have reported the use of wearable sensors for occupancy monitoring in office buildings. Devices could be in the form of a ring(Sokwoo et al., 1998) or wristwatch(Lötjönen et al., 2003), or neck tag. The use of these devices is widespread in health care monitoring. Korhonen et al.(2003) proposed the use of wearable sensors for monitoring recovering hospital patients, while Sungmee and Jayaraman(2003) suggested the use of a smart shirt for monitoring health conditions 10(such as heart beat rate, temperature etc.) of its users. This shirt may be useful in a heath care setting, but it is clearly impractical for use in other places such as public buildings. Radio frequency identification(RFID) based sensors can be effective for indoor occupancy monitoring. For example, Li et al.(2012) proposed an occupancy detection system based on RFID tags, which reported real-time occupancy numbers and the thermal zones where each occupant was located in an office building. A K- nearest neighbour algorithm was used for occupancy tracking, and the system produced an average zone detection accuracy of 88% for stationary occupants, 62% for moving occupants. Zi-Ning(2008) developed an occupancy detection system for lighting control. Occupants' localization was achieved using a support vector machine(SVM) algorithm that was aided by a round-robin rule based on some numerical logics. Tracking accuracy reached 93% for occupants' that wore the RFID tags. However, it was not clear how the system would address issues of latency and scalability in large non-domestic buildings with large occupancy profiles. Gillott et al.(2009) and Gillott et al.(2010) determined occupancy patterns in a residential building using ultra-wideband RF-based tags worn by occupants, the system tracked moving occupants to within an accuracy of 15cm in three dimensions. One advantage of these technologies is that they provide occupancy information that can be based on zones that are either physically or virtually partitioned, making them suitable for use in open-plan spaces with multiple thermal zones(Li et al., 2012). However, willingness and ability of occupants to wear these devices may be a critical issue for their uptake.

Past studies have also investigated the use of CO2-based occupancy detection systems in residential buildings, as opposed to a mixed-use building. For example, Cleveland and Schuh(2010) developed an occupancy monitoring system for automation of HVAC thermostats in residential buildings using CO2 and motion sensors, and a simple control algorithm based on the rate of change of CO2 levels. Occupancy detection was best inferred from CO2 levels in the house. CO2 levels of 525ppm or a change in CO2 concentration reaching 50ppm or above for two straight minutes, indicated occupancy, while concentration of 300ppm suggested vacancy. Results were not validated with a field test, and it remains unclear how the system would perform for occupancy number estimation. CO2-based systems may be susceptible to common operational limitations, since they generally have slow response in detecting incoming people(Wang and Jin, 1998), and also CO2 concentration levels may be affected by factors other than occupancy such as passive ventilation(e.g. open windows, air infiltration etc.). These sensors may suffer significant drift over time(say over a year) which may limit their functionality(Shrestha and Maxwell, 2010). Besides, there is a high level uncertainty between number of persons and CO2 concentration levels(Chenda and Barooah, 2010). Such limitations make accurate and robust prediction of real-time occupancy numbers using CO2-based systems challenging.

2.8 Knowledge gaps

Regarding the method of and instrumentation of measurement of occupant behaviour related research, knowledge gaps have been identified. Some of the more significant are identified below:

- There is a lack of detailed description and specification of how the relevant parameters were measured and what could be improved in terms of data collection method.

- The advantage and disadvantage of utilising instrument and methods in field studies are relative less researched

- Questionnaire survey, interview, visit to the building and observation are the most commonly used methods. However, in many cases, these methods can only represent glimpses of energy related behaviours, which can be difficult to interpret based on snapshots of corresponding parameters. Retrospective reporting of comfort and behaviour can be inaccurate and may give a false picture of what people felt at the time and how they behaved(Raina et al., 2009; Short et al., 2009).

- There are relatively fewer high quality research investigations in domestic sectors. Commercial and hospitality sectors are particularly overlooked given their significant carbon emissions.

- High resolution metering researches usually focused more on the technical side, such as the development of monitoring hardware, but less on the behavioural data analysis.

- Research into ethically accepted monitoring and non-intrusive format of long-term data collection methods are needed. The difficulties of attaining ethical approval or permission may partially explain the popularity of using one-off data collection method such of questionnaire, spot measurement where multiple samples can better understand the cause and consequences of energy related behaviour.

- In most studies, only several main instrumentation of measurement methods were used, few studies looked cross-referencing parameters. In dwellings, the interaction among parameter can be intense, for instance, thermostat set-point temperature can be directly affect by the duration and frequency of window opening, together indoor temperature, humidity and smoking habit.

To fill the gaps, research into how to robustly and ethically measure energy behaviours across a broad range of parameters is needed. This would underpin a segmentation of the domestic sector to be used energy relative behaviour analysis.

2.9 Summary

In previous occupant behaviour studies, the following methods and instrumentations have been commonly used to measure the parameters of energy related behaviours.

Table 2.17 below summarises the parameters and behaviours that this study focuses in dwellings and occupants with their potential advantages and disadvantages. Some their advantages and disadvantages are deduced from manufacturers' data sheet and review since they were not described detailed in existing studies. The next chapter, methodology, will choose the series of instrumentation and methods that based on their availability when conducting field data collection in order to address the knowledge gaps mentioned above at best attempt.

Table 2.17 Summary of parameter measuring method and instrumentation: advantages and potential disadvantages.

Behaviour	**Parameters**	**Data collection instrumentation/method**	**Potential Advantages**	**Potential disadvantages**
Space heating	Gas consumption	Main gas meter readings	Relatively easy to access without occupants being in Less intrusive	Only provide overview of total gas usage Requires research to visit
		Sub gas meter with pulse counter	Accurately record the gas consumption for gas boiler only, excludes gas cooking	Does not separate space heating from domestic hot water
	Thermostat control Individual radiator control	Video, Audio recorder		Video footage and audio recording take time to transcribe and can be perceived to be very intrusive to privacy
Domestic Hot water	Water volume	In-line flow meter	Capable of provide accurate hot water flow through the selected pipe at low cost	Require plumber to install and dismantle. May cause pressure drop
		Ultrasonic flow meter	Easy clamp-on installation, non-intrusive	Expensive
	Hot water demand event	Temperature sensor on pipe surface	Low cost and easy to install	Not able to differ active hot water flow from dormant hot water in pipe
Window operation/ventilation	Status of window	Contact switch	Low cost and relative easy to install	Need to test with each window to prevent false contact since magnetic switch only tells open or close two status
	Air flow	Tracer gas decay system	Accurately measure the air flow rate for all the rooms as a whole.	Intrusive as tracer gas need to be injected into dwelling and measure its concentration level and decay rate. Not suitable for long term monitoring
		CO2 concentration sensor		Expensive and the position of CO2 sensor does affect its accuracy and responding speed.
Electricity appliance/lighting	Appliance electricity usage	Appliance survey	Easy to conduct	Usually one off survey and the use of appliance(e.g. duration, frequency of use) is relied on occupants' memory.
		Device level plug sensor	Measure both current and voltage for highly accurate electricity consumption	Depends on household, the number of plug sensor can be large therefore increase the total cost
	Total electrcity usage	Current Transducer(clamp-on)	Easy to install and relatively	Error rate can be upto 15% since it does

Behaviour	Parameters	Data collection instrumentation/method	Potential Advantages	Potential disadvantages
			cheaper, mostly wireless	not measure the fluctuation of voltage
		Take meter readings	Relative easy to collect readings, most of the time can be done from outside of house	Metering readings only tell the overall consumption but no details of daily electricity usage profile.
	Certain circuit/room/lighting	In-line sub electricity meter	Relatively low cost and highly accurate.	Need electrician to install and dismantle. Can be too intrusive to obtain permission
Physical environment	Air temperature	Air temperature sensor	Low cost and easy to install	The location of sensor in a room does matter the reading in dwellings
	Relative humidity	Relative humidity sensor		
	Air flow	Handheld air flow meter	Comparing to tracer gas it gives quick air flow rate and easy to take measurement	Spot measurement only, location affects accuracy
	Illuminance	Illuminance meter	Quick and easy to measure illuminance level	Spot measurement only, location affects accuracy
Occupant	All biological, psychological social parameters	Questionnaire Interview	Easy to conduct	Consumes more time and
	Activity level	Activity tracker	Provide highly accurate information about activity level	May be considered intrusive
	Presence and occupancy	Occupancy sensor	Add the layer of occupancy data about room	Can be considered intrusive Relatively difficult to install without causing damage(to the ceiling)
	All behaviour without direct measurable parameter	Observation	Can quantify behaviour to an extent	Intrusive, especially observation is not really suitable for dwellings or long-term. Being watched by others may also affect how occupant would usually interact with dwellings
		Self-reported diary	Provide multiply samples for behaviours	Short term or will be considered annoying
		Comparing with identical buildings	Correlate the difference of energy consumption with behavioural difference may reveal the pattern and linkage	Identical building may not available nearby therefore the local climatic condition differs which may the comparison difficult

Chapter 3: Research design, monitoring methodologies and instrumentation

3.1 Introduction

The aim of this chapter is to develop a suitable research design to address the questions and gaps identified in Chapter 2.

This study proposes to test the methods and instrumentations that allows researchers to measure parameters that can be used to quantify energy related occupant behaviours in dwellings. The literature review and previous studies indicate that occupant behaviour and building energy consumption are tightly related and can be sophistically interlinked,

The goal is to test a range of methods for measurement, in space heating, domestic hot water, window operation, electric appliance, personal characteristics and physical indoor environment. The instrumentation and method have been selected based on the following criteria,

- Invasiveness- include disturbance to occupant in every possible way, such as visual, noise, disruption to normal functions of building component and appliance.
- Accuracy- error comes with the method or naturally built with measuring instrument
- Cost- the number of sensors and logger can quickly add up to the expenditure which may restrict the scale of monitoring.
- Ease of installation, uninstallation and data collection – the difficulty of deploying, removing monitoring system and collecting data can affect not only the study in terms of physical work and logistics but also
- Reliability for long-term monitoring—some methods and instrument may be more suitable for relatively short period of, such as memory capacity and power consumption.

Therefore, this chapter presents the instrumentation and measuring methods that have been selected for this study. Due to their availability and cost restriction, only those could be accessed and had actually been tested or installed are presented here.

3.2 Research design and methodology

3.2.1 Measure Space heating related parameters

The selected parameters for space heating are gas consumption, thermostat adjustment, individual radiator, boiler and its control signals.

In house with gas boiler powered central space heating system, the status of gas consumption is directly linked with boiler's activity that as a consequence of occupant space heating related behaviour. Available options are either measuring the main gas meter or installing additional gas sub-meter for the boiler. For main gas meter, the options are optical reader and infrared sensor that can almost non-intrusively measure movement of the dial without directly interfering with its enclosure which is not allowed since main gas meter actually belonging to utility company. Both sensors measures movement of an object at close distance which complies with regulation. On the other hand, gas sub-meter can provide only boiler gas consumption data which is separated from gas cooking. Such disaggregation can assist to focus on gas boiler related gas usage.

Thermostat adjustment has been only measured by qualitatively, such like questionnaire, interview and observation which are mainly based on the memory of the participant or cannot be conducted in domestic environment due to its invasiveness. Therefore, it would be more informative to test a new method of the measure setting temperature of thermostat. An exploratory method has been proposed to monitor value of resistance component of thermostat dial.

Similarly, individual radiator control measurement relies mostly on social science research methods. This study proposed to measure the status of individual radiator, at various locations across a range of radiators. The status and radiator can assist to better understanding of selected room in a dwelling if occupant operate each radiator differently.

Overall activity of boiler has yet been monitored in the previous literature. An exploratory method that have been developed to measure the boiler activity centrally. It is an alternative method of observing space heating activity indirectly. A pixel changing recognition software detects display panel icon appearance that represents various function which can be converted into each function's operation period.

Table 3.1: Methods of instrumentation selected for space heating related parameters

Method and instrument	Invasiveness	Accuracy	Cost	Ease of use	Reliability
Gas sub-meter	High, as it adds extra meter to gas pipe work	Up to 0.001m^3 per pulse	£150 plus £200 installation and removal fee	Requires professionals to install and remove, data collection is straight forward	Gas sub-meter is identical to the main meter, theoretically it performs as same a main meter
Optical reflector sensor/infrared sensor	Medium, a mini mast has to be set up and pointed to gas meter	Each round of rotation 0.001m^3 is counted as 1 pulse	£2.5 to £5 plus customised pulse converting circuit board £ 20	Does not require specialist to install but it is possible that gas meter cupboard does not have enough space	The exact alignment of sensor and dial of gas meter must be maintained precisely all the time
Resistance logger	Low, the logger can be wired internally inside existing thermostat enclosure	Up to 0.5 Ω.	£55 plus customised wirings	Can be installed and removed easily	The resolution depends on the actual resistive range of resistor
Temperature sensor	Low, sensors can be attached to radiator and take measurement	Up to 0.01°C	£40 to £80	Can be installed and removed easily	It serves well to archive the goal which is to capture sharp rise or decline of temperature
Infrared camera and pixel recognition software (Tincam)	Medium, as direct image is taken by camera	Software defined pixel change recognition	£20 for camera and £5	Can be installed and removed easily	Depends on ambient brightness, works better in total darkness

3.2.2 Window and door operation

Window and door operation was selected for this study because of its importance and implication on heat loss during winter. Mixed methods of observation and sensor based window status monitoring have been used in previous studies. In this study, the actual method that was permitted to install was contact switches, prior to which, several new sensors and settings have been trialled in controlled environment for accuracy purpose. Beside the data of window and door status itself, the data will be compared with purposely collected CO_2 concentration and room temperature.

The exact angle of windows and door have yet not been studied in the review literature. Therefore, experiments have been conducted with three customised methods, namely, rotatory resistive sensor, flex sensor and multi-reed switch board. The studied method of window and door operation related parameter are listed in table 3.2.

Table 3.2: Methods of instrumentation selected for windows and door related parameters

Method and instrument	Invasiveness	Accuracy	Cost	Ease of use	Reliability
Contact switch and event logger	Low, the sensors and wirings can be installed externally	Every time a window or door being opened or closed	£5 per sensor, £45 for event logger	Easy to install with double sided sticky pad and remove and dissolver	Standing alone and simplicity make the setting up robust
Rotary resistive sensor and Flex-sensor	Medium, the sensor has to installed either on frame or the	Up to 0.5 Ω.	£9-10 per sensor and £55 for resistance logger	Easy to install and remove	
multi-reed switch board	High, the board needs to be installed at the hinge of door and takes space	Varied by number of sensors and size of the board	£5 for 10 sensors plus £45 for event logger	Relatively harder to install and maintain position without adding screws	Relies on how well the sensor board is kept

3.2.3 Domestic hot water

Direct and indirect methods have been selected for this sector, which are inline flow and temperature meter and pipe surface temperature,

The goal of monitoring domestic hot water related parameters is to record the event of hot water demand which is one of highest energy consumption source and can vary substantially from people to people.

Due to the invasiveness of installing in low flow meter and high cost of ultrasonic flow meter, the permission was not granted in any participated dwellings. To minimise the disturbance, recording surface temperature of inlet and return hot water pipe has been employed as an alternative option. In field study, the accuracy will be tested with regards to the temperature difference and interpretation of hot water demand event.

Table 3.3: Methods of instrumentation selected for domestic hot water related parameters

Method and instrument	Invasiveness	Accuracy	Cost	Ease of use	Reliability
Inline flow meter	High, adding flow meter may lower the water flow speed	Up to 0.001m3	£150 plus £100 installation fee	Requires plumber to install	Act as same as common water flow meter
Temperature sensor	Low, sensors can be attached to radiator and take measurement	Up to 0.01°C	£40 to £80	Can be installed and removed easily	performs well at capturing rise or drop of temperature
Non-intrusive Ultrasonic flow meter	Low, clamps on pipe	0.001m3	£1200-1600	Can be installed by researcher	1% to 3% error rate

3.2.4 Electric appliance and lighting

The selected instrument for investigation of electric appliances and lighting related parameters are current transducer and individual appliance socket sensor, in order to test their accuracy and applicability in dwelling setting. Both method not no intrusive and do not require additional sensor to be wired to existing circuit. The goal to disaggregate electricity usage within dwelling to sub-circuit level details and compare the difference between current transducer based system that with and without voltage input.

Table 3.4: Methods of instrumentation selected for domestic hot water related parameters

Method and instrument	**Invasiveness**	**Accuracy**	**Cost**	**Ease of use**	**Reliability**
Owl energy monitor (without voltage input)	High, adding flow meter may lower the water flow speed	Error range not given, up to every minute's usage	£20 per sub-circuit plus a computer on-site (£120-220)	Can be installed by researcher,	Designed for long term monitoring, requires
Ecofront (with voltage input)	Medium, need to wire voltage input from live cable	Error range not given, 5 minute's accumulative data	£550 that includes 7 sub-circuit sensors	Requires electrician to install	Designed for long term monitoring
Plugwise appliance socket sensor		$\pm$1% error rate, hourly accumulative data	£350 for 9 sensors pack	Can be installed by researcher	Designed for long term monitoring

3.2.5 Physical parameters

A range of physical parameter measuring sensors have been select to monitor indoor environment while others are being recorded. The purpose is to test ease of use and whether different locations in the same room can affect measurement, especially the CO_2 concentration level. Selected monitoring instrumentations are listed in table 3.5 below. The selection was mainly restricted by the cost therefore only the available equipment in the department.

Table 3.5: Methods of instrumentation selected for physical parameters

Method and instrument	Invasiveness	Accuracy	Cost	Ease of use	Reliability
Arrex monitoring system, temperature humidity and CO_2	Low, discrete appearance, and battery powered	±0.5°C ±4% RH ±4% ppm	£35 per sensor	Can be installed by researcher, wireless data acquisition	Designed for long term wireless monitoring, requires computer on site
Tinytag Ultra 2	Low, discrete appearance, and battery powered	±0.35°C ±3% RH	£99 per sensor	Can be installed by researcher, measurement must be manually downloaded	Stand alone sensor and logger, 32000 readings

3.2.6 Occupant parameters

In preview studies, social science methods such like questionnaire, interview and self-report diary have been used as common measuring tools regarding occupant personal parameter. In this study, all these three tools will be tested in terms of ease of use. Self-reported diary is considered to be not accurate in measuring occupant satisfaction towards certain experience that based on memory. This study will compare the self-reported subjective thermal satisfaction and physical measurement calculated Predicted Mean Vote, in order to see how they differ from each other in domestic environment.

In addition, presence sensor and activity tracker were proposed to add to the investigation. The aim of presence sensor is to test various location of sensor installation and its sensitivity toward motion detection. Activity tracker has rarely been used especially in thermal comfort related study. The measure activity tracker data will help to verify self-reported activeness data.

Table 3.6: Methods of instrumentation selected for physical parameters

Method and instrument	Invasiveness	Accuracy	Cost	Ease of use	Reliability
Questionnaire	Low - Medium	Relies on participants' memory	Main the time to conduct questionnaire survey	Most commonly used tool	Very much depends on participants
Self-reported diary of past 30 minutes	High, requires very good cooperation from participants	Intensive report is better than recalling distant memory	Time of occupant and perhaps cash incentives	Entirely depends on permission granted by participants	Depends on participants
Interview	High, need to arrange appointment with participants	Face to face interview can discuss questions in depth	Time of occupant and perhaps cash incentives	Requires good interview and communication skill	Depends on participants
PIR sensor	Medium, occupant may perceive it as breaching privacy	Varies by distance	£5 for PIR sensor plus £22 for Arduino Micro controller board	Can be installed by researcher, measurement must be manually downloaded	To be tested in domestic environment

3.3 Monitoring space heating

This section presents the methods and instrumentation for measuring gas consumption, thermostat (central) control and individual radiator.

3.3.1 Gas consumption for individual purpose

As shown in Figure 3.1, some gas may be used for cooking purposes; the remainder is for boilers and fireplaces (if applicable) that heat space and domestic hot water. It is preferable to separate gas consumption for heating from that used for producing hot water, since these two are the greatest sources of gas consumption.

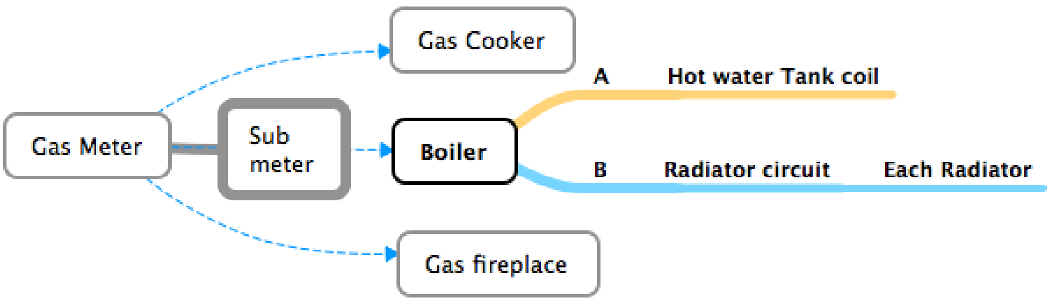


Figure 3.1: commonly domestic gas distribution

Gas powered space heating can be monitored by adding a dedicated sub gas meter to the boiler gas inlet pipe which provides information about total gas usage and high resolution boiler gas usage also indicates the boiler related behaviours, namely, space heating and hot water. A gas sub-meter provides the best measurement to the gas consumption with a pulse data logger (figure 3.2).

Figure 3.2: G4 gas sub-meter with pulse output and pulse counter logger

A Metrix G4 diaphragm gas meter was choosen for this study based on its similarity to existing main gas meter at designated dwelling. The main meter has a max flow rate of 6m^3 per hour. It was advised by plumber that any additional gas sub-meter must has maximum flow rate equal or higher that the main gas meter, otherwise the appliance performance might by affected due to slowness on its inlet gas flow. Considered this reason, Metrix G4 gas sub-meter was choose to avoid potential performance issue.

A gas sub-meter can only be installed beyond the main gas meter due to its ownership and installation of sub gas meter usually involves plumbing work and safety concerns. It is one of the intrusive way of measuring gas consumption. In some of the study houses, the gas meter and pipework have very restricted access and occupants can be reluctant to agree to have the installation of sub meter.

A non-intrusive method includes an optical sensor to read the physical moment of the dial of existing gas meter without physically altering it as shown in figure 3.3, e.g.

Figure 3.3: existing gas meter with dial(left) and reflective digit(right)

Both types of meters shown above can be monitoring by optical sensor, especially the one with reflective digit which is implemented optically rather than mechanically because the zero on the least significant digit is a shiny metallic oval rather than a painted white number. In this study, Optek OPB704 (figure 3.4) optical sensor was used, it has an infrared LED and a photo-transistor which both point at a spot some 4 mm at the front and can be powered by 5v battery with 5mA input for good response rate. The phototransistor starts conducting current when hit by infrared light reflected of whatever target is in front of the assembly, which is able to capture every time the dial turns one circle or reflective digit passes from 9 to 0 (0.001m^3 of gas equivalent) and generate 1 readable pulse for data logger.

Figure 3.4: Gas meter mounted with infrared reader, optical sensor and pulse counter

3.3.2 Monitoring thermostat adjustments

Thermostat adjustment has a crucial influence on occupant behaviour, regarding the space heating energy consumption and indoor thermal conditions. As mentioned in the literature review, thermal comfort requirements, such as the urgent need for warmth are usually reflected by thermostat control. Depending on how well occupants understand their thermostat, actual energy consumption can vary greatly according to different patterns associated with its adjustment. Thermostat setting has a direct effect on indoor air temperature; a higher setting means the heating system needs to work harder and longer to reach the set temperature.

The most common problem is the gap or lag time between occupant thermal comfort demand and the actual thermal condition. If a thermostat has been set too high for too long, the house can become overheated, but not necessarily uncomfortable, especially initially when quick warmth is required. The time the heating system takes to heat up a house to the desired level also varies according to different start conditions; for example, a colder/unoccupied house tends to take longer to heat than a regularly heated house. How quickly a house meets the desired temperature also hinges on the occupant's previous thermal experience; people who frequently experience colder conditions would prefer to be heated sooner rather than later. These variables all lead to different thermostat adjustment patterns and associated energy consumption results, which explains the importance of monitoring thermostat adjustment behaviour.

Figure 3.5: Thermostat dial type

A common dial-type room thermostat can be monitored by recording its dial position. Turning the dial changes its internal resistance value, as shown in Figure 3.6.

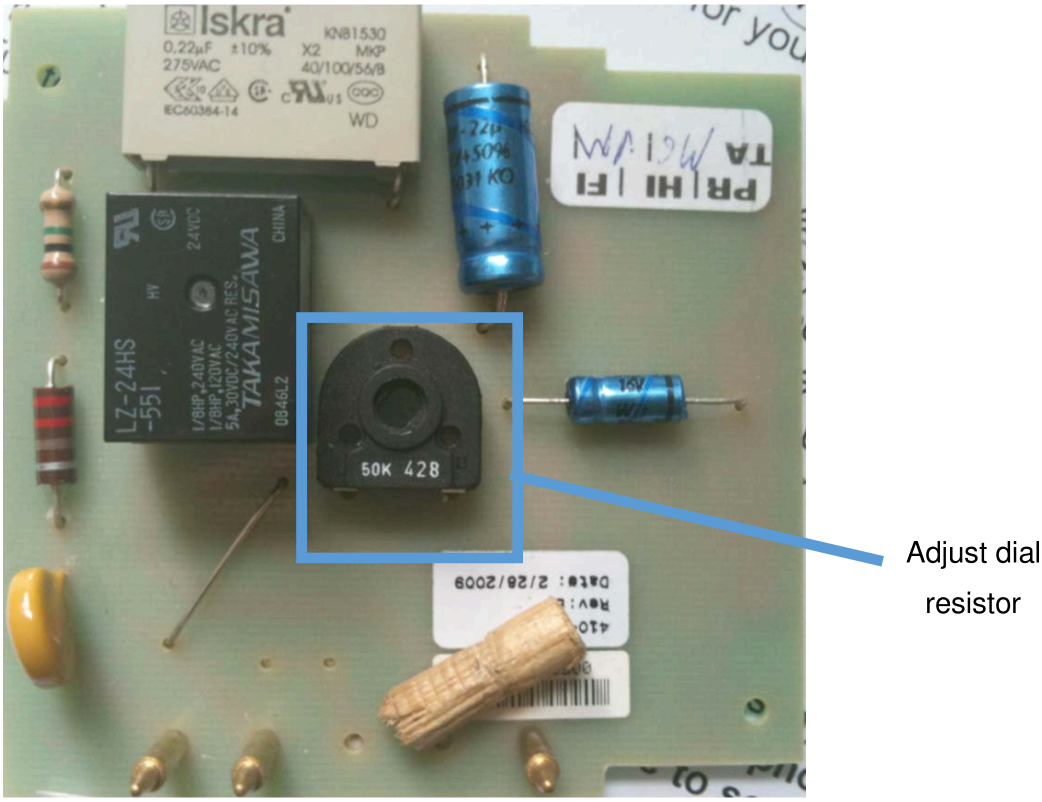


Figure 3.6: Thermostat internal circuit, resistor

The next series of picture (figure 3.7) shows how the resistance value changes. The Thermostat in this test has a range of 12˚C to 30˚C setting temperature and the resistance value varies from 8.97KΩ (at 25˚C) to 11.89KΩ (at 12˚C). This change represents the physical position of temperature.

Figure 3.7: Thermostat internal resistant value variation

Thermostat setting behaviour can be effectively monitored by Zeta-tec logger with 0.76Ω resolution and range of 0Ω to 50kΩ (Figure 3.8).

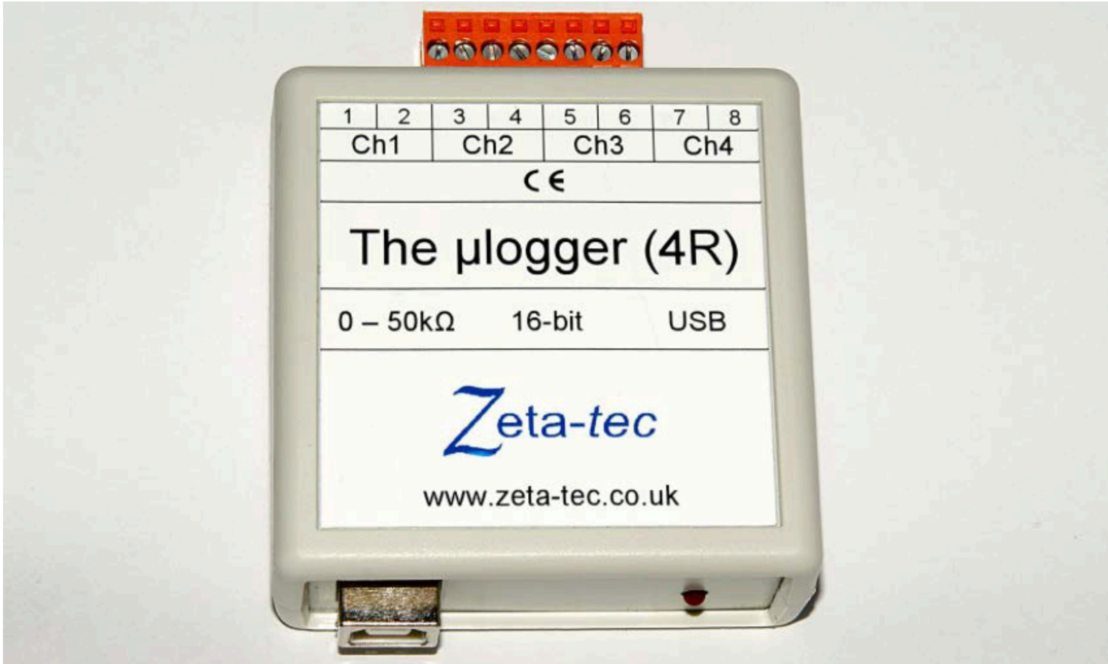


Figure 3.8: Resistance logger (source: http://www.zeta-tec.co.uk/resistance-data-loggers.htm)

3.3.3 Individual radiator and boiler

For a heating system with a boiler and radiators, there will usually be only one room thermostat to control the whole house. However, different temperatures can be achieved in each individual room by installing thermostatic radiator valves (TRVs) on the individual radiators (Fgiure4.9).

Figure 3.9: Radiator TRV control

An individual radiator’s temperature can be monitored by attaching a temperature sensor onto its surface Figure 3.10.

Figure 3.10: Radiator surface temperature monitoring as viewed from above.

The best position of temperature logger really depends on the type of the radiator. The general rule is to place logger as close as possible to the inner circulating pipe where hot water passes when boiler runs. This study will measure temperature of various location of the same radiator and compare their difference.

3.3.4 Boiler activity

Since 2002, Building Regulations require a certain level of control for new boilers or hot water cylinders. The control panel switches the boiler on/off with different on/off times for the hot water and space heating. It also sets a maximum temperature for the heat output of the system. The occupant adjusts the control panel much less frequently than the thermostat. The setting of the control panel (figure 3.11) reflects the occupant’s preferences on space heating and hot water usage at home.

Figure 3.11: Boiler control programmer

The method this study uses regarding the control panel setting is a pixel sensitive infrared camera pointed directly to the display panel (figure 3.12), in case of boiler being located in a dark space The camera will take still images if selected area shows any change in the pixels, such as the output temperature setting or a hand (of the occupant) changing the timer.

Figure 3.12: Control panel change monitoring by motion camera

Several personal computers were used to set and download the data recorded from the data loggers, and Microsoft Excel was used to analyse and demonstrate the graphical charts of the obtained results.

Figure 3.13: Computer server on site with wireless receivers.

An exploratory method was proposed which attempts to attach a temperature sensor on to boiler enclosure. This method is based on the fact that a gas condensing boiler generate heats when space heating and domestic hot water function is being demanded, therefore, capturing its enclosure surface temperature can be used as less intrusive method to record boiler activity when direct monitoring methods are not permitted such as gas sub-meter. The same method was also planned for AHSP boiler. Details will be described in next chapter where participated dwellings are presented.

3.4 Window and door operation

3.4.1 Determining open and closed status

Magnet based contact switch has been used to monitor the window and door open/close operation. As shown in the figure 3.14 and 3.15, the contact switch and logger record exactly when the state of a window or door changes. This method is more accurate and less labour intensive comparing to observation.

Figure 3.14: contact switch on a window

Figure 3.15: contact switch and event logger on a door

3.4.2 Angle and position

Limited methods for window and door status monitoring, such as observation, self-reported diary and contact switches are still the most commonly used methods. Observation takes a lot of time, and it is impossible for an observer to record all the window events or multiple windows and doors. A self-reported diary requires that participants write down their own window controlling behaviour, which involves constantly reminding people of their use, to the extent of altering the behaviour itself. A diary is not ideal method to reveal how people naturally interact and respond to the built environment. A contract switch consists of a tiny magnetic switch and magnets that attached to a window and a window frame respectively. When the magnet part moves closer to the switch, it will cause a closed circuit and vice versa. The major issue with a contact switch is that it only gives two readings: 'open' and 'closed', or to be more precise; those would be 'properly closed' or 'not properly closed'. When a window is tilted or opened wide, or not closed properly, a contact switch will only classify the window as 'open'. This limits accuracy when the researcher seeks to take account of the impact of the window position on indoor conditions.

Multiple contact switch

In order to improve the accuracy of door position monitoring, a multiple contact switchboard has been developed, as shown in figure 3.16.

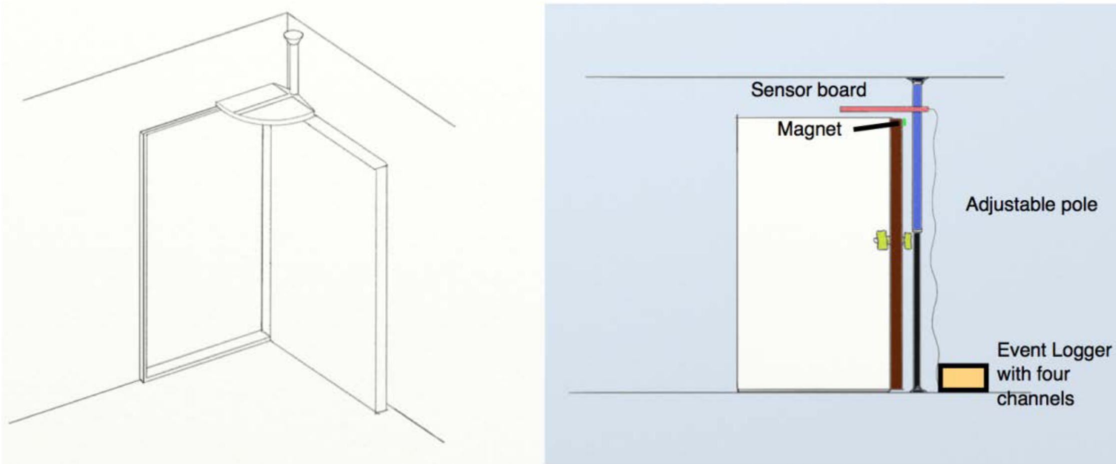


Figure 3.16: Internal door angle sensor monitoring system

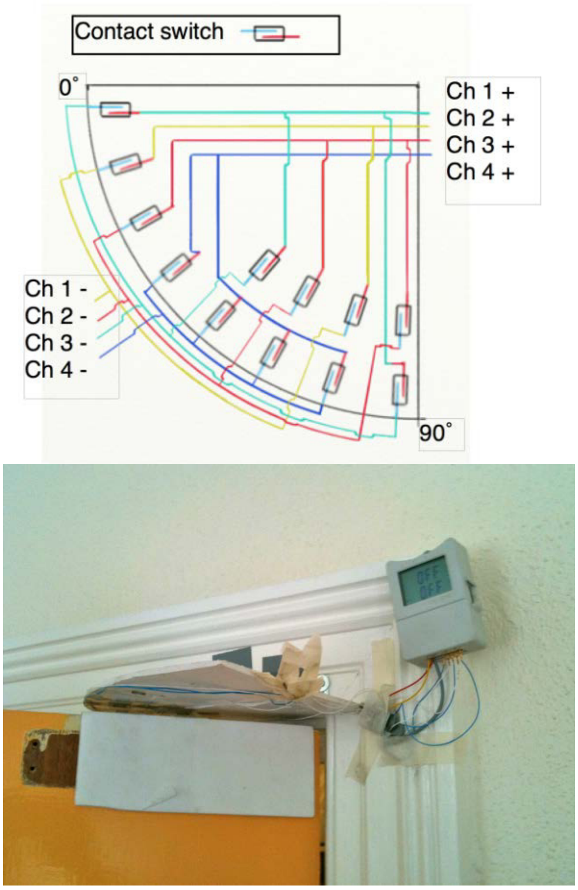


Figure 3.17: Sensor board layout

The principle means dividing the door-opening range into segments and monitoring their status.

A contact switch, as shown in figure 17 represents each segment. From 0˚ to 90˚, every 11.25˚ has its own switch, which can be triggered by a magnet attached to the door. The chosen contact switch has a 0.15 ms reacting time. The logger we tested is a simple 4-channel event logger and these channels have up to 16 binary combinations. We selected 9 combinations, as shown in Table 3.1.

Table 3.1: Internal door angle sensor range

Angle	Ch 1	Ch 2	Ch 3	Ch 4
0˚	0	0	0	0
11.25˚	1	0	0	0
22.5˚	0	1	0	0
33.75˚	0	0	1	0
45˚	0	0	0	1
56.25˚	1	0	0	1
67.5˚	0	0	1	1
78.75˚	0	1	0	1
90˚	1	0	1	0

Resistance based sensor

Two resistance base sensors have been selected to develop angle measurement, namely rotary resistor and flex sensor, as shown in figure 3.18 and 3.19. Their resistance value vary according to the physical position of operable part when a door's angle changes. Combining with battery powered resistance logger, these two customised sensor settings are able to monitor the angle changes, either a window or a door.

Figure 3.18: Rotary resistor angle measurement on a door

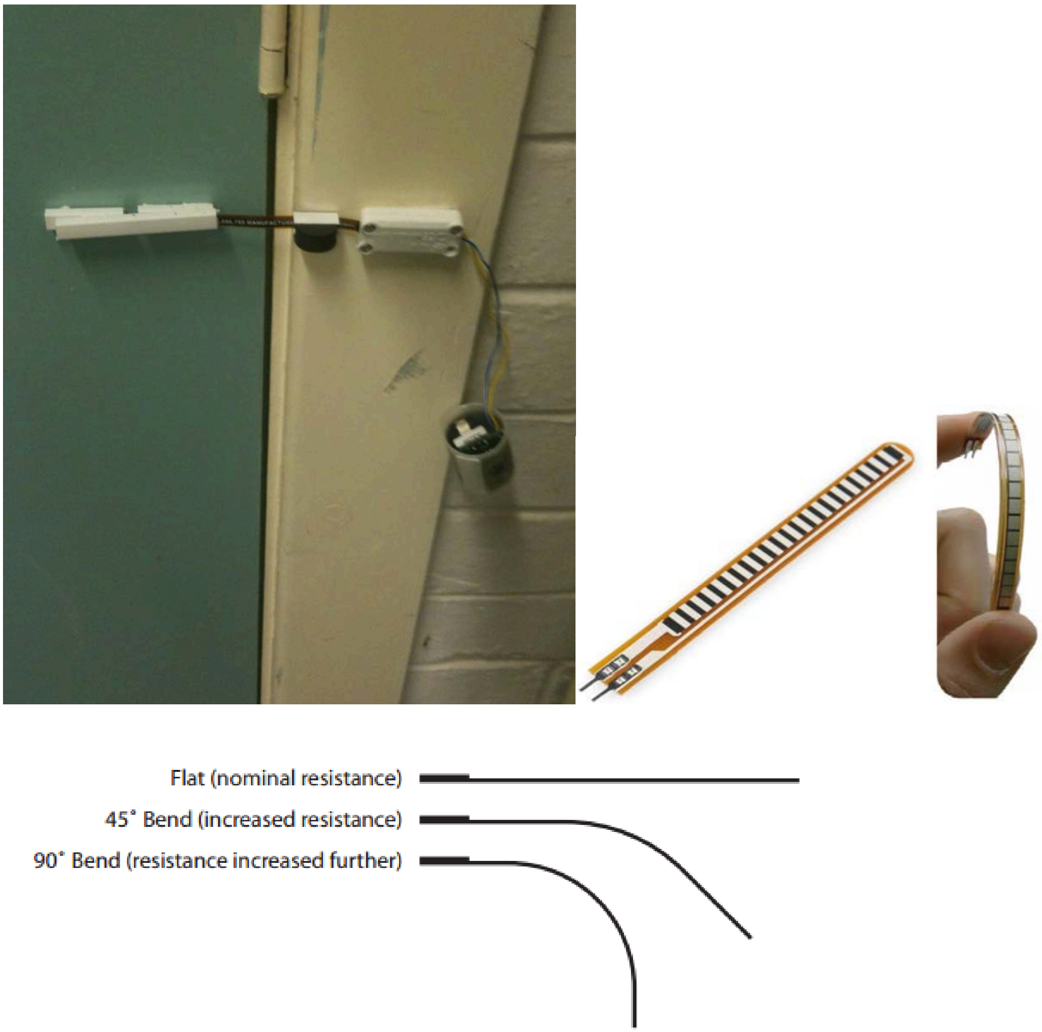


Figure 3.19: Flex sensor angle measurement on a door

3.5 Domestic hot water

3.5.1 Water volume and temperature

Domestic hot water demand behaviour, such as turning on a hot water tap, taking a shower or bath, or starting a warm washing machine cycle will directly cause hot flow change in pipes.

Another monitoring method involves using the heat meter. A heat meter works as shown in (figure 3.20 and 3.21). It contains two parts: a water flow meter and a pair of temperature sensors. The flow meter measures how much hot water passes through and the temperature sensors measure the inlet and outlet water temperatures. By multiplying the volume and temperature difference, a heater can calculate the heat loss and generate pulse signals representing energy, commonly 1000 pulses for 1 kWh. The pulse output will be recorded by a TinyTag Plus count logger (figure 3.22).

Figure 3.20: Sontex Heat flow meter

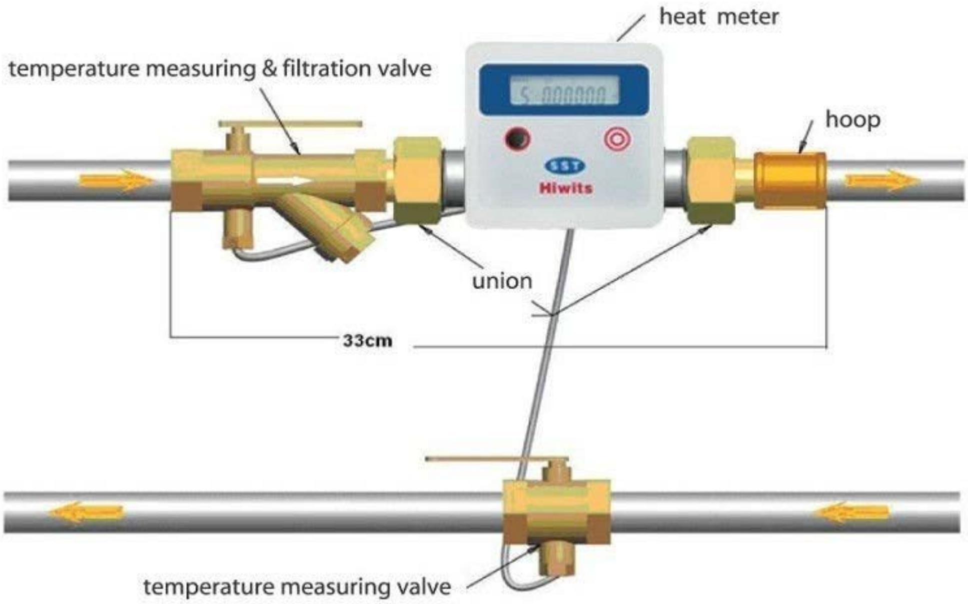


Figure 3.21: Heat flow meter (source from Haina Electric Automation Systems http://hainaelectric.en..com/)

Figure 3.22: Water flow installed in hot water supply pipe.

Figure 3.23: Clamp on non-intrusive ultrasonic water flow meter (source: Supplies ultrasonic flowmeters. http://www.ultrasonic-flow.com)

3.5.2 Hot water demand event detection

Installing a flowing meter may not be possible for all pipes. The surface temperature of a hot water pipe can also reflect the hot water demand behaviour. In order to monitoring this, a copper based surface temperature sensor (figure 3.24) can be mounted on the pipe.

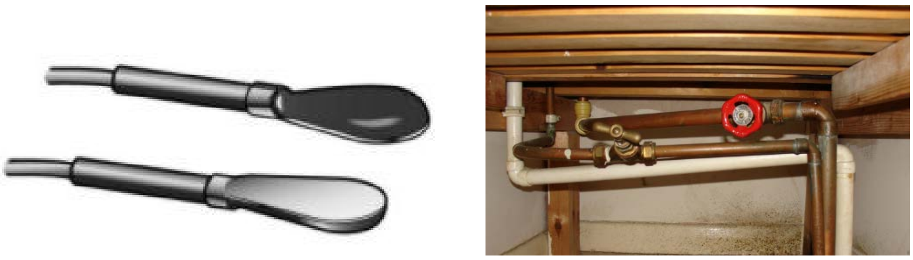


Figure 3.24: Copper based temperature sensor

The Eltek Squirrel Data logger (Figure 3.25) is a compact, portable instrument with many applications. The data is recorded using a transducer to convert the data into electrical outputs. It accepts a wide range of input sensors, including temperature, humidity, RH, pulse, frequency and digital inputs, all of which can be configured and displayed locally, using the Squirrel panel controls; it can also be displayed remotely using Eltek's “Darca" software, which is designed to run on Windows equipped systems. The logging rate can be set from 1 second to daily basics. Moreover, the logger has numerous input channels enabling up to 2 million readings, facilitating connection with multiple measuring sources at the same time. In the field study, one Eltek logger was placed at the top of a building to record horizontal solar radiation and two were used indoors to record surface temperatures.

Figure 3.25: Eltek Squirrel Logger. Source: author.

3.6 Electric appliance and lighting

3.6.1 Current transducer with and without voltage input

The majority of domestic appliances are powered by electricity. In some homes, space heating and domestic hot water also rely on electricity. A common electrical distribution in dwellings is schematised in Fig. 3.26.

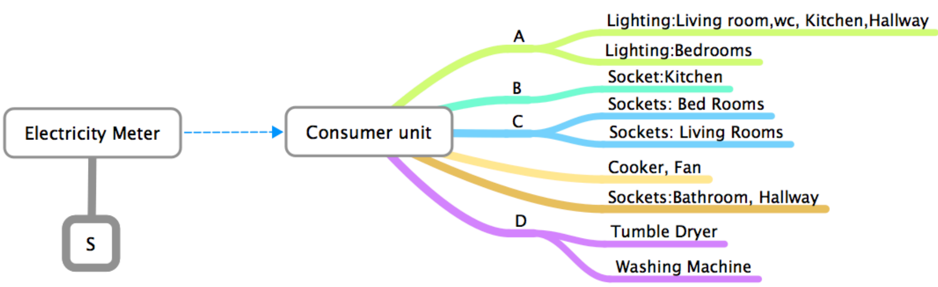


Figure 3.26: Electricity distribution in a typical home consumer unit

The main meter is usually located at the front of a home, and electricity is further split into several fused sub circuits according to their possible maximum power load. Common sub circuits are lighting, sockets, and sockets for individual high power appliances. Actual situations may vary, due to the increasing number of high power rate appliances in use, such as tumble dryers or immersion water heaters. It is also necessary to consider having a separate circuit for the kitchen socket, because in that setting, a single high power appliance like an electric fryer that may be in use.

Common individual circuits can then be monitored by a current transducer(figure 3.27), a non-intrusive, clip-on sensor. The current transducer generates a current or voltage proportional to the current passing through the centre of the transducer.

Figure 3.27: Current transducer (CT)

Using figure 3.26 as an example, there are several points that can be used to monitor electricity by clamping CTs onto:

- Point S represents total electricity consumption,
- Points A, B, C and D measure individual usage by the sub circuits.

Figure 3.28: Owl Energy electricity monitoring system

Figure 3.29 shows the example of installation of Owl electricity meter(figure 3.28) being installed to main meter and sub-circuits.

Figure 3.29: Owl energy meter transmitter, receiver and computer set up

Individual circuits have also been monitored in conjunction with high power rate appliances, in order to disaggregate all the circuits from total consumption. Figure 3.30 illustrates how electricity enters a home and is then distributed to many circuits controlled by sub-switches.

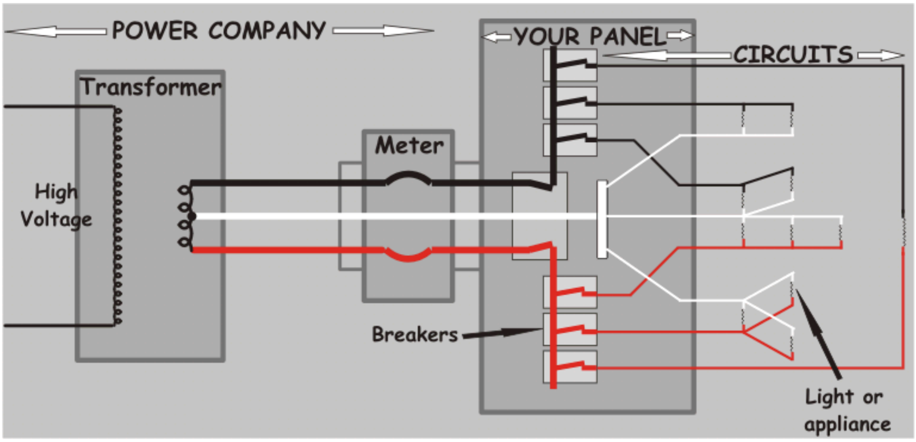


Figure 3.30: domestic electricity meter and consumer unit

Usually, all higher power rate appliances, such as electric cookers, sockets in a room and similar have their own circuits and sub-switches. This enables the possibility of installing multiple current transducers and then monitoring the electricity usage separately. Figure 3.0 shows six current transducers being installed inside of a consumer unit onto sub circuits.

Figure 3.31: Consumer unit and sub-circuit sensors installation

Most of the clamp-on current transducers based non-intrusive electricity monitoring system use an estimated voltage to multiply with the measured current therefore calculate energy consumption. The actual voltage may vary from time of day or geographic distance from nearest transformer of national grid. Having voltage measured together with current would definitely increase the accuracy of electricity consumption. Ecofront (figure 3.32) basic version was chosen for this purpose. Fundamentally, it uses the similar current transducer as previously described but Ecofront has its own voltage sensor that directly connected the main circuit and take real-time voltage measurement alone with current records of other sub-circuits.

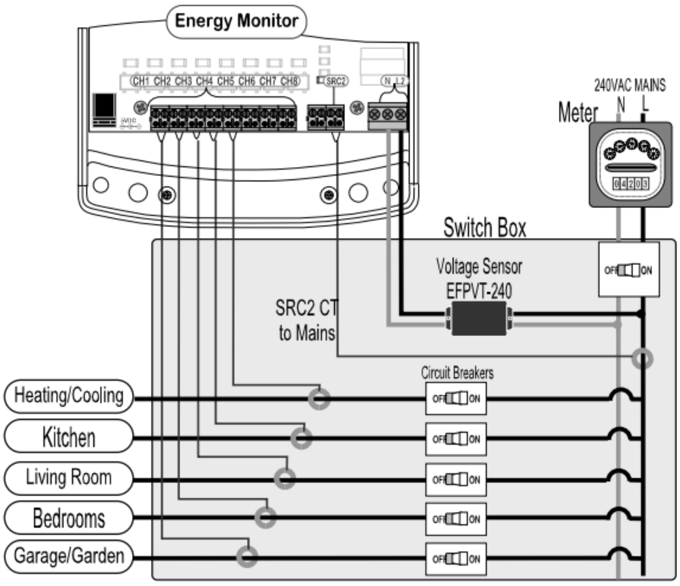


Figure 3.32: Ecofront energy monitor's CTs and voltage input setup with sample sub-circuits

Voltage measuring input of Ecofront energy monitor is matched to CT sensor mains measuring channels and is used to help accurately calculate power consumption and power factor()figure 3.33P. The voltage sensor is a potential transformer that provides a linear output voltage proportional to the input voltage. The output voltage is 2 volt when the input voltage is 250VAC and will work with most standard mains AC circuits up to 380VAC.

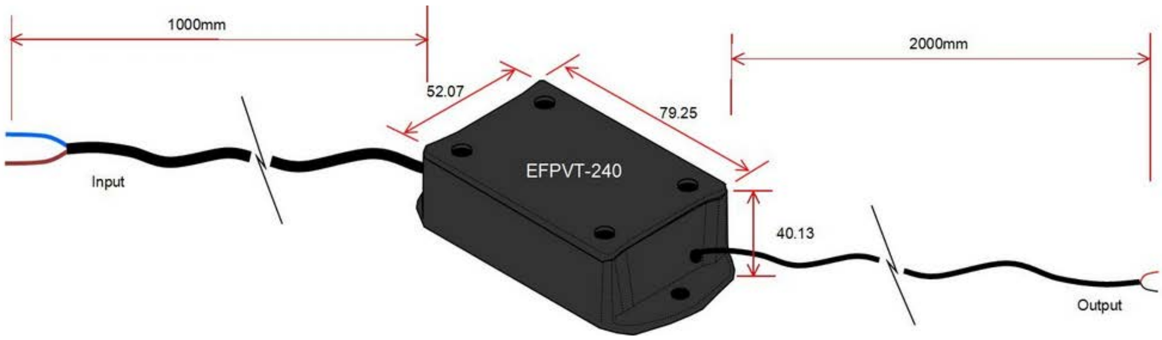


Figure 3.33: Ecofront's own wired voltage sensor

3.6.2 Appliance electricity usage

Having reviewed the pros and cons of both approaches; in this study, a mixed method was selected in order to balance out the barriers: the selected appliances and selected circuits, are therefore, monitored separately and simultaneously.

Individual appliance energy consumption is monitored using the Plugwise system (figure 3.34), which measures electricity used by appliance being plugged to each socket type sensor and transfer the data wirelessly via Zigbee mesh network.

Figure 3.34: Plugwise system sockets and USB receiver

The Plugwise system is comprised of three components, as pictured above and described below:

1. **Circle** - a plug which goes between the plug of for the appliance and the mains power socket.

2. **Stick** - a USB device plugged into a personal computer to receive data wirelessly from the Circle(s). This Stick can also transmit instructions wirelessly to turn the appliances on or off.

3. **Circle+** - a Circle containing a real-time clock and battery. Circle+ is used to co-ordinate the Circles within the network. This also acts as a regular Circle as described above.

4. **Source** - software installed on a computer to process the electricity consumption data collected in realtime, displaying it numerically and in charts, and logging it for later analysis. The Source software is also used to manually or automatically turn the appliances on or off.

Each Circle has a unique ID code. The name of the appliance plugged into it can be entered in the Source software and energy consumption tracked immediately. Plugwise Circles communicate with one another and with the Stick via the ZigBee wireless communication protocol. These Circles form a mesh network between themselves and the Stick.

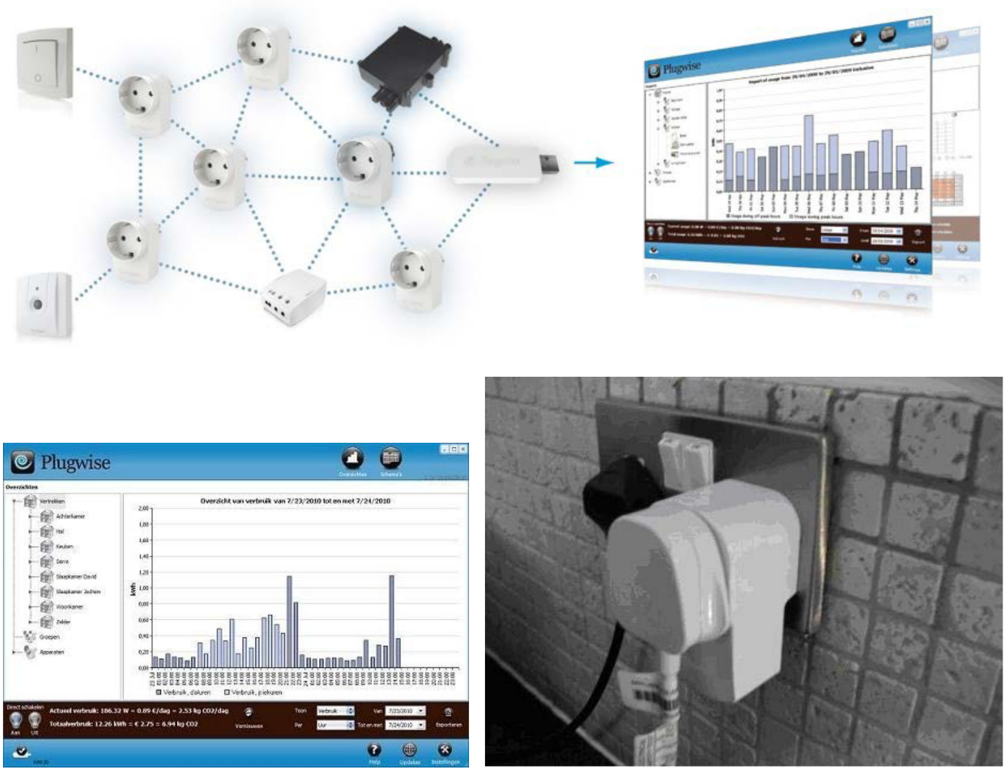


Figure 3.35: Plugwise home appliance monitoring set up

Common high power rated domestic appliances are: the plasma TV, electric cooker, fan oven, kettle, microwave oven, convection heater, washing machine, tumble dryer, electric shower and so on.

3.7 Physical parameters

Gemini Tinytag Ultra and Tinytalk data loggers were used to evaluate the thermal performance of selected residential buildings, which have been widely used in building performance evaluation research.

The Gemini Tinytalk data logger (Figure 3.36) is a small, lightweight, cell-contained device with an 1800 reading memory and log rates ranging between 1 second and 4.5 hours. It is used to record environmental data inside and outside buildings and has up to 3 years of battery life. It can also be used in other fields, such as industry and food transportation. In this study, it was used in internal spaces to measure the globe temperatures of interior spaces in all the case studies.

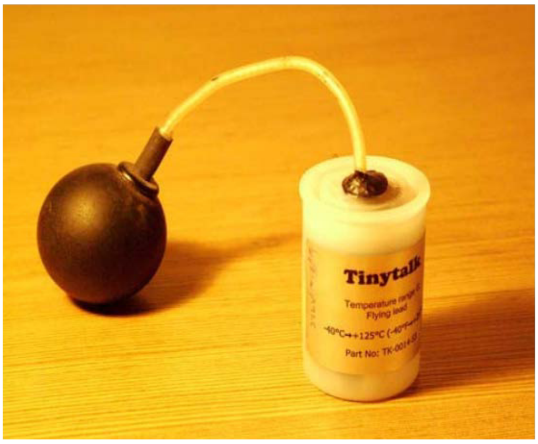


Figure 3.36: Gemini Tinytalk Data Logger. Source: author.

Another type of Gemini tiny data logger is the Tinytag Ultra (Figure 3.37 left); this has the ability to measure air temperature and relative humidity (RH) simultaneously on two separate charts. It is capable of measuring air temperatures ranging from -30°C to +50°C and RH from 0% to 95%, which covers the environmental situation in Wales during monitoring period. Tinytag Ultra has a memory of 7800 readings and programmable alarms. It has a logging rate ranging from 1 second to 10 days with minimum, maximum and actual readings, plus up to 5 years battery life. Moreover, the Gemini Tinytag Plus (Figure 3.37 right) shares the same features as the Tinytag Ultra, but is a different in shape.

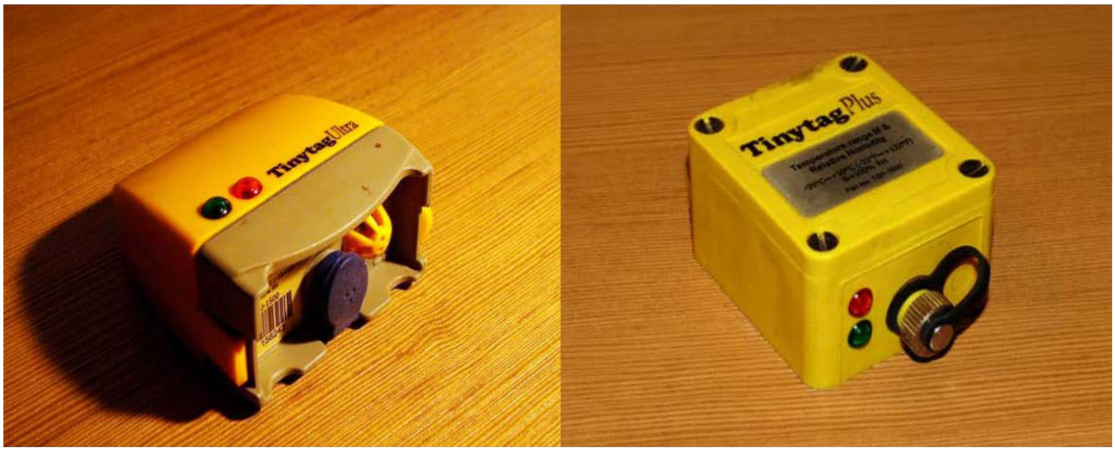


Figure 3.37: Tinytag Ultra and Tinytag Plus for Air Temperature recordings. Source: author.

The Gemini data loggers were launched via a personal computer, using Gemini Tinytag Explorer (GTE) software. The GTE software was used to set up the loggers to begin logging, and to permit the download of data after logging. The downloaded data was viewed, saved, printed, copied to the clipboard and exported into Excel software to be translated into tables and charts. All loggers were instructed to delay the start of recording until 11:00 am as a first reading. They were also instructed to record environmental data every fifteen minutes, and to stop once the devices were full of data. Figure 3.38 shows a sample of the first page of the GTE software after the data was downloaded from the external recording function of a Tinytag Ultra logger, in the first case study.

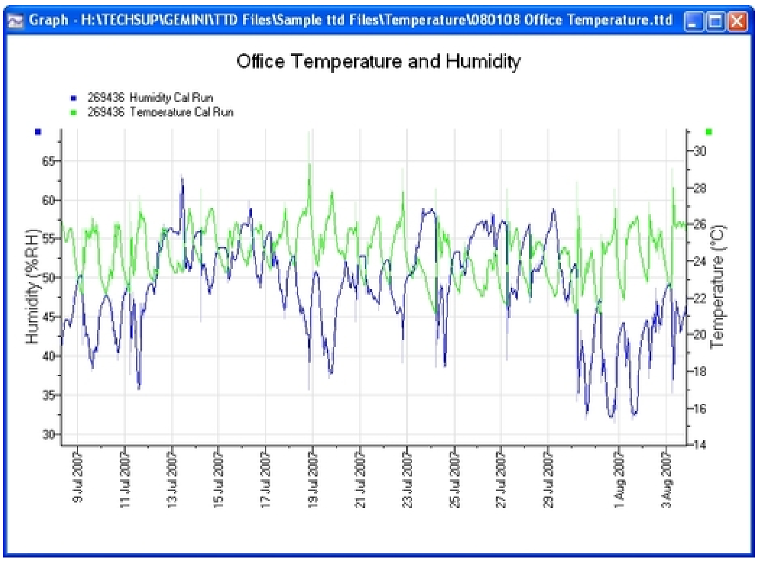


Figure 3.38: Tinytag Explorer

Tinytag is a stand along sensor with built logger and the data collection has to be conducted by manual download with its data transfer cable. Alternatively, a wireless system, Arexx BS-500 which monitors air temperature, relative humidity and CO2 level was selected (Figure 3.39). Comparing with other wireless monitoring systems, Arexx BS-500 (Figure 3.40) cost substantially less as it requires a computer to store high resolution data, as well as smaller range, suitable for individual dwelling.

Figure 3.39: Arexx BS-500 wireless temperature humidity and CO2 monitoring system

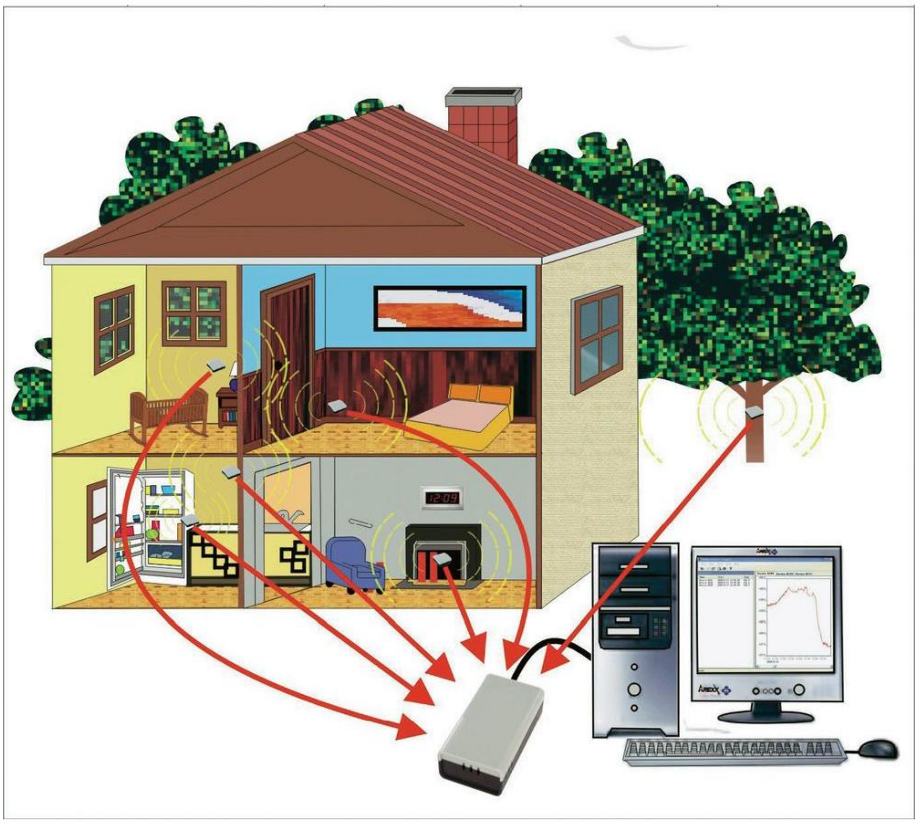


Figure 3.40: Demonstration of domestic setting up with Arexx BS-500 system

3.8 Monitoring occupant related parameters

3.8.1 Biological psychological and social parameters

Thermal comfort questionnaire

Regarding the perception of comfort, three methods were selected in this field of study, to gather the occupant's opinions about their surrounding built environment: comfort questionnaire, self-administrated diary and post monitoring informal interview.

Subjective measurements were conducted using a comfort questionnaire survey. The comfort questionnaire contained questions about how occupants like their home environment to be. It also provides faster and easier comfort votes than measuring the thermal, visual or acoustics environment associated with votes. Any member of a family is welcome to fill complete their own copy of the diary whenever they feel inspired to do so. It takes a couple of seconds to tick a response each time. Occupant's comfort perceptions and satisfaction with the rooms in the home were measured using a thermal comfort rating form during the monitoring period, based on their indoor experience across summer and winter. Figure 3.41 shows an example of a thermal comfort diary. Occupants are encouraged to feel free to tick their feelings about a room for both winter and summer. Compared to 7 points scale, the questionnaire is simplified to 5 points in order to shorten the answering time.

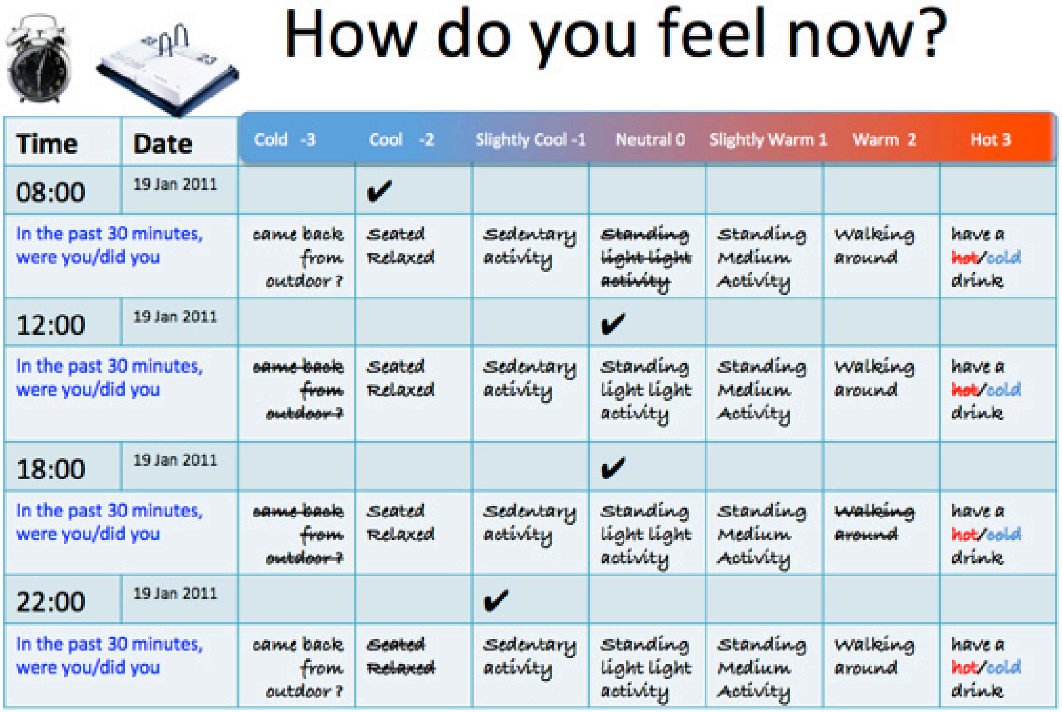
	In winter I prefer my indoor environment to be				
Warmth	Much warmer	A bit warmer	no change	A bit cooler	much cooler
Air movement	Much less air movement	a bit less air movement	no change	a bit more air movement	Much more air movement
Humidity	much drier	a bit drier	no change	a bit more humid	much more humid
Natural light	much dimmer	a bit dimmer	no change	a bit brighter	much brighter
Noise	much quieter	a bit quieter	no change		
	In Summer I prefer my indoor environment to be				
Warmth	Much warmer	A bit warmer	no change	A bit cooler	much cooler
Air movement	Much less air movement	a bit less air movement	no change	a bit more air movement	Much more air movement
Humidity	much drier	a bit drier	no change	a bit more humid	much more humid
Natural light	much dimmer	a bit dimmer	no change	a bit brighter	much brighter
Noise	much quieter	a bit quieter	no change		

Figure 3.41: Sample of indoor comfort questionnaire

Self-reported dairy

Self-administrated comfort diary has been designed to combine the frequent asked questions in comfort research, namely, thermal experience, thermal satisfaction, clothing insulation level and activity level.

The dairy was formatted as figure 3.42 shows: four fixed time in a day, 8am, 12am, 6pm and 10pm. Occupants were encouraged to tick their thermal sensations at these moments and there is also blank rows in between when they feel like to add more information such as whether they returned from outdoor in the past 30 minutes, how active they were, whether they had a hot or cold drink earlier. These optional questions can further help to collect personal factor samples.



How do you feel now?

Time	Date	Cold -3	Cool -2	Slightly Cool -1	Neutral 0	Slightly Warm 1	Warm 2	Hot 3
08:00	19 Jan 2011		✔					
In the past 30 minutes, were you/did you		came back from outdoor ?	Seated Relaxed	Sedentary activity	~~Standing light light activity~~	Standing Medium Activity	Walking around	have a ~~hot~~/cold drink
12:00	19 Jan 2011				✔			
In the past 30 minutes, were you/did you		~~came back from outdoor ?~~	Seated Relaxed	Sedentary activity	Standing light light activity	Standing Medium Activity	Walking around	have a ~~hot~~/cold drink
18:00	19 Jan 2011				✔			
In the past 30 minutes, were you/did you		~~came back from outdoor ?~~	Seated Relaxed	Sedentary activity	Standing light light activity	Standing Medium Activity	~~Walking around~~	have a hot/~~cold~~ drink
22:00	19 Jan 2011			✔				
In the past 30 minutes, were you/did you		came back from outdoor ?	~~Seated Relaxed~~	Sedentary activity	Standing light light activity	Standing Medium Activity	Walking around	have a ~~hot~~/cold drink

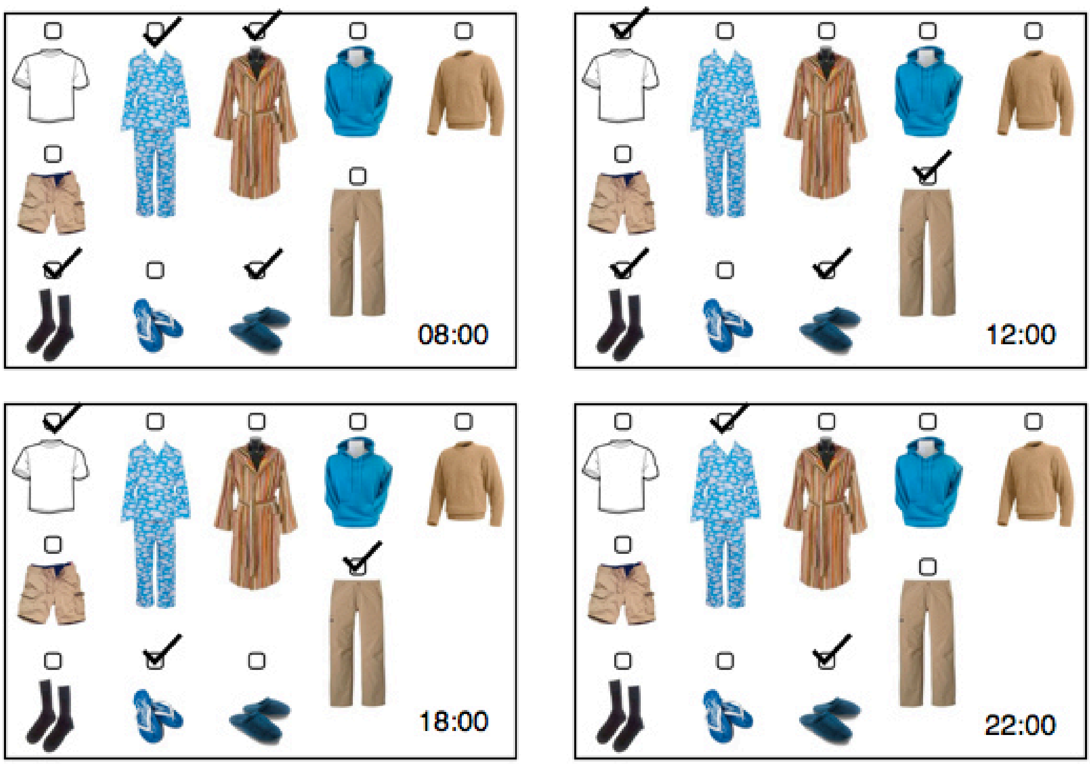


Figure 3.42: Self-admitted comfort diary example.

The self-administrated diary can be customised for different occupants on request. An example of a shower diary has been made and is as shown below, which only focus on shower and bathing activities.

Date	Shower or Bath Please Circle	Start time	Finish time	Is space heating on? (Optional)
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF
__ / __ / 2011	Shower or Bath	__ : __ : __	__ : __ : __	ON/ OFF

Figure 3.43: Shower and Bath activity diary

3.8.2 Occupancy and presence

Occupancy is also helpful when interpreting human behaviour and indoor comfort. Motion sensors are those most frequently used in occupancy monitoring.

There are two types of motion sensor: Active sensors inject energy (light, microwaves or sound) into the environment in order to detect a change; passive sensors measure energy radiating from objects in their field of view.

Stores, for example, usually have a beam of light crossing the room near the door, and a photosensor on the other side of the room. When a customer breaks the beam, the photosensor detects the change in the amount of light and rings a bell. Many grocery stores have automatic door openers, which use a very simple form of radar to detect when someone passes near to the door. The box above the door sends out a burst of microwave radio energy and then waits for the reflected energy to bounce back. When a person moves into the microwave energy field, it changes the amount of reflected energy, or the time it takes for the reflection to arrive, and the box opens the door. Since these types of devices use radar, they often set off radar detectors. The same can be achieved using ultrasonic sound waves; bouncing them off a target and waiting for the echo.

In this study, PIR (Passive Infrared sensor) based motion detectors (figure 3.44). Apparent motion is detected when an infrared source at one temperature, such as a human, passes in front of an infrared source at another temperature, such as a wall. This is not to say that the sensor detects the heat from the object passing in front of it, but that the object disrupts the field, which the sensor has determined as in a "normal" state. Any object, even one exactly the same temperature as surrounding objects will cause the PIR to activate if it moves through the sensor field.

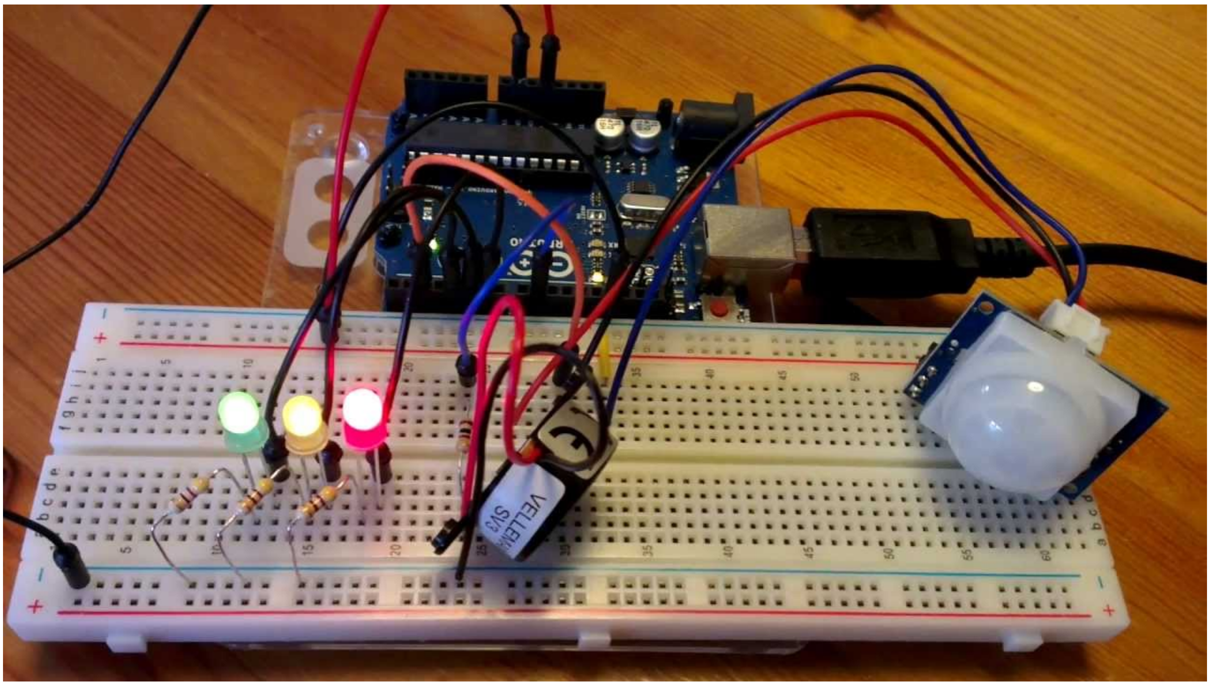


Figure 3.44: PIR sensor module and Arduino controller circuit board

Often, PIR technology will be paired with another model to maximise accuracy and reduce energy usage. In order to make a sensor that can detect a human being, you must make it sensitive to the temperature of the human body. Humans, have a skin temperature of about 33.8˚C; they radiate infrared energy at a wavelength between 9 and 10 micrometres. Therefore, sensors are typically sensitive in a range of 8 to 12 micrometres. The infrared light bumps the electrons off a substrate, and these electrons can then be detected and amplified into a signal. PIR sensor is sensitive to motion, but not to a person standing still. That is because the electronics package attached to the sensor looks for a fairly rapid change in the amount of infrared energy it sees. When a person walks by, the proportion of infrared energy in the field of view changes rapidly and the sensor easily detects it.

3.8.3 Activity tracker

In addition to self-reported activity level, wearable trackers was proposed to the field study. The Walkwithme activity meter (figure 3.45) is a clip accelerometer that tracks the occupant's steps. In order to measure this a wristband modification was added to record the occupant's activity level. Every valid movement of the wrist can be recorded and uploaded wirelessly to a game console, on which the occupant can view graphs and charts of steps and activity time (figure 3.46).

Figure 3.45: Walkwithme wrist activity sensors

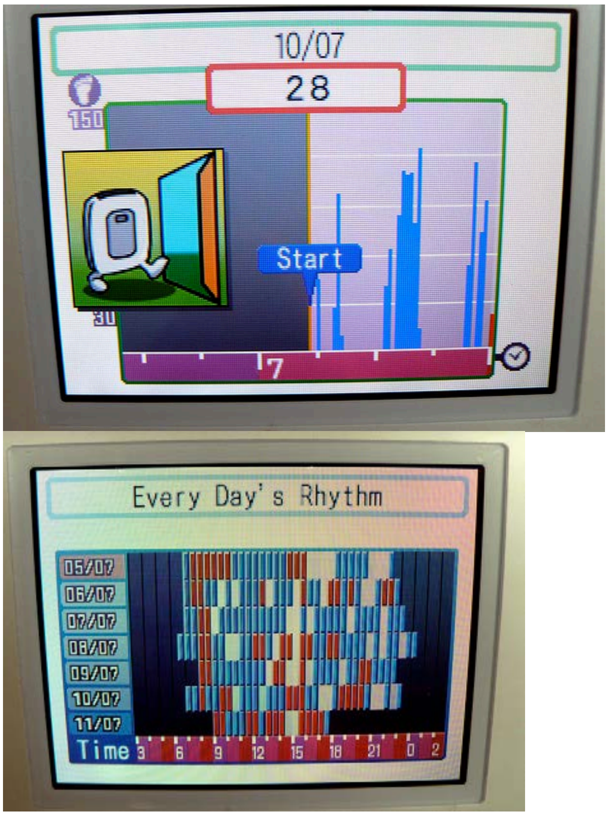


Figure 3.46: Walkwithme wrist activity tracker data

Walkwithme tracker was chosen due to its availability and reviews by consumers. For the purpose of comparison between reported and recorded activity level, it was considered reasonably informative enough. More importantly, occupant who agreed to wear tracker has compatible devices at home and more willing to participate since they would be able to access the data too.

3.8 Summary

In this chapter, the research methodologies employed are discussed. Measurement methods and instrumentations selected for investigation focus on parameters related to space heating, domestic hot water, window and door, electrical appliance and lighting, physical environment, and occupant factors.

Need to emphasis, selection of the instrumentation and method have been mainly restricted by their invasiveness, accuracy, cost, ease of use and reliability. Table 3.7 summarises all the selected methods and instrumentations that will be studied in the actual dwellings.

Table 3.7: Summary of selected methods and instrumentations for field investigation

Sector	Type of parameter	Methods and/or instrumentations
Physical measurement	Space heating	Gas sub-meter and pulse counter
		Gas boiler surface and temperature sensor
		ASHP boiler outdoor unit and temperature sensor
		Thermostat dial and resistance logger
		Individual radiator and fireplace and temperature logger
	Domestic hot water	Customised shower diary
		Hot water inlet and return pipe surface and temperature logger
		Boiler control panel display icon recognition
	Windows and door	Opening angle and Multiple contact switch board
		Opening angle and Flexi resistive sensor
		Opening angle and Rotary resistive sensor
		Opened or closed status and single contact switch event logger
	Electrical appliance and lighting	Electricity sub-circuit and current transducer with and without voltage input
		Individual appliance and socket electricity meter
	Indoor physical environment	Temperature, humidity and CO_2
Subjective measurement	Occupant	Questionnaire and indoor condition satisfaction
		Self-reported recent thermal satisfaction, activity and clothing level
		Face to face interview
Physical measurement		Occupancy and PIR presence sensor
		Wearable activity tracker

In chapter4 the next, participated dwellings are described with sensor deployment details. Results for each type of parameters grouped into three chapters. The chapters are namely, Chapter 5: Physical measurement; Chapter 6: Subject measurement; Chapter 7: Integrated measurement.

Chapter 4: Field study dwellings

4.1 Introduction

The aim of this chapter is to present the setup and test of instrumentation and measuring methods in a range of dwellings. The objectives of the chapter are:

- to establish the criteria used for selecting suitable dwellings for use in this study;
- to identify and describe the study dwellings and explain their selection;
- to describe the specific sensor installations and what data they were intended to collect.

Dwellings have been selected for best fit of methods and instrumentation investigation. Dwelling 1, 2 and 3 have been selected more for pilot study purposes which enabled author to be familiar with equipment and social science survey. The experience gained in these three sites continued to serve a better installation and communication with households and occupants in dwelling 4 to 8. Details of aim and of how dwelling fits the requirement are present at the start of each section.

4.2 Study dwelling 1

Dwelling 1 was selected primarily to pilot both physical measurement and social science survey. Permission to access dwelling 1 was granted the earliest among several other high rise apartment where recruitment of participates for questionnaire survey live in apartment with identical building fabric and performance. Physical measurement tools selected for dwelling 1 sites are electrical sub-circuits, indoor environment and short questionnaire survey regarding occupants' opinions towards their indoor environment. There is another benefit in electricity only dwellings as space heating, domestic hot water, electrical appliances and lightings are all measurable with sub-circuit current transducer which usually is considered as a non-intrusive method.

Equipment was only available to be installed in on apartment and the building manager has granted access to the central electricity meter room where individual meter readings could be taken for an overall glance of off-gas apartments in this site.

4.2.1 Forms and plan

This selected development is located in central Cardiff, south Wales. The building is 72 metres (232 ft) high and has 23 floors. The tower was the tallest residential building in Wales upon its completion in 2005, and remains one of the tallest buildings in Cardiff and in Wales.

Figure 4.1: North façade of dwelling 1, Source: Author

Figure 4.2: Form and surroundings of dwelling 1

The Y-shaped building (Figure 4.2 left) contains 292 one to three bedroom apartments with views across the city. (Figure 4.2 right). The typical apartment plan is similar to figure 4.3. Each apartment has mixed ventilations: natural vents and mechanical extract fans; both can be closed or switched off. The windows are restricted from fully open and can only be opened up to 20 cm wide due to safety reason. Each room has at least one electrical panel radiators installed in each room with plus one heater in bathroom. The external wall is 350mm thick. Each apartment has its own electric immersion heater to provide domestic hot water. The windows are double-glazed.

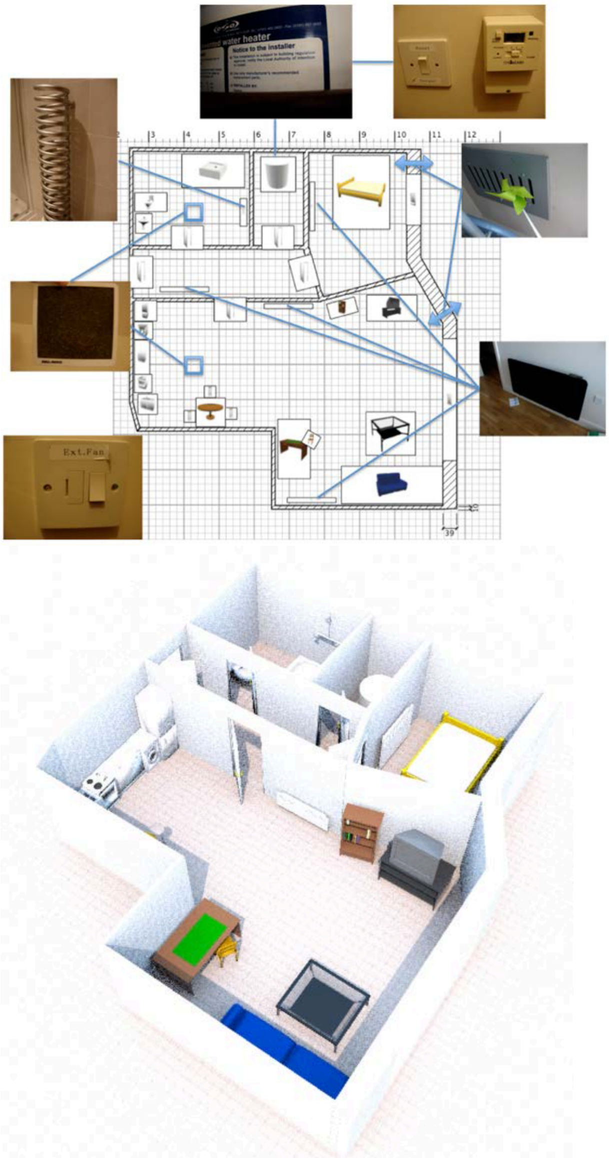


Figure 4.3: Typical flat plan and HVAC systems

4.2.2 Space heating

The apartment does not have central heating. Each room has its own electrical heater and has to be operated individually. There is no timer function and occupants have to manually turn it on or off or adjust the heating output. As show in the figure 4.4, the control panel has four bottoms: mode, and temperature up and down with scale from 1 to 9. This type of panel radiator cannot store heat, therefore, it will cool down very quickly once it is turned off.

Figure 4.4: Electric radiator control panel

In order to monitor the status of space heating behaviour, each radiator has its dedicated temperature logger, a Tinytag Plus 2 sensor. It is hoped capture the high temperature readings of the radiators which can only be caused by being turned on. The handheld infrared temperature meter shows that when running, the front surface of this type of electrical radiator can rise up to 70˚C which is not only too high for the plastic enclosure but also can be risky for the battery inside of Tinytag. Spot measure shows that the next hottest spot is the top but behind the heating element, only goes up to 50˚C, enough to be differentiated from room temperature and capable of indicating the status of radiator.

Additionally, each participant was given a diary to write down the time and the setting temperature when a change is made for a period of 14 days. The diary keeping is not mandatory but occupants were asked to fill as much as possible but it is completely up to them if it becomes too annoying.

4.2.3 Domestic hot water

Domestic hot water is provided by a 210 litres immersion water heater as shown in figure 4.6. Its control panel has very basic feature:

- a power rate switch, it toggles between normal rate(3kW) and Boost mode normal mode(6kW),
- a boost button, it is designed for urgent hot water demand which enable immersion heater to work at 6kW, each press gives one hour of boost running and can be pressed up to three times
- a timer, it can store four periods of running time during 24 hour cycle

Figure 4.6: Control pannel for immersion water heater and Efergy electricity meter

In order to monitoring the domestic how water related behaviour and energy consumption, an Efergy electricity meter has been clamped on the sub circuit inside the consumer unit, in order to keep eyes on the domestic water consumption (figure 4.7).

4.2.4 Electrical sub-circuit and current transducer

Given the access to the consumer unit, total electrical appliance and lighting were monitored with current transducers. Each sub circuit has its own clamp-on electric current transducer in order to measure the electric current come through the current transducer.

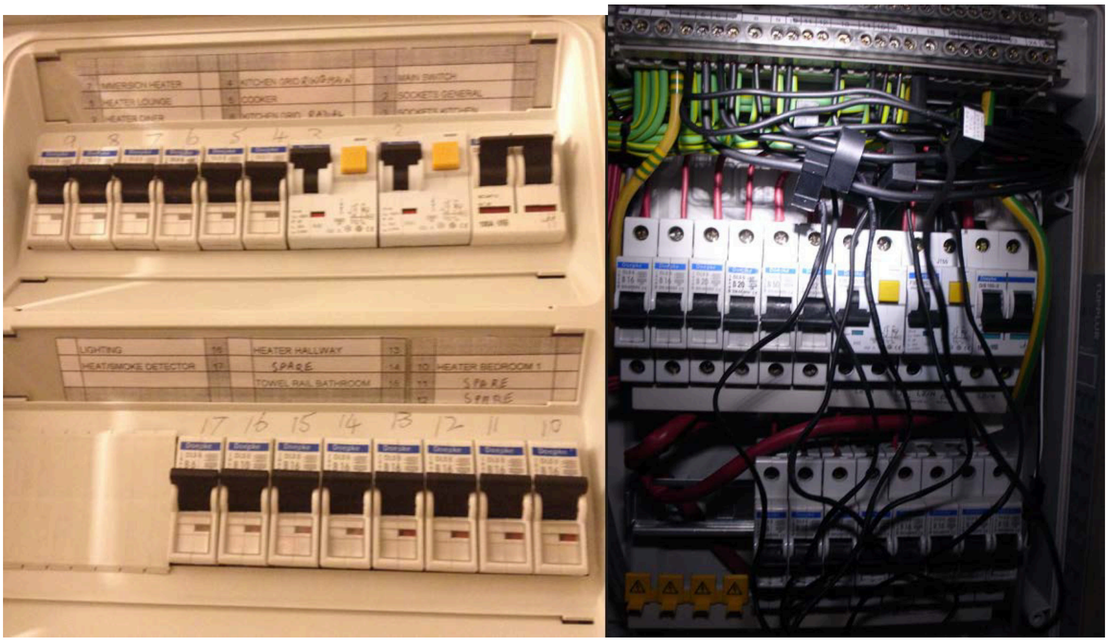


Figure 4.7: Consumer unit and installation of clamp-on sensor (current transducer)

4.2.5 Occupant subject indoor environment satisfaction

In total, 150 occupants were asked to fill questionnaires about their satisfaction of the internal conditions, namely, temperature, humidity, ventilation, lighting and noise for both winter and summer. The whole process takes approximately 5 minutes. At the end of survey, occupants were shown the sample of self-administrated dairy of indoor thermal comfort.

4.2.6 Indoor physical environment

Tinytag plus 2 temperature and humidity logger were installed at various locations of the participated apartment (figure 4.8). Apart from the dedicated sensors near radiators, each zone has another Tinytag logger. Given the fact that this apartment has an open planed kitchen and living room, kitchen worktop has an additional

Tinytag logger to detect the temperature and humidity changes caused by cooking behaviour, which can may affect the rest zones of the apartment.

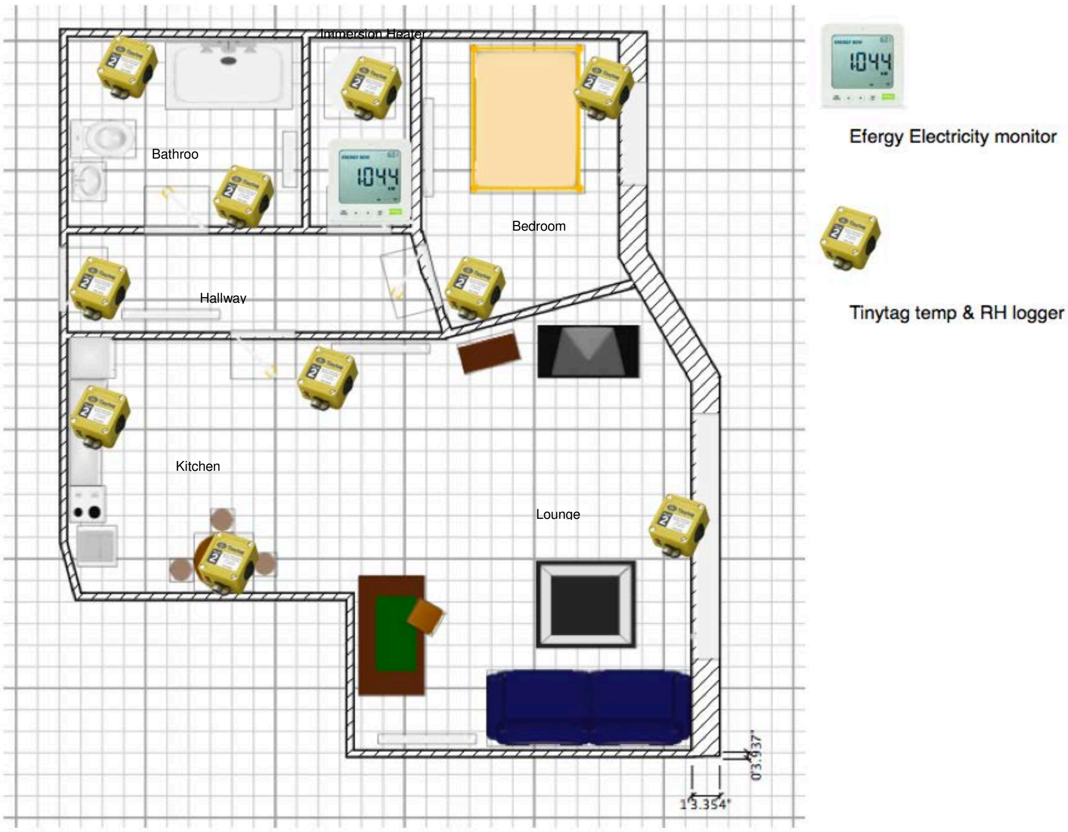


Figure 4.8: Tinytag sensors set up in dwelling 1.

4.3 Study dwelling 2

The second study dwelling is a semi-detached house which has northeast facing and next the former canal and surrounded by trees and bushes. It was selected for piloting methods and sensor installations, namely, non-intrusive optical reader and infrared sensor on main gas meter, individual radiator, gas fire place operation, electrical appliance, domestic hot water pipe surface temperature and indoor physical conditions. Dwelling 2 has a main gas meter with reflective plate which is suits the testing sensors. The access to its hot water inlet and return pipe is convenient. Dwelling2 contains 2 bedrooms, 1 bathroom at first floor, kitchen and Lounge at ground floor. It is equipped with Economy-7 tariff electricity meters.

4.3.1 Individual heating appliances monitoring

Both gas and electricity are used for space heating. Besides a gas fireplace (figure 4.10 top right) in the lounge, there are two electrical storage heaters (bottom left) in bedrooms and one fan heater (top left) in the bathroom to provide space heating. Occupants bought one additional convention heater (bottom right) and placed it in the main bedroom for additional warmth that storage heater couldn't provide.

Figure 4.10: Space heating appliances in dwelling 3

In this household, gas is also used for cooking. The permission of installing a sub gas meter was not granted, there for only total gas consumption was monitored by attaching a tailored optical sensor and pulse counter, as shown in figure 4.11. All gas passes through the meter before being distributed to the cooker and fireplace. A tailored optical sensor has been made and mounted onto the gas meter (figure 4.11). Since there is strict limitation on what can be installed on the main gas meter, the method is considered to be most appropriate and indirect as possible. The reader will generate one pulse signal when the last digit of dial rotates one complete circle, which is equal to consumption of 0.001m^3 of gas.

Figure 4.11: Gas meter mounted with optical reader and pulse generator circuit board.

Each radiator also has its own Tinytag plus 2 sensor in order to record their operating status. Since there are three type of space heating appliances with different capacity of space heating output. For instance, the storage heater will emit heat very slowly but it is able to continue release heat for several hour after being turned off. Gas powered fire place is located at ground floor and can heat up the ground floor very fast but it is never left unattended. The additional electrical heater is only turned when both of earlier mentioned heating element fail to provide sufficient warmth.

In addition to the Tinytag placed close to these two heating appliances, an additional one was placed outside of the house, next to the exhaust vent, in order to provide another set of data of gas fireplace operating status (figure 4.12).

Figure 4.12: Gas fireplace exhaust vent

4.3.2 Surface temperature of domestic hot water pipes

Domestic hot water is supplied by immersion heater (figure 4.13). The Immersion heater is controlled by a simple ON-OFF switch only. There is no timer or programmer. Occupant has to manually control the water tank

Figure 4.13 Immersion water heater, control switch and hot water outlet pipe underneath

A temperature probe was mounted on the hot water supply outlet pipe underneath the immersion heater. When there is hot water demand at any tap, it will go through the outlet pipe and immediately cause pipe surface temperature rise.

4.3.3 Electricity monitoring

In this household, the consumer unit is bolted and access to the sub-circuits was very limited and participants did not give permission due to the potential disturbance and damage. Socket level appliance sensors were not available during the monitoring period of dwelling 2. As a result, only total electricity consumption was monitored.

Economy 7 tariff has two sets of meters and supply wires: one for peak hours in the day and another one for off-peak supply in night hours. There is a teleswitch and communication cable which can toggle the counting between two meters. Peak hour's electricity price is generally three time higher than off-peak, e.g. Peak hour rate is 13.45 pence per kWh, and off-peak rate is 4.95 pence per kWh. It encourages occupant to avoid consume electricity during peak hours for financial benefit.

In order to monitor both peak and off-peak hour electricity usage, two sets of current transducers have been clamped as illustrated in figure 4.13.

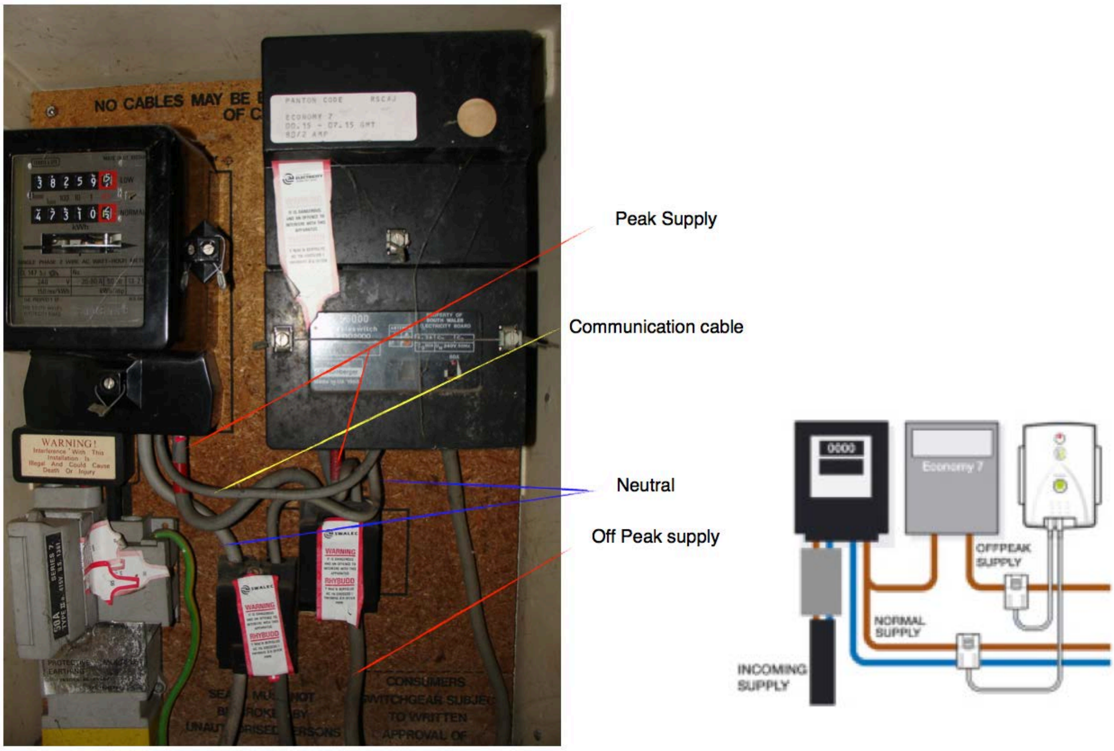


Figure 4.13 Economy 7 electricity meter monitoring setting

4.3.4 Indoor and outdoor environment

Several Tinytag Plus 2 temperature and humidity logger were installed at different rooms to record their internal and external environmental conditions. Their locations are shown in figure 4.14.

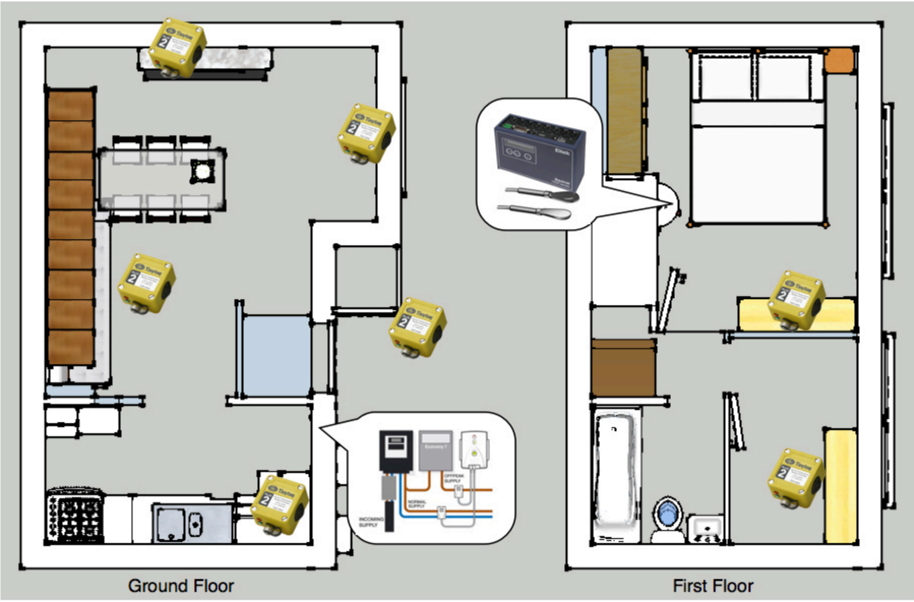


Figure 4.14: Sensor installation plan in pilot study 3.

4.4 Study dwelling 3

Study dwelling 3 is actually an office room shared by three people. The purpose of this selection is to test the windows and door operation behaviour and its effects on indoor air temperature and humidity. It suits the purpose due to it window type and both windows and door are being frequently used by three users. This office has relatively simpler occupancy and few variables in such a closed space: two windows that can only be tilted open and one door (figure 4.15). The window facade is southeast facing but the mostly shaded in the afternoon due to a higher wall southwest shown in figure 4.15, two desks are placed next to the windows.

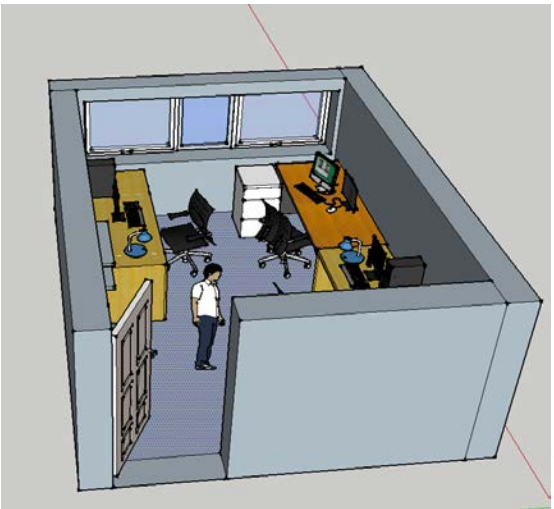


Figure 4.15: Room plan prospective view (left) and top view (right)

The entrance to this office is connected with a mini corridor with fire door and emergency stairwell. This means the only good ventilation source is through opening the windows. The orientation of this office also causes too much glare on one desk's computer screen and closing blinds will block the window from fully open. In a sunny summer afternoon, the office's blinds has to be closed but two windows are only tilt open with limited access to fresh cool air. Consequently, the feeling of insufficient ventilation and restricted window opening make office users feels worse regarding the overheating.

Propping door open is the usually the quickest solution but it also brings noise from the corridor and adjacent offices such as telephoning and walking on the stairs. Two windows and one door have been monitored during this experimental study as shown in figure 4.16. The purpose is to test the windows/door monitoring and method in field and conduct analysis between window/door operation and indoor thermal comfort. Voluntary comfort diaries have been provided to all the three office users in order to keep additional record of their thermal comfort perception.

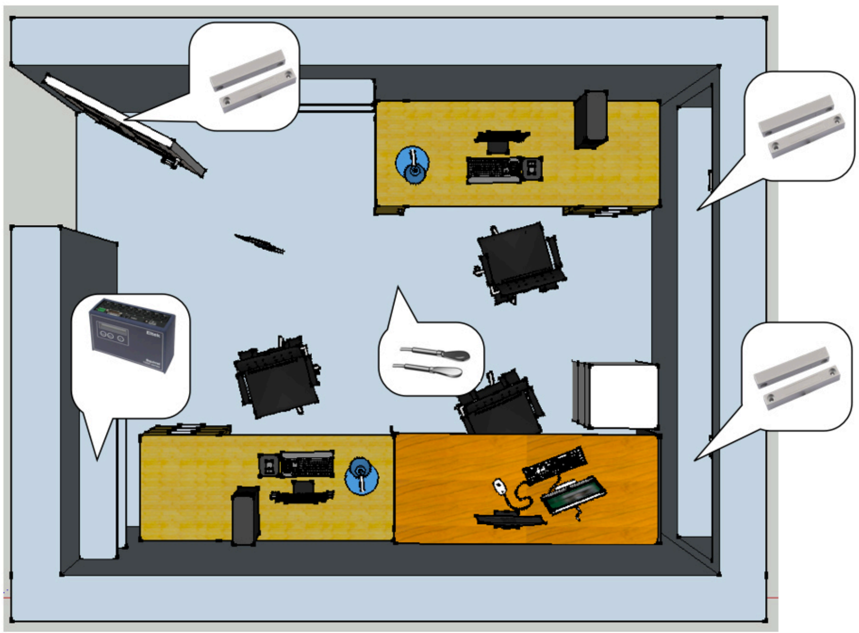


Figure 4.16: Sensor allocation in selecting office

Three pairs of contact switches have been installed on windows and door in this office. A temperature sensor is place in the centre of the ceiling. All the records are feeding into Eltek data logger located on the shelf.

4.5 Study dwelling 4 & 5

Dwelling 4 and 5 have been selected for field study primarily they make an unique case:

- Exactly the same occupants
- Structurally identical form and location but dwelling 5 is completed renovated in every aspect.
- It was possible to install a gas sub-meter before the new boiler being fitted.
- It was possible to reserve access to electrical sub-circuits before consumer unit being installed.
- Gas in dwelling 4 is identical to one of the gas meter that has been tested in lab with satisfactory results of optical reader.

Study dwelling 4 & 5 are occupied by the same family who moved from dwelling 4 to newly refurbished dwelling 5 with much higher energy efficiency standard on the same street. Both houses are terraced houses and have been built for over 50 years. The property is built on a hillside in Western face of valley with North-West/South-East road orientation. It consists of South-West lounge and a bath room at ground floor, three bedrooms at 1st floor and a North-East facing kitchen at lower ground level as shown in figure 4.17 and 3D model in figure 4.17.

Figure 4.17 : location of dwelling 4 (A) and 5 (B), source from: Googlemap.

4.5.1 Form and plan

Dwelling 4 comprise principally a living room, a bathroom, three bedrooms (small, medium and large) and a kitchen spacious enough for dining. Living room and bathroom are located on the ground floor. Kitchen is located at lower floor. The first floor contains three bedrooms with various size. They have very similar structure and the exterior appearance and the major difference is that dwelling 4 has its kitchen at lower ground floor and dwelling 5 has it at ground floor as shown in the 3D models in figure 4.18.

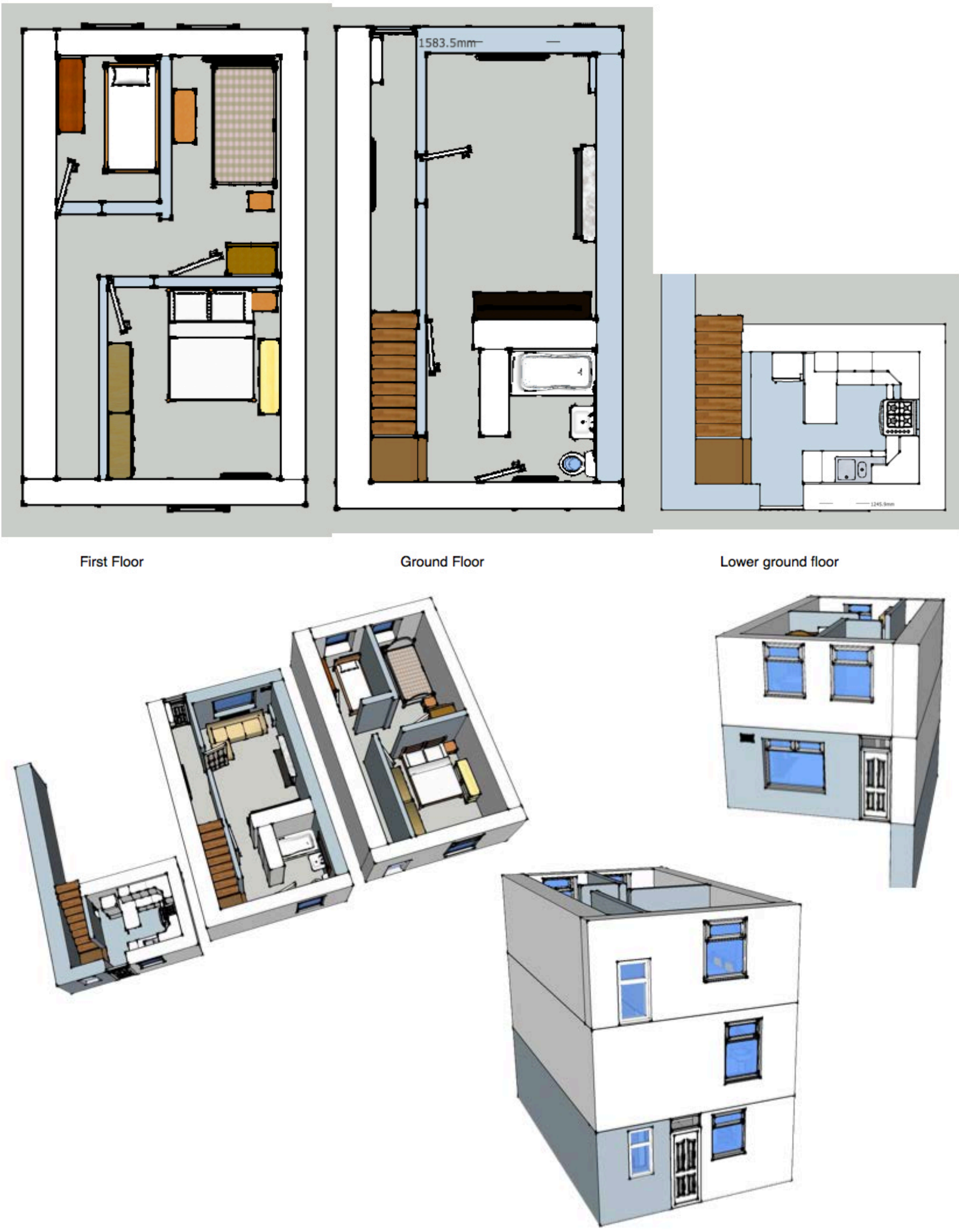


Figure 4.18: Room plans of dwelling 4, first, ground and lower ground floor.

Figure 4.19: Views from front entrance and rear kitchen door, dwelling 4

Dwelling 5 is one house of Eco Terrace project completed by Cynon Taf Housing Group in 2010-2011. It is use to be a single-skin solid stone-walled Victorian house. It is now updated into low carbon home that meets 'EcoHomes' excellent standard (figure 4.20). The property is located on Western face of valley with North West / South East Road Orientation.

Dwelling 5 consists of North-East lounge and three bedrooms, a bath room a South-West facing kitchen. Comparing to dwelling 4, it has following features:

- EcoHomes excellent standard.
- Front of residence faces: North East
- Triple glazing, 'A' rated doors and internal insulation
- Roof mounted solar thermal collectors linked to A-rated condensing boilers
- Water butts, low capacity baths and water flow regulators
- Skylights in order to Introduce daylight to internal spaces

Figure 4.20: Fabric upgrade and skylight in the kitchen of Dwelling 5

Besides the improvement above, the major difference happened to the occupants is probably the orientation. The lounge window is now facing north-east which is the opposite of the place they used to live in.

Figure 4.21: Dwelling 5, triple glazing windows and solar hot water collectors on the roof

4.5.2 Space heating

The boiler in dwelling 4 in sealed behind the fireplace and not easily accessible. The main gas meter is located in the cabinet next to the boiler without enough space for an additional sub gas meter. Therefore, only the total gas consumption was monitored by optical sensor that was attached on the main gas meter, as illustrated in figure 4.22. There are three gas consumption sources: back boiler, gas fire place, gas cooker (with oven and grill built-in), among them, the fireplace is not functional.

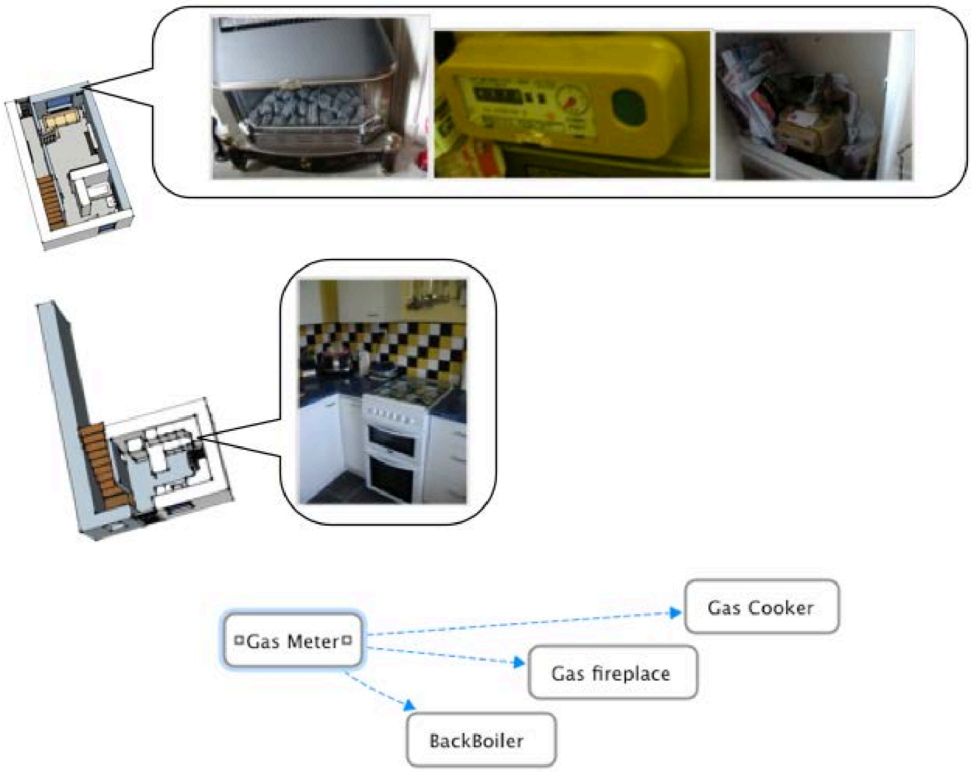
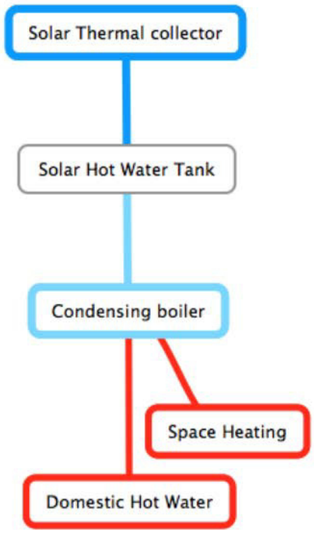


Figure 4.22: Space heating and gas distribution in dwelling 4

Dwelling 5 has new boiler and hot water system fitted. Space heating is provided by a Worcester 24Ri condensing boiler with 8-24kW of central heating output. There is also a 210 litres hot water cylinder working together with the solar collector on the roof (Figure 4.21).



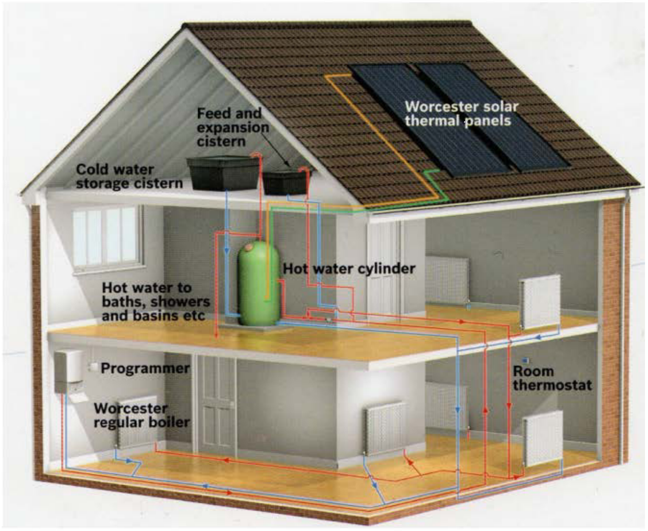


Figure 4.23: Space heating and gas distribution in dwelling 5

In dwelling 5, a sub gas meter has been installed to the boiler gas inlet pipe to record its gas usage. Additionally, a Tinytag temperature logger has been attached to the side of the boiler. Having both gas usage and surface of condensing boiler monitored, it shall provide some side to side comparison of the work status of boiler since a sub gas meter takes much more effort to install than attaching a sensor onto boiler enclosure.

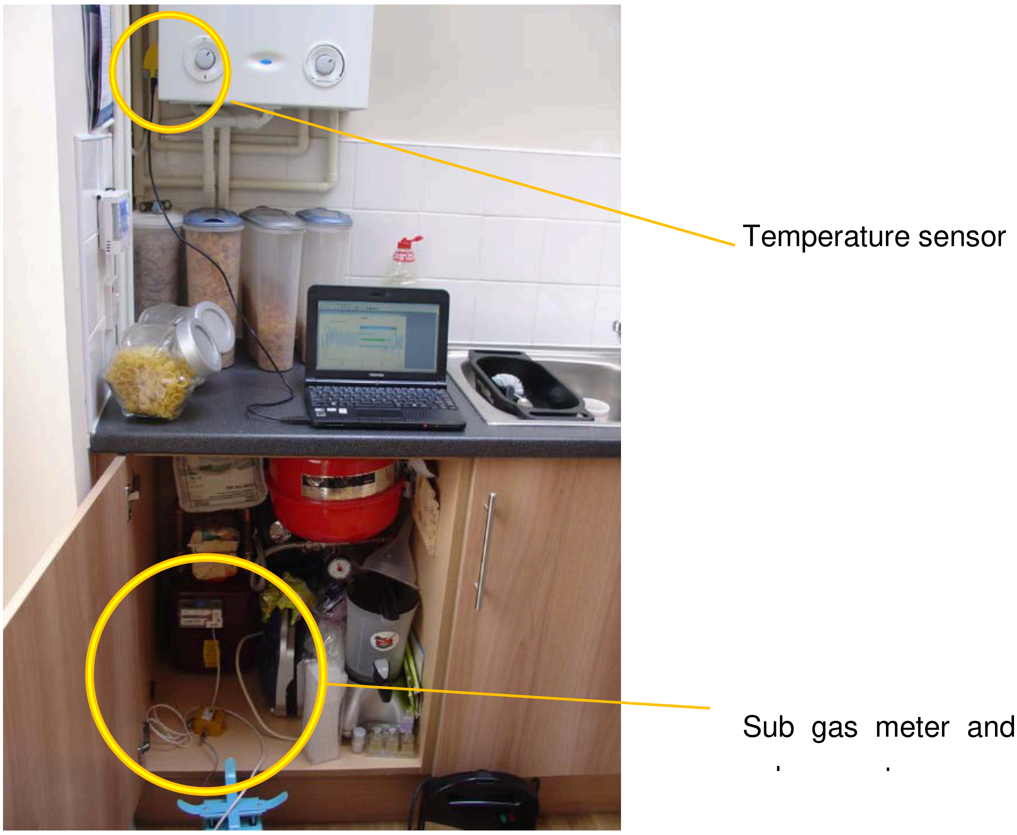


Figure 4.24: gas sub-meter installation with boiler in dwelling 5

In both dwelling 4 and 5, radiator in each room has its own Tinytag plus 2 temperature logger for the individual radiator control behaviour. The thermostat is newly fit digital type. It was not possible to install an electric resistance logger that can monitor its setting point temperature.

Figure 4.24: Individual radiators and temperature sensor in dwelling 4 & 5

4.5.3 Monitoring window side temperature

Contact switches has been installed to the windows of main bedroom and living room. In both dwellings, their windows are tilt-open only. Each window has an extra temperature sensor installed from inside next to the top of window (Figure 4.25)

Figure 4.25: Additional temperature next to tilt-open windows

4.5.5 Electricity

Current transducers have been installed on the main electricity and meter reading were taken for secondary set of usage data in order to correct the potential error that current transducer built up with.

There are four circuits in dwelling 4, as illustrated in figure 4.26, respectively control lightings, lower floor sockets, ground floor socket and first floor sockets.

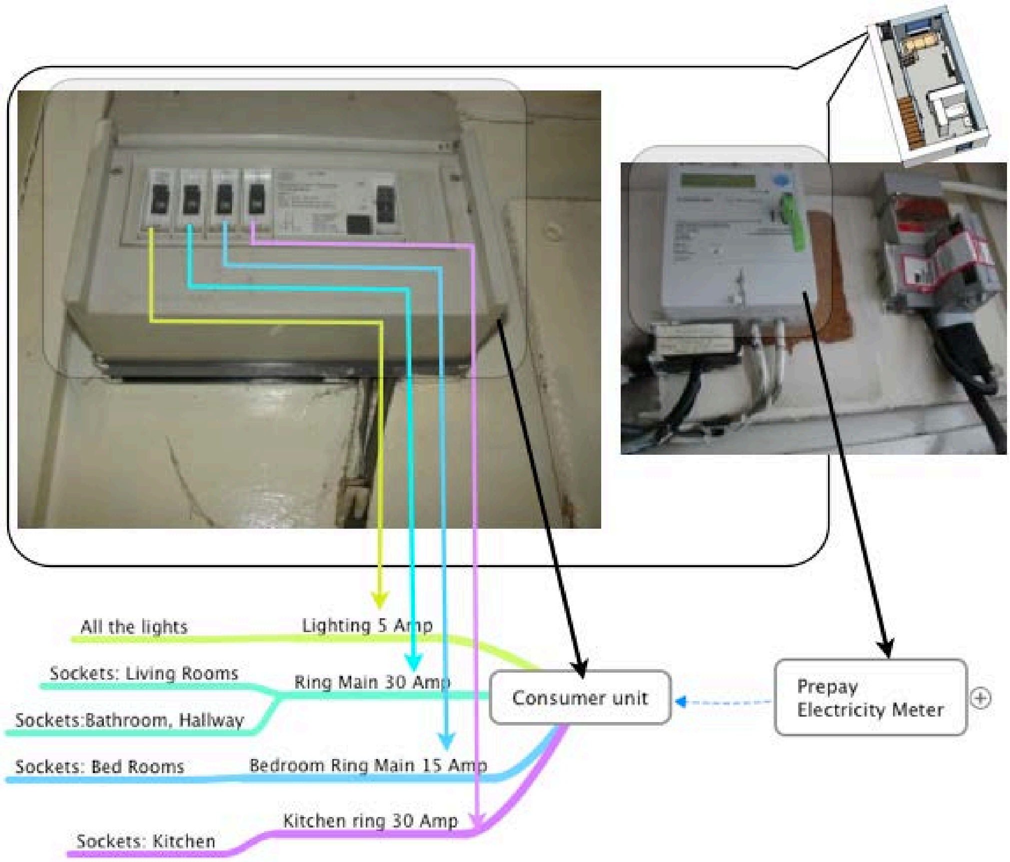


Figure 4.26 Electricity meter and sub circuit distribution in dwelling 4

In both dwellings, the issue with separating these four circuits from each other was consumer unit which has too little space to fit electricity monitoring sensors to all the sub-circuits and it may jeopardise the function of prepay meter. Due to this space and restriction of prepay electricity meter, current transducer was only installed to the main circuit.

Figure 4.27: Owl current transducer on prepay electricity in dwelling 4 (left) and dwelling 5 (right)

High power-rated appliances has socket type sensor installed, e.g. kitchen appliances, washing machine and tumble dryer. Electrical appliance survey has been conducted in both households to gain a list of alliance power rate and locations. Electrical appliance that generates heats also has it own temperature logger placed nearby, as shown in figure 4.28 below, a hot air fryer and kettle with Tinytag sensors placed adjacently.


Figure 4.28: Additional temperature sensor placed nearby high power rated appliances

4.5.6 Occupant

Occupant opt-out of self-kept diary, presence sensor and activity trackers in dwelling 4 and 5. The only method of occupant behaviour related data was face to face interview at beginning and end of each monitoring period. This interview contains question of activity level, thermal satisfaction, clothing preferences at home and usual occupancy habit.

4.5.7 Indoor environment.

Room temperature and relative humidity are monitored as illustrated in figure 4.29. Wireless temperature and humidity measuring system have been placed at designated position. Each room has two sensors, in the bedroom, one sensor was placed at the centre of the room but underneath the bed, and the other one was installed at higher but less intrusive point such like top of wardrobe. In reality, it is difficult to install sensor at the most appropriate spot of a room because it can cause disturbance to occupant’s daily life and shorten the permission of monitoring study.

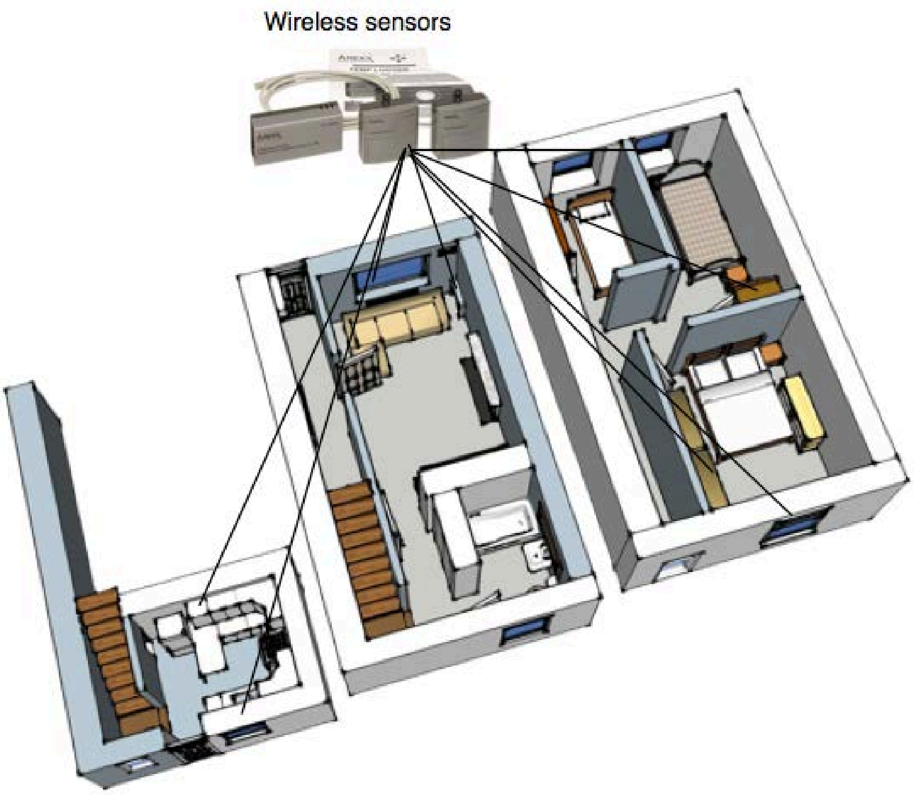


Figure 4.29: Environmental monitoring sensor locations in dwelling 4

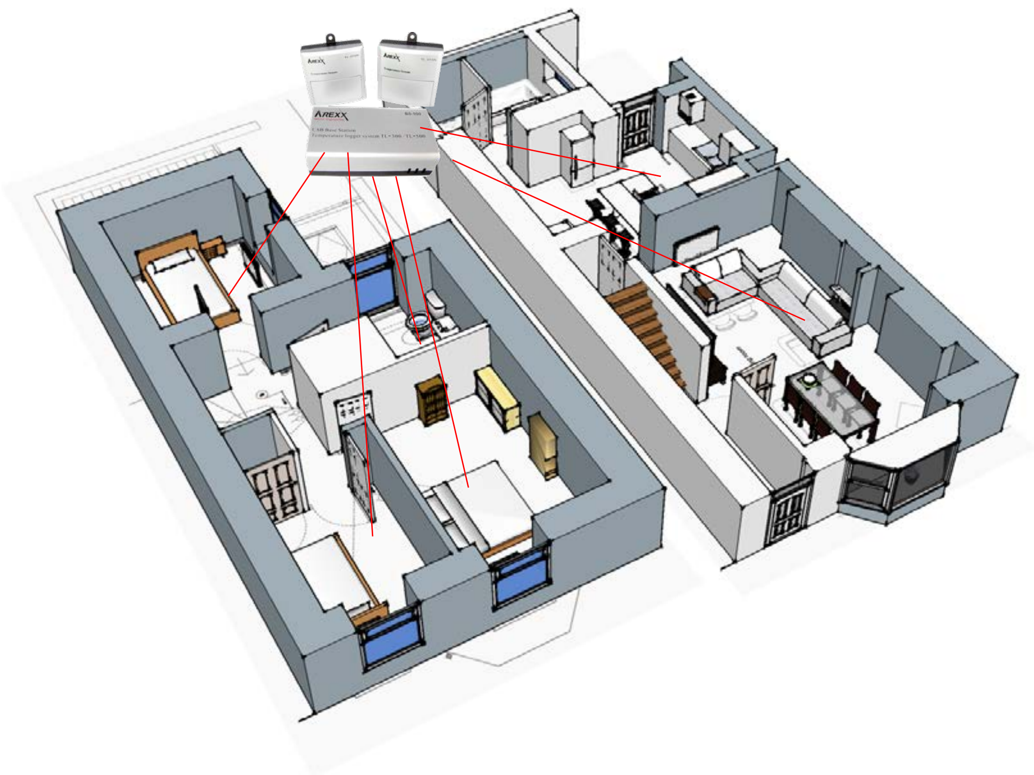


Figure 4.30: Environmental monitoring sensor locations in dwelling 5

4.6 Study dwelling 6 and dwelling 7

Dwelling 6 and 7 were monitored simultaneously with identical sets of sensor, therefore they are grouped and described together in this section.

They were selected due to identical building fabric, form and plan but different occupants with different life styles routines and preference of indoor environment during winter. They are ideal for investigation of following methods and instrumentation:

- Off-gas, means every energy related parameter can be monitored by non-intrusive method (current transducers and appliance socket meter).
- Both are bungalows easy access to install windows and door sensors without risking climbing with height.
- Occupants are very keen to take part in field study, as a result of that, agreement of keep self-reported diary, permissions of install all type of sensors include PIR presence sensor, have been granted by both families.

4.6.1 Plan and form

The second case study consists two newly built homes at the southmost of Brecon Beacon national park. Dwelling 6 and 7 are located next each other. As shown in figure 4.31, they are almost the mirrored version of each other, with identical building system, fabric with slight difference in total area size. Dwelling 6 has a gross floor area of 120 m^2 and dwelling 7 is 126m^2 but the number of rooms remains the same. The occupant composition is similar, both households have two adults and three children whose age range is the major difference. Dwelling 6 has two adult children and one teenage, where dwelling 7 has three younger kids and the oldest is only 10 years old.

These two bungalows are specially built for disability needs. In dwelling 6, both parents have different level of accessibility problem but not the children. Dwelling 7 has the opposite situation, parents are completely free from disability but two children are not. The typical occupancy is different due the employment status varies substantially between two households.

Figure 4.31: Dwelling 6(Right) and 7 (left)

Both dwellings were completed at the end of 2009 as part of a Ecohome scheme and there were built with standard level 4 of Code for Sustainable Homes (CSH) in December 2009. The type is a bungalow with the main entrance on the west side and the north facade overlooking the rear garden. It consists of a north facing kitchen/diner and lounge, two east facing bed rooms, a south facing master bedroom with en-suite, a store near the main entrance, and a west facing bathroom. It features as followings:

- Code level 4 for Sustainable Home
- Front of residence faces: South
- Air Source Heat Pump produces space heating and domestic hot water with top-up immersion.
- Mechanical Heat Recovery Ventilation

- Rainwater collection system for toilet flashing with 3000 litres underground storage tank.

Dwelling 6 and 7 are not connected to main natural gas. Everything appliance is driven by electricity, including the mechanical ventilation and heat recovery system (MVHR) installed in the loft.

4.6.2 Space heating and domestic hot water

Occupants in these two houses used to live in stone-walled terrace houses heated by with gas boiler. The new bungalow is significantly different in terms of building fabric, space heating and domestic hot water system. One of the most fundamental change is probably the Air Source Heat Pump (ASHP), which is the electrical alternative of gas boiler.

Air Source Heat Pump provides space heating and domestic hot water system as illustrated in figure 4.32. Tenants control their heating by setting their target water temperature and timed schedule on the remote controller located in storage room. Thermostat with built in temperature sensor is located in the hallway. There is also a 300 litres hot water cylinder equipped with immersion heater for urgent hot water demand. Immersion heater will boil the hot water from heat pump and top it up to standard domestic required temperature. Tenants were advised by the manufacturer that ideally the heat pump target temperature should be 40 ˚C and immersion heater will do the rest 20 ˚C to make the water reaches up to 60 ˚C.

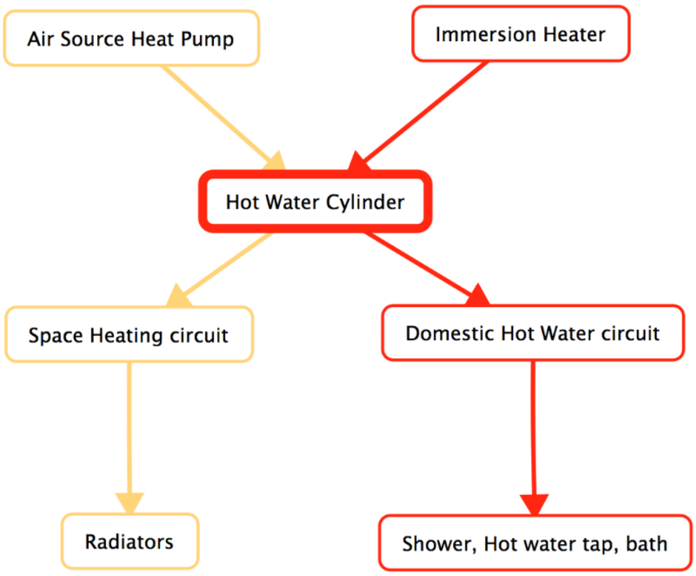


Figure 4.32: Air source heat pump system

ASHP and immersion are both in charge of supplying hot water and powered by electricity, see electricity section in following section for details regarding their energy monitoring setup. The electricity usage profile represents the total running energy consumed for both space heating and domestic hot water, therefore, additional sensors have been installed in order to be able to differ hot water event from space heating event.

Pipe surface temperature have been monitored by Arexx wireless sensor as shown in figure 4.33, it measures the temperature rise when ASHP is running. It was safe to attach as the ASHP only heat water to 40˚C, which is also the maximum temperature of all the radiator.

Figure 4.33: Surface temperature sensor on hot water outlet pipe

The control panel of ASHP has it own camera installed ash show in figure 4.34. This camera is modified to take infrared image due to the ASHP is located in a dark storage room and mostly remains dark. An infrared LED is also installed to provide constant light which is only visible by this special camera but not by occupants for minimised disturbance. The control panel shows the individual function that the whole system runs and displays different icons (figure 4.35).

Figure 4.34, infrared camera points at ASHP and immersion heater controller panel

Figure 4.35, Icons for not running, immersion heater running and ASHP running from left to right

The camera is set to take picture only when the pixel of the image changes. Such setting is to reduce the amount the picture it takes and only does when the icon changes.

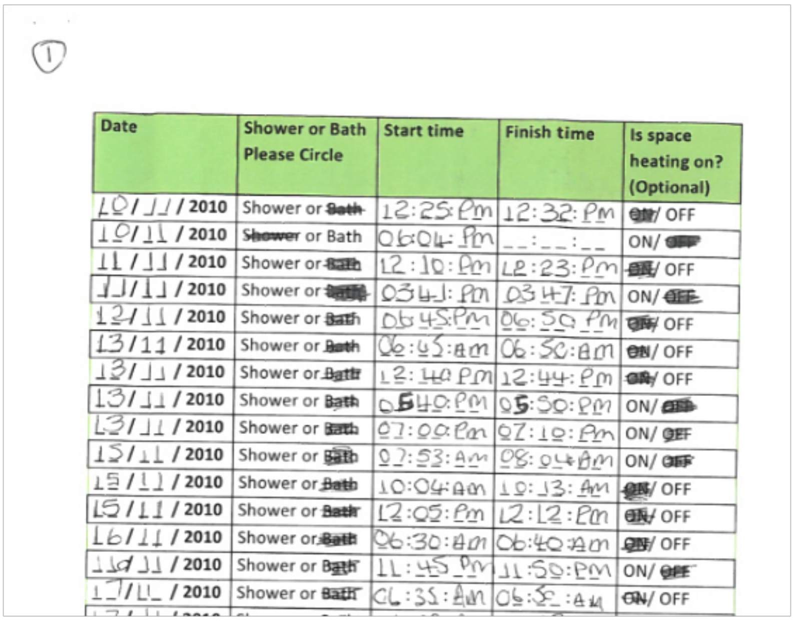
The key of ASHP is the outdoor unit which is usually installed outside of house (figure 4.36). It imports ambient air into by a fan unit and exports colder air after heat exchange/extraction. Considering this characteristic, a temperature logger has been installed to the outdoor unit. Having this sensor installed, it captures the sudden temperature changes that theoretically can only be caused by the outdoor unit extracting movement.

Figure 4.36: temperature on ASHP outdoor unit

The setting temperature of thermostat has been monitored by recording its electrical resistance value that corresponding to the change of the position of the control dial. The purpose is to obtain when and how much occupant adjust thermostat which is controls the space heating output (figure 4.37).

Figure 4.37: Thermostat in the hallway and electrical resistance logger

Occupants agreed to keep a diary of space heating and hot water demand, however, they preferred to only record shower and bathing. A simple of this diary is shown in figure 4.38. The diary contains date, either taking shower or bath, start and finish time, and whether the space heating is on. Occupants claimed that the status of space heating can be judged by touching the radiator in the bath room, where the diary has been kept at.



Date	Shower or Bath Please Circle	Start time	Finish time	Is space heating on? (Optional)
10/11/2010	Shower or ~~Bath~~	12:25:Pm	12:32:PM	~~ON~~/ OFF
10/11/2010	~~Shower~~ or Bath	06:04:Pm	__:__:__	ON/ ~~OFF~~
11/11/2010	Shower or ~~Bath~~	12:10:Pm	12:23:Pm	~~ON~~/ OFF
11/11/2010	Shower or ~~Bath~~	0341:Pm	0347:Pm	ON/ ~~OFF~~
12/11/2010	Shower or ~~Bath~~	0645:Pm	06:50 Pm	~~ON~~/ OFF
13/11/2010	Shower or ~~Bath~~	06:45:am	06:50:am	~~ON~~/ OFF
13/11/2010	Shower or ~~Bath~~	12:40 Pm	12:44:Pm	~~ON~~/ OFF
13/11/2010	Shower or ~~Bath~~	0540:PM	05:50:PM	ON/ ~~OFF~~
13/11/2010	Shower or ~~Bath~~	07:00:Pm	07:10:Pm	ON/ ~~OFF~~
15/11/2010	Shower or ~~Bath~~	07:53:Am	08:04Am	ON/ ~~OFF~~
15/11/2010	Shower or ~~Bath~~	10:04:Am	10:13:Am	~~ON~~/ OFF
15/11/2010	Shower or ~~Bath~~	12:05:Pm	12:12:Pm	~~ON~~/ OFF
16/11/2010	Shower or ~~Bath~~	06:30:Am	06:40:Am	~~ON~~/ OFF
16/11/2010	Shower or ~~Bath~~	11:45 Pm	11:50:PM	ON/ ~~OFF~~
17/11/2010	Shower or ~~Bath~~	06:35:Am	06:5_:Am	~~ON~~/ OFF

Figure 4.38: Shower or bath diary kept and filled by participants

Additional temperature and humidity sensors have been attached next to the shower space to capture the changes of these two variables that can only be trigger by hot water related behaviour in the bathroom (figure 4.39)

Figure 4.39: temperature and humidity logger next to shower in the bathroom

4.6.3 Windows and doors

Contact switches have been installed to front door, back door connects kitchen and garden, bath room window and main bedroom window.

4.6.4 Electrical appliance and lighting

It was convenient to disaggregate end uses by their functions in these two electricity only properties. Sub circuits have been monitored individually as shown in figure 4.40. As a mandatory requirement of level 4 CSH house, dwelling 6 and 7 have been installed with mechanical ventilation and heat recovery system (MVHR) installed in the loft space. It was not possible to separate it from all the other

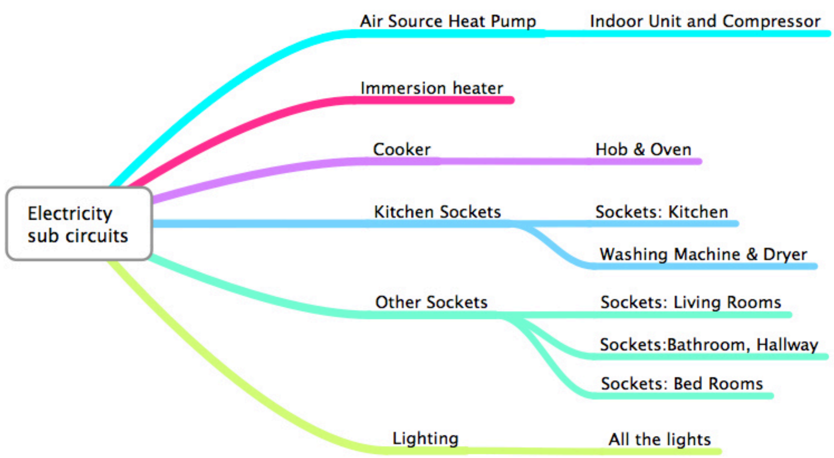


Figure 4.40 of sub-circuits monitoring and consumer unit

The first tier of sub-circuit are accessible within the consumer unit, namely, Air Source Heat Pump, immersion water heater, cooker, sockets in kitchen, sockets in all other rooms and all the lighting sockets. Fire alarm circuit is excluded.

Figure 4.41: Consumer unit and sub-circuit sensors

Air source heat pump circuit: the consumption represents the amount of electricity. ASHP system is supposed to be more energy efficient but works slower than traditional gas boiler. To overcome the speed limit, immersion water heater is combined with ASHP at the moment of sudden and high volume of hot water demands either at hot water or space heating pipeline, for example, series of showers, bath, high temperature washing machine run and high space heating setup.

In the kitchen, there are two sub-circuits: electric cooker and kitchen sockets. Electric cooker includes hob and oven where cooking is conducted. Kitchen sockets means all the sockets in the kitchen, namely, washing machine, tumble dryer and other sockets with small but high power rate appliances such as kettle, deep fryer and so on.

High power rated appliances have been installed with socket electricity sensors and the total electricity of individual sub-circuit have been monitored by clamp-on current transducer.

Lighting circuit represents all the light bulbs consumption. Sockets of living room, three bedrooms and two bathrooms are connected the others socket circuit.

There is a 3000 litres underground water tank and pump buried in the garden to collect rainwater for toilet flashing purpose. When there is not enough rain water collection, the water tank will top itself up from the main water supply. This is measures by a dedicated socket electricity sensor for the pump.

4.6.5 Occupant monitoring

Occupants agreed fill the diary continuously for two weeks. This diary contains, Thermal satisfaction and clothing. There is an optional question that occupant may freely add comments of what did they do on occasions when they felt the internal space is not sufficiently heated to their required warmth.

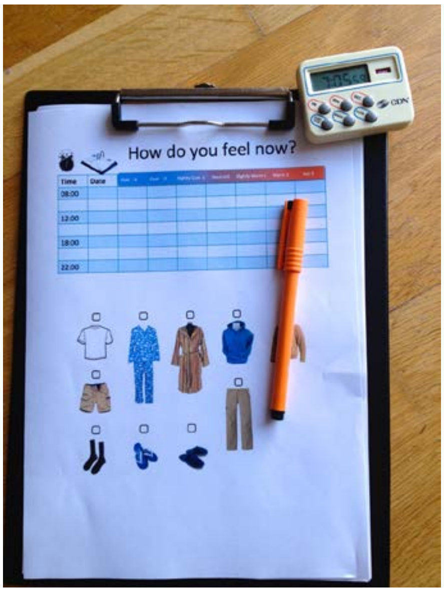


Figure 4.42: Behaviour diary and timer clock

Diary needs to be filled at four fixed time, 8am, 12am, 6pm and 10pm every day. Occupants were encouraged to tick their thermal sensations at these moments and there are also blank rows in between when they feel like to add more information such as whether they returned from outdoor in the past 30 minutes, what activity were they doing, whether they had a hot or cold drink earlier. These optional questions can further help to collect personal factor samples. The thermal sensation scale is identical to PMV values. The purpose of keeping comfort diary is to compare the thermal sensation (Ts) with PMV results that are calculated from indoor environmental monitoring data in order to see if their relationship. This diary also has a digital alarm clock attached on the board in order to remind occupant to fill, but of course they are free to turn it off. Clothing diary is provided to the occupants to mark down their clothing level at the moment when they tick the thermal sensation scale.

Participants also agreed to wear activity meters onto wrist. The activity meter measures the whole body's acceleration, not just the wrist and it convert the activity profile format and then transmitted to handhold terminal.

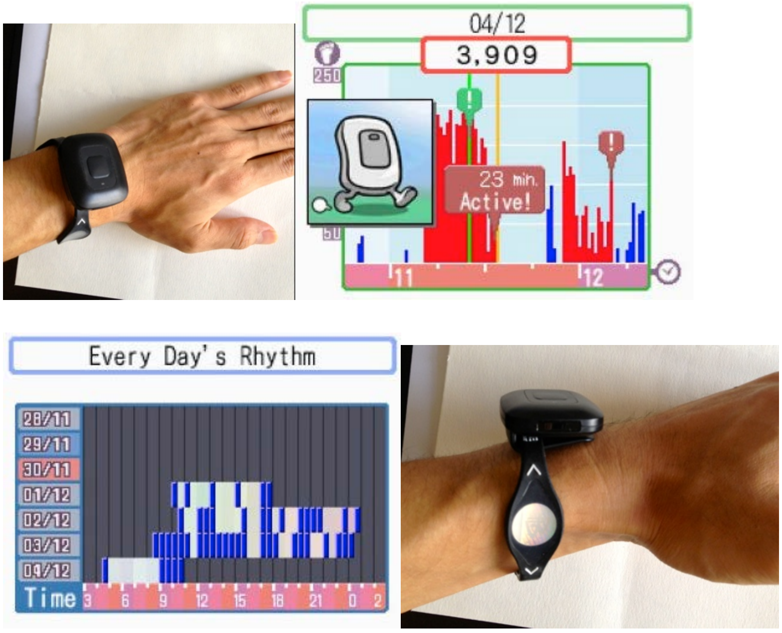


Figure 4.43 wearable activity meter

4.6.6 Indoor and outdoor environment

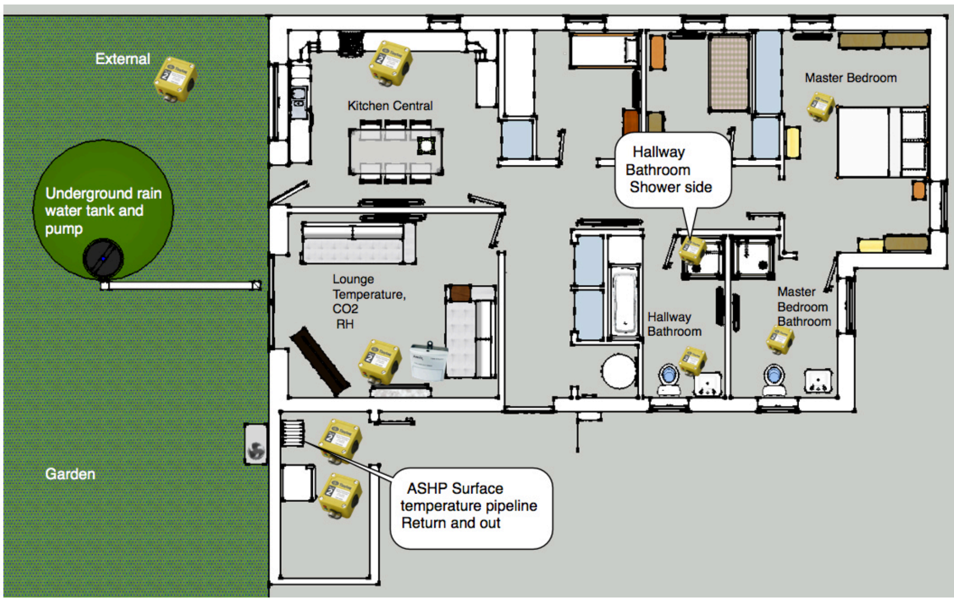


Figure 4.44: sensor settings dwelling 6 and 7

As shown in figure 4.44 a number of wireless temperature and humidity sensor have been installed in kitchen living room, bathrooms, hallway and main bedroom. Two wireless CO_2 sensor were placed in the living room, initially at different locations, on at ceiling and the other one at height of 1.2 meters. However, the second week occupants moved both sensors to the ground level next to the decorative fireplace. The effect of CO2 concentration level at difference height will be compared. The CO_2 density could indicate the CO2 concentration level of the room as well as occupant behavioural responses such as rapid CO_2 drop from ventilation.

Figure 4.45: Wireless CO_2 sensor

Wireless presence sensors were agreed to be placed in the kitchen and living room of dwelling 6 only, for a period of 14 days.

Figure 4.46: Wireless presence sensor in dwelling 6

4.7 Study dwelling 8

4.7.1 Plan and form

Dwelling 8 is in a new award-winning development (figure 4.47), delivered by local Housing association to provide modern, eco-friendly home. It is also a part of Welsh Government pilot scheme of how new homes can meet higher levels of Code for Sustainable Homes. As one of the completed home, dwelling is a four-bedrooms house which has reached Code Level 4 and been offered with eco-measures such as solar hot water panel and Air Source Heat Pump. It is located only 500 meters north from dwelling 6 and 7.

Figure 4.47: front and rear view of dwelling 8

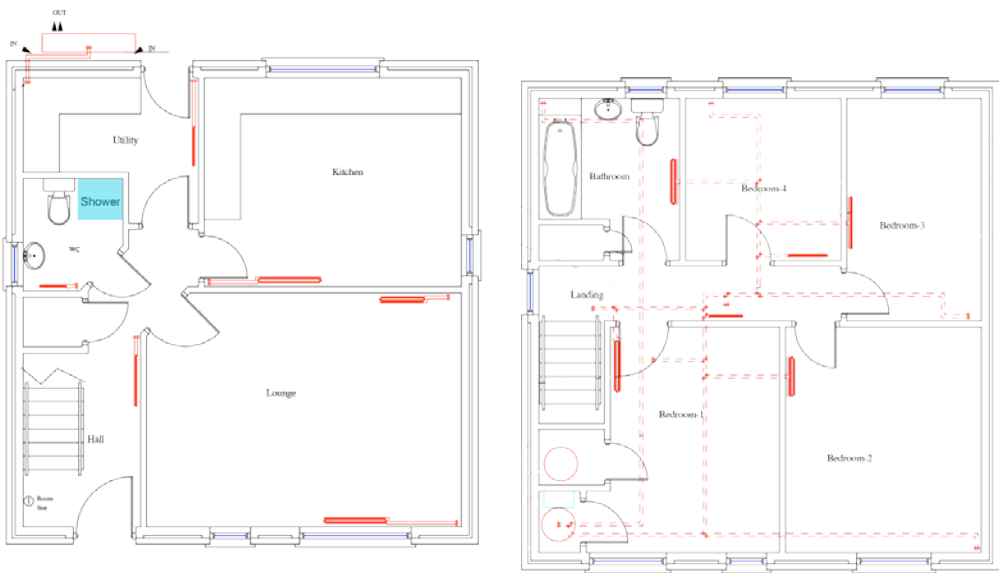


Figure 4.48: Room plans of dwelling 8, Ground Floor (left), First Floor (right)

The space heating and domestic hot water system are fairly similar to dwelling 6 and 7. One the major difference is the heating system, whereas dwelling 8 has a buffer tank and solar thermal water heater on the roof to further assist the ASHP (Figure 4.49). The solar water heater works with a300 litres hot water cylinder equipped with a 3kW immersion heater. It also has an additional 95 litres buffer tank to prevent the main hot water cylinder from working too often. ASHP is supposed to work most time but when it could satisfy a big demand and the immersion heater will begin to work.

Besides the bath at the first floor, there is an electric power shower at ground floor. Tenant mentioned that she doesn't use the electric shower very much as it has higher power rate and electricity consumption associated but most of the time when all the kids want to take a shower they often use electric shower at the ground floor when the first floor bathroom is in
use.

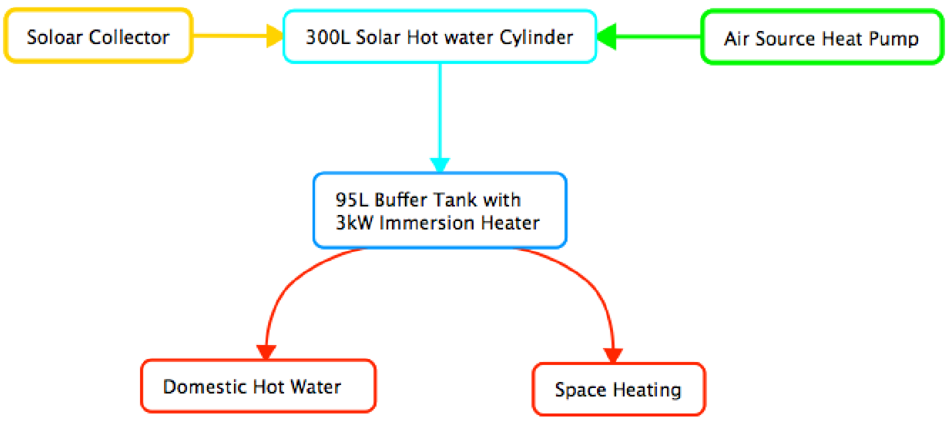


Figure 4.49: DHW and space heating system of dwelling 8

The gas is only used for cooker; everything else is powered by electricity. Cooking is a big demand in this household. There are two large fridges and one chest freezer which may indicate large amount of cooking activities.

4.7.2 Space heating, domestic hot water and electrical appliances

Beside gas cooker, everything in the dwelling 8 is driven by electricity. Due to availability of data logger, six circuits have been monitored as shown in figure 4.xx:

1. Air Source Heat Pump,
2. Immersion heater
3. Electric power shower
4. Sockets downstairs (washing machine, Tumble dryer)
5. Sockets upstairs
6. Lighting, Oven and kitchen sockets

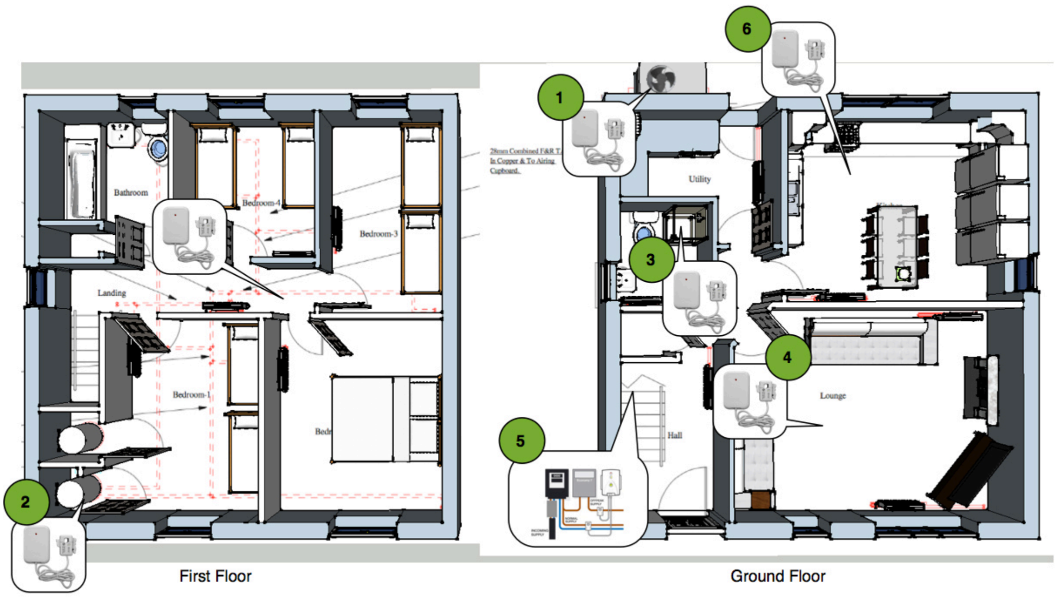


Figure 4.xx: Sub circuit monitoring set up for dwelling 8

Tenant uses pay as you go token to top up electricity credit when it runs low. They reported that when they were all out for holiday, the house consumed £39 worth of electricity in 9 days (during February 2012) without anyone in the house. The energy bill become even higher when tenants are in and this raised a complaint since the house is suppose to provide capability of saving energy.

The purpose of study of this household is the first consultancy work with regards of identify potential cause of high energy and further test clamp-on current transducers with house that equipped with ASHP and solar thermal water system.

No other monitoring instrumentation and method were agreed by occupants of dwelling 8. It has been monitored for relatively shorter for a period of 30 days during the winter. The occupancy is one adult with six children, range from 4 to 10 years old.

4.8 Summary

This chapter described the methods and instrumentations that have been selected and corresponding dwellings where they would be deployed for field investigation. Dwelling selection criteria are based on individual household's characteristics that fit as convenient as possible in order to suit for the installation of hardware. The purpose of field study is to

The investigation focus on how these frequently studied parameters can be measured in domestic environment and what factor may affect invasiveness, accuracy, cost and reliability. In term of measurement type, results can be sorted into physical measurement, social science survey and integration of both, respectively presented in the following chapters.

Chapter 5 Physical measurement results

5.1 Introduction

This chapter will present physical measurement results from studies of dwelling 1-8 by applying a range of instrumentation and method for variables as listed below:

- Space heating
- Domestic hot water
- Windows and doors operation
- Electrical appliance and lighting
- Indoor environment

The results are presented and grouped by type that they belong to and mainly focus on the investigation of method and instrumentation regarding their difference on the same parameter monitoring. A short discussion follows after every sections.

5.2 Space heating

5.2.1 Gas meter monitoring method

Dedicated sub gas meter with pulse out was only installed in dwelling 5, on its boiler gas inlet pipe. The other two gas meters are different types, reflective spot and dial type, have been applied with the optical sensor. Their accuracy is compared by the actual meter readings and monitored pulse count. Table 5.xx list the average daily meter readings and pulse count of 14-days period.

Table 5.1: daily average comparison of actual meter reading and pulse count

Instrumentation	**Meter reading (m3)**	**Pulse count (pulse)**	**Difference (%)**
Sub gas meter with pulse output	5.732	5755	0.40%
Reflective spot and optical sensor	6.892	6532	-5.22%
Dial meter with optical sensor	4.279	3983	-6.92%

Theoretically, every 0.001m3 on the gas meter reading should be recorded as 1 pulse. From the comparison, it appeals that pulse count of sub gas meter with pulse output is the most accurate, only 0.4% more than actual reading. Optical sensor reads fewer pulses, 5.22% on the reflective spot type and 6.92% on the dial meter type.

All these three method used the same type of pulse counter data logger which is set to write down the total number of pulse count every 5 minutes. At the begin of monitoring, each method had an initial side by side comparison between manual reading and pulse counts for a 30-minutes period. During this period, boiler was adjusted with different rate of heat output which generate varied gas consuming speed of testing purpose. The test results are illustrated in figure 5.2 to 5.4.

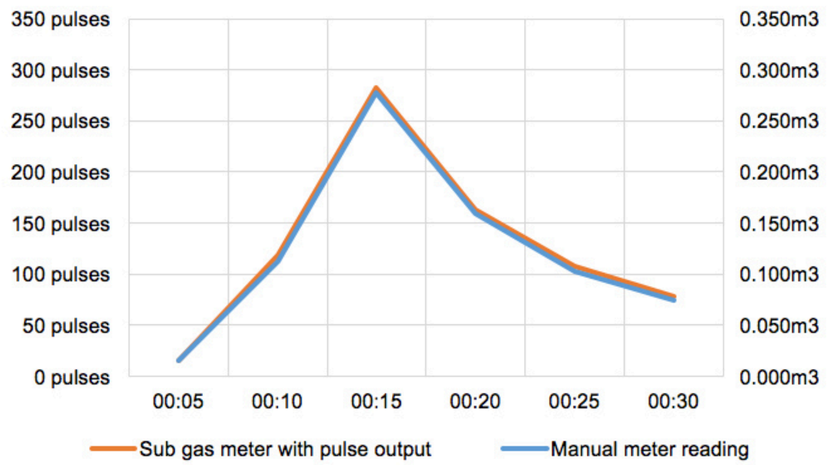


Figure 5.2: Manual reading and pulse count comparison - Sub gas meter with pulse output

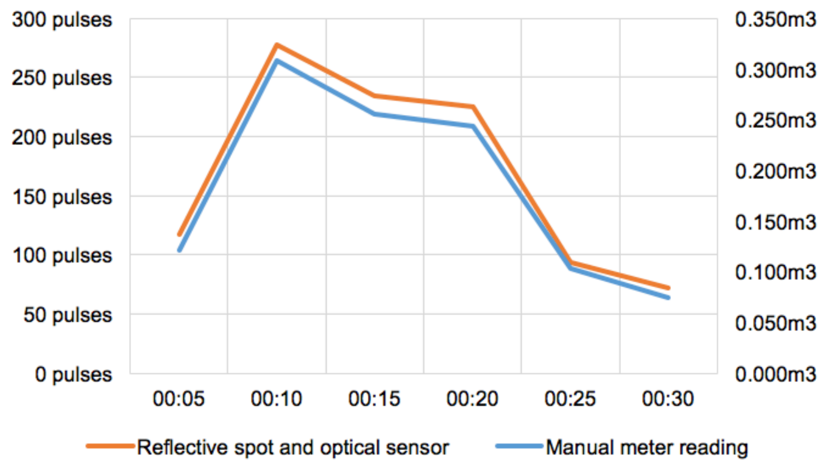


Figure 5.3: Manual reading and pulse count comparison – Optical sensor and reflective spot

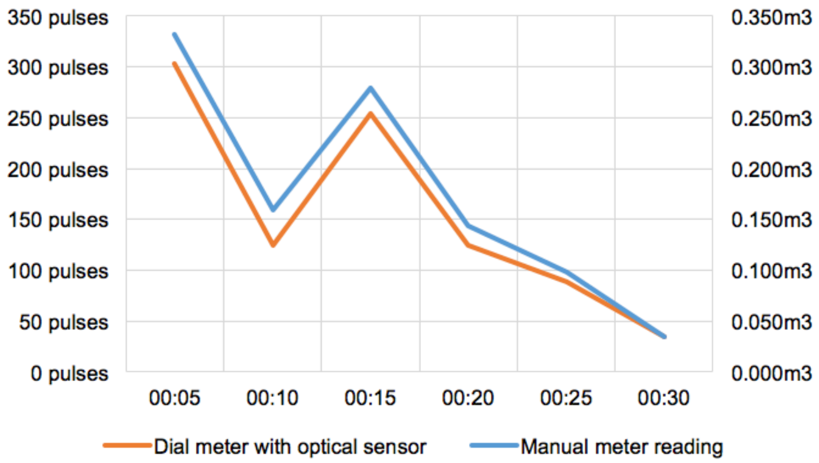


Figure 5.4: Manual reading and pulse count comparison – Optical sensor and dial meter

It can be seen that gas sub meter with built-in pulse output had very little difference between the pulse counter and manual readings during the test. However, the number of missed counts are visible with optical sensor method with the other two gas meter types. Such a gap becomes widened as the speed of gas consumption increases.

In principle, gas sub meter with built-in pulse output is contact switch based. Every round last digit wheel rotates, a magnet attached would triggers a reed switch which generates a pulse. This could only be achieved by its manufacturer who had access to the internal mechanism and able to build mini contact switch, any other tempt would bring up serious safety and legal issues. On the other hand, optical sensor based monitoring method is mainly relying on either the detecting beam being cut or receiving a reflected beam. Larger number of misreading seems to correlate to the higher speed of rotation. Even at close distance, gas meter with either reflective plate or with dial show reasonable amount error at peak gas consuming period. However, interestingly, the combination of optical sensor and reflective plate gave higher measured gas consumption whereas the combination of optical sensor and dial measured fewer gas consumption than actual meter itself measured.

5.2.2 Gas boiler surface temperature

The surface temperature of gas boiler in dwelling 5 has been monitored for 28 days. The 24-hour temperature profile of these 28days are plotted in figure 5.5 and 5.6 for clear glance of the pattern.

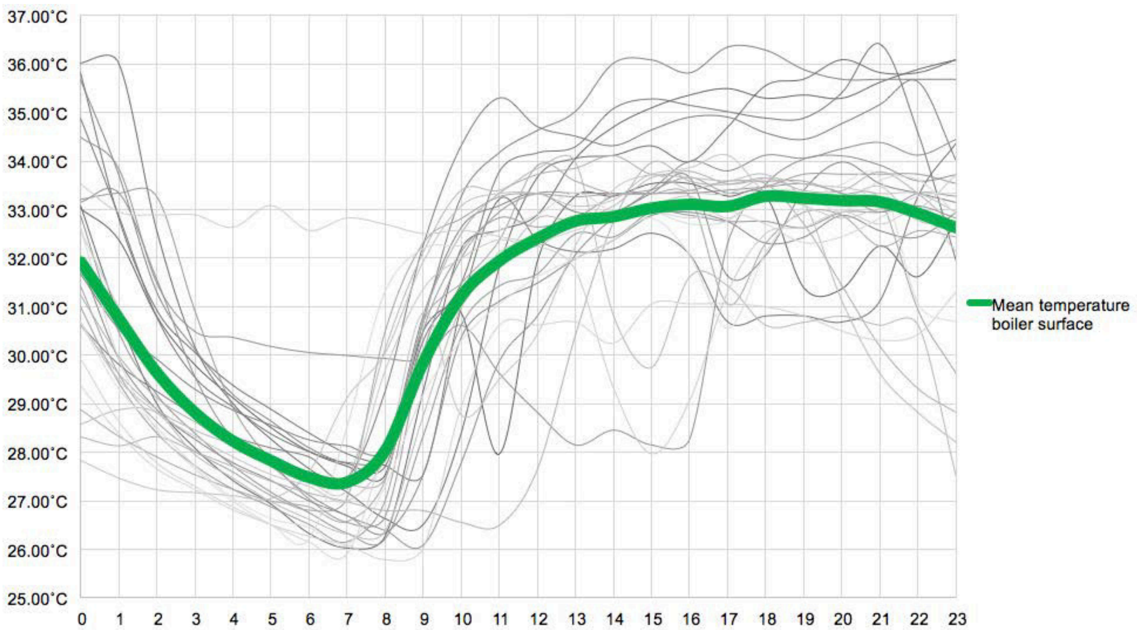


Figure 5.5: 24-hour boiler mean surface temperature profile, dwelling 5

A pattern was found in the majority where the surface of boiler slowly begins to cool down 5~10˚C from 10pm in evening to 7am next morning, then gradually rise 5-10˚C again in 4 hours and fluctuates mildly within much smaller range through the day until 10pm at night. This pattern matches the interview result of occupant's usual daily space heating habit: space heating is commonly turned off before bedtime and turned back on first thing in the morning (around 7:30) and left on at 26˚C for the rest of day except the time occupant goes out. There are exceptions, who surface temperature did not drop sharply overnight and potentially occupant chose to left space heating at lower output. The occupant of dwelling 5 is retired earlier, who stays at home most of the time and prefers warmer and constant indoor environment.

The 24-hour temperature of dwelling 5's living also matches well with the boiler surface temperature. As shown in figure 5.xx, majority of the living room temperature begins to decrease sharply and constantly from 10pm in evening to 7am in morning, then rises in 3-4 hours to a much warmer level.

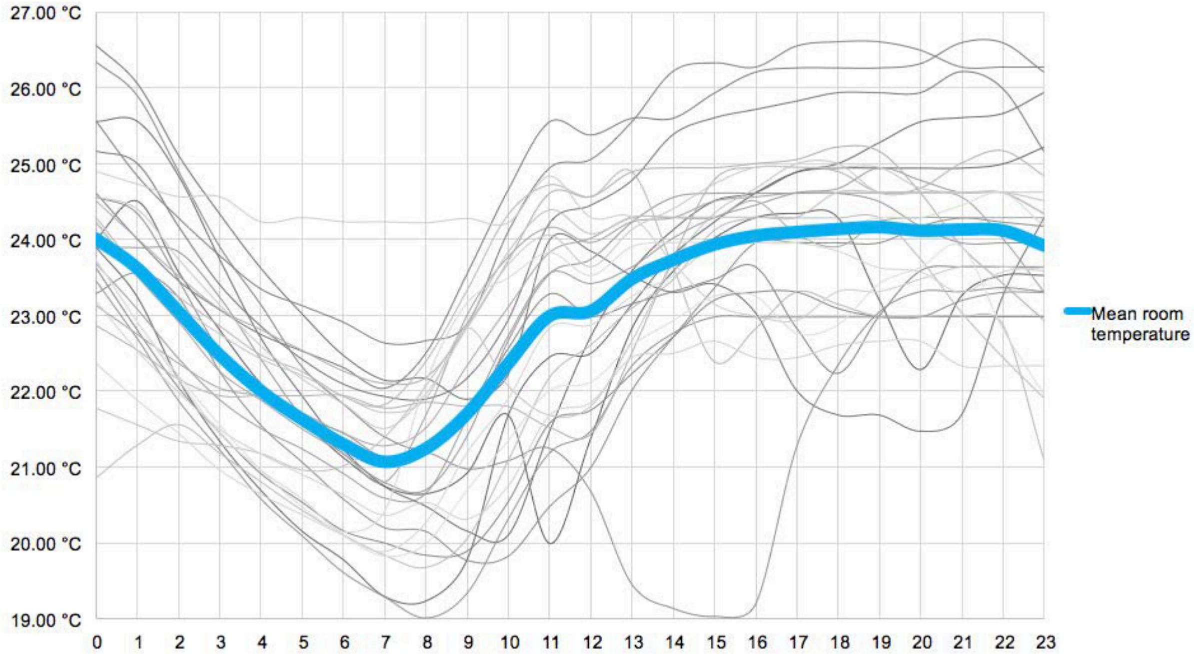


Figure 5.6: 24-hour mean room temperature profile, in dwelling 5

The pulse count of the sub gas meter installed for the boiler in dwelling 5 further proved this space heating pattern (figure 5.7). The number of pulse remains dormant from 10pm to 7am, only few counts per hour for its pilot flame. These two nights of space heating being left on can also be spotted easily from their boiler gas consumption activity during night time.

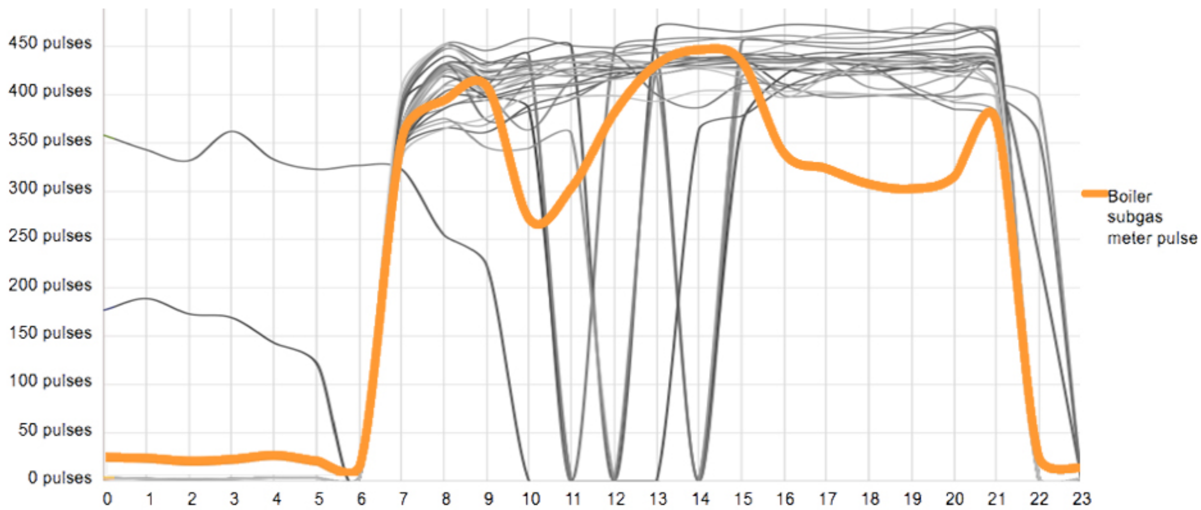


Figure 5.7: 24-hour boiler sub gas meter mean pulse count profile, dwelling 5

Surface temperature of boiler's enclosure functions reasonably well as a qualitative indicator of status boiler. Installation does not require sophisticate process nor specialist. Mean room temperature and boiler surface temperature share a good similarity which is useful to estimate the space heating status and the general indoor temperature. On other hand, mean gas consumption pulse count profile shows that boiler has two periods of less worked, whereas both room and boiler surface temperature remain more stable in daytime and evening. Occupant in dwelling 5 opted out for questionnaire and self reported dairy but agreed to an informal interview. According to interview, occupants have a preference of taking showers early morning and before bedtime. In addition, laundry and cook activities usually occurs after lunch hour, both may lead to sudden domestic hot water demand which may have caused boiler work harder to offer, therefore higher gas sub-meter pulses counted for condensing boiler.

5.2.3 ASHP- Outdoor unit

The outdoor unit of ASHP in dwelling 6 and 7 had sensors attached to the outdoor unit which according to the design, is an evaporator and contains fans. After ambient air being taken into the ASHP, the heat will be extracted inside and exhaust the cooled air through this outdoor unit. This characteristic of ASHP mechanism makes the surrounding of exhaust fan of outdoor unit cooler than ambient air. In other words, when ASHP is working, its outdoor unit should be slightly cooler than external air temperature. Also, some moisture of ambient air is condensed inside the ASHP compressor which theoretically should makes the exhausted air dryer.

Figure 5.8 shows mean air temperature and relatively humidity difference between external ambient air and outdoor unit over 24-hour circle for 18 days. The external air temperature is also added into the figure as a reference line.

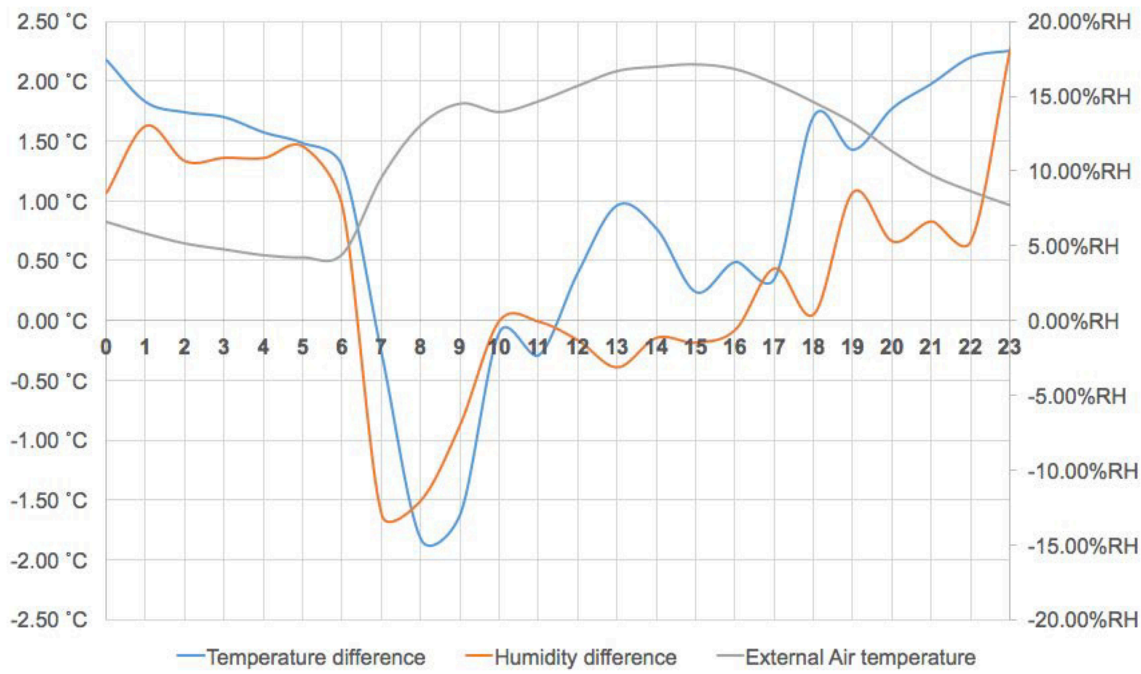


Figure 5.8: mean indoor, outdoor temperature, humidity 24 hour profile, dwelling 6

The positive difference value represents the measurement of ASHP outdoor unit is cooler and dryer than external environment, without disturbance from any other convection or radiant heat source. If it was the effect of the ASHP outdoor unit, the difference between these two sensors should be zero or close to.

The temperature difference is mostly positive during the daytime, evening and night. Greater difference remains overnight, from 11pm to 6am next morning at 1.5-2.2˚C and drops sharply to -1.8˚C at 8am and rises to positive from the middle of day. Humidity difference demonstrates the similar pattern, positive difference above 10 %RH occurs at night time but not so much from 10am to 7pm.

Theoretically, ASHP shall be able extract more heat from ambient air when it is warmer and lead to greater temperature difference between exhausted air and common external air. However, it behaves oppositely, the sharp drop of temperature occurs when external air temperature begins to rise from 6am onwards. One of possible explanation is that there is heating/hot water demand in the morning and such demand cannot be provided by ASHP. Interview results support this hypothesis, one the occupant usually get up at 6am in the morning due to early work commitment and he prefers to take showers and warmer house to being days with.

5.2.4 Thermostat dial monitoring

Since the rotating the dial of thermostat physically changes value of a 50 kΩ variable resistance inside, a set of spot measurements has been taken in order to estimate the internal resistance value that corresponding to the setting temperature positon of thermostat dial.

Table 5.2, Spot measurement of resistance of thermal and dial position

Thermostat setting temperature	Spot measured internal resistance- Dwelling 6	Spot measured internal resistance-Dwelling 7
10 °C	13.2 kΩ	12.9 kΩ
11 °C	12.9 kΩ	12.5 kΩ
12 °C	12.6 kΩ	12.3 kΩ
13 °C	12.3 kΩ	12.1 kΩ
14 °C	12.0 kΩ	11.7 kΩ
15 °C	11.7 kΩ	12.3 kΩ
16 °C	11.4 kΩ	11.3 kΩ
17 °C	11.1 kΩ	10.9 kΩ
18 °C	10.8 kΩ	12.3 kΩ
19 °C	10.5 kΩ	10.5 kΩ
20 °C	10.2 kΩ	10.1 kΩ
21 °C	9.9 kΩ	12.3 kΩ
22 °C	9.6 kΩ	9.7 kΩ
23 °C	9.3 kΩ	9.3 kΩ
24 °C	9.0 kΩ	12.3 kΩ
25 °C	8.7 kΩ	8.9 kΩ
26 °C	8.4 kΩ	8.5 kΩ
27 °C	8.1 kΩ	12.3 kΩ
28 °C	7.8 kΩ	8.1 kΩ
29 °C	7.5 kΩ	7.7 kΩ
30 °C	7.2 kΩ	7.1 kΩ

The physical position of thermostat has been monitored by resistance logger as the knob of thermostat actually adjust a variable resistance inside. By recording its value, the physical position or the setting temperature can be monitored. Figure 5.9 and 5.10 show the average 28-days mean resistance value of dwelling 6 and 7 respectively and compared with the actual air temperature recorded nearby thermostat in 24-hours circle.

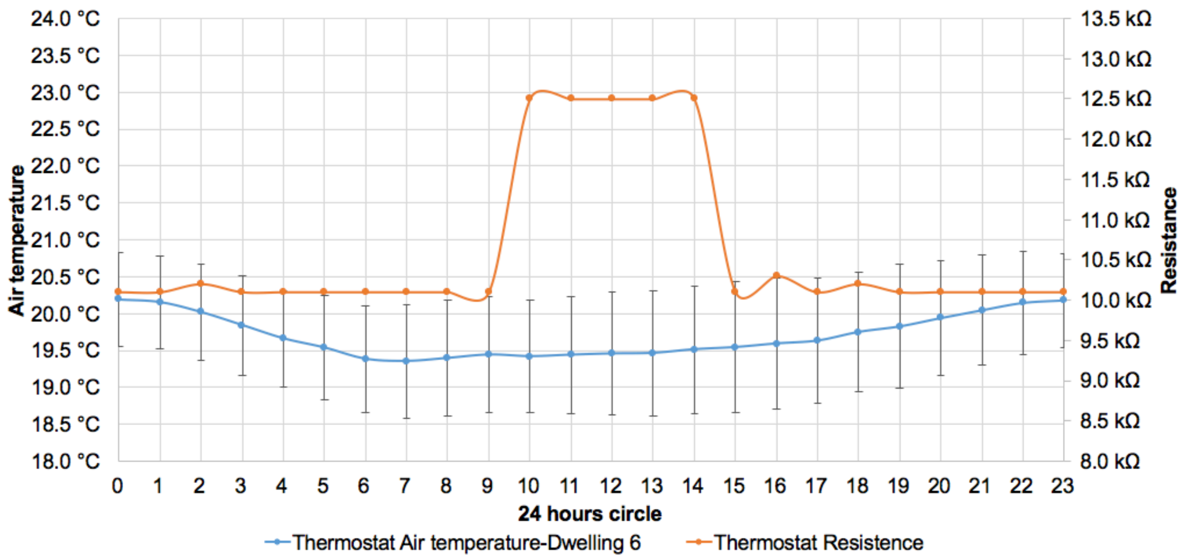


Figure 5.9: 24-hours profile of thermostat air temperature and resistance dwelling 6

The standard deviation represents hourly variation of air temperature measured nearby the thermostat, which is located in the identical spot of dwelling 6 and 7. The thermostat resistance stands for the physical position of the dial. The higher value, the lower setting temperature. Dwelling 6 has very stable temperature profile in the hallway through out of day, the standard deviation is ranged from 0.6°C to 0.9°C. The thermostat remains unadjusted most of the time, except 10am to 3pm. The converted physical position of the dial indicates that dwelling 6's setting temperature mostly stays between 19-20°C and usually get turn to the lowest/off during these hour during day time, which may be the habit of the occupant in order to conserve the energy spent on space heating.

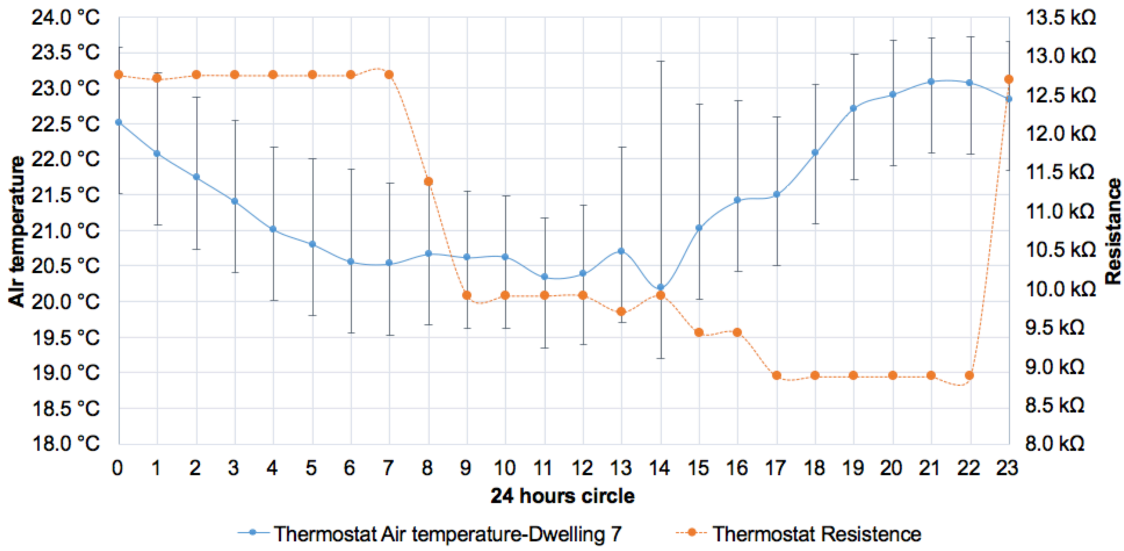


Figure 5.10: 24-hours profile of thermostat air temperature and resistance dwelling 7

Comparing to its neighbour, dwelling 7 has rather fluctuated temperature nearby its thermostat and the setting temperature. As shown in figure 5.xx, The thermostat dial is usually turn to the lowest/off overnight, right after the temperature in hallway reaches the peak at 10pm in evening, then setting temperature is adjusted higher gradually during the day time. Averagely, thermostat is turned to the 23-24°C at 5pm. Dwelling 7 has a rather large value of temperature standard deviation during 24 hours. Hourly variation is from 0.6°C to 3.2°C.

Post monitoring interview with regards to the thermostat adjustment confirms the pattern. Occupants of dwelling 6 hold a belief that it is best to keep the thermostat at constant setting which brings the optimal practice of whole house warmth and heating cost. Occupants of dwelling 7 think the ASHP system is less warm than the combi-boiler in previous house and they felt the thermostat often need to be adjusted to the highest setting during cold days in winter and turned to low overnight for energy saving.

Monitoring the resistive component of a dial type thermostat managed to capture the different habits of two dwellings. Comparing to direct monitoring method and questionnaire survey, records the physical position of a dial on thermostat is beneficial in both reducing invasiveness and the accuracy. Once the testing measurement is finished, resistance value can be converted directly to certain temperature setting of thermostat. However, such testing measurement may need to take as many as possible, due to the resistive value changes varies by the physical position of small electrical parts. Even dwelling 6 and 7 have identical thermostat model, their resistive values and corresponding positions are slightly different but enough to be interpreted up to 2°C difference on setting temperature.

5.2.5 Individual radiator monitoring methods

Gas boiler driven radiator

Temperature loggers have been place at various locations of the same radiator in order to find out the difference in terms of the surface temperature that can be made by sensor location. In dwelling 4, two sensors have been placed to the radiator in two rooms, one at the inlet pipe and the other one at the middle of the radiator panel, where in Figure 5.11 shows the comparison of them for 7days during heating season in the format of average hourly measurement. The surface temperature of panel is always higher than the inlet pipe and higher than the room(centre) temperature, therefore, the temperature differences are depicted as below.

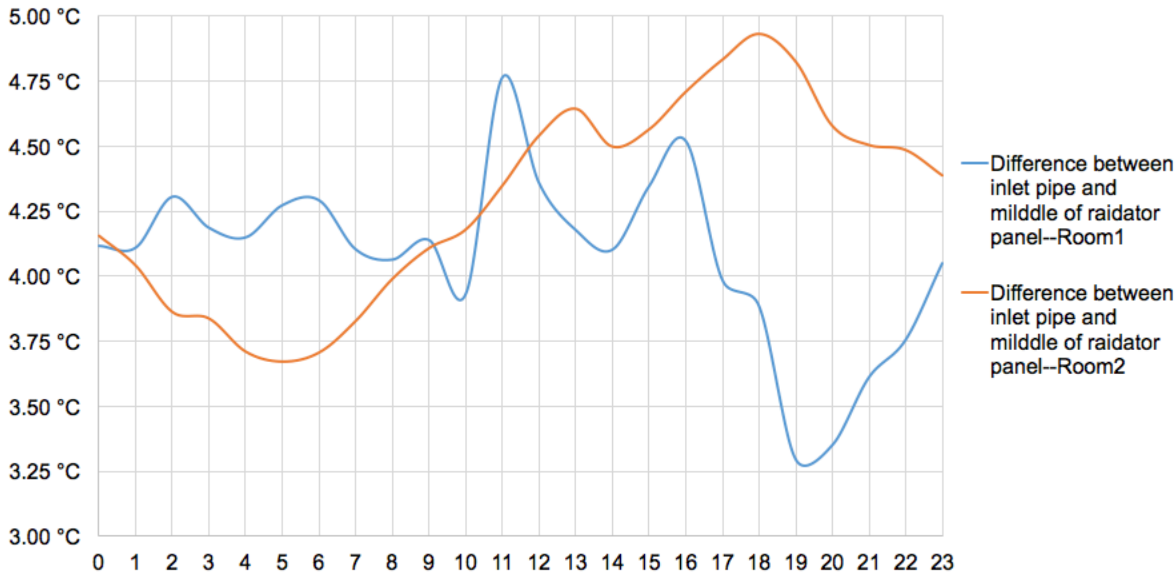


Figure 5.11: Surface temperature of individual radiator inlet pipe and middle of panel, dwelling 4

Room 1 does not have any operable window or ventilation and room 2 has one small window. It can bee seen in figure 5.12 that 24hour temperature profile of room 1 is more stable, ranging from 16.41°C to 16.88°C over 24-hours period, whereas room 2 varies from 17.16°C to 18.24°C.

The average temperature difference between the middle of radiator panel and the inlet pipe of radiator are 4.08°C and 5.19°C respectively for room 1 and room2.

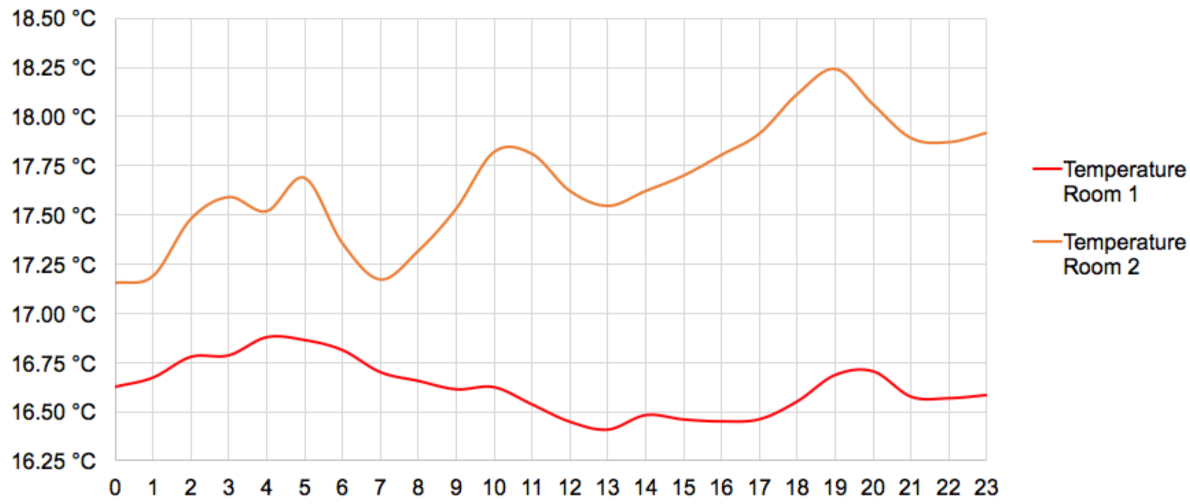


Figure 5.12: Air temperature comparison between room 1 and 2, dwelling 4

Electrical storage heater

Dwelling 2 has electrical storage heater in its master bedroom. This bedroom's air temperature, upper position temperature of storage heater and and it electricity consumption have been monitored and compare as shown in figure 5.13. The electricity consumption of this storage heater suggests it is usually turned off in the morning and turned on around 10pm in the evening and left on over night. It is noticed that topside temperature of storage heater begins to drop as soon as it is turned off. The room temperature begins to drop alone with the topside temperature of storage heater and eventually become almost identical to the room temperature until being turned on again in evening.

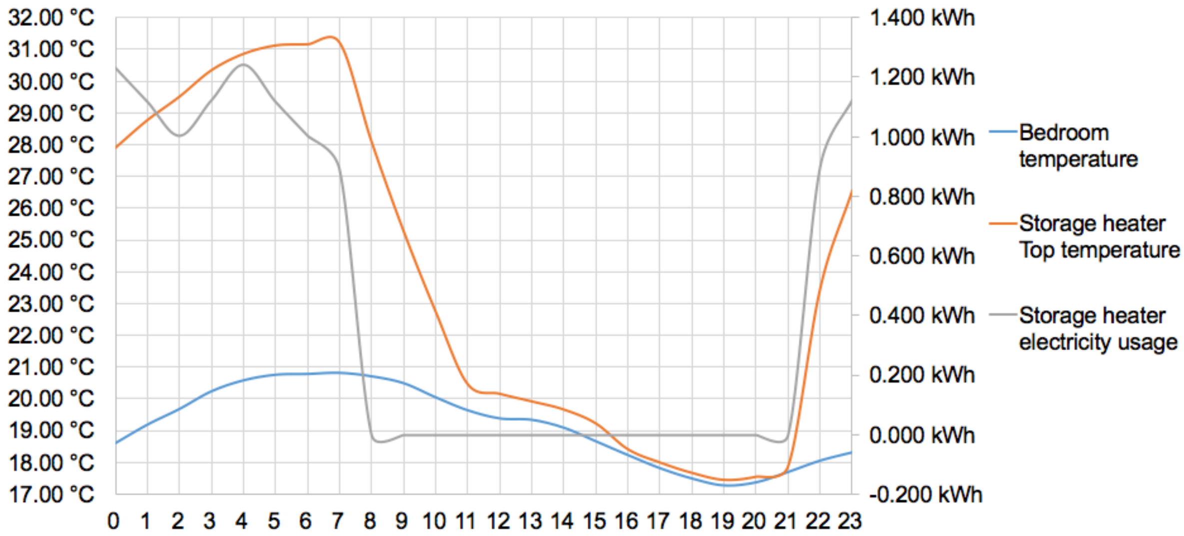


Figure 5.13: Various measuring locations of storage heater and electricity consumption

ASHP driven radiator

Various locations of radiator surface temperature measurements were taken at dwelling 6 with one selected radiator that always left on. ASHP powered radiator is also fluid based but the maximum output temperature was set to 40 °C, compared to condensing boiler which can circulate up to 70°C to radiators.

Three Tinytag sensors have been used in the measurement, one at the central spot behind the panel, one on the top and one at the bottom. Three sets of measurement are compared with temperature of the centre of the room where this radiator belongs to. The comparison measurement lasted 7 days when whole house under the same timer setting without adjustment and hourly average comparison is shown as figure 5.14.

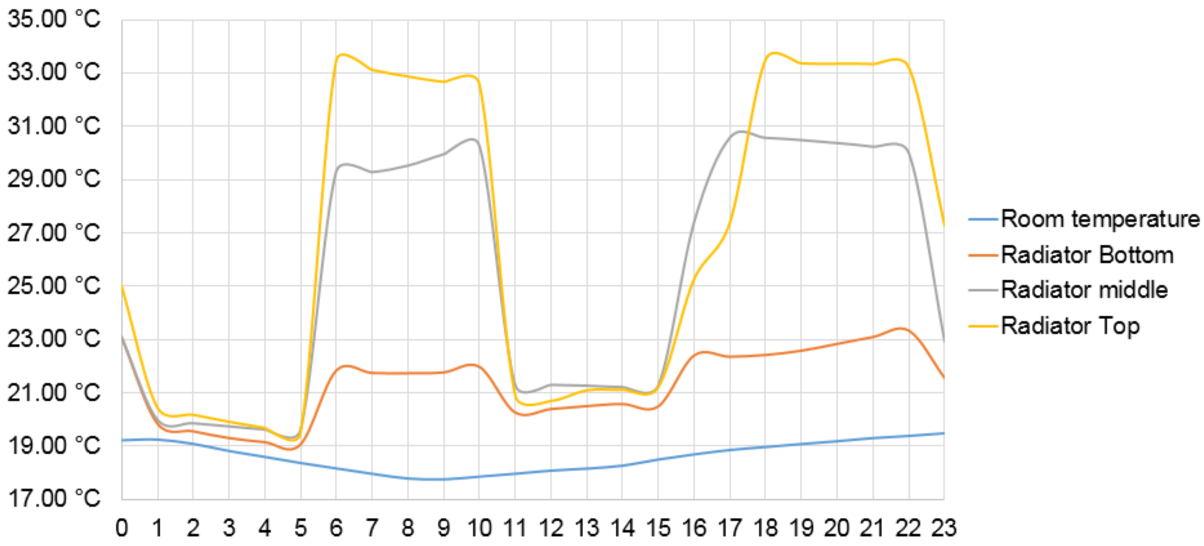


Figure 5.14: Various measuring locations of ASHP radiator and room temperature

Compared to the radiator temperature, the room where selected radiator belongs to remains relatively stable. Surface temperature measurements taken from three location of the same radiator share similar pattern which clearly indicates the running status of radiator. From high to low, namely, the top, middle and bottom of the radiator panel.

Electrical panel radiator

In dwelling 1, the the radiator top temperature has been monitored and compared with the room temperature measurement where the radiator belongs to. Figure 5.15 shows the average hourly temperature measured at the upper position of the electrical radiator in the living room for a 24 hours period. It can be seen that they are match to each other most of time but the upper spot of radiator rises sharply from 6pm to 9pm which indicates the radiator was turned on. However, the room temperature does not seem to be significantly linked with the radiator but a small trend of temperature increase can be seen while the radiator being turned on.

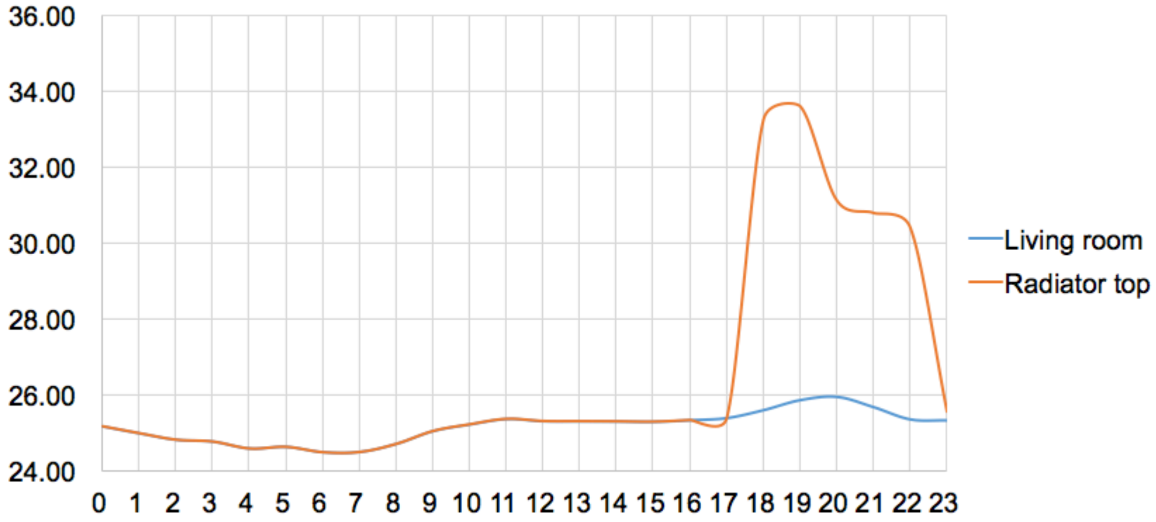


Figure 5.15: temperature measurement of living room and its radiator top

Various radiators and the ways they are heated affect the best monitoring position for temperature sensor as a direct method of recording its running status. The inlet pipe of radiator is less idea than the middle of radiator panel since the surface temperature seems to be lower in field study. This is perhaps caused by the smaller effective area in touch with the Tinytag logger which has its sensor embedded within enclosure. In principle, hot water will pass through inlet pipe of a fluid based radiator first before it emits heat by the rest of radiator panel. However, the pipe is much smaller than sealed temperature logger type and could potentially reduce the heat conductivity, therefore, reduces its measuring sensitivity. Surface temperature also seems to vary according to the position of a fluid based radiator, where higher position has warmer temperature readings and it may assist sensitivity of monitoring.

For electrically heated storage heater, measuring its surface temperature may not reflect its status. This is because storage heater continues to emit heat after being turned off. It would be accurate to measure its electricity consumption.

Directly attaching stand-along logger on a radiator panel may cause safety concern, due to the battery exposure to heat. Considering all the strength and weakness, it might be best to use logger with externally extended sensor that can be installed to the upper position of radiator panel.

5.2.6 Gas fireplace

Fireplace operating

In dwelling 2, the only heating element is the gas fireplace in its living room. Two sets of temperature loggers have been installed. One set in the living, at the centre of the room and one at the top of fireplace, the other set outside of the house, on the gas fireplace exhaust vent and the air temperature sensor of the local weather station. Dwelling 2 has gas cooker and it was not possible to separate its gas usage from fireplace due to potential disturbance of sub gas meter installation. Fig 5.16 compared the hourly temperature of living room and the top of fireplace. Figure 5.17 is the comparison between pulse count of main gas meter and temperature of fireplace exhaust vent and local external air temperature. Both figures include 7 days of monitoring data and presented in 24-hourly format.

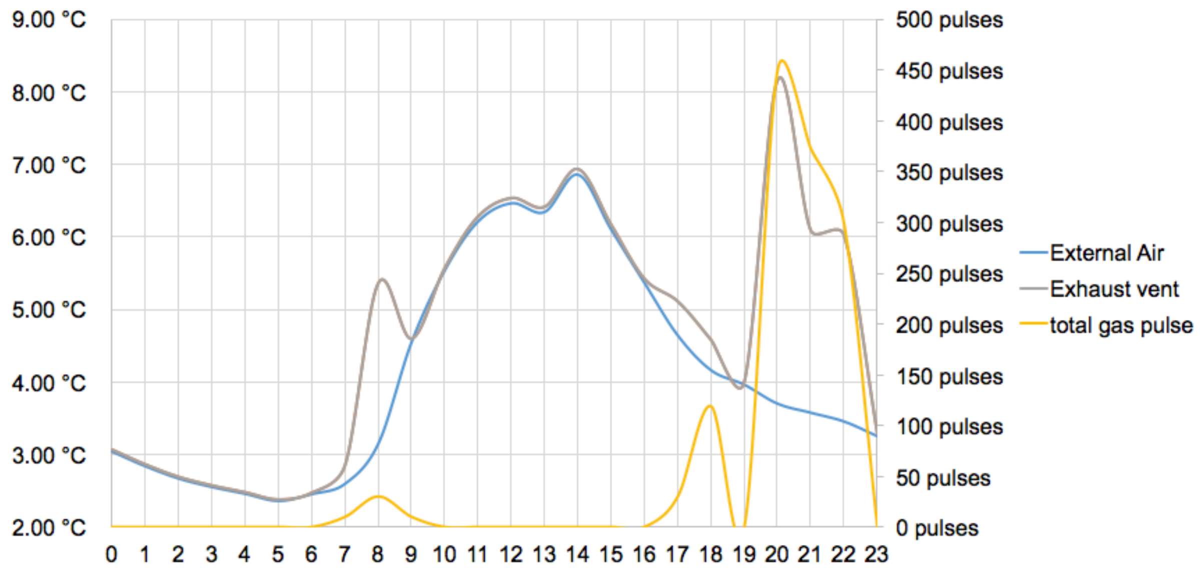


Figure 5.16: 24-hours mean temperature fireplace exhaust, outdoor and gas meter pulse

Comparing the external ambient air temperature and the fireplace exhaust vent temperature, a pattern can be found that the temperature of exhaust vent is generally similar to temperature taken from local weather station except a few hours in the morning, late afternoon and evening. Having these hours compared with gas meter pulses, it seems that when gas pulse increases, the temperature of exhaust vent also does correspondingly. However, one exception exists, which is between 5 to 6 pm. This is perhaps the gas consuming activity of gas cooker which was not separated from gas fireplace.

The temperature measurement taken from the top of fireplace matches very well with the living room and remains constantly above 30°C when it is operating. Averagely it takes 3-4 hours to cool down to same level as living room after being turned off.

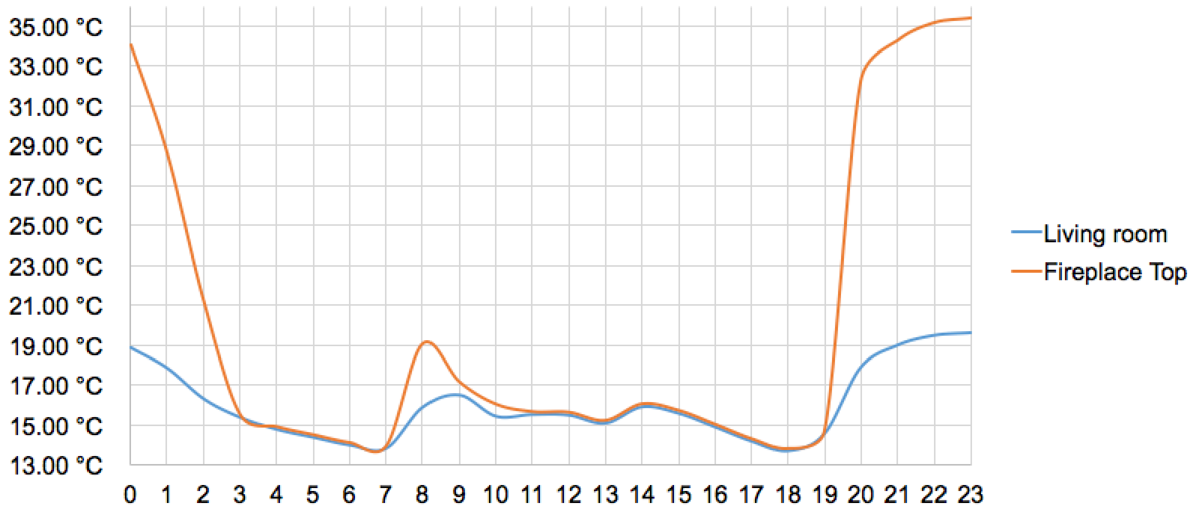


Figure 5.17: 24-hours mean temperature of living room and the top of fireplace.

Comparing measurement exhaust vent air of a gas powered fire place with external air temperature seems to be a valid method of monitoring whether a fireplace is being used. The temperature logger picked warmer readings at exhaust vent while gas consumption pulse count raised. During the period of no gas consuming activities, the exhaust vent has identical temperature reading as external air measures.

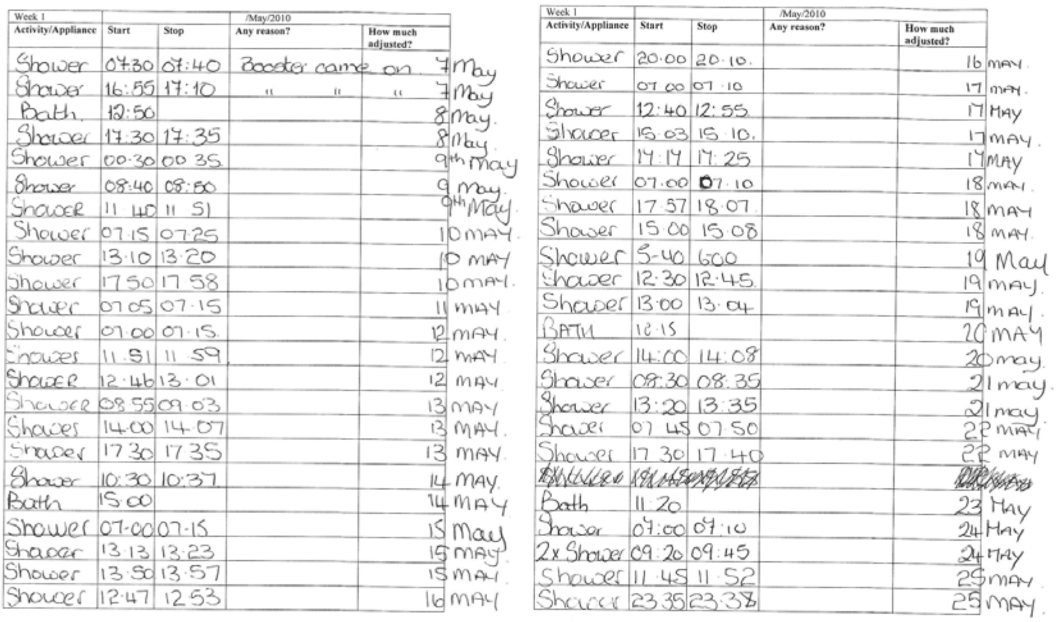
In a small space with only gas fireplace as space heating method, fire place top temperature matches very well with the room temperature and when it is turned on. Gas fire place seems to produce convective heater quickly and a temperature logger on its top is able to record such a sudden rise as a indicator of operating status. After being turned off, it immediately begins to cool down and temperature measurement on its top drops sharply.

5.3 Domestic hot water

5.3.1 Shower diary and Domestic Hot Water (immersion heater energy usage)

Occupant of dwelling 6 volunteered to keep a shower diary in order to investigate the relationship between shower time and energy efficiency. Two dairies have been kept before and after boiler setting adjustment. First dairy keep period was 14 days. In the period the immersion heater mainly supplies hot water demand, as ASHP unit was set to only work the first 45 minutes. Space heating was not in use during the first shower diary- keeping period. Figure 5.18 shows two pages of shower diary. Occupant wrote down the start and finish times of shower events as accurate as possible.

The shower/bathing events have been manually projected to the time on to immersion heater energy usage which were measured at 1 minute resolution, a few days have been picked randomly (day 1, 3, 5, 7, 9) and it can be seen that there is a clear linkage between them in the following figures 5.19 to 5.23. Shower/bath events written on the diary are illustrated with immersion energy usage in 24-hours format.



Week 1			/May/2010		
Activity/Appliance	Start	Stop	Any reason?	How much adjusted?	
Shower	07:30	07:40	Booster came on		7 May
Shower	16:55	17:10	" "	"	7 May
Bath	12:50				8 May.
Shower	17:30	17:35			8 May
Shower	00:30	00:35			9th May
Shower	08:40	08:50			9 May.
Shower	11 40	11 51			9th May
Shower	07:15	07:25			10 MAY.
Shower	13:10	13:20			10 MAY
Shower	17 50	17 58			10 MAY.
Shower	07 05	07:15			11 MAY
Shower	07:00	07:15.			12 MAY.
Shower	11:51	11:59			12 MAY
Shower	12:46	13:01			12 MAY
Shower	08:55	09:03			13 MAY
Shower	14:00	14:07			13 MAY.
Shower	17 30	17 35			13 MAY.
Shower	10:30	10:37			14 MAY.
Bath	15:00				14 MAY
Shower	07:00	07:15			15 May
Shower	13:13	13:23			15 MAY
Shower	13:50	13:57			15 MAY.
Shower	12:47	12:53			16 MAY

Week 1			/May/2010		
Activity/Appliance	Start	Stop	Any reason?	How much adjusted?	
Shower	20:00	20:10.		16	MAY.
Shower	07:00	07:10		17	MAY.
Shower	12:40	12:55		17	MAY
Shower	15:03	15:10.		17	MAY.
Shower	17:17	17:25		17	MAY
Shower	07:00	07:10		18	MAY.
Shower	17:57	18:07		18	MAY
Shower	15:00	15:08		18	MAY.
Shower	5-40	600		19	May
Shower	12:30	12:45.		19	MAY.
Shower	13:00	13:04		19	MAY.
BATH	12:15			20	MAY
Shower	14:00	14:08		20	may.
Shower	08:30	08:35		21	may.
Shower	13:20	13:35		21	may
Shower	07 45	07 50		22	MAY
Shower	17 30	17 40		22	MAY
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Bath	11:20			23	May
Shower	07:00	07:10		24	May
2x Shower	09:20	09:45		24	MAY
Shower	11 45	11 52		25	MAY.
Shower	23 35	23 38		25	MAY.

Figure 5.18: part of shower diary kept for wave 1, before re-commission being made

The power rate of immersion heater is fixed, which means it will either be on or off at full power of 3 kW. The electricity used by immersion heater is 49 to 49.5Wh per minute which is very close to its actual power rate. The power rate of ASHP is variable and it also provide space heating simultaneously with domestic hot water, which is the reason to list its electricity usage together with the others.

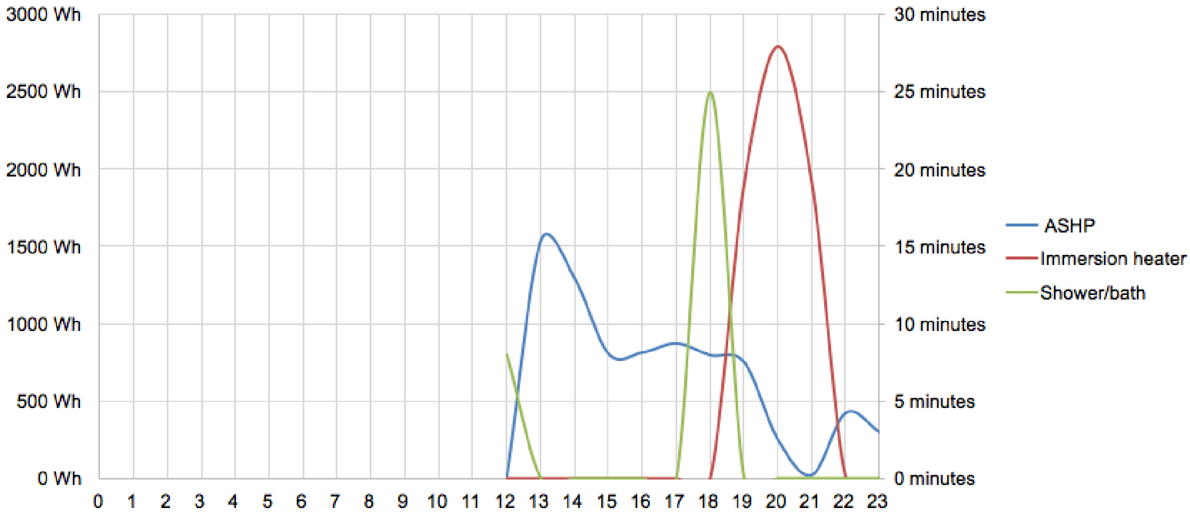


Figure 5.19: ASHP, Immersion heater electricity usage and shower/bath duration-dwelling 6- day 1-wave1

In figure 5.19, day 1's monitoring only started at 12am with only one shower of 8 minutes and then a bathing of 25 minutes. The ASHP had been running continuously right after the shower at higher power rate for 2 hours then half the power consumption for another 6 hours. The immersion heater was triggered right after the bathing with high energy consumption while ASHP ran at relatively lower power rate.

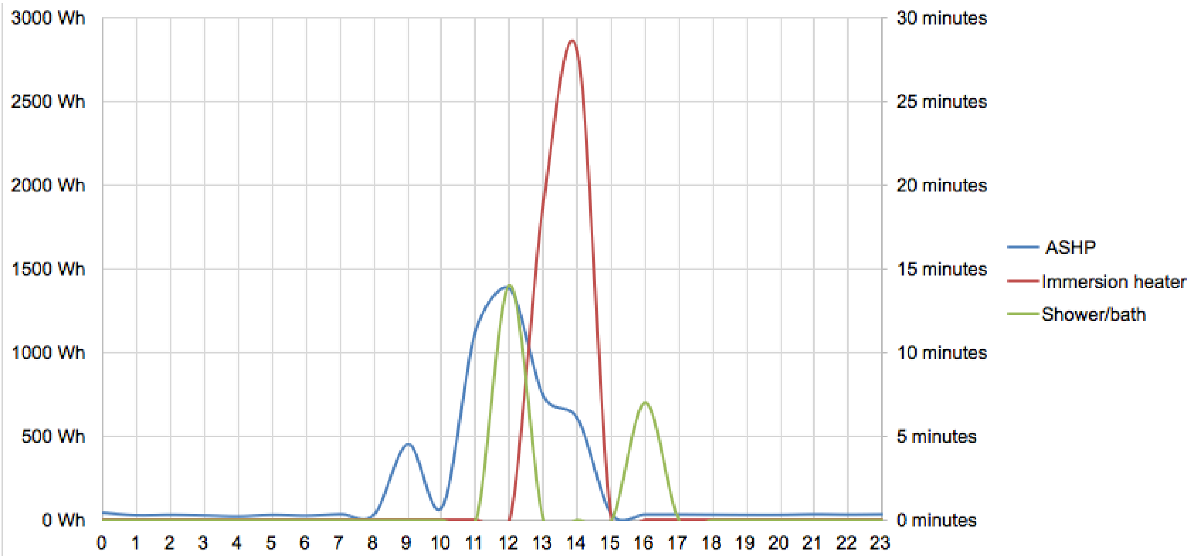


Figure 5.20: ASHP, Immersion heater electricity usage and shower/bath duration-dwelling 6- day 3-wave1

On day 3, a 14 minutes shower event was followed by a peak of immersion heater which used 4699Wh in two hours. The ASHP was not running at low power rate while the peak occurred.

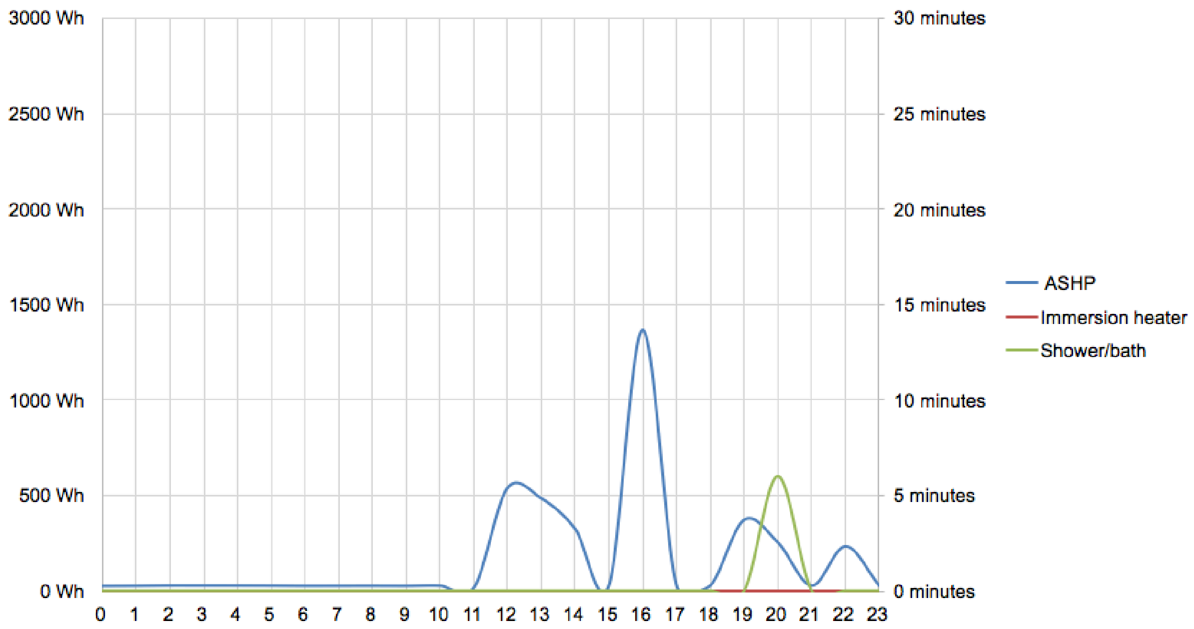


Figure 5.21: ASHP, Immersion heater electricity usage and shower/bath duration-dwelling 6- day 5-wave1

On day 5, only one 6 minutes shower and it did not trigger the immersion heater.

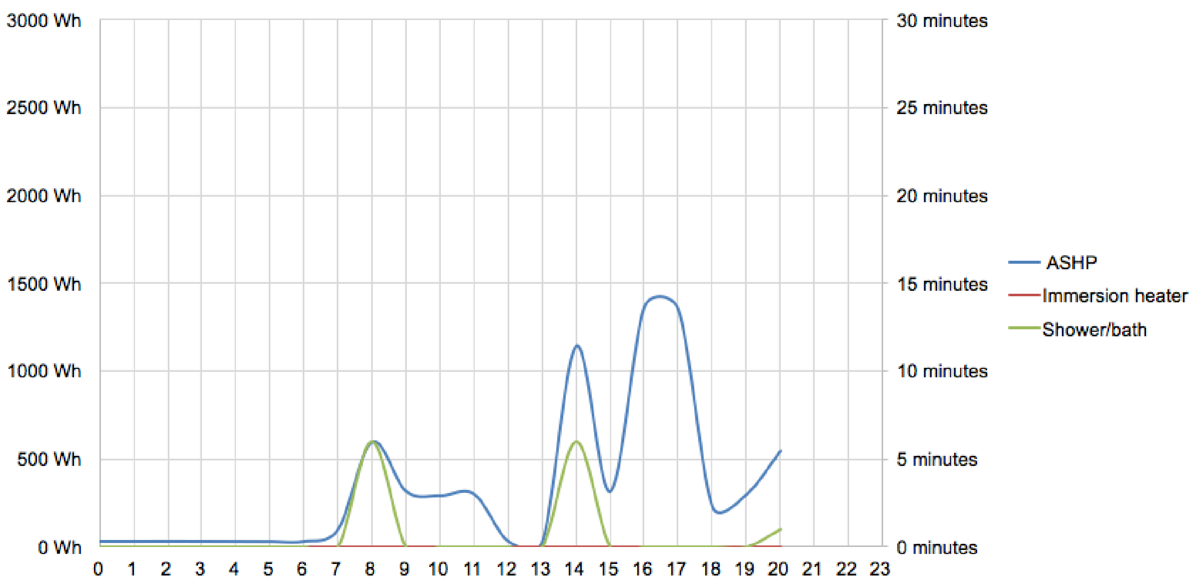


Figure 5.22: ASHP, Immersion heater electricity usage and shower/bath duration-dwelling 6- day 7-wave1

On day 7, two shower events of 6 minutes, one in the morning and one in the afternoon. They match very well with peaks electricity consumptions of ASHP.

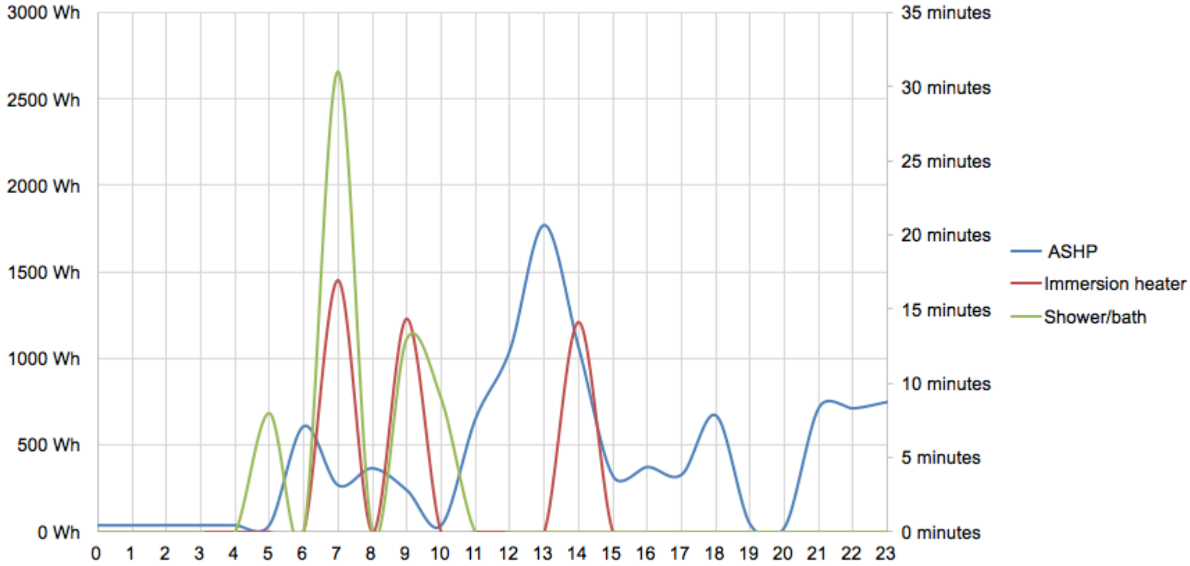


Figure 5.23: ASHP, Immersion heater electricity usage and shower/bath duration-dwelling 6- day 9-wave1

On day 9, three consecutive shower events are followed by peaks of electricity consumption of immersion heater right after each event.

The rest of the days are very similar in terms of pattern in their daily view. It seems that the majority of shower/bathing events have triggered the immersion to run. The longer a shower or bath event lasted, the longer and more frequently the immersion worked.

Having suffered from the high energy bill after the first wave of shower/bath diary keeping, occupants of dwell 6 decided to have their ASHP and immersion heater re-commissioned in order to reduce their cost. More importantly, they became more knowledgeable than before and made some behavioural changes on shower and bathing taking. According to the interview after the re-commissioning, occupants in dwelling 6 began to adjust both their behaviour and system in order to find the balance between energy consumption and daily life style.

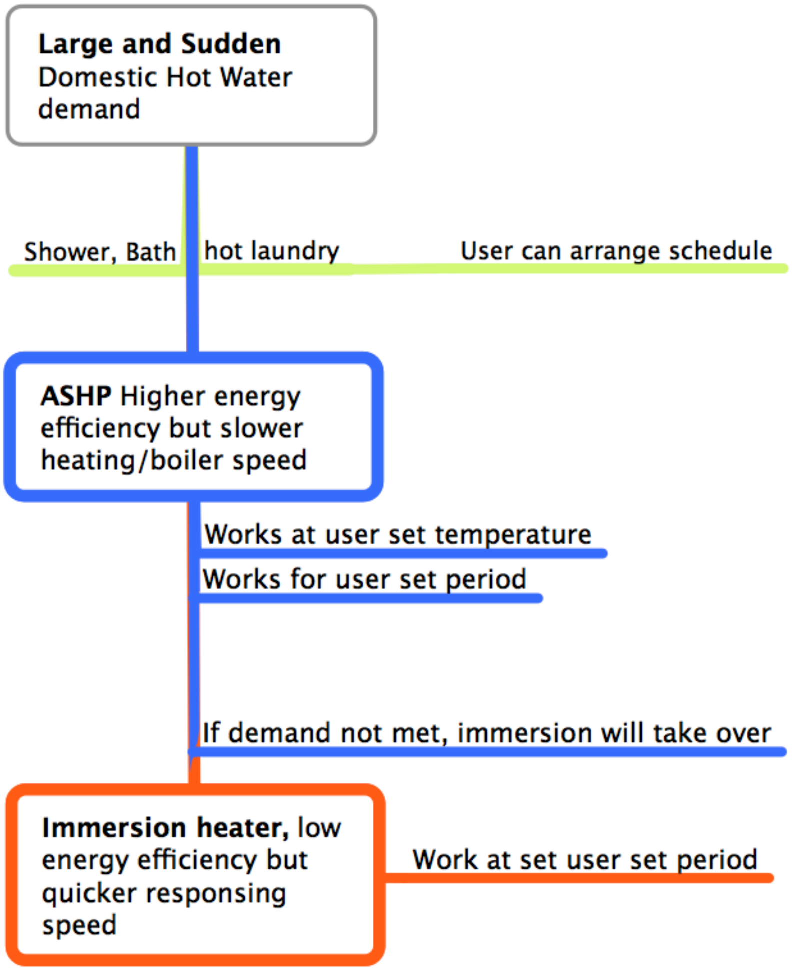


Figure 5.34: Dwelling 6 and 7 domestic hot water supply and demand flow

As shown in figure 5.34, immersion heater is usually trigger by rapid and large domestic hot water demand. The energy efficient option for water heating is through ASHP unit, which is slower in responding speed especially in cold as there is less energy can be extracted from ambient air.

The following behavioural changes, ASHP and immersion heating setting adjustment were made:

- Tried to avoid taking shower or bath at late night or early morning
- Tried to spread hot water uses throughout the day instead concentrated pattern.

- Set the ASHP temperature to 40 and maximise its working time prior to immersion heater, changed from 45 minutes to 95 minutes.

- Minimised immersion heater working time from 5 minutes to 1 minute.

- Maximised the anti-recycling time from 0.5 hour to 3 hours, which means system won't be re-boiling within this set period.

The second shower diary session lasted 14 days during the half of heating season.

Date	Shower or Bath Please Circle	Start time	Finish time	Is space heating on? (Optional)
10/11/2010	Shower or Bath	12:25:Pm	12:32:PM	ON/ OFF
10/11/2010	Shower or Bath	06:04:Pm	--:--:--	ON/ OFF
11/11/2010	Shower or Bath	12:10:Pm	12:23:Pm	ON/ OFF
11/11/2010	Shower or Bath	03:41:Pm	03:47:Pm	ON/ OFF
12/11/2010	Shower or Bath	06:45:Pm	06:50:Pm	ON/ OFF
13/11/2010	Shower or Bath	06:45:am	06:50:am	ON/ OFF
13/11/2010	Shower or Bath	12:40:Pm	12:44:Pm	ON/ OFF
13/11/2010	Shower or Bath	05:40:Pm	05:50:Pm	ON/ OFF
13/11/2010	Shower or Bath	07:00:Pm	07:10:Pm	ON/ OFF
15/11/2010	Shower or Bath	07:53:Am	08:04:Am	ON/ OFF
15/11/2010	Shower or Bath	10:04:Am	10:13:Am	ON/ OFF
15/11/2010	Shower or Bath	12:05:Pm	12:12:Pm	ON/ OFF
16/11/2010	Shower or Bath	06:30:Am	06:40:Am	ON/ OFF
16/11/2010	Shower or Bath	11:45:Pm	11:50:PM	ON/ OFF
17/11/2010	Shower or Bath	06:35:Am	06:5?:Am	ON/ OFF
17/11/2010	Shower or Bath	04:09:Pm	04:13:Pm	ON/ OFF
17/11/2010	Shower or Bath	06:38:Pm	06:48:Pm	ON/ OFF
17/11/2010	Shower or Bath	06:56:Pm	07:15:Pm	ON/ OFF
18/11/2010	Shower or Bath	07:50:Am	08:05:Am	ON/ OFF
18/11/2010	Shower or Bath	08:34:Am	08:40:Am	ON/ OFF
18/11/2010	Shower or Bath	08:35:Am	08:45:Am	ON/ OFF
18/11/2010	Shower or Bath	08:50:Am	08:55:Am	ON/ OFF
19/11/2010	Shower or Bath	11:17:Am	11:21:Am	ON/ OFF
19/11/2010	Shower or Bath	04:25:Pm	04:30:Pm	ON/ OFF
19/11/2010	Shower or Bath	06:16:Pm	06:30:Pm	ON/ OFF
20/11/2010	Shower or Bath	05:01:Pm	05:04:Pm	ON/ OFF
21/11/2010	Shower or Bath	03:15:Pm	03:29:Pm	ON/ OFF
22/11/2010	Shower or Bath	08:00:Am	08:10:Am	ON/ OFF
22/11/2010	Shower or Bath	11:40:Am	11:45:Am	ON/ OFF
22/11/2010	Shower or Bath	11:42:Am	11:52:Am	ON/ OFF

Date	Shower or Bath Please Circle	Start time	Finish time	Is space heating on? (Optional)
23/11/2010	Shower or Bath	06:00:Am	06:08:Am	ON/ OFF
23/11/2010	Shower or Bath	06:17:Am	06:35:Am	ON/ OFF
23/11/2010	Shower or Bath	04:07:Pm	04:17:Pm	ON/ OFF
25/11/2010	Shower or Bath	02:30:Pm	02:40:Pm	ON/ OFF
25/11/2010	Shower or Bath	06:50:Pm	--:--:--	ON/ OFF
26/11/2010	Shower or Bath	11:08:Am	11:13:Am	ON/ OFF
26/11/2010	Shower or Bath	11:00:Am	--:--:--	ON/ OFF
26/11/2010	Shower or Bath	04:19:Pm	04:28:Pm	ON/ OFF
28/11/2010	Shower or Bath	12:41:Pm	12:52:Pm	ON/ OFF
29/11/2010	Shower or Bath	08:47:Am	08:58:Am	ON/ OFF
29/11/2010	Shower or Bath	03:21:Pm	03:26:Pm	ON/ OFF
29/11/2010	Shower or Bath	07:45:Pm	07:55:Pm	ON/ OFF
31/12/2010	Shower or Bath	07:45:Am	08:00:Am	ON/ OFF
31/12/2010	Shower or Bath	08:25:Am	08:30:Am	ON/ OFF
1/12/2010	Shower or Bath	09:05:Pm	09:25:Pm	ON/ OFF
02/12/2010	Shower or Bath	08:55:Am	09:05:Am	ON/ OFF
02/12/2010	Shower or Bath	11:43:Am	11:54:Am	ON/ OFF
03/12/2010	Shower or Bath	08:36:Am	08:40:Am	ON/ OFF
03/12/2010	Shower or Bath	02:16:Pm	--:--:--	ON/ OFF
04/12/2010	Shower or Bath	10:03:Am	10:15:Am	ON/ OFF
04/12/2010	Shower or Bath	04:15:Pm	04:20:Pm	ON/ OFF
05/12/2010	Shower or Bath	08:42:Pm	08:46:Pm	ON/ OFF
06/12/2010	Shower or Bath	5:00:Pm	5:08:Pm	ON/ OFF
07/12/2010	Shower or Bath	06:32:Am	06:42:Am	ON/ OFF
08/12/2010	Shower or Bath	05:30:Pm	05:40:Pm	ON/ OFF
08/12/2010	Shower or Bath	06:00:Pm	06:05:Pm	ON/ OFF
09/12/2010	Shower or Bath	06:20:Am	06:30:Am	ON/ OFF
09/12/2010	Shower or Bath	12:30:Pm	12:35:Pm	ON/ OFF
10/12/2010	Shower or Bath	10:22:Am	10:27:Am	ON/ OFF
10/12/2010	Shower or Bath	04:05:Pm	04:15:Pm	ON/ OFF

Figure 5.35: part of shower diary kept for wave 2, after re-commission being made

Figure 5.36 to 5.40 show the day 1, 3, 5, 7, 9 of wave 2 after the the behavioural change and re-commission being made to the ASHP and immersion control panel.

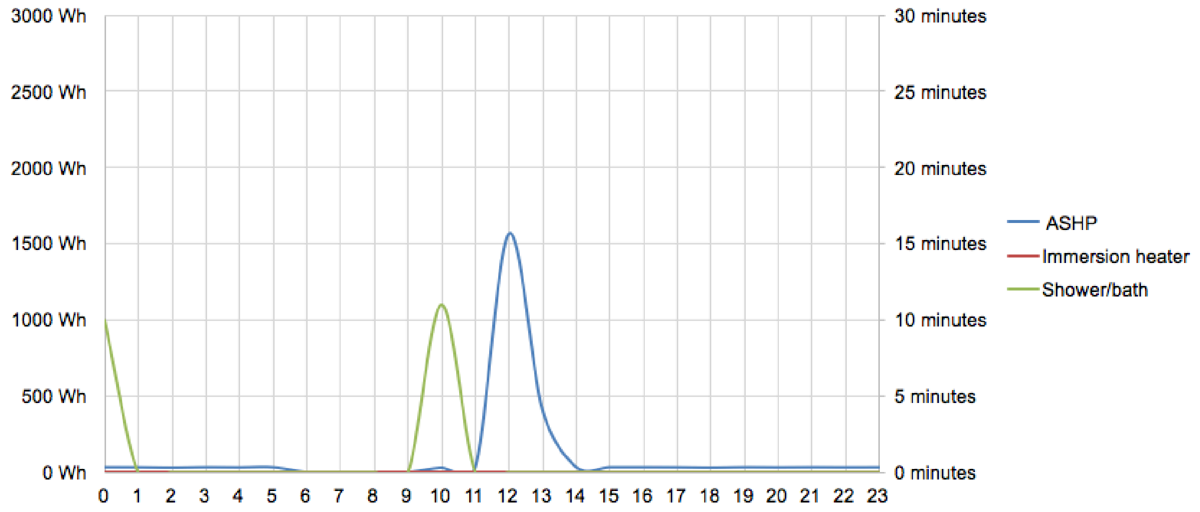


Figure 5.36: ASHP, Immersion heater electricity usage and shower/bath duration-dwelling 6- day 1-wave2

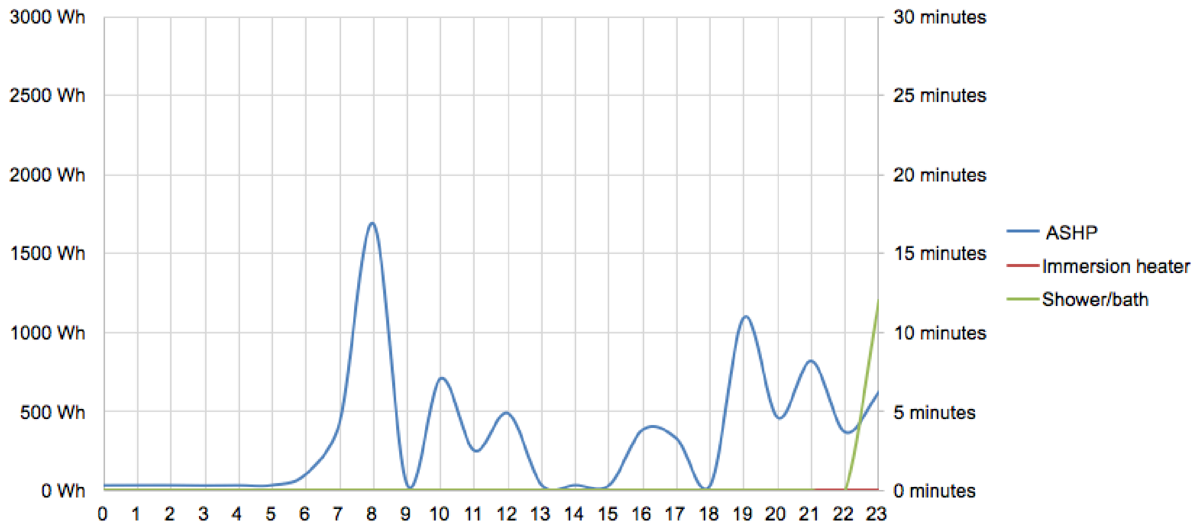


Figure 5.37: ASHP, Immersion heater electricity usage and shower/bath duration-dwelling 6- day 3-wave2

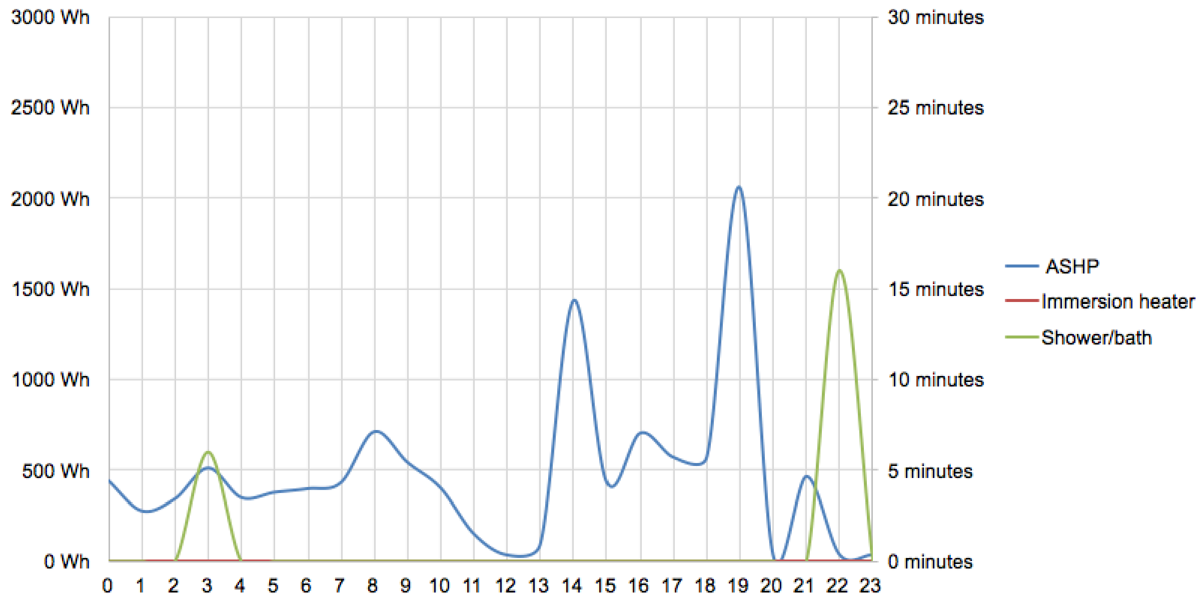


Figure 5.38: ASHP, Immersion heater electricity usage and shower/bath duration-dwelling 6- day 5-wave2

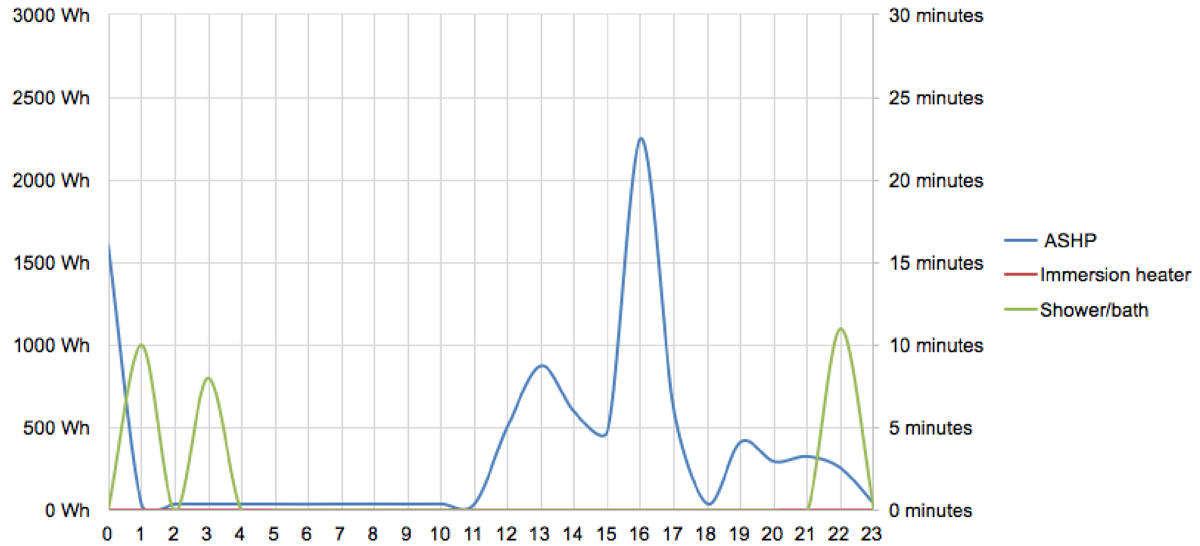


Figure 5.39: ASHP, Immersion heater electricity usage and shower/bath duration-dwelling 6- day 7-wave2

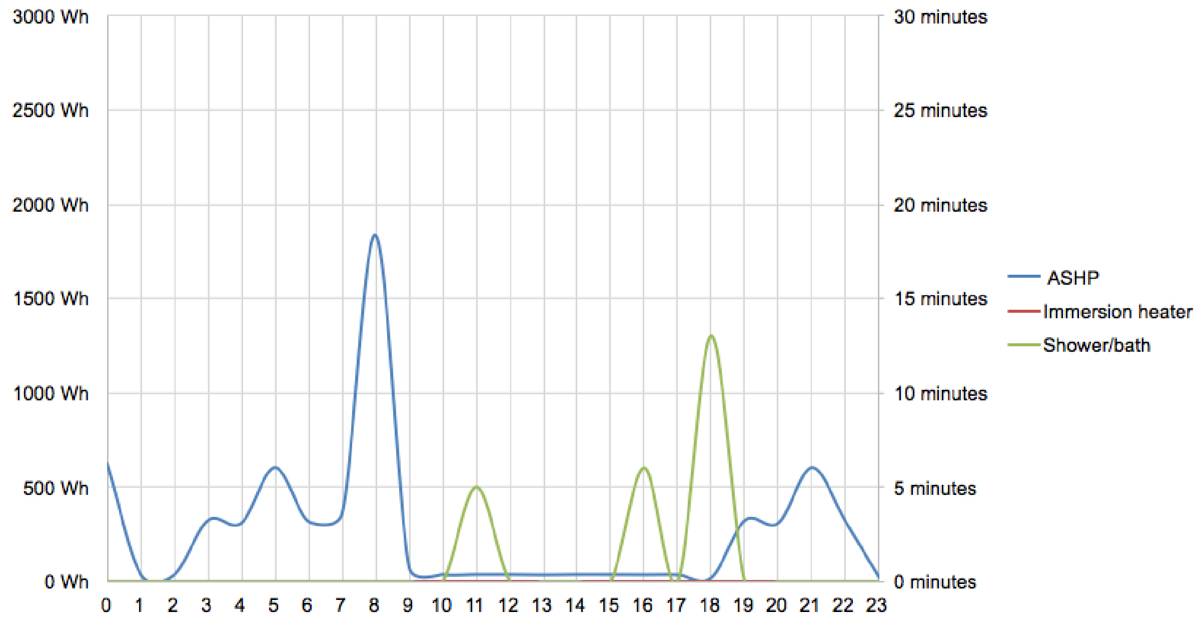


Figure 5.40: ASHP, Immersion heater electricity usage and shower/bath duration-dwelling 6- day 9-wave2

The immersion heater was not trigged in these 5 days and only triggered twice during entire 14 days of wave 2. It can be seen that between the shower events, there are clear gaps of ASHP as well. Without hot water demand from taking shower or bathing, ASHP seems work noticeably less. This is a very positive improvement as the ASHP had much less heat available for extraction in wave 2. In addition, the space heating was turned on more often in this wave2 which means that ASHP electricity consumption also include space heating. As a result of the new setting made to the control panel gives ASHP priority over the Immersion heater, this enables ASHP to run 95minutes to fulfil hot water demand before switching to emergent immersion heater. The new setting also enables a period of 3 hours anti re-boiling feature that prevents immersion heater from running if the desired temperature has been reached inside the water tank.

These changes are well reflected when comparing shower events along with ASHP and immersion energy consumption. Table 5.3 shows the comparison of ASHP electricity usage with the same shower/bath events.

Table 5.3: Shower/bath behaviour and ASHP energy usage comparison

Daily average	**ASHP (Wh)**	**Immersion (Wh)**	**Shower/bath (minute)**
Wave 1	6855	3041	28.4
Wave 2	7015	343	27.6

It is interesting to see that daily average showering time is 28.4 minutes in wave 1 and 27.66 minutes wave 2. This indicates that daily shower or bath demand is quite stable over the time and actually it is almost identical, averagely only differ 0.8 minute between from other wave. It represents the consistence of shower/bath behaviour.

Comparing the daily energy usage between two waves, average daily electricity consumption of immersion heater is 3041 Wh in wave 1 and it dropped down to only 343 Wh per day in wave 2.

Figure 5.41 compares the hourly shower events allocation. In wave 1, most of the shower behaviour taken place in hourly slots of 07:00-07:59, 12:00-12:59 and 17:00-17:59, there are also a few in the late night as well. In wave 2, most shower and bathing event are in 06:00-06:59, 08:00-08:59 and 11:00 to 11:59 from 10th November to 15th December 2011.

Self-reported shower/bath diary is an effective tool to record heating demand and it provides more accurate data than the interpretation of boiler and immersion heating energy activity. This is perhaps caused the built-in time lag with domestic hot water usage with storage tank, where certain amount of water will be always heated ready to stand by any demand. Although the there is clearly a link between shower/ bathing event and water heating system energy consumption, the time lag makes it difficult to estimate when a hot water demand activity occurred. Self-reported shower/bath diary may be considered to take too much effort to keep and might be objected by occupant for this reason, especially a family with several members as it entirely relies on self motivation to fill.

In addition, figure 5.41 and 5.42 illustrate the difference before and after behaviour change.

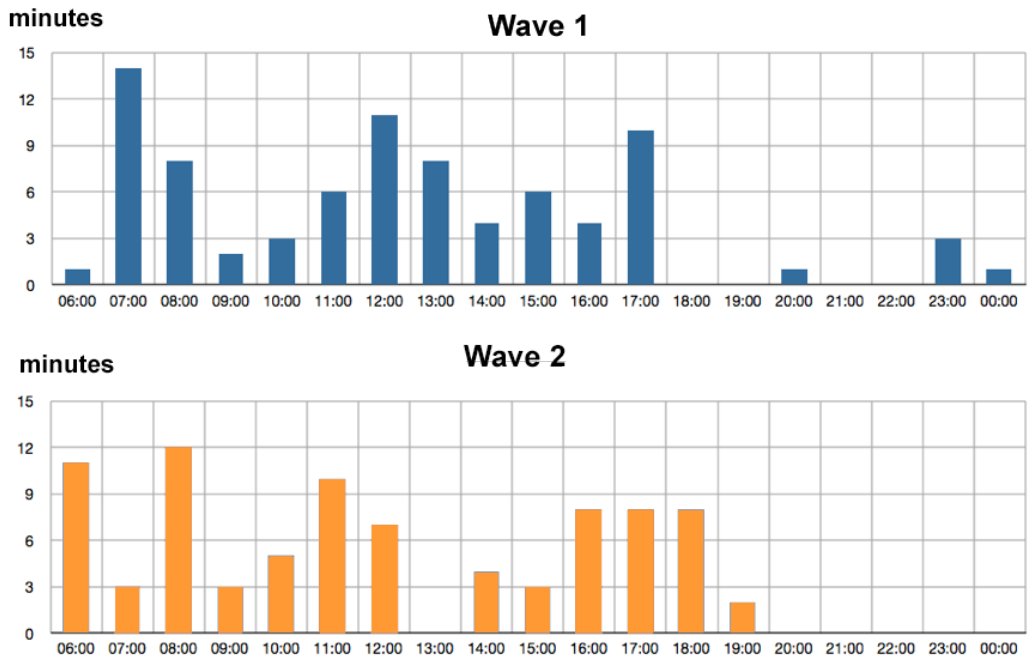


Figure 5.41: Shower and bathing hourly allocation comparison

Figure 5.42 illustrates hourly differences of between wave 1 and 2. Orange (positive) columns are the increase of shower numbers in 2011 period and the white (negative) columns are the drops comparing to 2010 period. Starting from early morning, it is like occupant has shifted shower time one hour earlier as the rise in 06:00 slot followed by a reduction in 07:00 slot. The major increases are in AM hours before 12:00 from 08:00 to 12:00. In the PM hours, there is significant increase in 18:00 slot. Occupants ceased to take use shower after 19:00 o'clock as they mentioned in one of the behavioural improvement.

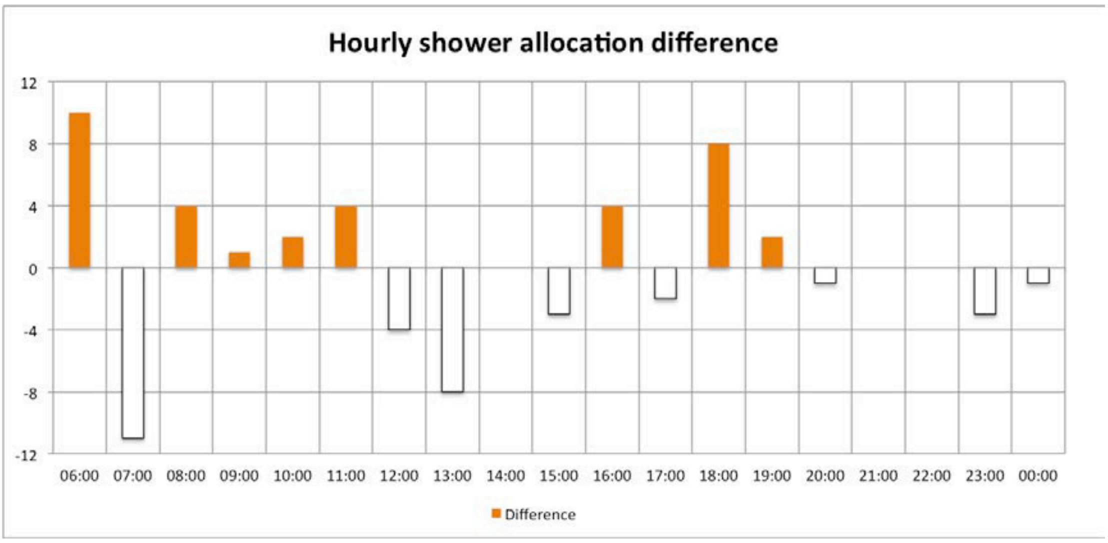


Figure 5.42: Shower and Bathing hourly allocation difference

5.3.2 Hot water outlet pipe

Surface temperature of ASHP outlet pipe and return pipe have been monitored in dwelling 6. Figure 5.43 to 5.45 respectively illustrate the average, maximum and standard deviation of each hour of 14 days periods.

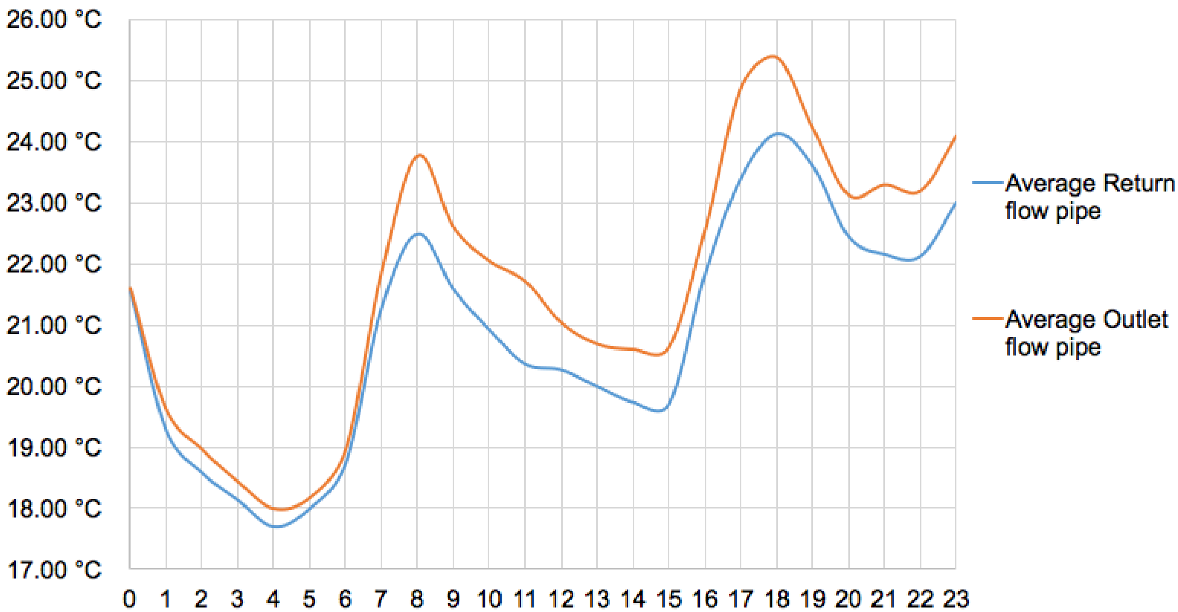


Figure 5.43: average surface temperature of ASHP outlet and return pipes

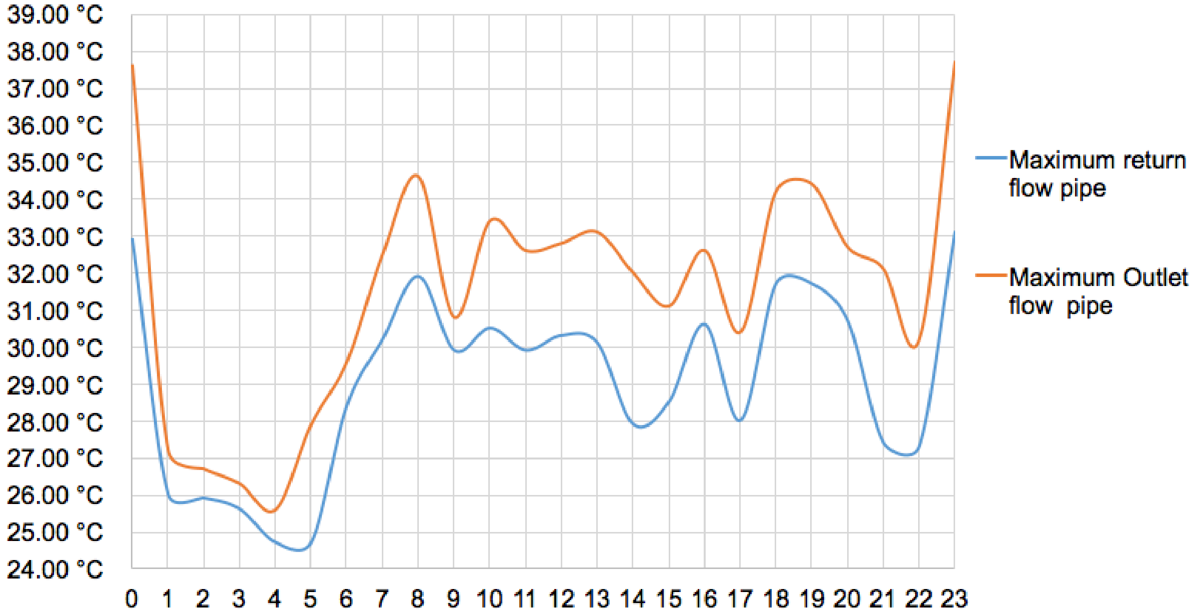


Figure 5.44: maximum surface temperature of ASHP outlet and return pipes

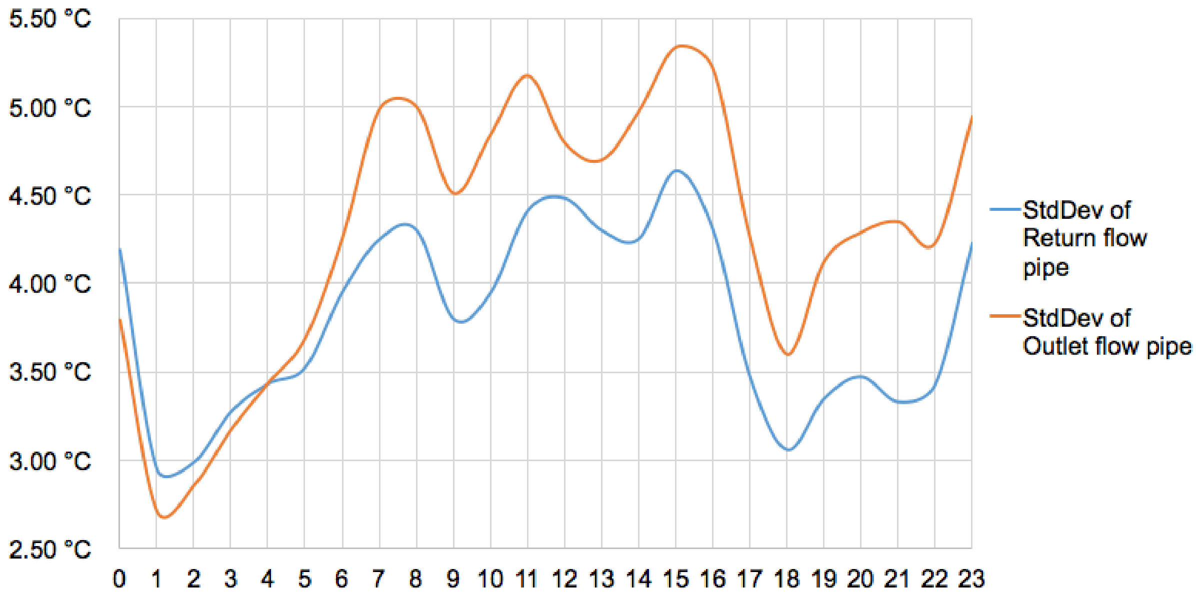


Figure 5.45: Standard deviation of surface temperature of ASHP outlet and return pipes

In these figures, three sets of comparison have shown little difference between two pipes and the return flow pipe is always slight cooler than the outlet pipe. Average deviation of outlet pipe surface temperature is 0.77°C warmer than the return flow pipe.

Although it is a non-intrusive method, measuring surface temperature difference between outlet and return flow pipes of boiler tells very little more than general status of whether if boiler is operating or not. The surface temperature of outlet flow pipe seems always higher than return flow which is caused by the heat loss through circulation within a dwelling. It cannot replace the information that a inline flow meter or heat meter can provide with regards to domestic hot water related monitoring.

5.3.3 Boiler control panel display

An infrared camera and pixel detecting software have been used to monitor the display panel of AHSP unit of dwelling 6. However, the interpretation o f each image has to be conducted manually. Table 5.xx shows the number of images and images with actual icon changes over 14-days period.   The average recognition rate of image pixel change is 80%. The unrecognised pictures are either has no icon change or caused by increase of brightness by opening door of the storage room where the camera installed.

Table 5.4: recognition rate of pixel change detection software and infrared camera images

	Total image	With icon change	Recognition rate
Day 1	85	60	71%
Day 2	82	66	80%
Day 3	160	120	75%
Day 4	73	62	85%
Day 5	65	57	87%
Day 6	68	60	88%
Day 7	221	144	65%
Day 8	88	73	83%
Day 9	69	57	82%
Day 10	179	140	78%
Day 11	73	58	80%
Day 12	98	81	83%
Day 13	82	66	81%
Day 14	67	55	82%

There are five possible icons on the panel (figure 5.xx):

- ASHP COMPRESSOR This icon indicates that the compressor in the outdoor unit of the installation is active.

- BACKUP HEATER These icons indicate that the backup heater is operating, The backup heater provides extra heating capacity in case of low ambient outdoor temperature

- IMMERSION BOOST HEATER ICON This icon indicates that the booster heater is active. The booster heater provides auxiliary heating for the domestic hot water tank.

- PUMP This icon indicates that the space heating circulation pump is active.

- SET TEMPERATURE -88.8 The display shows the water temperature for space heating circuit.

Figure 5.46: Icons on the display panel of ASHP, dwelling 6

Although the camera and take images at dark and the software has average 80% rate of recognising changes of icon on the display panel, the interpretation work still has to be done manually. Table 5.5 lists the frequency (times) of these icons which have been manually counted for 14 days.

Table 5.5: Frequency of Icons appeared on display panel- 14 days in wave 1

Wave1	ASHP Compressor	Pump	Backup Heater	Immersion Boost heater	Setting temperature
Day 1	12	11	3	10	0
Day 2	13	12	3	11	0
Day 3	24	22	8	20	0
Day 4	12	11	3	11	1
Day 5	11	10	3	10	0
Day 6	12	11	3	10	0
Day 7	29	26	7	24	0
Day 8	15	13	4	12	2
Day 9	11	10	1	10	0
Day 10	28	25	12	24	0
Day 11	12	11	3	10	1
Day 12	16	15	7	14	0
Day 13	13	12	3	11	0
Day 14	11	9	3	9	0

There are few patterns found wave 1 as followings:

- Immersion boost heater mostly appears on its own,
- If ASHP Compressor appears the Pump will follow, sometimes Backup heater does too.
- The Setting temperature remains as 40°C, it only appeared few times without icon change but seems to be caused by the brightness change, possibly occurred when occupants entered the storage room.

Wave 2 lasted as long as 14-days after re-commission being made to the ASHP and control (see surface pipe temperature section). Its immersion boost icon only appeared on two days for few times. The ASHP compressor icon and the pump were much more active and constant than wave 1.

Table 5.6: ASHP control panel icon appearance counts

Wave 2	ASHP Compressor	Pump	Backup Heater	Immersion Boost heater	Setting temperature
Day 1	17	16	5	0	0
Day 2	23	22	6	2	0
Day 3	25	22	4	0	0
Day 4	22	21	6	0	0
Day 5	19	20	7	0	0
Day 6	22	21	3	0	0
Day 7	22	26	7	0	0
Day 8	24	23	9	0	0
Day 9	21	22	5	0	0
Day 10	28	25	6	0	0
Day 11	22	21	8	0	0
Day 12	24	15	8	0	0
Day 13	23	22	6	4	0
Day 14	21	10	2	0	0

This method, taking motion triggered pictures of the display icons of boiler panel, works as an indirect observer that keeps eyes of boiler status 24/7. The strength is that it is less invasive and does not require a researcher to be on site. This is favourable in domestic building research as most occupancy expands outside of working hours where direct observation of space heating usually would be difficult to conduct.

There is two main weaknesses. For one, it takes long time to manually interpret still images into meaningful boiler activities as every time an icon change in the view field of camera will be captured. This may become a problem for long-term monitoring. For another, the motion detection works much better in environment with strictly controlled brightness which might not be possible in some household.

5.4 Windows and door

Three tailored instrumentations that designed for angle measurement of internal door and windows have been tested in dwelling 3, an office environment. None of other participated households were in favour of internal door angle monitoring. Permission of window installation was granted however all the customised set up are either too visible or not weather proof. Therefore, only the field study results of from 'dwelling 3', author's office are presented in this section, by comparing measured angle and observed angle.

5.4.1 Multiple contact switches board

Testing results of multiple sensor board a close data observation, as shown in 5.47. A multiple sensor board can determine the angle of a door as operated and record the period during which it was maintained at a certain angle. Testing results are very close to observation.

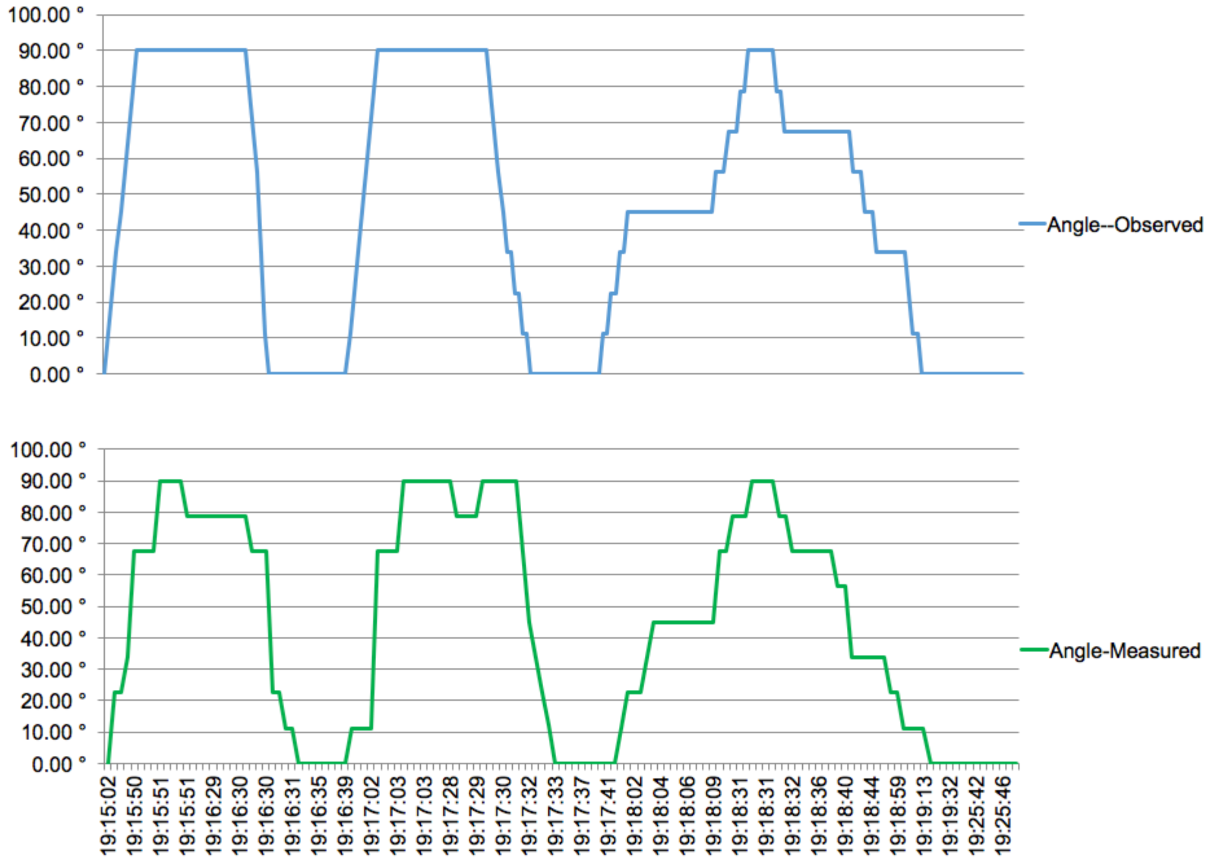


Figure 5.47: Comparison of observed and measured door angle, multi contact switches

5.4.2 Flexi sensor

The range of selected flexi sensor to monitor door angle is between 7000 Ω to 13000 Ω depends the level of being bent (0° to 180°) (Figure 5.48).

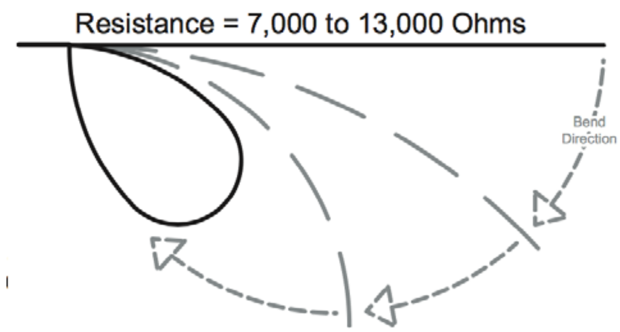


Figure 5.48 Flexi sensor resistance and bending level

The the comparison between observed and measured angles are illustrated in figure 5.49. The results show a clear relationship between resistance value and the angles of door. However, resistance value flexi sensor seems to have small variation for identical door angle which may be caused the physical position of the tested door. It is not possible to move exactly the same angle every time. The positioned angle is ranged from 0° to 90° which has a measured resistance value between 9030 Ω to 13000 Ω. Given the resistance value varies in line enough with the door angle, it is difficult to interpret the data directly. Averagely, every degree the door turned is equivalent to 30Ω drop on flexi sensor measurement.

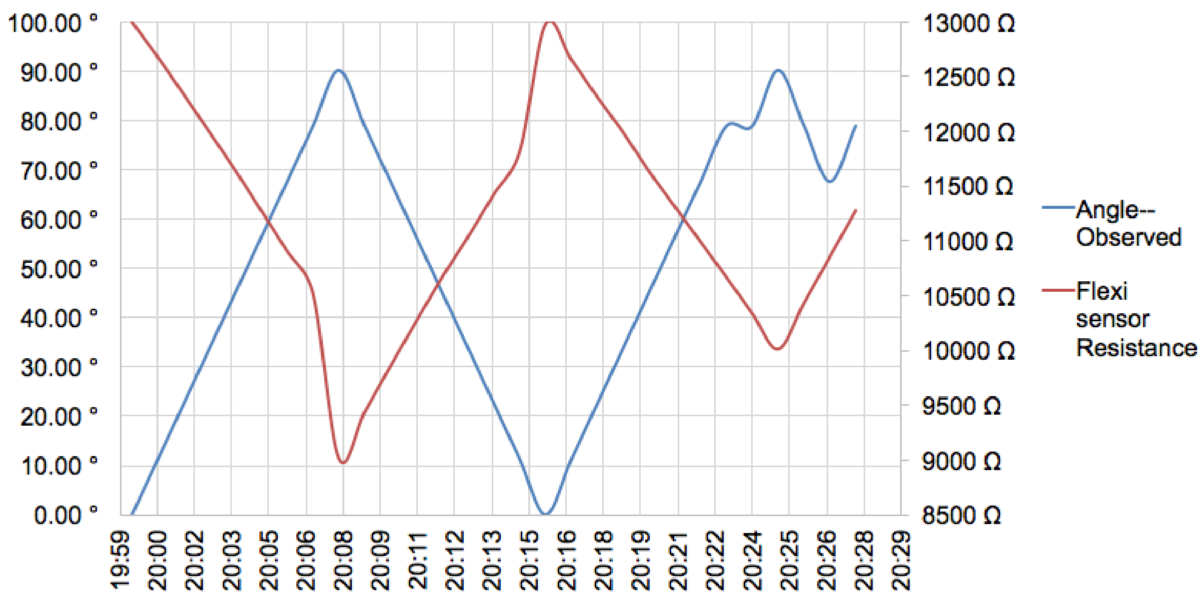


Figure 5.49: Comparison of observed and measured door angle, Flexi sensor

5.4.3 Rotary position sensor

A rotary resistive position sensor was selected to test the measurement accuracy on the same door where flexi sensor was tested simultaneously. It measured the same positions that a door was manually adjusted. Figure 5.50 shows its resistance value that compared with door angles. The rotary position sensor is capable of measuring from 0° to 330° with resistive range of 2500 Ω to 10000 Ω. The measured resistance value of rotary position sensor match very well with tested door at various angles with great consistence in terms of its readings.

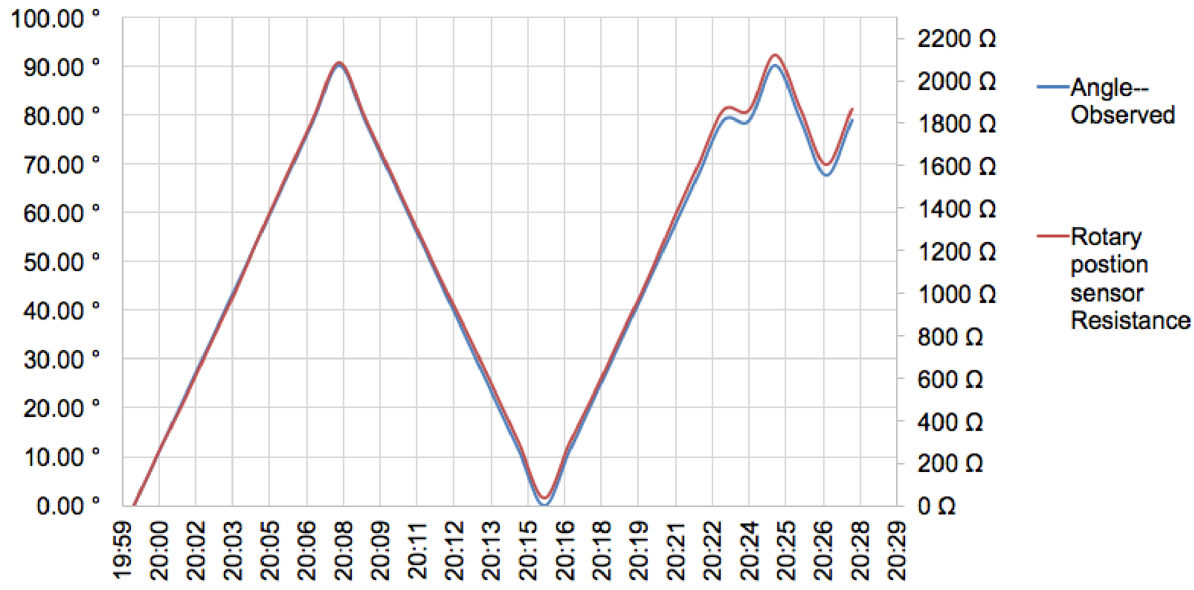


Figure 5.50: Comparison of observed and measured door angle, rotary position sensor

5.4.4 Single contact switch

Prior to long term monitoring, two combination of single contact switch and different data loggers have been tested in dwelling 3 the office environment, one is pulse counter with interval setting and other one is pulse counter with event setting. The major difference between two methods is the resolution of data points. Pulse counter with interval has fixed data format which presents the number of times that a contact switch trigged within that interval. The longer the interval is set, the fewer data points at cost of less detailed measurement. The event logger takes exactly the time when a contact switch is triggered, whose raw data does not have fixed time interval.

Given the simplicity of contact switches is only magnet triggered and gives either open or close status, both types of loggers have been tested for 5 working days, with same contact switches installed in dwelling 3 the tested office at different settings each day. The event logger is not changeable, but the pulse counter was set to record total number of pulses at 1 minute, 5 minutes, 15 minutes, 30 minutes and 60 minutes respectively for these 5 days. Figure 5.xx to 5.xx shows the comparison result between them with regards to number of times that windows and doors being opened and closed.

Table 5.7: Comparison of pulse between pulse counter and event logger

	1 minute		5 minutes		15 minutes		30 minutes		60 minutes	
Hour	**Pulse counter**	**Event logger**	**Pulse counter**	**Event logger**	**Pulse counter**	**Event logger**	**Pulse counter**	**Event logger**	**Pulse counter**	**Event logger**
00:00	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0	0	0	0
05:00	0	0	0	0	0	0	0	0	0	0
06:00	4	4	4	4	2	2	2	2	0	0
07:00	0	0	0	0	0	0	0	0	4	4
08:00	1	1	0	0	4	5	1	1	1	1
09:00	12	15	3	3	4	3	1	1	3	3
10:00	4	4	4	4	4	4	4	4	4	4
11:00	0	0	10	13	0	0	0	0	0	0
12:00	5	5	5	5	5	5	5	5	5	5
13:00	1	1	1	1	1	1	1	1	1	1
14:00	4	4	3	3	9	13	4	4	4	4
15:00	0	0	0	0	0	0	0	0	0	0
16:00	10	12	0	0	0	0	0	0	0	0
17:00	3	3	3	3	4	4	8	8	13	17
18:00	0	0	0	0	0	0	0	0	0	0
19:00	0	0	0	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0

As listed in table 5.7, the total number of contact switches being triggered are almost completely identical except several occasions when event logger seems counted a few more than the pulse counter measured, despite its interval length settings. Longer interval settings, such like 60 minutes, cannot provide enough evidence on this occasions to examining exactly what caused the difference count. There is one thing in common that intensive triggering a contact switch seems to generate higher number of pulse to event logger due to its higher sensitivity. A close examination of the monitoring date on day 1 whose pulse counter was set to 1 minute interval supported this hypothesis. In general, pulse counter and event logger are matching very closely to each other.

Operations of two bedroom windows and front door have been monitored simultaneously from June 2011 to Mar 2012. One bedroom window, one bathroom window, the front door have been individually monitored, plus the kitchen/garden door at Dwelling 6. Their opening times are illustrated in figure 5.51 and listed in table 5.8.

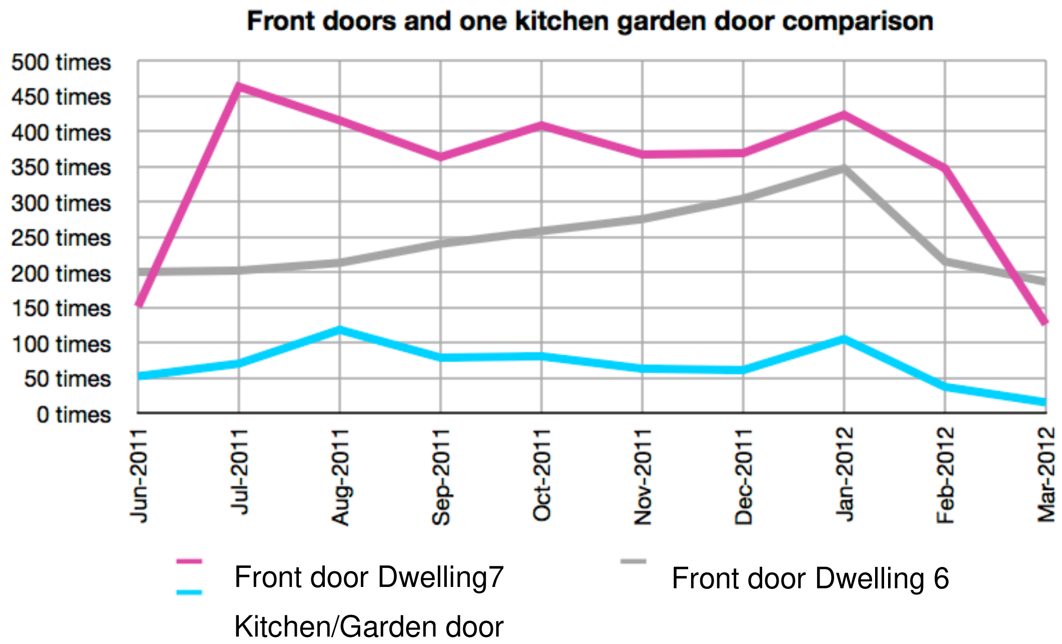


Figure 5.51: Door opening times comparison between dwelling 6 and 7

Table 5.8: Door opening times comparison between dwelling 6 and 7

Monthly	Front Door-Dwelling 7	Kitchen/Garden door Dwelling 7	Front Door-Dwelling 6	Kitchen/Garden door Dwelling 6
Jun-2011	151	Not in use	201	52
Jul-2011	463		202	70
Aug-2011	415		213	118
Sep-2011	363		240	78
Oct-2011	408		258	80
Nov-2011	366		275	62
Dec-2011	368		304	60
Jan-2012	423		347	105
Feb-2012	347		215	37
Mar-2012	126		186	15

It can be seen that in July 2011 that front door of dwelling 7 has been opened 463 times, averagely 15 times per day. Dwelling 6's front door was opened 202 times in the same month, equivalent to 7 times per day. Over the whole 10 months, dwelling 7's front door has been opened more frequently than dwelling 6. Front door's opening usually represents the frequency of occupant entering and exiting the bungalow.

The opening frequency of dwelling 6's front door gradually rises until Jan 2012 then drops. This may be explained by one the habit that the occupants have. The front door area of dwelling 6 has another function which is used as a covered smoking spot even had a cigarette butt collector installed to the external wall. It was observed several times that during the winter occupants of dwelling6 used the front door as first choice of smoking spot instead of the kitchen/garden door. While smoking, occupants in dwelling 6 often left the door partially open and they are aware of opened door may lead to the loss of warmth in the kitchen.

Regarding the bedroom windows operation, window 1 of dwelling 7 have been opened up to 288 times in July 2011 the frequency continues to drop. Window 1 is the kid's bedroom window and the parents do not want kid's bedroom to be over ventilated too cold during the winter, as a result, the window are operated less frequently in the wintery month than summer. The same tendency is also found in Window 1 of dwelling 6.

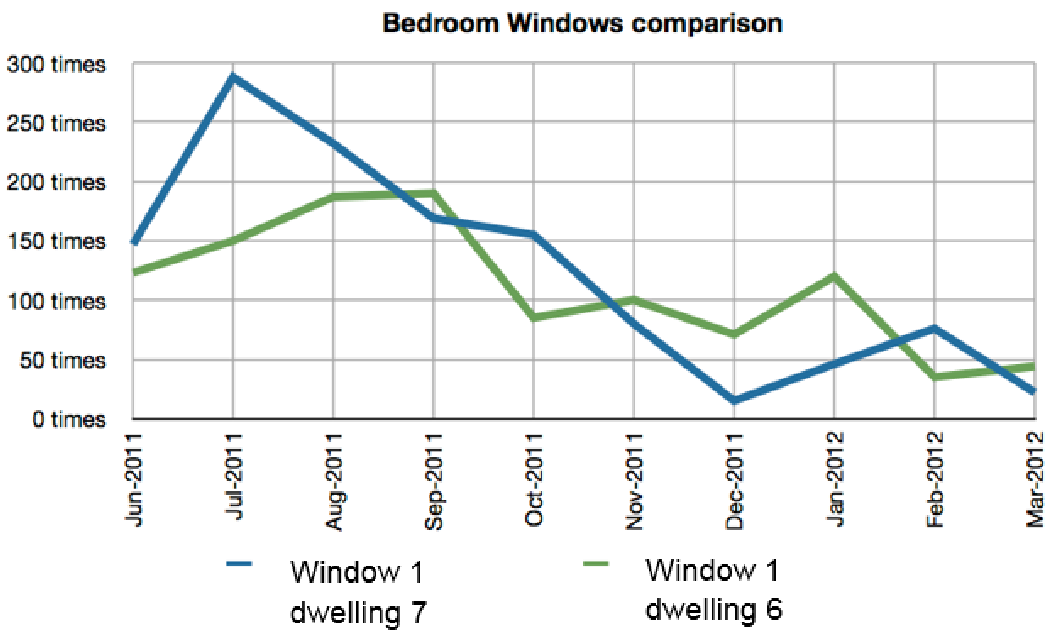


Figure 5.52: Bedroom window opening behaviour comparison

Table 5.9: Bedroom window opening behaviour comparison

Monthly	Window 1 Dwelling 7	Window 1- Dwelling 6
Jun-2011	147	123
Jul-2011	288	150
Aug-2011	232	187
Sep-2011	169	190
Oct-2011	155	85
Nov-2011	80	100
Dec-2011	15	71
Jan-2012	46	120
Feb-2012	76	35
Mar-2012	22	44

Window 2 belongs to the bedroom bathroom in both dwellings. Since the houses were built with high standard especially the air tightness, occupants always ventilate their bathroom after use to prevent condensation and unpleasant mould growing issue. Both Window 2s have very stable opening frequency from summer to winter. The only difference is that dwelling 7's Window 2 have been opened less frequently in winter than summer. Occupant of dwelling 6 operates its window 2 slightly more often in winter. Over all, dwelling 6's operates window 2 more than its neighbour dwelling 7.

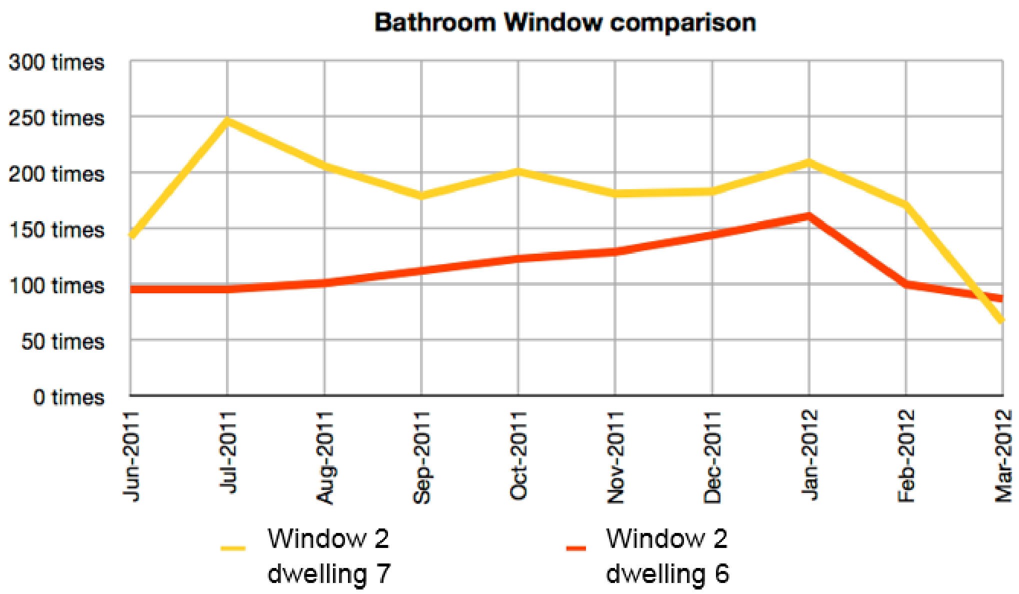


Figure 5.53: Bathroom window opening behaviour comparison

Table 5.10: Bathroom window opening behaviour comparison

Monthly	Window 2-dwelling 7	Window 2-Dwelling 6
Jun-2011	142	96
Jul-2011	246	96
Aug-2011	206	101
Sep-2011	179	112
Oct-2011	201	123
Nov-2011	181	129
Dec-2011	183	144
Jan-2012	209	161
Feb-2012	171	100
Mar-2012	66	87

5.5 Electrical appliance and lighting

There are two methods have been applied in participated households, namely, current transducer with and socket appliance sensor, either one or both methods are applied in dwelling 1 to 8, exclude dwelling 3.

5.5.1 Current transducer and voltage

The main differences between current transducer and socket appliance is real time voltage measurement. Current transducer measures the only electric current and multiplies with a fixed voltage value in order to calculate electricity consumption, unlike individual socket sensor which measures real-time values of both. Theoretically, the latter is more accurate as voltage can slightly fluctuate from household to household. Table 5.11 compares the difference between measured total electricity usage and actual meter readings for various number of days.

Table 5.11: Actual meter reading and Current transducer measurement comparison

	Number of days	Actual meter readings	Current transducer measurement	Error rate
Dwelling 1	56	674 kWh	573 kWh	15%
Dwelling 2	42	1047 kWh	921 kWh	12%
Dwelling 4	89	588 kWh	488 kWh	17%
Dwelling 5	165	2354 kWh	2119 kWh	10%
Dwelling 6	141	1369 kWh	1164 kWh	15%
Dwelling 7	121	2050 kWh	1825 kWh	11%
Dwelling 8	18	155 kWh	127 kWh	18%

The measured electricity consumption values of all householder are 10% to 18% lower than the actual metering reading results. It seems that the longer the monitoring period, the lower the error rate. It is possibly caused by the variation of voltage

One set of trial current transducer based electricity monitoring system does actually measure the real time voltage. It was briefly tested for 24 hours at dwelling 1, side by side with current transducer without voltage input monitoring system (figure 5.54).

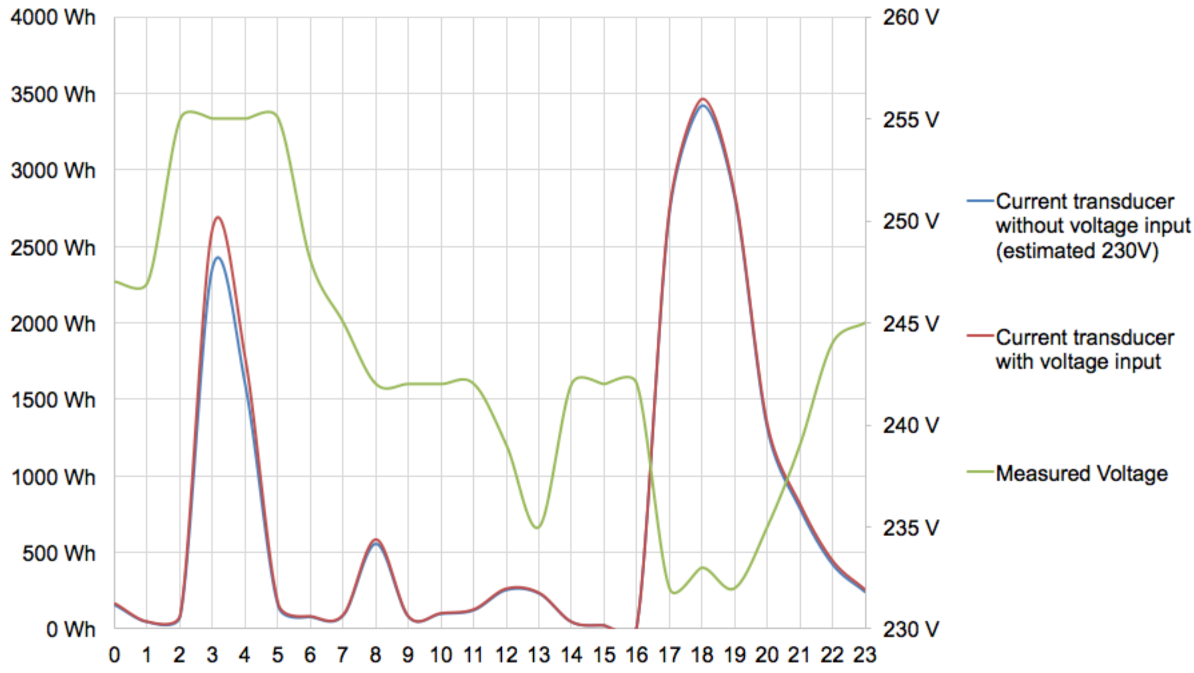


Figure 5.54: Comparison between current transducer with and with voltage measurement

The total electricity consumption of meter reading of these 24 hours is 18911 Wh, while current transducer with and without voltage show 18475 Wh and 17234 Wh respectively. Both measured electricity consumptions are lower than actual usage calculated by main meter readings, current transducer with voltage input is only 2.6% lower, whereas current transducer without voltage input is 9% lower. Over these 24 hours, the voltage varied from 232V to 255 V, such fluctuation seems to the reason of lower measured consumption taken by sensor without voltage. A close examination show positive relationship between the difference of these two monitoring system and real time voltage measure (table 5.12).

Table 5.12: Comparison between current transducer with and without voltage input

Hour	Electricity consumption measurement difference	Voltage difference
0	7.39%	17 V
1	7.39%	17 V
2	10.87%	25 V
3	10.87%	25 V
4	10.87%	25 V
5	10.87%	25 V
6	7.83%	18 V
7	6.52%	15 V

8	5.22%	12 V
9	5.22%	12 V
10	5.22%	12 V
11	5.22%	12 V
12	3.91%	9 V
13	2.17%	5 V
14	5.22%	12 V
15	5.22%	12 V
16	5.22%	12 V
17	0.87%	2 V
18	1.30%	3 V
19	0.87%	2 V
20	2.17%	5 V
21	3.91%	9 V
22	6.09%	14 V
23	6.52%	15 V

The difference between current transducer with and without voltage import directly affect the accuracy of measured electricity consumption. The error increases proportionally with the difference between actual voltage and estimated voltage setting. Where absolute accuracy is required, it is probably best to choose current transducer with voltage input as up to 10.87% difference was found in field study. Measuring voltage requires electrician to connect since it need direct wiring to the live line with high voltage, therefore, increase the cost and invasiveness of installation.

5.5.2 Socket appliance sensor and current transduce

In dwelling 6, the sub circuits for all sockets in kitchen were monitored simultaneously by individual socket sensor and current transducer. The accuracy of socket appliance sensor has been compared with current transducer without voltage input. The most detailed level of measurement current transducer could take is whole sub-circuit. Therefore, for the testing period of 14 days, every appliance in the kitchen was installed either with its own dedicated socket sensor or shared with power strips. All the sockets in the kitchen, namely, kettle, hob, oven, microwave fryer, washing machine, tumble dryer, TV, fridge-freezer, and miscellaneous sockets, are added up to compare with current transducer measured electricity (table 5.13).

Table 5.13: Comparison between current transducer and socket sensor measurement

	Current transduce for kitchen Sub-circuit	**Total socket sensor measurement**
Day 1	3578 Wh	3907 Wh
Day 2	3614 Wh	3939 Wh
Day 3	3579 Wh	3865 Wh
Day 4	3615 Wh	3940 Wh
Day 5	3796 Wh	4061 Wh
Day 6	3871 Wh	4173 Wh
Day 7	5807 Wh	6330 Wh
Day 8	3484 Wh	3801 Wh
Day 9	5575 Wh	5965 Wh
Day 10	2787 Wh	3038 Wh
Day 11	4739 Wh	5118 Wh
Day 12	3317 Wh	3516 Wh
Day 13	2322 Wh	2531 Wh
Day 14	3483 Wh	3796 Wh

Total electricity consumption added by all the socket sensors' measurement in the kitchen is slightly higher than the current transducer for every day of this monitoring period. The selected current transducer has a default estimated voltage of 230V, where spot measurement of socket voltage are all above 240V which can be the cause of higher but more accurate measurement taken by socket sensor.

Total number of socket sensors in this studying kitchen is 12, due to each unit has limited power rate restriction. Appliance with higher power rate, such like fryer, kettle and tumble dryer must have its own socket sensor rather than one with power strip extension. After 14 days, the sensor installed for kettle become broken, possibly due to momentary current overload of this kettle (power rated 2000kW).

The only downside of socket appliance sensor is probably the cost in this study, in domestic environment, the number of high power rated appliance can be high and as a result the cost may increase. The selected sensor, Plugwise, worked very well in terms of built-in memory and wireless system. Data collection could be done without entering the house as long as within its network coverage. Accuracy wise, socket appliance sensor measured higher electricity usage than current transducer without voltage import. This is consistent with the previous comparison where CT with voltage is generally lower.

5.5.3 Long term electricity monitoring for off-gas dwellings

All the six sub electrical circuits of dwelling 6 and 7 have been monitor continuously for 14 months in total, with an exception at dwelling 6 when a power failure occurred during April and May 2011.

Table 5.14: Monthly summary of electricity consumption in dwelling 6

Monthly	ASHP	Immersion Heater	Cooker	Kitchen Socket	Other Sockets	Lighting	Total consumption
2011-Jan	375 kWh	74 kWh	22 kWh	130 kWh	237 kWh	44 kWh	**882 kWh**
2011-Feb	261 kWh	49 kWh	20 kWh	90 kWh	138 kWh	37 kWh	**595 kWh**
2011-Mar	171 kWh	26 kWh	20 kWh	81 kWh	94 kWh	37 kWh	**429 kWh**
2011-Apr	Missing data						
2011-May							
2011-Jun	55 kWh	10 kWh	12 kWh	74 kWh	43 kWh	5 kWh	**199 kWh**
2011-Jul	77 kWh	14 kWh	24 kWh	128 kWh	173 kWh	8 kWh	**424 kWh**
2011-Aug	90 kWh	3 kWh	38 kWh	37 kWh	175 kWh	9 kWh	**352 kWh**
2011-Sep	88 kWh	11 kWh	31 kWh	43 kWh	109 kWh	9 kWh	**291 kWh**
2011-Oct	145 kWh	17 kWh	25 kWh	103 kWh	158 kWh	18 kWh	**466 kWh**
2011-Nov	223 kWh	16 kWh	33 kWh	73 kWh	146 kWh	31 kWh	**522 kWh**
2011-Dec	344 kWh	12 kWh	22 kWh	103 kWh	119 kWh	41 kWh	**641 kWh**
2012-Jan	226 kWh	13 kWh	24 kWh	130 kWh	237 kWh	44 kWh	**674 kWh**
2012-Feb	180 kWh	12 kWh	23 kWh	90 kWh	138 kWh	37 kWh	**480 kWh**
2012-Mar	111 kWh	16 kWh	21 kWh	81 kWh	94 kWh	37 kWh	**360 kWh**

The rest months show good mixture of electricity end used over seasons. ASHP and immersion usage change significantly from winter to summer. ASHP supplies space heating and domestic hot water while immersion heater acts as backup option when ASHP cannot cope large and sudden hot water demand especially under cold climatic conditions. Peak consumption of ASHP and immersion heater usage are found in December 2010. As listed in table 5.xx, in December 2010 ASHP circuit used 508 kWh and immersion heater consumed 112kWh. Both ASHP and immersion heater consumption decreased sharply in January 2012 and continued to drop gradually. Lowest ASHP electricity consumption occurred in June 2011, only 55kWh that is almost 90% less. Immersion heater consumed only 3kWh for the whole month in August. Lighting usage also varied along with season nicely. Summer month used up to eight times less than winter possible due to longer daylight hour.

Proportionally, the distribution of every sub circuits are listed and illustrated in table 5.15 and figure 5.55 respectively. During wintery months, ASHP and other sockets usually take the highest of part of electricity consumption of whole house.

Table 5.15: Monthly percentage of electricity consumption in dwelling 6

Monthly	ASHP	Immersion Heater	Cooker	Kitchen Socket	Other Sockets	Lighting
2011-Jan	43%	8%	2%	15%	27%	5%
2011-Feb	44%	8%	3%	15%	23%	6%
2011-Mar	40%	6%	5%	19%	22%	9%
2011-Apr	Missing data					
2011-May						
2011-Jun	28%	5%	6%	37%	22%	3%
2011-Jul	18%	3%	6%	30%	41%	2%
2011-Aug	26%	1%	11%	11%	50%	3%
2011-Sep	30%	4%	11%	15%	37%	3%
2011-Oct	31%	4%	5%	22%	34%	4%
2011-Nov	43%	3%	6%	14%	28%	6%
2011-Dec	54%	2%	3%	16%	19%	6%
2012-Jan	34%	2%	4%	19%	35%	7%
2012-Feb	38%	3%	5%	19%	29%	8%
2012-Mar	31%	4%	6%	23%	26%	10%

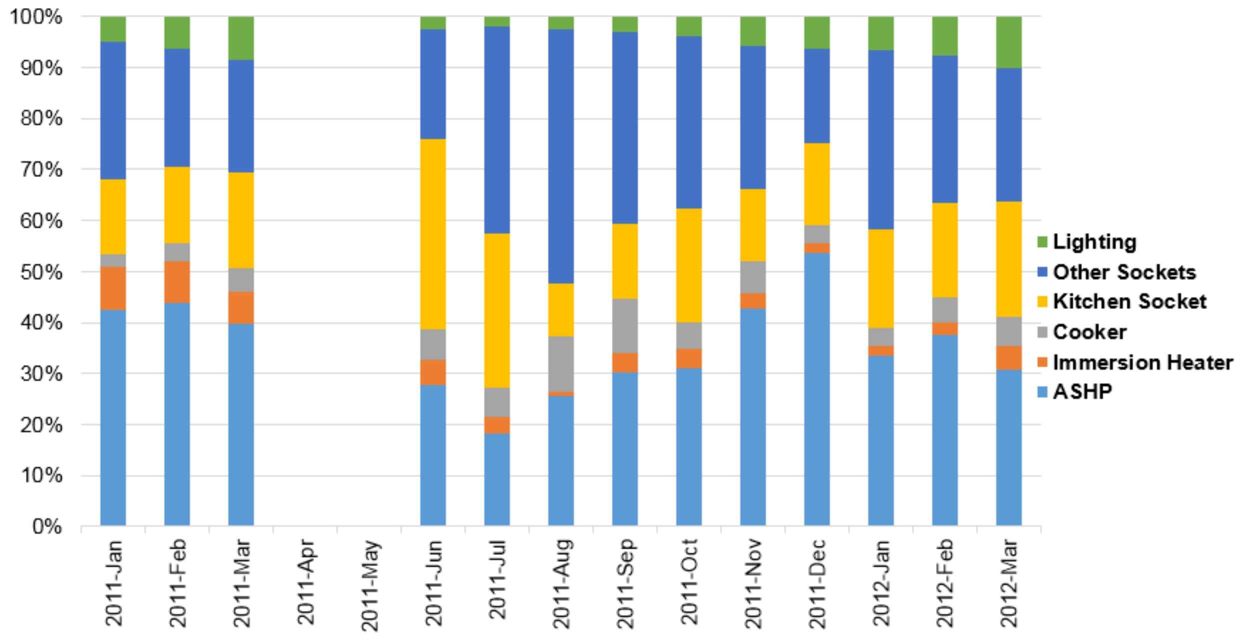


Figure 5.55: Monthly percentage summary of electricity consumption in dwelling 6

Dwelling 7 has been monitored simultaneously with it neighbour, as listed in table 5.16, highest ASHP consumption months are January 2011 and Feb 2012. In January 2011, ASHP consumed 444kWh and 530 kWh respectively. Lowest ASHP usage was June 2011 that only consumed 108 kWh. Immersion water heater consumption has been relatively stable throughout winter and summer. The highest immersion heater consumption was in August 2010, one of the warmest months in summer. The lowest month was February 2011 in the winter.

Table 5.16: Monthly summary of electricity consumption in dwelling 6

Month	ASHP	Immersion Heater	Cooker	Kitchen Socket	Other Sockets	Lighting	Total consumption
2011-Jan	444 kWh	135 kWh	38 kWh	190 kWh	267 kWh	49 kWh	**1123 kWh**
2011-Feb	286 kWh	87 kWh	24 kWh	122 kWh	172 kWh	42 kWh	**733 kWh**
2011-Mar	403 kWh	149 kWh	31 kWh	156 kWh	322 kWh	42 kWh	**1103 kWh**
2011-Apr	183 kWh	138 kWh	36 kWh	178 kWh	249 kWh	25 kWh	**809 kWh**
2011-May	197 kWh	148 kWh	45 kWh	225 kWh	276 kWh	28 kWh	**919 kWh**
2011-Jun	108 kWh	103 kWh	32 kWh	158 kWh	294 kWh	19 kWh	**714 kWh**
2011-Jul	136 kWh	105 kWh	39 kWh	194 kWh	344 kWh	23 kWh	**841 kWh**
2011-Aug	156 kWh	181 kWh	52 kWh	262 kWh	317 kWh	24 kWh	**992 kWh**
2011-Sep	184 kWh	121 kWh	39 kWh	194 kWh	322 kWh	24 kWh	**884 kWh**
2011-Oct	251 kWh	156 kWh	47 kWh	235 kWh	317 kWh	38 kWh	**1044 kWh**
2011-Nov	343 kWh	156 kWh	46 kWh	232 kWh	294 kWh	36 kWh	**1107 kWh**
2011-Dec	435 kWh	180 kWh	46 kWh	229 kWh	276 kWh	46 kWh	**1212 kWh**
2012-Jan	449 kWh	139 kWh	62 kWh	311 kWh	322 kWh	49 kWh	**1332 kWh**
2012-Feb	530 kWh	125 kWh	52 kWh	260 kWh	249 kWh	42 kWh	**1258 kWh**
2012-Mar	343 kWh	129 kWh	43 kWh	216 kWh	267 kWh	42 kWh	**1040 kWh**

In terms of percentage, ASHP consumption in dwelling 7 varied well with season, reached up to 42% in each winter. From January 2011, ASHP consumption gradually reduced until June, and began to rise again until February 2012. Compared with ASHP, immersion heater, cooker, kitchen sockets and lighting are relatively more stable. Consumption of other sockets increased substantially in summer, up to 41% in June and July.

Table 5.16: Monthly percentage of electricity consumption in dwelling 7

Monthly	ASHP	Immersion Heater	Cooker	Kitchen Socket	Other Sockets	Lighting
2011-Jan	40%	12%	3%	17%	24%	4%
2011-Feb	39%	12%	3%	17%	23%	6%
2011-Mar	37%	14%	3%	14%	29%	4%
2011-Apr	23%	17%	4%	22%	31%	3%
2011-May	21%	16%	5%	24%	30%	3%
2011-Jun	15%	14%	4%	22%	41%	3%
2011-Jul	16%	12%	5%	23%	41%	3%
2011-Aug	16%	18%	5%	26%	32%	2%
2011-Sep	21%	14%	4%	22%	36%	3%
2011-Oct	24%	15%	5%	23%	30%	4%
2011-Nov	31%	14%	4%	21%	27%	3%
2011-Dec	36%	15%	4%	19%	23%	4%
2012-Jan	34%	10%	5%	23%	24%	4%
2012-Feb	42%	10%	4%	21%	20%	3%
2012-Mar	33%	12%	4%	21%	26%	4%

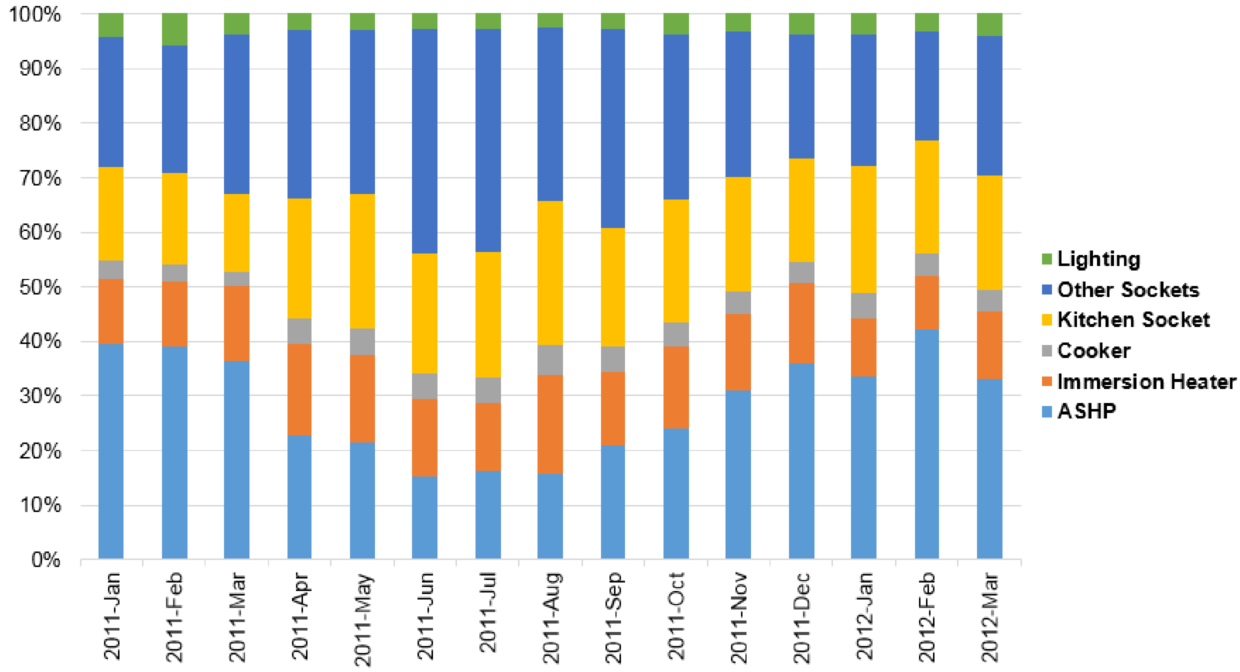


Figure 5.56: Monthly percentage summary of electricity consumption in dwelling 7

5.6 Indoor physical environment

Detailed monitoring data of household are presented in later section where participated dwellings are compared. In general, both standing alone and wireless sensor and loggers are very well functional. Wireless monitoring system has one weakness that it relies on the on site computer to receive and record measurement. There are a few times that the on-site computers were powered off due to unforeseen reasons and caused data loss.

The number of available sensors reached peak while studying dwelling 6. There was period that the living room and kitchen were installed with multiple temperature and humidity sensors in order to compare the effect of different locations within the same room.

5.6.1 Location of temperature measurement in same room

For the testing period, three Tinytag temperature and humidity loggers have been installed in the living room for a 28 days period. They were placed near entrance, under window and the decorative fireplace. They are all place away from radiator and direct sunlight and any other direct heat source.

Figure 5.57: Different locations temperature humidity logger in living room –dwelling 6, top left: near window, top right: near entrance, bottom: fireplace

The average hourly temperature measurements taken from these three locations are listed in table 5.17. All the sensors were calibrated before installation and have accuracy of 0.01˚C. Comparing the hourly temperature measurements and their standard deviations, most of the results are exactly the same, except fireplace and window side. It seems that the temperature taken from the window side is slightly lower than the other two, the highest difference is 0.12˚C. During the day time, the measurement taken by sensor near the entrance are slightly higher, which is possibly caused by its furthest distance from external wall.

Table 5.17: Temperature comparison of multiple sensors in living room of dwelling 6

Hour	Fireplace	Fireplace standard deviation	Near window	Near window standard deviation	Near entrance	Near entrance standard deviation
0	19.75 ˚C	0.66 ˚C	19.77 ˚C	0.65 ˚C	19.77 ˚C	0.66 ˚C
1	19.72 ˚C	0.66 ˚C	19.70 ˚C	0.64 ˚C	19.74 ˚C	0.66 ˚C
2	19.60 ˚C	0.64 ˚C	19.51 ˚C	0.65 ˚C	19.62 ˚C	0.64 ˚C
3	19.43 ˚C	0.62 ˚C	19.30 ˚C	0.64 ˚C	19.45 ˚C	0.63 ˚C
4	19.25 ˚C	0.62 ˚C	19.07 ˚C	0.62 ˚C	19.27 ˚C	0.62 ˚C
5	19.07 ˚C	0.59 ˚C	18.89 ˚C	0.59 ˚C	19.09 ˚C	0.59 ˚C
6	18.91 ˚C	0.60 ˚C	18.70 ˚C	0.60 ˚C	18.93 ˚C	0.60 ˚C
7	18.81 ˚C	0.60 ˚C	18.59 ˚C	0.62 ˚C	18.83 ˚C	0.60 ˚C
8	18.75 ˚C	0.56 ˚C	18.58 ˚C	0.58 ˚C	18.77 ˚C	0.56 ˚C
9	18.72 ˚C	0.52 ˚C	18.55 ˚C	0.51 ˚C	18.74 ˚C	0.52 ˚C
10	18.68 ˚C	0.47 ˚C	18.54 ˚C	0.48 ˚C	18.70 ˚C	0.47 ˚C
11	18.71 ˚C	0.49 ˚C	18.64 ˚C	0.50 ˚C	18.73 ˚C	0.50 ˚C
12	18.75 ˚C	0.52 ˚C	18.67 ˚C	0.53 ˚C	18.77 ˚C	0.52 ˚C
13	18.75 ˚C	0.53 ˚C	18.68 ˚C	0.55 ˚C	18.77 ˚C	0.53 ˚C
14	18.70 ˚C	0.70 ˚C	18.64 ˚C	0.68 ˚C	18.72 ˚C	0.70 ˚C
15	18.60 ˚C	0.91 ˚C	18.55 ˚C	0.88 ˚C	18.62 ˚C	0.91 ˚C
16	18.76 ˚C	0.62 ˚C	18.73 ˚C	0.66 ˚C	18.78 ˚C	0.62 ˚C
17	18.92 ˚C	0.58 ˚C	18.93 ˚C	0.59 ˚C	18.94 ˚C	0.58 ˚C
18	19.10 ˚C	0.59 ˚C	19.10 ˚C	0.59 ˚C	19.12 ˚C	0.59 ˚C
19	19.23 ˚C	0.57 ˚C	19.25 ˚C	0.56 ˚C	19.24 ˚C	0.57 ˚C
20	19.32 ˚C	0.59 ˚C	19.34 ˚C	0.58 ˚C	19.34 ˚C	0.59 ˚C
21	19.42 ˚C	0.60 ˚C	19.43 ˚C	0.58 ˚C	19.44 ˚C	0.60 ˚C
22	19.52 ˚C	0.63 ˚C	19.53 ˚C	0.59 ˚C	19.54 ˚C	0.63 ˚C
23	19.66 ˚C	0.63 ˚C	19.68 ˚C	0.62 ˚C	19.68 ˚C	0.63 ˚C

The same pattern is found with measurement of three locations in the kitchen (table 5.18), namely, worktop, near internal door and under the window (figure5.58).

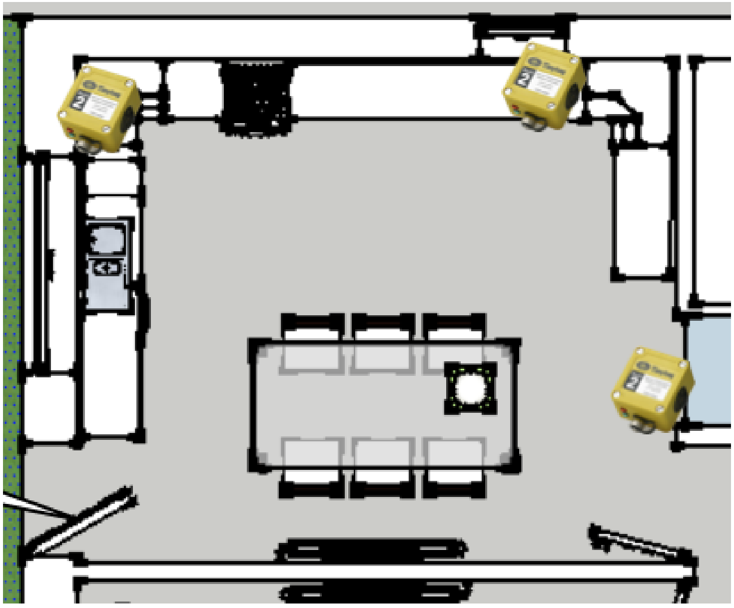


Figure 5.58: Different locations temperature humidity logger in living room –dwelling 6, top left: worktop, top right: under the window and bottom right: near internal door

Table 5.18: Temperature comparison of multiple sensors in kitchen of dwelling 6

Hour	Worktop	Worktop standard deviation	under window	under window standard deviation	Near internal door	Near internal door standard deviation
0	19.42 ˚C	0.90 ˚C	19.35 ˚C	0.53 ˚C	19.44 ˚C	0.93 ˚C
1	19.37 ˚C	0.90 ˚C	19.23 ˚C	0.56 ˚C	19.39 ˚C	0.93 ˚C
2	19.25 ˚C	0.90 ˚C	19.01 ˚C	0.58 ˚C	19.27 ˚C	0.93 ˚C
3	19.09 ˚C	0.90 ˚C	18.82 ˚C	0.59 ˚C	19.11 ˚C	0.92 ˚C
4	18.98 ˚C	0.91 ˚C	18.69 ˚C	0.62 ˚C	19.00 ˚C	0.94 ˚C
5	18.86 ˚C	0.92 ˚C	18.50 ˚C	0.62 ˚C	18.88 ˚C	0.94 ˚C
6	18.75 ˚C	0.90 ˚C	18.44 ˚C	0.62 ˚C	18.76 ˚C	0.93 ˚C
7	18.68 ˚C	0.91 ˚C	18.34 ˚C	0.60 ˚C	18.70 ˚C	0.94 ˚C
8	18.63 ˚C	0.88 ˚C	18.32 ˚C	0.55 ˚C	18.64 ˚C	0.90 ˚C
9	18.55 ˚C	0.80 ˚C	18.26 ˚C	0.52 ˚C	18.57 ˚C	0.82 ˚C
10	18.56 ˚C	0.75 ˚C	18.32 ˚C	0.57 ˚C	18.58 ˚C	0.77 ˚C
11	18.60 ˚C	0.76 ˚C	18.36 ˚C	0.56 ˚C	18.61 ˚C	0.78 ˚C
12	18.63 ˚C	0.68 ˚C	18.42 ˚C	0.63 ˚C	18.65 ˚C	0.70 ˚C
13	18.75 ˚C	0.71 ˚C	18.55 ˚C	0.65 ˚C	18.76 ˚C	0.73 ˚C
14	18.78 ˚C	0.70 ˚C	18.64 ˚C	0.69 ˚C	18.80 ˚C	0.72 ˚C
15	18.83 ˚C	0.70 ˚C	18.67 ˚C	0.73 ˚C	18.85 ˚C	0.73 ˚C

Hour	Worktop	Worktop standard deviation	under window	under window standard deviation	Near internal door	Near internal door standard deviation
16	18.85 ˚C	0.74 ˚C	18.67 ˚C	0.67 ˚C	18.87 ˚C	0.76 ˚C
17	18.91 ˚C	0.76 ˚C	18.76 ˚C	0.65 ˚C	18.93 ˚C	0.78 ˚C
18	18.98 ˚C	0.76 ˚C	18.84 ˚C	0.67 ˚C	19.00 ˚C	0.78 ˚C
19	19.05 ˚C	0.81 ˚C	18.96 ˚C	0.61 ˚C	19.07 ˚C	0.83 ˚C
20	19.09 ˚C	0.84 ˚C	19.00 ˚C	0.63 ˚C	19.11 ˚C	0.87 ˚C
21	19.14 ˚C	0.87 ˚C	19.05 ˚C	0.56 ˚C	19.16 ˚C	0.89 ˚C
22	19.25 ˚C	0.88 ˚C	19.19 ˚C	0.52 ˚C	19.27 ˚C	0.90 ˚C
23	19.39 ˚C	0.88 ˚C	19.32 ˚C	0.49 ˚C	19.41 ˚C	0.91 ˚C

It can be seen that in both tested room. The temperature variation between different measurement locations is not greater than 0.45°C. This is potentially a joint result of the built-error of Tinytag logger and activity type in the room. Manufacturer claimed reading accuracy is 0.01°C or better and each logger had been calibrated before installation. There is still room for measurement and each logger may have small response difference built-in with itself. Despite this possible source of error, the standard deviation in living room is generally lower than measurement taken in kitchen. This is possibly caused by the use of appliances and cooking activities that occurred in the kitchen with unregulated heat gains. In general, the difference is within an acceptable range where a central location cannot be permitted to install sensor at.

5.6.2 Temperature and humidity of different room

Dwelling 1

Dwelling 1 has relatively smaller space and all the radiators have to be controlled individually. Its kitchen and living room are one connected open space. Table 5.19 compared the mean and standard deviation of air temperature and relative humidity measurement of various room during heating season for 14 days. Given the fact that this apartment does not have central heating, the mean air temperature of bedroom centre, living centre, hallway and bathroom centre are almost identical. Living room centre and bathroom centre are 0.2°C higher, possibly due to the cooking and shower activity. Kitchen area is 0.9°C warmer than the next adjacent sensor at living room entrance. Both windows in bedroom and living room are slightly colder than the central spot measurement of each room.

Kitchen has the highest temperature deviation, 5.45°C, however, it seems that the cook activities did not affect the living room entrance and centre which have identical standard deviation of 2.45°C. Living room window has higher temperature fluctuation which is possibly caused by heat loss through window operation. The next highest standard temperature deviation is found at bathroom where sensor placed next to the shower enclosure, potentially can be explained by the heat of hot water.

Table 5.19: Indoor air temperature and relative humidity in dwelling 1

	Mean air temperature	Temperature Std Dev	Mean relative humidity	Relative humidity Std Dev
Bedroom centre	25.00°C	1.95°C	67.20%	6.55%
Bedroom next to window	24.40°C	2.05°C	67.10%	9.75%
Kitchen	25.90°C	5.45°C	64.50%	31.05%
Living room Entrance	25.00°C	2.45°C	65.40%	8.45%
Living room next to window	23.90°C	3.45°C	67.10%	11.25%
Living room centre	25.20°C	2.45°C	64.00%	7.40%
Bathroom Centre	25.20°C	2.45°C	69.00%	18.05%
Bathroom next to Shower	25.10°C	2.95°C	73.00%	22.00%
Hallway	25.00°C	1.90°C	69.10%	13.40%
Average	24.97°C	2.79°C	67.38%	14.21%

Highest mean relative humidity is found at the Bathroom as moisture relate activity can be expected to take place. The moisture seems transferred to the hallway which is a small space connecting living room and bedroom. Hallway mean relative humidity is higher than bedroom centre and living room entrance. The lowest mean relative humidity is the centre of living room.

In terms of standard humidity deviation, kitchen area has the highest value of 31.05%, and the then bathroom and hallway. Relative humidity deviated more nears windows of bedroom and living room than their centre spots.

Dwelling 2

As a two storey house, dwelling 2 contains clearly defined rooms. Similar to dwelling 1, the heating system is individually controlled and often at night time due to the financial concern of Economy-7 tariff and storage heater. 14-days' worth mean air temperature and relative humidity results are listed in table 5.20. Two bedroom are warmer than rest of rooms. Like what was found in dwelling 1, kitchen also has the highest temperature and relative humidity deviations in dwelling 2. The relative humidity deviated similarly as kitchen, which is possible caused by its space heating appliance which is a gas powered fire place. In dwelling 2, the temperature varied from room to room significantly, potentially due to its older building age, use of night storage heater and gas fireplace.

Table 5.20: Indoor air temperature and relative humidity in dwelling 2

Location	Mean air temperature	Temperature StdDev	Mean relative humidity	Relative humidity StdDev
Bedroom 1	19.20°C	4.55°C	46.20%	6.80%
Bedroom 2	18.20°C	4.75°C	45.74%	6.73%
Living room	15.50°C	6.75°C	52.60%	16.05%
Bathroom	15.74°C	5.78°C	60.84%	35.95%
Kitchen	15.60°C	7.45°C	52.07%	15.89%
Average	16.85°C	5.86°C	51.49%	16.28%

Dwelling 4 and dwelling 5

14 days during the winter have been selected and compared between dwelling 4 and 5, in table 5.21 and 5.22 separately. The same family moved from dwelling 4 to 5 and the selection of measurement are from two winters. Dwelling 5 is basically a fully upgraded version of dwelling 4. The space heating system is centrally controlled and during these 14 days, individual radiator have not been adjusted. Building structure-wise, dwelling 4 has is kitchen located at lower ground floor whereas dwelling has its kitchen adjacent to living room at ground level.

Table 5.21: Indoor air temperature and relative humidity in dwelling 4

Location	Mean air temperature	Temperature StdDev	Mean relative humidity	Relative humidity StdDev
Living room central	18.00°C	0.80°C	35.40%	14.55%
Master Bedroom Central	18.60°C	1.25°C	35.20%	13.45%
Bath room Central	18.90°C	0.95°C	37.90%	9.60%
Guest Bedroom Central	18.10°C	1.15°C	34.80%	14.75%
Kitchen Central	17.70°C	3.65°C	31.80%	20.55%
Hallway	18.10°C	1.80°C	31.40%	7.65%
Average	18.23°C	1.60°C	34.42%	13.43%

Table 5.22: Indoor air temperature and relative humidity in dwelling 5

Location	Mean air temperature	Temperature StdDev	Mean relative humidity	Relative humidity StdDev
Living room Central	20.90°C	2.90°C	34.65%	12.30%
Master bedroom Central	18.10°C	2.10°C	35.10%	11.75%
Bathroom Central	16.30°C	2.05°C	36.20%	13.75%
Guest bedroom Central	19.80°C	2.15°C	34.30%	14.55%
Kitchen Central	21.80°C	2.30°C	32.60%	18.15%
Hallway	19.60°C	2.15°C	34.40%	17.55%
Average	19.42°C	2.28°C	36.23%	14.68%

Comparing the mean results of measurement of same family, the temperature and standard deviation are stable in both dwellings. In dwelling 4, kitchen seems to have the lowest mean air temperature but twice the deviation than average. This was changed in dwelling 5 where kitchen became overall the warmest room. At a glance, it is fair to estimate that the family has preference of evenly heating every room in the both houses, where hydro-thermal measurements in dwelling 5 are slightly improved, perhaps due to its upgraded energy efficiency and fabric performance. Although the external weather was not exactly the same in each period, the standard deviations is also more constant across all the room in both dwelling 4 and 5.

Dwelling 6 and 7

Dwelling 6 and 7 were monitoring for 14-month continuously, during which dwelling 6 had a power failure with its on-site computer therefore caused missing data for April and May in 2011. Dwelling 7 fortunately did not experience any problem with data collection. Table 5.22 and 5.23 below show the mean monthly indoor temperature of different rooms of dwelling 6 and 7. Hallway bathroom of dwelling 7 was not part of this long term monitoring due to number of sensor available.

Both houses have ASHP driven space heating system and occupants claimed that they usually only adjust the space heating through thermostat located in hallway and very rarely turn off any individual radiator even a room in not in use.

Table 5.22: Indoor air temperature and relative humidity in dwelling 6

Month	Master Bedroom	Kitchen	Hallway	Living Room	Master Bathroom	Hallway Bathroom
2011-Jan	19.97°C	20.93°C	19.71°C	19.00°C	20.15°C	20.48°C
2011-Feb	20.77°C	20.31°C	20.26°C	19.58°C	20.48°C	20.04°C
2011-Mar	20.33°C	20.88°C	19.89°C	19.65°C	20.04°C	20.58°C
2011-Apr	missing data due to logger power failure					
2011-May						
2011-Jun	20.70°C	20.44°C	20.61°C	21.15°C	20.91°C	20.16°C
2011-Jul	22.03°C	20.50°C	23.39°C	21.58°C	20.58°C	20.26°C
2011-Aug	20.59°C	22.44°C	21.58°C	21.45°C	20.26°C	20.75°C
2011-Sep	21.50°C	22.43°C	21.52°C	20.75°C	20.75°C	21.34°C
2011-Oct	19.66°C	23.11°C	21.93°C	20.51°C	21.34°C	22.07°C
2011-Nov	19.48°C	20.73°C	20.61°C	20.04°C	22.07°C	19.19°C
2011-Dec	19.93°C	21.02°C	21.58°C	19.58°C	19.39°C	20.13°C
2012-Jan	19.97°C	21.06°C	19.07°C	19.12°C	20.08°C	20.43°C
2012-Feb	20.67°C	21.36°C	19.14°C	18.66°C	20.18°C	20.03°C
2012-Mar	20.23°C	21.16°C	19.51°C	19.00°C	19.94°C	20.28°C
Average	**20.45°C**	**21.41°C**	**20.68°C**	**20.01°C**	**20.47°C**	**20.44°C**

Table 5.23: Indoor air temperature and relative humidity in dwelling 7

Monthly	Master Bedroom	Kitchen	Hallway	Living Room	Hallway Bathroom
2011-Jan	21.26°C	18.96°C	21.55°C	22.47°C	21.08°C
2011-Feb	20.76°C	18.12°C	21.15°C	21.82°C	20.72°C
2011-Mar	20.38°C	17.11°C	21.15°C	22.07°C	20.64°C
2011-Apr	20.67°C	18.93°C	20.85°C	21.91°C	20.67°C
2011-May	20.34°C	18.84°C	21.82°C	21.68°C	20.42°C
2011-Jun	21.13°C	20.21°C	22.01°C	22.72°C	21.38°C
2011-Jul	21.49°C	20.59°C	21.46°C	22.92°C	21.60°C
2011-Aug	20.87°C	20.67°C	21.85°C	22.44°C	20.96°C
2011-Sep	21.14°C	20.78°C	21.98°C	22.77°C	21.38°C
2011-Oct	22.08°C	18.93°C	21.82°C	23.06°C	21.31°C
2011-Nov	21.89°C	16.63°C	21.70°C	22.73°C	21.41°C
2011-Dec	21.76°C	16.12°C	20.50°C	22.87°C	21.00°C
2012-Jan	21.38°C	16.60°C	20.28°C	22.74°C	20.77°C
2012-Feb	20.86°C	16.13°C	20.06°C	22.25°C	20.55°C
2012-Mar	20.17°C	16.25°C	21.41°C	21.59°C	19.39°C
Average	**21.08°C**	**18.69°C**	**21.31°C**	**22.40°C**	**20.89°C**

In general, both dwellings have higher indoor temperature across all the measured room during summer, e.g. July to September. During winter, kitchen of dwelling 7 seems to be much colder among all the rooms, where in dwelling 6 temperature profile is more constant. Such temperature difference is less during the summer.

5.6.3 Location and CO_2 measurement in same room

Two identical CO_2 sensors have been placed near by the fireplace of living room in dwelling 6 for comparison purpose. The main difference is the height, one CO_2 sensor is left on floor level and the other one is place at the decorative fireplace top (1.2 meter high).

Table 5.24: CO_2 level comparison of different heights in living room, dwelling 6

Hour	CO_2 **fireplace top**	**standard deviation**	CO_2 **Fireplace floor level**	**standard deviation**	Difference between top and floor level	**Difference in standard deviations**
0	493 ppm	19 ppm	551 ppm	26 ppm	58 ppm	7 ppm
1	495 ppm	18 ppm	553 ppm	26 ppm	58 ppm	8 ppm
2	498 ppm	18 ppm	553 ppm	25 ppm	55 ppm	7 ppm
3	499 ppm	17 ppm	553 ppm	25 ppm	54 ppm	8 ppm
4	499 ppm	18 ppm	553 ppm	26 ppm	54 ppm	8 ppm
5	499 ppm	18 ppm	553 ppm	26 ppm	54 ppm	8 ppm
6	498 ppm	18 ppm	552 ppm	25 ppm	54 ppm	7 ppm
7	496 ppm	18 ppm	551 ppm	25 ppm	55 ppm	7 ppm
8	492 ppm	19 ppm	549 ppm	25 ppm	57 ppm	6 ppm
9	489 ppm	19 ppm	547 ppm	26 ppm	58 ppm	7 ppm
10	485 ppm	20 ppm	546 ppm	26 ppm	61 ppm	6 ppm
11	483 ppm	20 ppm	545 ppm	27 ppm	62 ppm	7 ppm
12	483 ppm	20 ppm	546 ppm	28 ppm	63 ppm	8 ppm
13	483 ppm	21 ppm	545 ppm	28 ppm	62 ppm	7 ppm
14	483 ppm	21 ppm	546 ppm	28 ppm	63 ppm	7 ppm
15	483 ppm	22 ppm	547 ppm	28 ppm	64 ppm	6 ppm
16	484 ppm	22 ppm	547 ppm	28 ppm	63 ppm	6 ppm
17	484 ppm	22 ppm	547 ppm	28 ppm	63 ppm	6 ppm
18	485 ppm	21 ppm	547 ppm	28 ppm	62 ppm	7 ppm
19	486 ppm	21 ppm	547 ppm	28 ppm	61 ppm	7 ppm
20	488 ppm	21 ppm	546 ppm	28 ppm	58 ppm	7 ppm
21	489 ppm	21 ppm	547 ppm	28 ppm	58 ppm	7 ppm
22	490 ppm	20 ppm	548 ppm	28 ppm	58 ppm	8 ppm
23	492 ppm	21 ppm	551 ppm	27 ppm	59 ppm	6 ppm

As shown in table 5.24, the CO_2 concentration level at fireplace top is always lower than the measurement of sensor at floor level. The hourly measurement taken at the floor level is always 54-64 ppm higher than the measurements at fireplace top which is 1.2 meters vertically higher. Such pattern is also found in their hourly standard deviation, floor level measurements is 6-8ppm higher.

The height seems do make a different with regards to CO_2 concentration level. This is probably caused by the higher density of CO_2 in the air and it tends to sink therefore, a higher concentration could be expected to be measured by CO_2 sensor at lower position.

5.6.4 CO_2 concentration level and season

Living room CO_2 levels in both dwelling 6 and 7 living room areas have been measured. The reason of choosing living room area for the CO_2 density monitoring is based on the balance between time spent in a room (apart from sleeping) and number of windows or doors lead to outdoors.

Living rooms in dwelling 6 and 7 are identical, both have a big sliding glass door adjacent to the rear garden. Since it is carpet covered, occupant only use the kitchen door to go to the garden to in order to avoid dropping dirt and soil onto the nice carpet. Occupant in dwelling 7 had a full size sofa placed in front of it sliding door window that clearly indicates it is not in use for access to the garden. Figure 5.59 compares the CO_2 level in both living room areas and their individual monthly average values are listed in table 5.25. Dwelling 6 missed data of April and May in 2011 due to power failure of its onsite computer and wireless receiver.

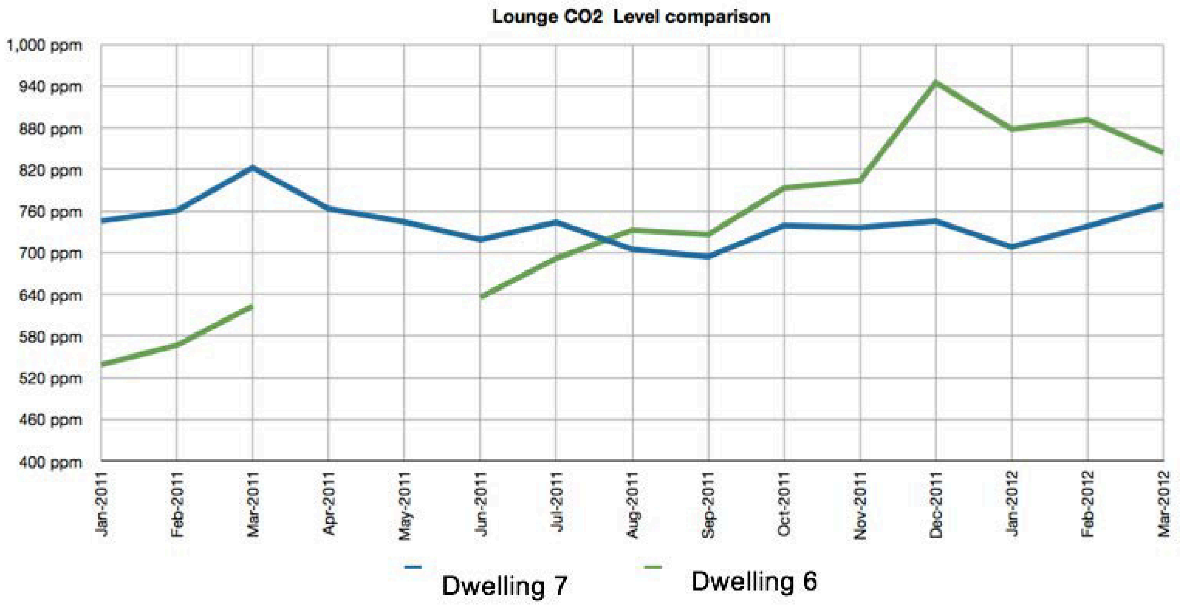


Figure 5.59: Living room CO_2 level comparison between dwelling 6 and 7

Table 5.25: Monthly Living room CO_2 level comparison summary

Monthly	Dwelling 6	Dwelling 7
Jan-2011	539 ppm	746 ppm
Feb-2011	567 ppm	761 ppm
Mar-2011	623 ppm	823 ppm
Apr-2011	Missing	763 ppm
May-2011	Missing	744 ppm
Jun-2011	636 ppm	719 ppm
Jul-2011	692 ppm	744 ppm
Aug-2011	733 ppm	705 ppm
Sep-2011	726 ppm	694 ppm
Oct-2011	793 ppm	739 ppm
Nov-2011	804 ppm	736 ppm
Dec-2011	945 ppm	746 ppm
Jan-2012	878 ppm	708 ppm
Feb-2012	892 ppm	738 ppm
Mar-2012	844 ppm	769 ppm
Average	744 ppm	742 ppm
Maximum	945 ppm	823 ppm
Minimum	539 ppm	694 ppm

Both homes have their CO_2 kept below 1000 ppm but dwelling 7 is more stable and constant than its neighbour. Highest CO_2 level at dwelling 7 is 823 ppm in March 2011 and lowest is 694 ppm in September. Afterwards it remains close to its annual average level of 742 ppm.

Dwelling 6 living room's CO_2 level kept rising in the whole year of 2011. It peaked in December with recorded value of 945 ppm, which is pushing the 1000ppm boundary towards poor air quality. Then the concentration level gradually decreases in the first three months of 2011 but no less than 844 ppm.

Besides the window opening behaviour, the major difference on ventilation behaviour is the use of Mechanical Heat Recovery Ventilation (MVHR). As occupant of dwelling 7 explains:

> "*We always have our mechanical ventilation on, the house was designed with it and it has a good reason in this air-tight house. Earlier this year my wife accidently switched the ventilation off. It made us to do a good clean-up as mould and condensation are spotted at ceiling corners. Living room is even worse as it is kind of opposite to the bathroom in the hallway. Oh, it*

is quiet you can't hear a thing. That is why we didn't realise it was turned off for a few month. I remember it was end of February may be early March something like that. Contractor came to fix the thermostat and the ventilation circuit got knocked off. Do I feel any draught come down from the vents? A little bit sometime but at least we don't have to wipe the mould with bleach and vinegar every Sunday morning. "

As occupant stated, dwelling 7's MVHR only switched off unexpectedly between around February and March in 2011. This may explains the higher value of CO_2 concentration level in March. The constant use of MVHR is also reflected on the stable CO_2 level in the following months.

The use of MVHR is completely different in dwelling 6. Since the occupant moved in winter. The cycled air comes down from the ceiling vent makes occupant feel it is draught. As a consequence, MVHR was turned off in March 2011. Minor condensation and mould have been spotted but not significant at all according to one of the occupant's statement:

"It is definitely making difference. Switching the ventilation off actually stops the draught. I don't understand why they installed it as it makes us feel colder especially when we moved in. Yeah I do appreciate the high standard and quality of this bungalow. One of the vent is located right next our bedroom bathroom. We had to wear pajamas before coming out of bathroom after taking a shower. Condensation is not really a problem, we close the bathroom door and left a window open for a while so the hot humid air could get out. "

As a result of the MVHR being switched off, the condensation actually occurred in the loft within the heat exchanger, which is a core unit of MVHR system. Although the MVHR system is off, cold air can still get in through the inlet and condenses on the heat exchanger. This cumulative amount of water keeps increasing but couldn't evaporate quickly enough. Eventually condensed water overflowed and began to drip through the ceiling vents. Contractors were called when this happened and they cleaned the excessive water in the loft space. Occupants were suggested to keep the system, however, one of the occupants has asthma and he doesn't feel too well when the MVHR is running. This caused the occupant to switch off the system and called maintenance contractor again. In the second inspection, the air filter was found heavily moulded as shown in figure 5.64.

Figure 5.60: Air filter in MVHR system at dwelling 6

Despite the new filter was replaced, a visit on 5th October 2011 shows that occupants in dwelling 6 have manually covered the ceiling vents that means they choose to not to use the MVHR system.

Without MVHR system, the average CO_2 concentration level in dwelling 6 living room area has been rising since September 2011. Comparing with dwelling 7, whose CO_2 level of December 2011 is 199 ppm less. In the following month, January, February, and March 2012, Dwelling 6's CO_2 level is 169, 153 and 75 ppm less respectively.

5.7 Summary

The chapter presents the findings of selected instrumentations and methods that have been applied in participated dwelling 1 to 8 in south Wales. All the measurements were taken during heating season, with exception of dwelling 6 and 7 where the summer was also included between two winters.

Space heating monitoring methods have tested in terms of various types of heating system, position of heating appliance, location of room, location of house. A number of gas meter monitoring method and hardware has been studied and compared.

Domestic hot water related behaviours has been studied by self–kept hot water demand event diary, compare surface temperature of hot water pipes and icon recognition of boiler control panel display.

Windows and doors was monitoring by single contact switch after testing a few other possible sensors and loggers. All the methods have satisfactory level of accuracy.

Electricity consumption has been monitored individual circuits and appliance level. This method worked well at homes has ASHP since their major demands like space heating and domestic hot water are all powered by electricity.

Indoor physical condition have been mainly focused on temperature, relative humidity and CO_2. Difference has been found at different locations of sensor installed in a room but not significantly varying across each other.

Next chapter will discuss the methods with regards to occupant related parameter using both social science survey methods and sensory technologies.

Chapter 6 Social science survey results

6.1 Introduction

This chapter the following field study results are presented:

- Questionnaire and interview of indoor condition satisfaction
- Self-reported recent thermal satisfaction, activity level, and clothing level
- Occupancy and PIR presence sensor
- Wearable activity tracker

6.2 Questionnaire and interview results

In Dwelling 1 the complex high-rise apartment, 150 participants were asked to fill a 5 minutes comfort questionnaires, 103 of them answered. 43 of them claimed that they fully understood the questions and the rest 60 participants had doubts with at least one question or its answer. The results are shown in table 6.1 in terms of occupants' preference of indoor warmth, air movement, humidity, natural light and noise conditions in both winter and summer.

Table 6.1: Questionnaire result of dwelling 1

In winter I prefer my apartment to be					
Warmth	Much warmer 3%	A bit warmer 24%	no change 73%	A bit cooler	much cooler
Air movement	Much less air movement 45%	a bit less air movement 33%	no change 10%	a bit more air movement 12%	Much more air movement
Humidity	much drier	a bit drier 22%	no change 66%	a bit more humid 12%	much more humid
Natural light	much dimmer	a bit dimmer 15%	no change 80%	a bit brighter 5%	much brighter
Noise	much quieter 78%	a bit quieter 21%	no change 1%		
In summer I prefer my apartment to be					
Warmth	Much warmer	A bit warmer	no change 27%	A bit cooler 28%	much cooler 45%
Air movement	Much less air movement	a bit less air movement	no change 53%	a bit more air movement 13%	Much more air movement 34%
Humidity	much drier	a bit drier	no change 85%	a bit more humid 15%	much more humid
Natural light	much dimmer	a bit dimmer 25%	no change 75%	a bit brighter	much brighter
Noise	much quieter 78%	a bit quieter 21%	no change 1%		

Compare the preferences of indoor physical conditions between winter and summer, it seems that majority of occupants consider their apartments to be comfortable (73%), 24% prefer a bit warmer in the winter. Excessive amount of air movement is considered to be less favourable. Humidity and natural light are generally satisfactory but 78% and 21% prefer their apartment to be much quieter and a bit quieter.

Preferences towards warmth and air movement are opposite in the summer, occupant would like to be cooler and more air movement. Humidity, natural light, noise have similar or identical votes.

The differences between summer and winter suggests these well insulated apartments are possibly having overheating issue in the summer. Given the fact that the same ventilation system works passively except windows, it is perceived to be excessive in winter but insufficient in summer. Noise is commonly agreed issue, despite the seasons, possibly caused by its closeness to railway and busy roads. There is a vague trend between the height and noise complaint, occupant lives in higher floor are less bothered by the noise.

The option of keeping self-administrated diary was proposed to the participants, just over half of them expressed that they would not mind keeping one as long as it is fixed period, ideally no more than 4 weeks maximum.

6.3 Self administrated diary

Self-administrated comfort diary has been given to occupants of dwelling 6 and 7 in order to continuously collect personal factors, namely, thermal experience, thermal satisfaction, clothing insulation level and activity level.

The dairy was formatted as figure 6.1 shows: four fixed time in a day, 8am, 12am, 6pm and 10pm. Occupants were encouraged to tick their thermal sensations at these moments and there is also blank rows in between when they feel like to add more information such as whether they returned from outdoor in the past 30 minutes, how active they were, whether they had a hot or cold drink earlier. These optional questions can further help to collect personal factor samples.

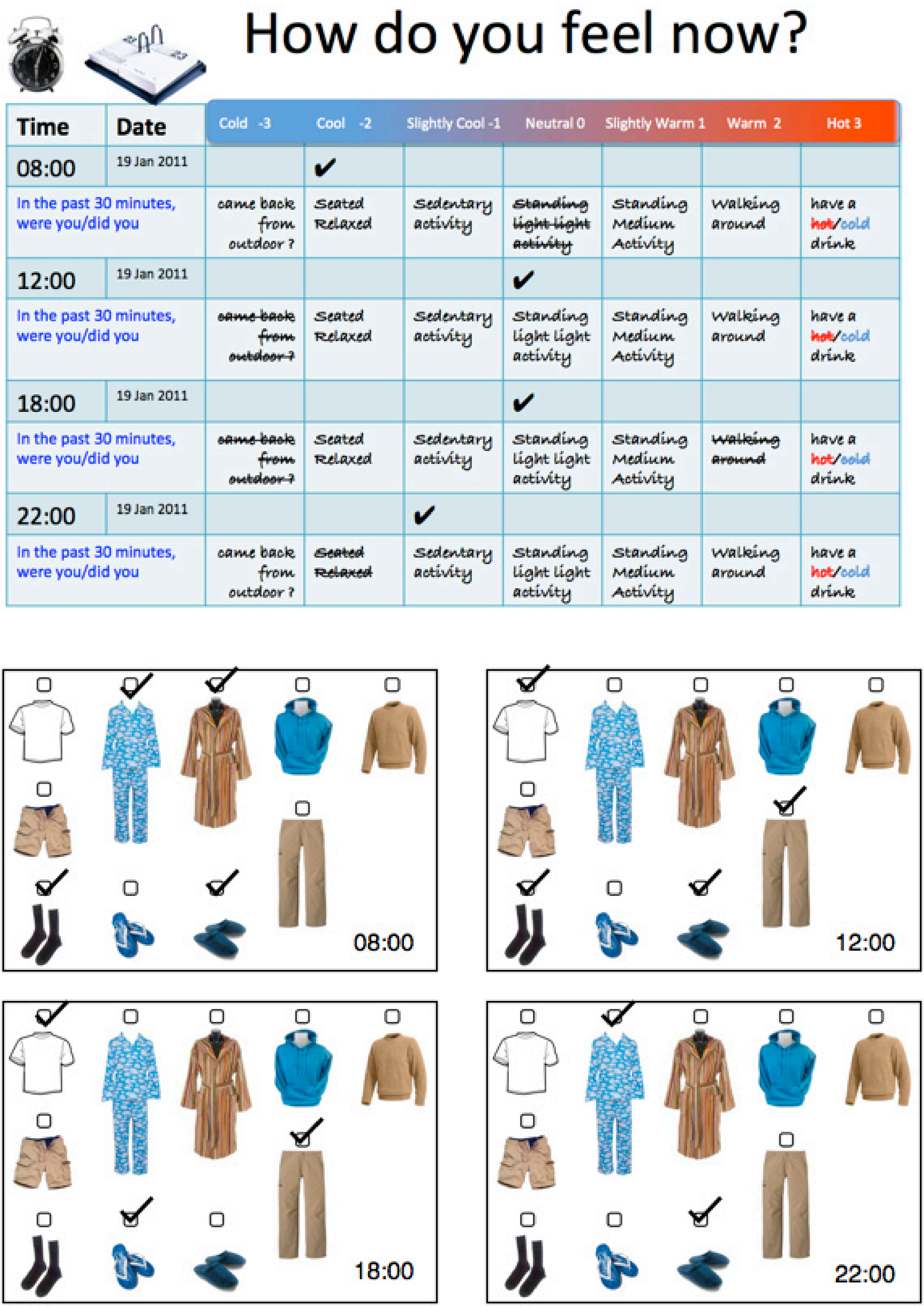


Figure 6.1: Self-admitted comfort diary daily example.

The results of dairy and activity meters are shown in table 6.2, filled by occupant during identical 28 days in the winter. In total, the dairy has 112 entries, occupants of dwelling 6 filled 93 entries and dwelling 7 filled 69 entries, due to the absent from being at home or simply forgot to fill.

Table 6.2, self-administrated dairy comparison between dwelling 6 and 7

In the past 30 minutes,	Dwelling 6	Dwelling 7
had a hot drink	39 times	17 times
had a cold drink		18 times
Came back from outdoor	14 %	38 %
Seated relaxed	21%	8%
Sedentary activity	32%	4%
Standing light activity	32%	17%
Standing medium activity	15%	12%
Walking around	2%	59%
How do you feel right now		
Cold	29%	11%
Cool	32%	13%
Slight cool	25%	28%
neutral	14%	48%

Occupant of dwelling 6 seems prefer to take hot drink such like tea or coffee more often than occupant of dwelling 7 who took similar number of cold drink as well. Dwelling 6 occupant may go out less, judging by the higher number of dairy entries and lower percentage of 'coming back from outdoor' choice. Regarding the activity level, occupant in dwelling 6 is much less active than its neighbour.

As shown as table 6.3, occupant in dwelling seems to have preference of light level clothing when she is at home in both heating seasons, mostly ticked garment are T-shirt, trousers and slippers, perhaps due to the higher level of t house works like washing, cleaning, cooking meals that give her higher metabolic rate. On the contrary, occupant from dwelling 6 choose more garments, especially sleeping wearing such like pyjama and robe, which were never selected by occupant of dwelling 7. For footwear, dwelling 7's occupant seems always to wear slippers and socks whereas in dwelling 6 occupant wears flip-flops without socks half of the time.

Table 6.3: Clothing level comparison between dwelling 6 and 7

Garment	Dwelling 6	Dwelling 7
T-Shirt		78%
Pyjama	90%	
Robe	47%	
Hoody	40%	
Sweater		12%
Shorts		
Trousers	53%	89%
Woolly Hat		
Scarf		
Socks	40%	100%
Flip flop	60%	
Slippers	40%	100%

The ease of use of the dairy has been discussed with occupants at the end of interview. Both occupants reached agreement on several points that self-administrate diary which they felt need improvement. The first one is to fill the diary at designated time of day. The timer and alarm was useful as a reminder but somehow begin to annoy and got turned off in both dwellings.

6.4 Activity meter

In addition the dairy keeping in dwelling 6 and 7, activity level was measured by wearable activity meter which records the whole body's acceleration, not just the wearing wrist and it convert the activity date into step format and then transmitted to handhold terminal.

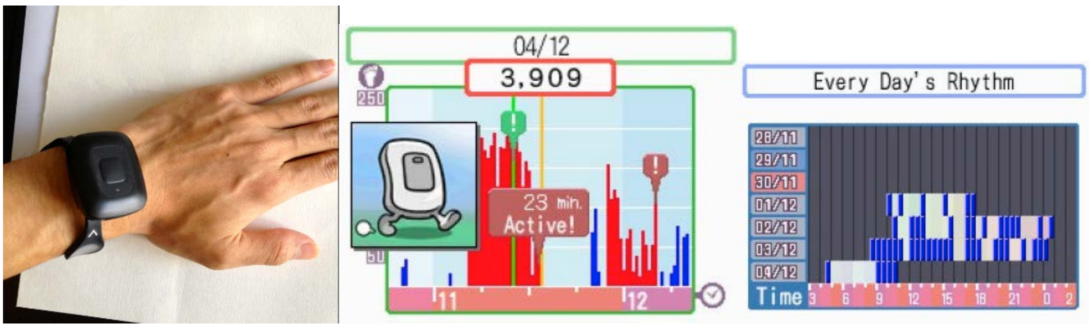


Figure 6.2: wearable activity meter

The activity is measured by steps taken during these 28 days periods. Both participants have been wearing their trackers most of time and results comparison between them is shown as table 6.4.

Table 6.4: activity trackers comparison between dwelling 6 and 7

	Dwelling 6	**Dwelling 7**
Day 1	3296 steps	7828 steps
Day 2	2471 steps	5629 steps
Day 3	3528 steps	8058 steps
Day 4	3449 steps	7950 steps
Day 5	4930 steps	12419 steps
Day 6	3498 steps	9008 steps
Day 7	2243 steps	8996 steps
Day 8	2417 steps	11445 steps
Day 9	5295 steps	10047 steps
Day 10	1084 steps	16116 steps
Day 11	4784 steps	13081 steps
Day 12	4492 steps	13123 steps
Day 13	2218 steps	7125 steps
Day 14	1398 steps	11178 steps
Day 15	5150 steps	12363 steps
Day 16	5507 steps	9013 steps
Day 17	3311 steps	15510 steps
Day 18	3964 steps	12440 steps
Day 19	3983 steps	8264 steps
Day 20	3863 steps	11064 steps
Day 21	3825 steps	11570 steps
Day 22	2573 steps	11440 steps
Day 23	571 steps	8484 steps
Day 24	3655 steps	10750 steps
Day 25	3835 steps	13648 steps
Day 26	3764 steps	11137 steps
Day 27	3614 steps	13679 steps
Day 28	3814 steps	11547 steps

It is obvious that the participant of dwellings 7 was much more active, whose daily average steps taken is 10818 steps, compared to participants of dwelling 6 who average walks 3448 steps per day. Their average hourly steps profile over 24-hours is illustrated in figure 6.3 and 6.4, which show hours that are more active. Due to the restricted export function of the activity tracker's software, these two figures are screenshots. It can be clearly seen that occupant of dwelling 7 is much more active by taking more steps.

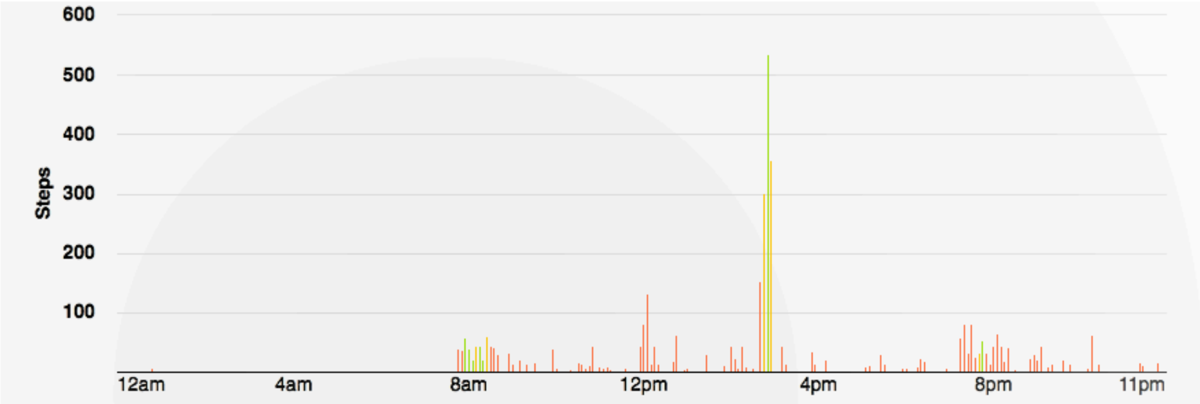


Figure 6.3: Average daily steps profile of participant, dwelling 6

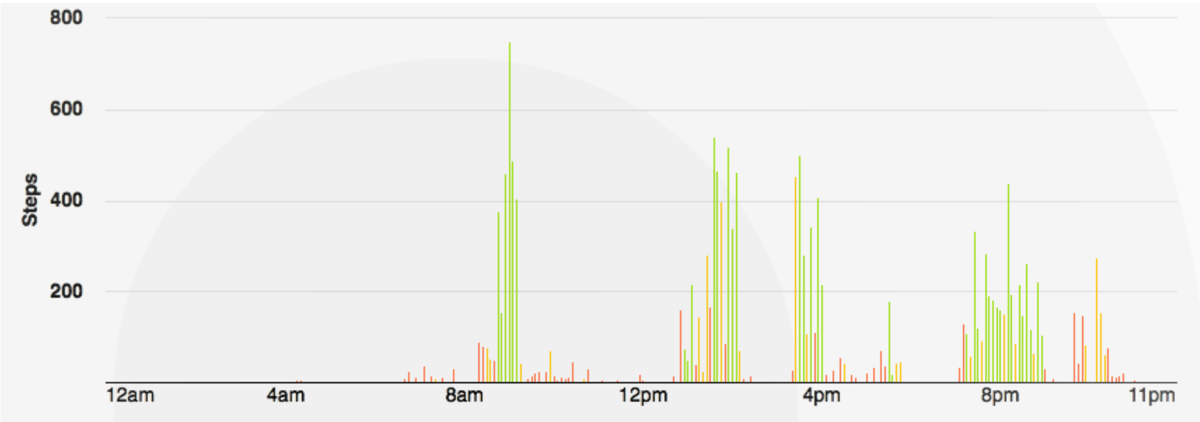


Figure 6.4: Average daily steps profile of participant, dwelling 7


Figure 6.5: Reported clothing level: Left-dwelling 6, Right-dwelling 7

Answers to Clothing level question are almost the same. Occupant of dwelling 7 occupant usually wears short t-shirt and trousers with summer slippers. Occupant of dwelling 6 generally wears long sleeves pyjama and robe, plus socks and winter slippers. Self reported clothing level has very good consistency: Dwelling 7 prefers to wear more summerly and dwelling 6 shows preference of sleeping wears such like robe and pyjama. This is possibly caused by their difference activity at home, since dwelling 7's occupant does lots of house works from throughout the day but occupant of dwelling 6 mostly is more sedentary.

The WalkWithMe activity trackers have been capable of measure the difference of activity level between two participated occupants. Post monitoring interview also confirms this finding, occupant of dwelling 6 has back problem which limits her movement to a certain extent, whereas occupant of dwelling 7 does not have difficulty to move and she claims herself to be mostly walking around throughout a day with various housework tasks. Feedback as wearer of these trackers is positive without any complaint regarding disturbance to their daily life, thanks to its waterproof feature and durability especially. Occupants even expressed the interesting of purchasing an activity tracker for their own health interest. From data collection prospective, lack of data exportation is a weakness, as it took a reasonable amount of time process steps counts manually.

6.5 PIR Presence sensor

Permission of PIR motion sensor installation has been granted to the living room in dwelling 6. The range and motion sensitivity have been tested by placing two sensors at different location, record motions diagonally at ceiling corners of living room (figure 6.6). PIR sensor 1 is closer to the front area of two sofas where occupant usually sit. PIR sensor 2 was installed at the ceil corner of entrance of living room.

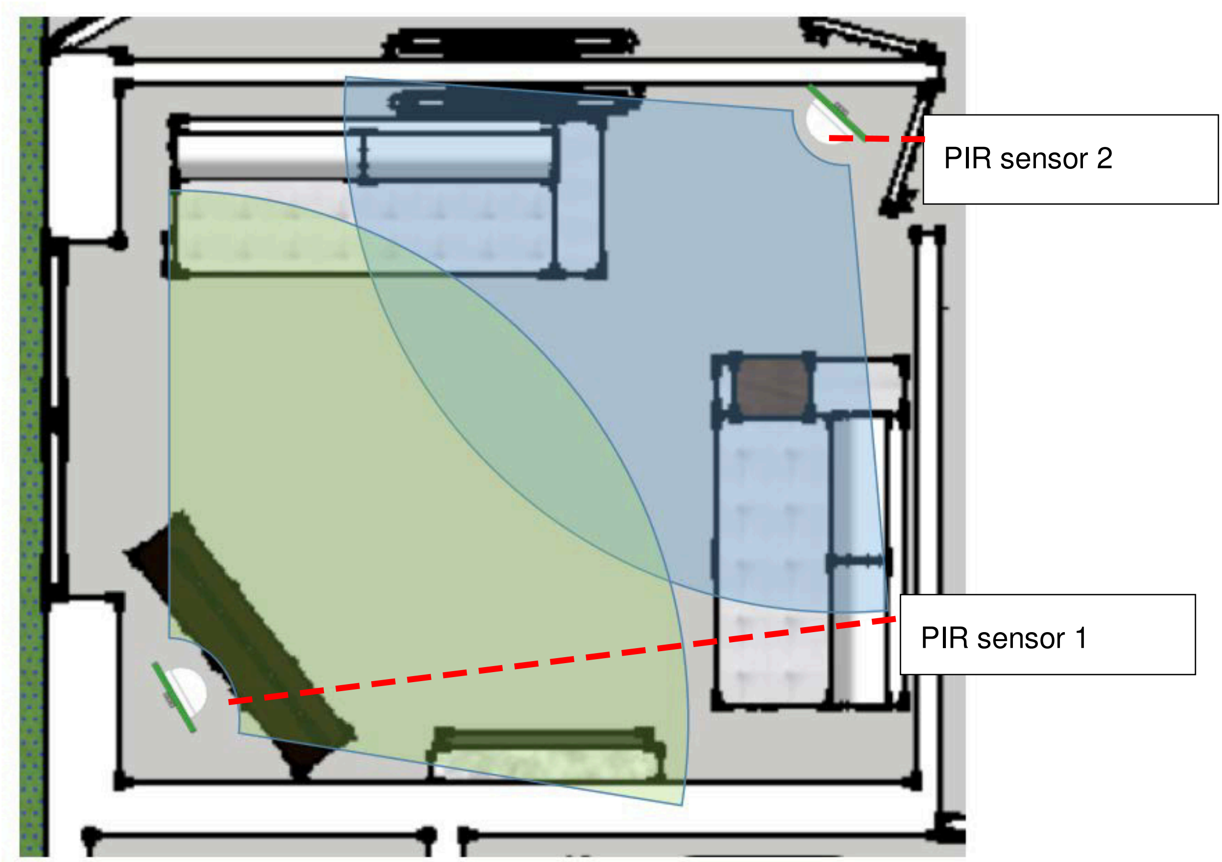


Figure 6.6: location comparison of PIR motions sensors

14 days of comparison between locations is shown in 24 hours cycle (figure 6.7). Both sensors detected little activity during night time. For the rest of time, PIR sensor 1 measured more hourly average activity than PIR sensor 2 did. Details of pulse counted are listed in table 6.5.

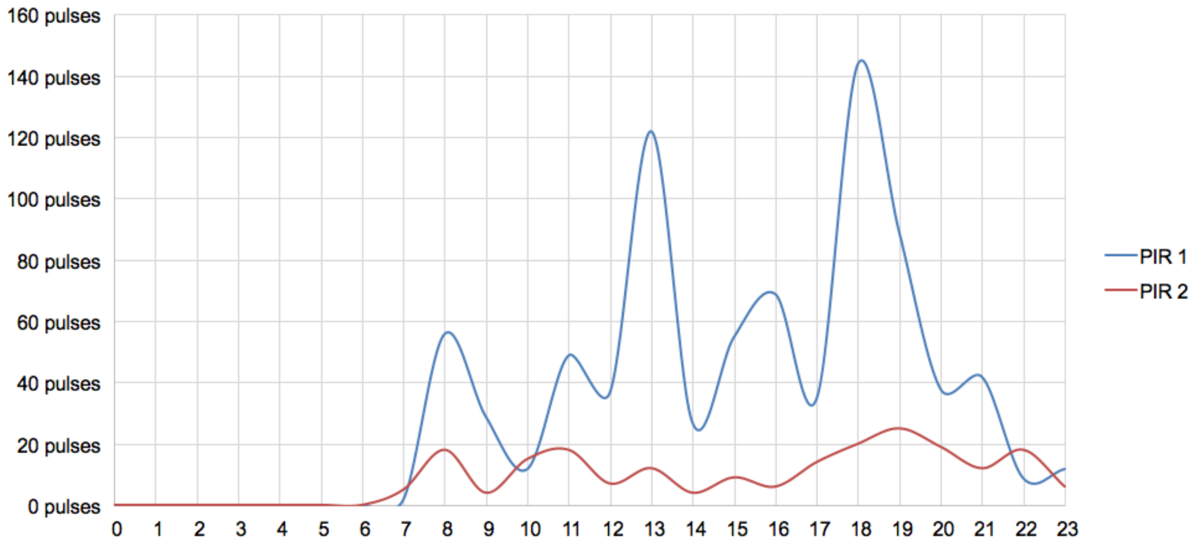


Figure 6.7: location comparison of PIR motions sensors

Most of the time, PIR sensor 1 records 100% to 1050% more motion triggers pulses than PIR sensor 2, except very few occasions, such like early morning and late night. The difference reached several peaks, especially 13:00 to 14:00, 16:00 to 17:00 and 18:00 to 19:00, according to occupant, these hours are their common tea and meal time that two occupants normally prefer to have in the living room. It is possible that the PIR sensor's sensitivity of capturing sedentary activities PIR 2 dropped significantly due to angle from where is it was installed. Compared it, PIR sensor 1 points to the front of two sofas more straight which might helped it to record small movements while occupant remains seated.

Table 6.5: Hourly average motion pulses comparison

Hour	PIR 1	PIR 2	Difference (PIR1 - PIR 2)
0	0 pulses	0 pulses	0%
1	0 pulses	0 pulses	0%
2	0 pulses	0 pulses	0%
3	0 pulses	0 pulses	0%
4	0 pulses	0 pulses	0%
5	0 pulses	0 pulses	0%
6	0 pulses	0 pulses	0%
7	2 pulses	5 pulses	-60%
8	56 pulses	18 pulses	211%
9	29 pulses	4 pulses	**625%**
10	12 pulses	15 pulses	-20%
11	49 pulses	18 pulses	172%

Hour	PIR 1	PIR 2	Difference (PIR1 - PIR 2)
12	37 pulses	7 pulses	429%
13	122 pulses	12 pulses	**917%**
14	27 pulses	4 pulses	575%
15	55 pulses	9 pulses	511%
16	69 pulses	6 pulses	**1050%**
17	35 pulses	14 pulses	150%
18	144 pulses	20 pulses	**620%**
19	89 pulses	25 pulses	256%
20	38 pulses	19 pulses	100%
21	42 pulses	12 pulses	250%
22	9 pulses	18 pulses	-50%
23	12 pulses	6 pulses	100%

In this field study, PIR presence sensor measures the pulse of raw motion detection rather than processed activity count. This because most PIR detectors incorporate an anti-false alarm feature which is designed to avoid misreading caused by insects, or air temperature. With the feature being turned on, raw motioned triggered pulse would be filtered first, for example, only three consecutive pulse will be reckoned as human movement. PIR sensor in this study report only the raw pulses rather processed human movement.

The number of raw pulse is affected by threshold that built-in with the PIR sensor. The sensor starts with voltage output and only a voltage higher than manufacturer set threshold would be processed as valid pulse. However, this threshold was not programmable and further test was not possible.

PIR sensor 1 pointed from the front of the two sofas picked higher number of raw pulse count than the identical PIR sensor 2 pointed from side. Their distance to the sofa area are very similarly positioned. One possible explanation could be that the PIR sensor 1 could pick up more motions changes of sedentary activity than PIR Sensor 2 because it measure from the front, not from side. There are few occasions PIR sensor 2 recorded more pulses than PIR sensor 1, but predominately the PIR sensor 1 measures higher motions.

6.6 summary

In this chapter, methods and instrumentations of measuring occupant related parameters have been presented in terms of questionnaire and interview of indoor condition satisfaction. Self-reported recent thermal satisfaction, activity level, and clothing level, occupancy and PIR presence sensor and wearable activity tracker.

In next chapter, measurements taken from each section have been used for co-incidental analysis, namely, window opening and CO2 concentration level, CO2 concentration level and external temperature, presence and CO2 concentration level, physical condition and occupant related variables, calculated PMV and self rated subjective thermal satisfaction.

Chapter 7 Integration of physical measurement and social science survey

7.1 Introduction

This chapter aims to integrate some measured parameters from different category and explore their relationship. The selected combinations of parameters are:

- Window/door operation, CO_2 concentration level and external temperature
- Presence and CO_2 level
- Recent thermal experience, activity level, clothing value and thermal satisfaction
- Calculated PMV and voted thermal satisfaction scale

These combinations are selected based on their possible relationships that worth to inspect as a whole.

7.2 Window opening, CO_2 concentration level and external temperature

Air exchange caused windows and doors operation can affect the CO_2 level in the living room, especially the front door that is the closest exit to the living room area. Figure 7.1 compares the windows/doors opening time with living room area CO_2 level.

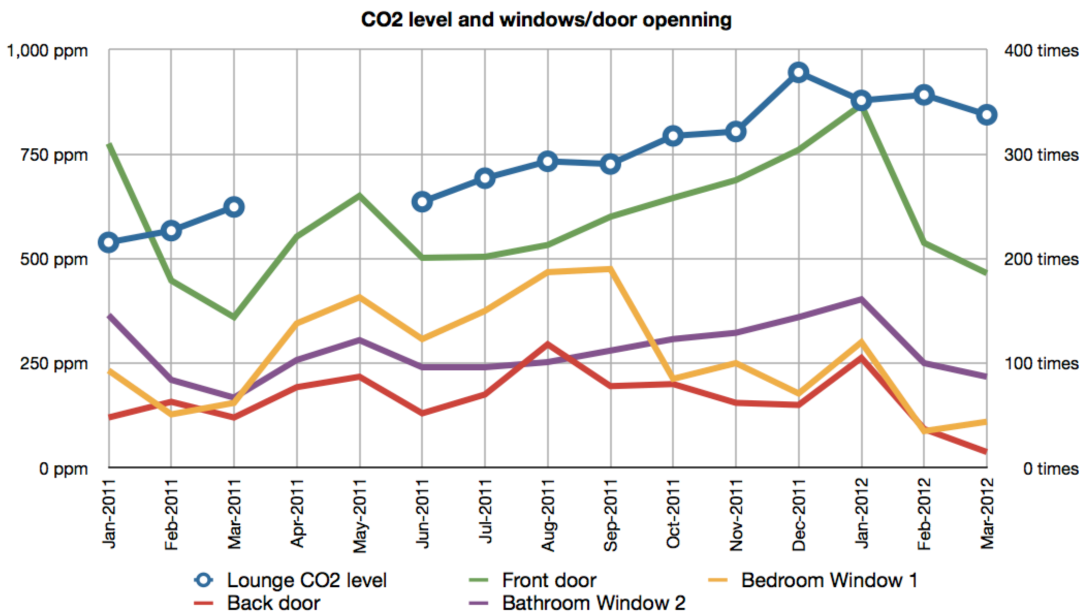


Figure 7.1: Dwelling 6 Living room CO_2 level and window/doors opening comparison

It can be seen that before March 2011. Frequencies of windows and doors operating behaviour was decreasing but after MVHR being turned off in March the number of operating began to increase especially the Bedroom window and Front door. CO_2 level record is missing from April and May. Since June 2011, the bathroom window and front door opening frequencies are having similar tendencies.

Dwelling 6 ‘s CO_2 level also seems to be related with external temperature during heating season (figure 7.2). In the summery month from June to September 2011, CO_2 level increases as external air temperature does. From October, it is found that external temperature began to descend while CO_2 continues going up.

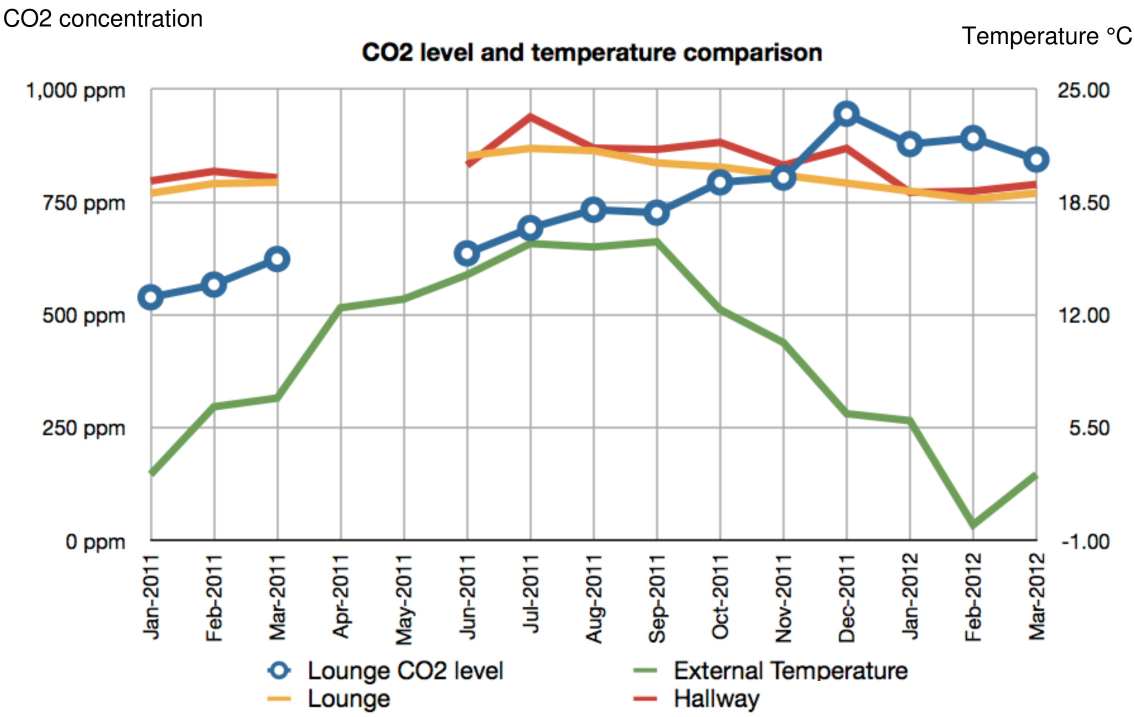


Figure 7.2: Dwelling 6’s Living room CO_2 level and air temperature comparison

Combining tendencies from windows, doors and external air temperature together, plus the fact that Dwelling 6’s MVHR was completely switched off and the occupant sealed ceiling vents, it is estimated that colder weather actually trigger the occupant in Dwelling 6 to operate windows more frequently than summer as indoor temperature is more influential by outdoor conditions. Higher frequency means less time that window being left open. Also without the help from mechanical ventilation, CO_2 level could cumulatively raise in the heating season.

In Dwelling 7, since its MVHR has been used all the time. Front door opening time and Living room CO_2 level show good similarity from June to December 2011 (figure 7.3). However, Front door opening frequencies began to drop sharply but CO_2 level in living room area was not greatly affected. It only increased 60ppm from January to March 2012. Comparing with Dwelling 6, Dwelling 7's CO_2 concentration level has been very stable throughout the whole period. Figure 7.4 shows that the temperatures in living room and the hallway next to it are as stable as CO_2 level when external temperature dropped from 16.1˚C to -0.1˚C.

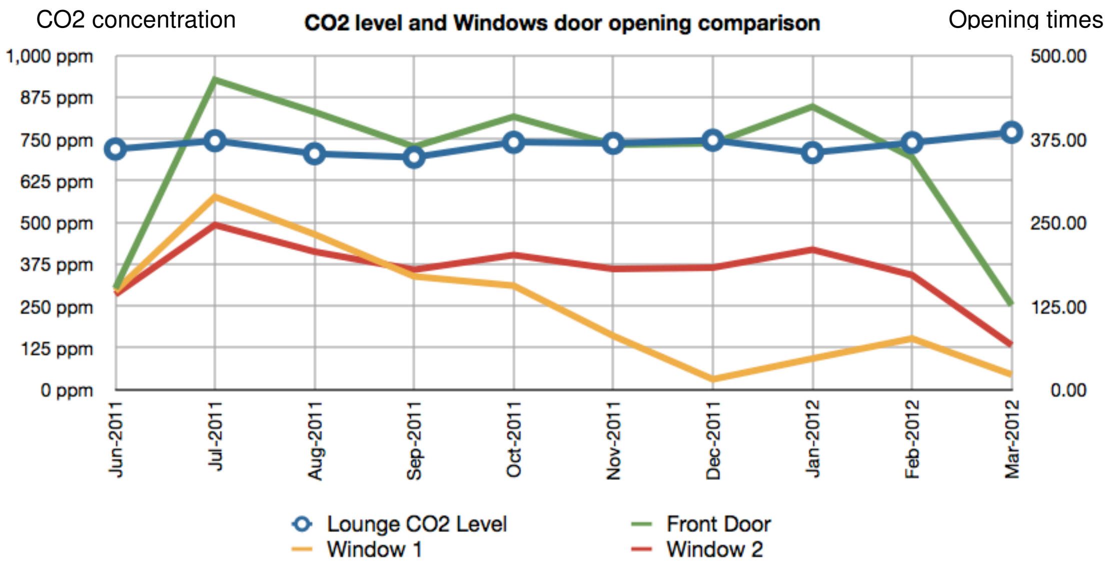


Figure 7.3: Dwelling 7's living room CO_2 level and window/doors opening comparison

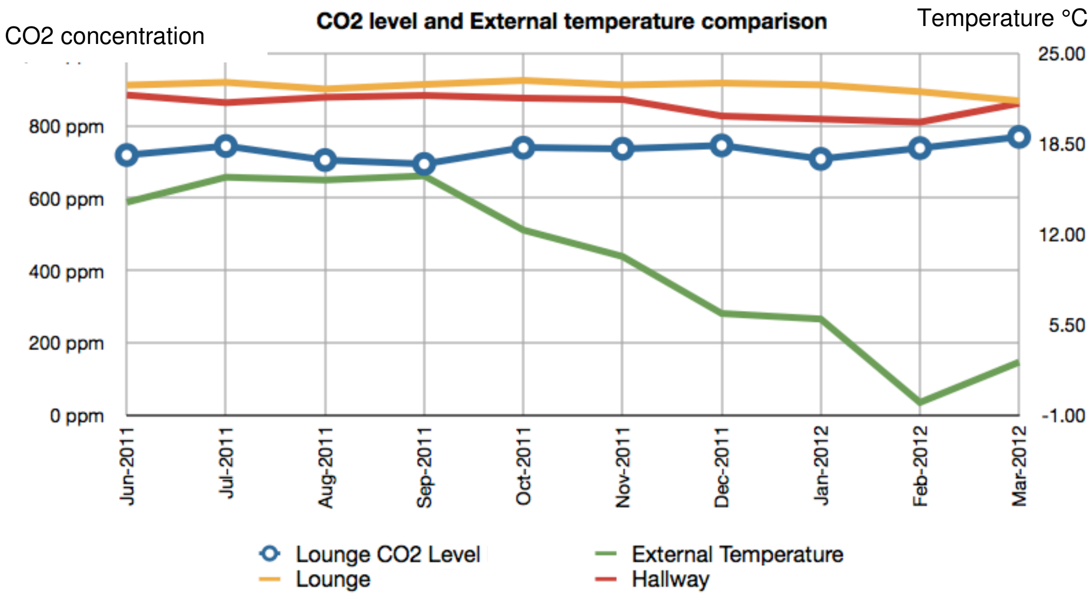


Figure 7.4: Dwelling 7's living room CO_2 level and air temperature comparison

7.3 Presence and CO_2 level

14-days worth of presence monitoring results which were collected by two PIR sensors installed in the living room are compared with the CO2 concentration level data (Figure 7.5). In general, the CO2 level reaches its peak value after midnight, without any activity being recorded and then begins to drop gradually until 1pm in the afternoon. There is a sharp reduction corresponding to the increased activity pulses at between 12am to 1pm then slowly builds up in the next hour. However, such pattern did not repeat between 5pm to 8pm, where the highly condensed activity pulses were detected while CO2 level stably climbed up. Within these 14 days, it was difficult to identify a pattern between CO2 concentration level and presence in the living room

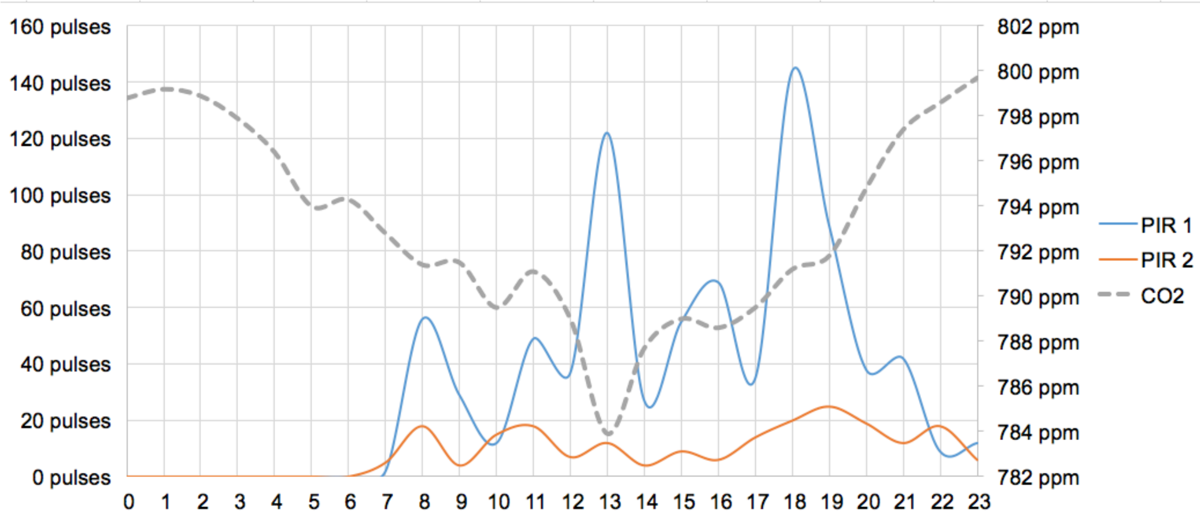


Figure 7.5: 24-hours presence comparison with CO_2 concentration level profile - Dwelling 6

7.4 Physical condition, personal factor and thermal satisfaction

Occupants from dwelling 6 and 7 are similar in age and gender, however, their activity level, life style and routines are different. The following charts compared thermal satisfaction vote with various factors that reported by occupants and recorded by temperature logger in the past 30 minutes before each vote made between dwelling and 6 and 7.

Figure 7.6 and 7.7 illustrate the distribution of mean thermal satisfactory vote over 4 times a day with mean indoor temperature of whole house. Dwelling 6 has much higher vote towards 'slight cool' at 08:00, when sensation of being 'Cool' was only votes at. The vote of 'about right' increases gradually from morning to evening, whereas 'Slight cool' vote decreases. The recent 30 minutes of mean indoor temperature rises only 0.93°C from 19.09°C to 20.02°C stably.

Occupant of dwelling 7 rated her thermal satisfaction significantly different. The proportion of felling Cool is 55% at 8:00. The satisfied vote, 'about right', is 100% at 12:00 and 22:00 and 88% at 18:00 with 12% vote of 'slight cool'. Mean indoor air temperature rises from 21.16°C to 24.61°C from early morning to late evening, which is 3.45°C increase.

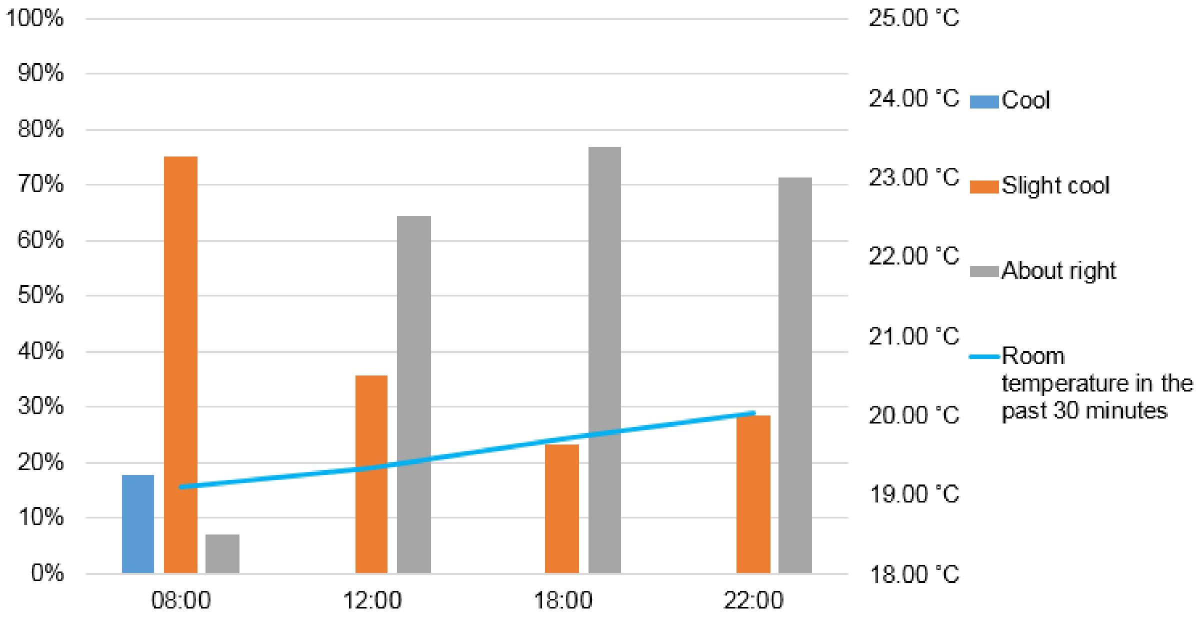


Figure 7.6: thermal satisfaction, time of day and recent indoor temperature—dwelling 6

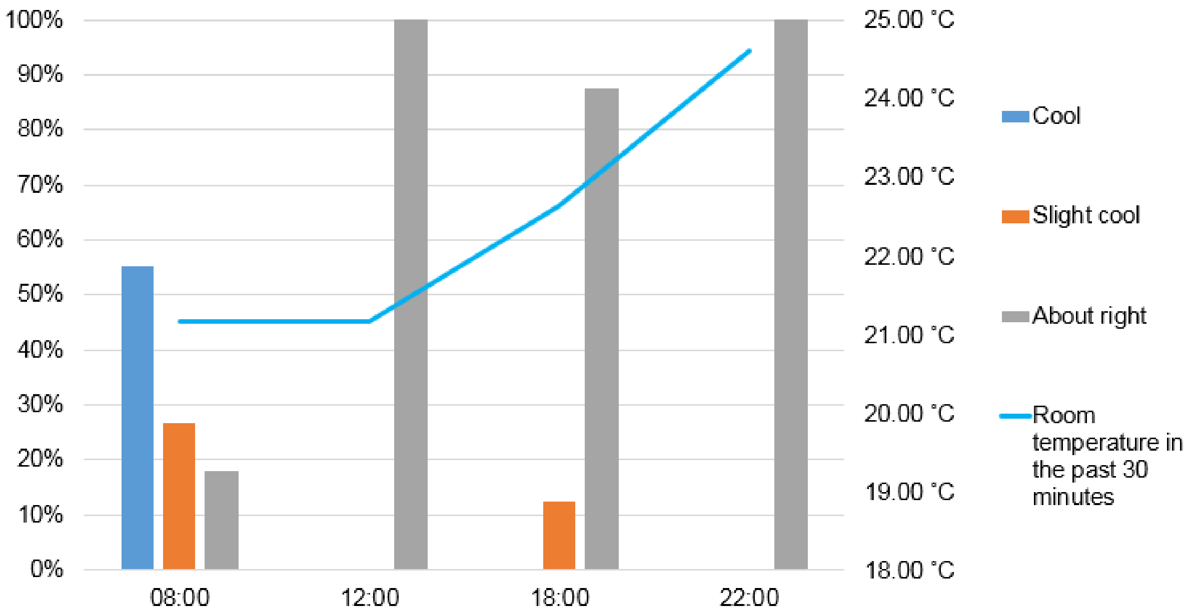


Figure 7.7: thermal satisfaction, time of day and recent indoor temperature—dwelling 7

Participated occupant of dwelling 6 seems to rate thermal satisfaction lower when they were less active, such like seated relaxed and sedentary activity. Feeling cool is only found when occupant was seated relaxed. As activity level goes up, the satisfactory state of 'about right' was rated more when occupant was more active and had been conducting sedentary, standing and walking activity. The dissatisfactory vote of 'slight cool' gradually declines as occupant become more active.

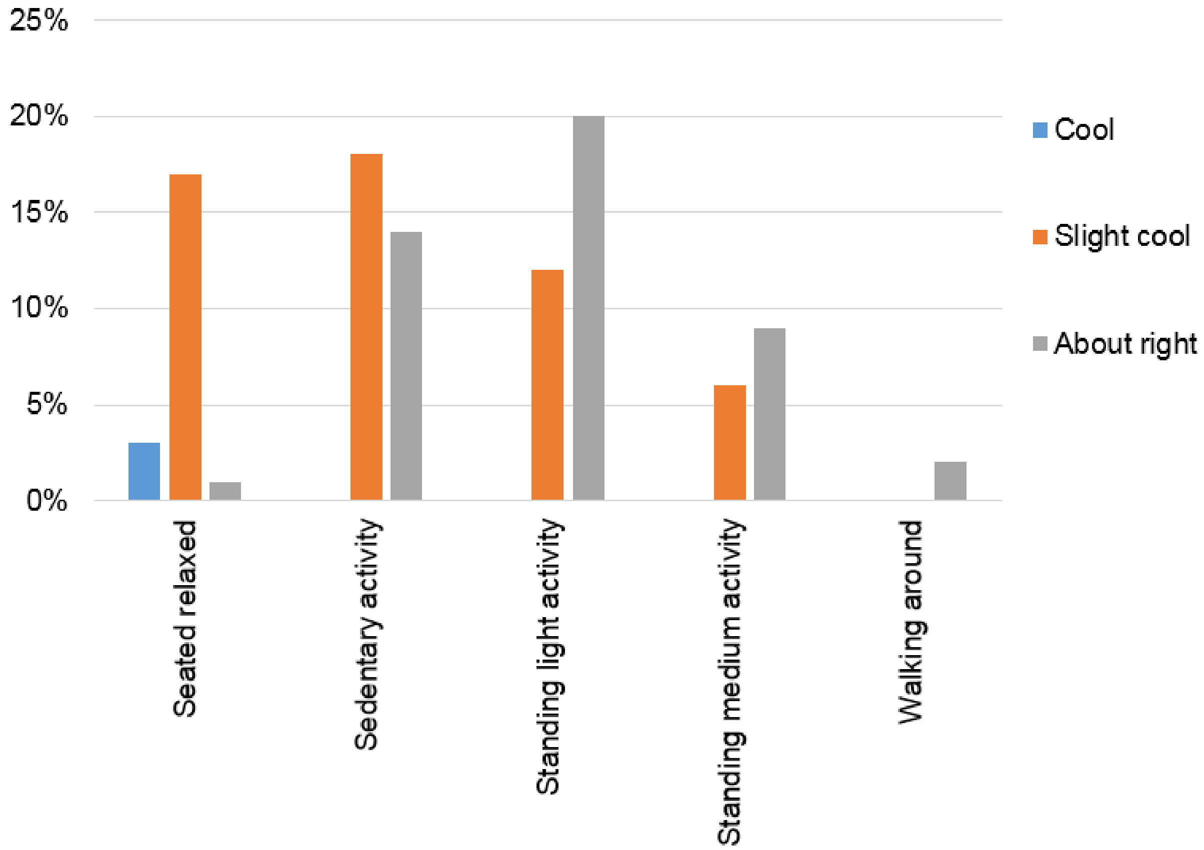


Figure 7.8: thermal satisfaction, and recent activity—dwelling 6

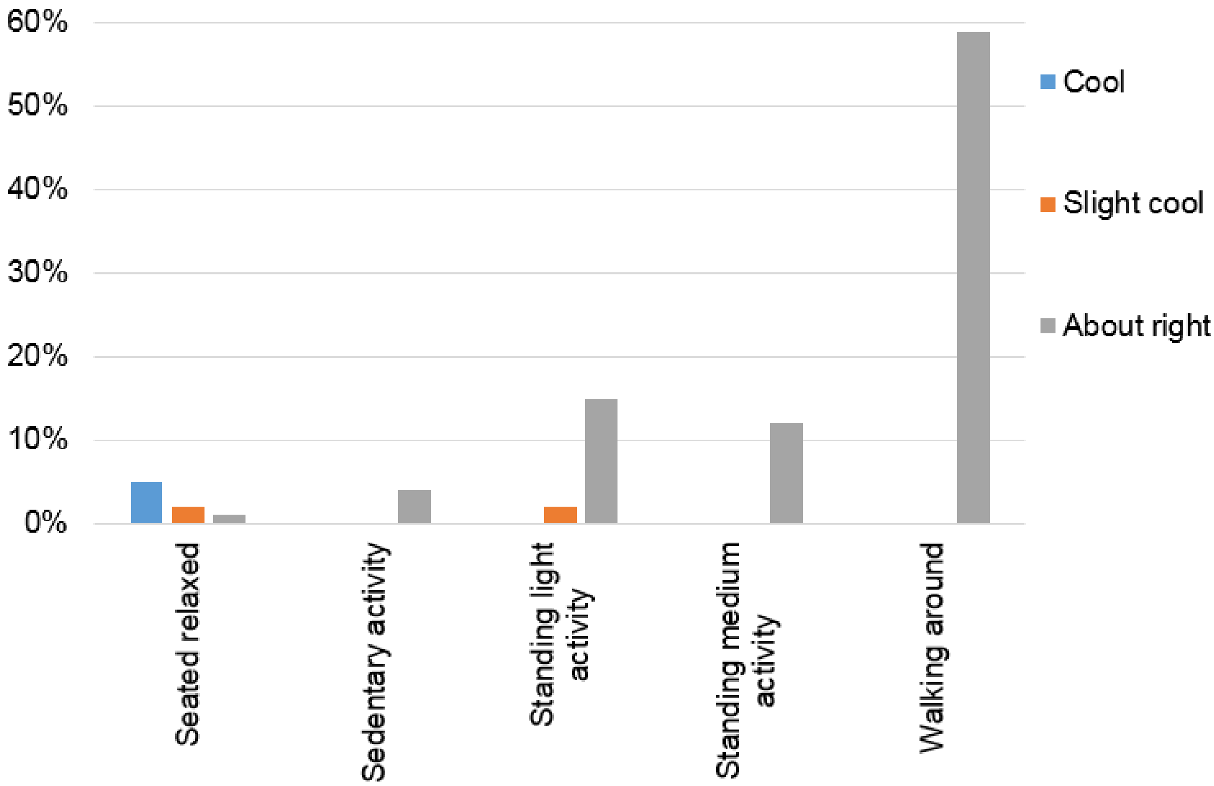


Figure 7.9: thermal satisfaction, and recent activity—dwelling 7

Up to 60% of vote of ‘about right’ occurred when occupant of dwelling 7 was walking around which is the most active available in the dairy. The other active levels have few thermal satisfaction votes, whereas the ‘Cool’ only appeared when occupant claimed to be seat relax in the past 30 minutes.

Occupant of dwelling 6 did not record any consumption of cold drink at all. After had a hot drink in the past half hour, votes from high to low, are about right, slight cool and cool (figure 7.10). This seems suggest the possibility of hot beverage consumption and improved thermal satisfaction. Recent thermal experience, in this dairy, refers to cold experience from outside in the past 30 minutes. In dwelling 6, participant rated them four times more with 'about right' than 'slightly cool'.

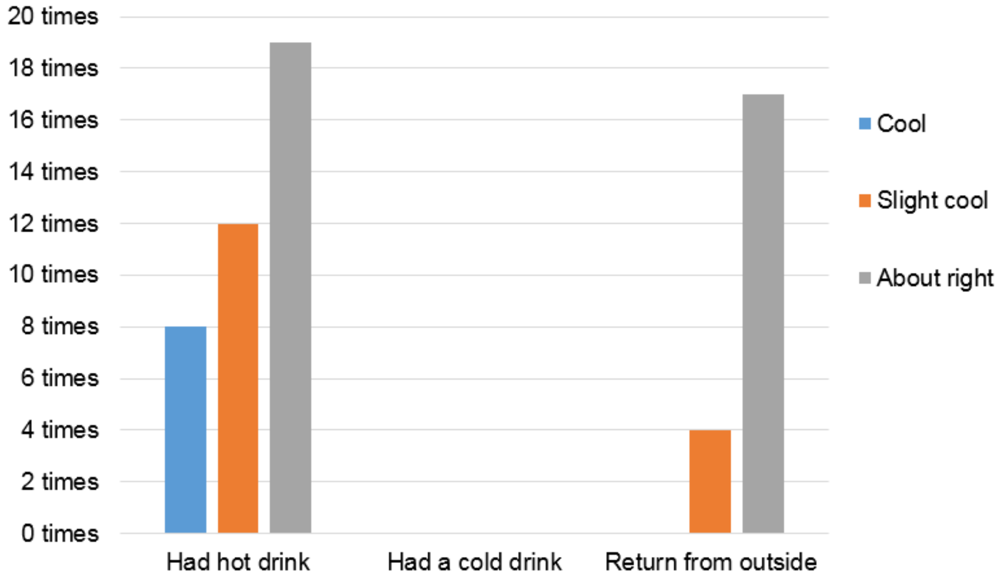


Figure 7.10: thermal satisfaction, beverage and recent thermal experience—dwelling 6

The responses in dwelling 7 is substantially different, where the relationship between consuming hot/cold drinks and thermal satisfaction seems to be vague (figure 7.11). Vote of 'about right' similarly distributed to hot beverage, cold beverage and return from outside, and so does the vote of 'slight cool'.

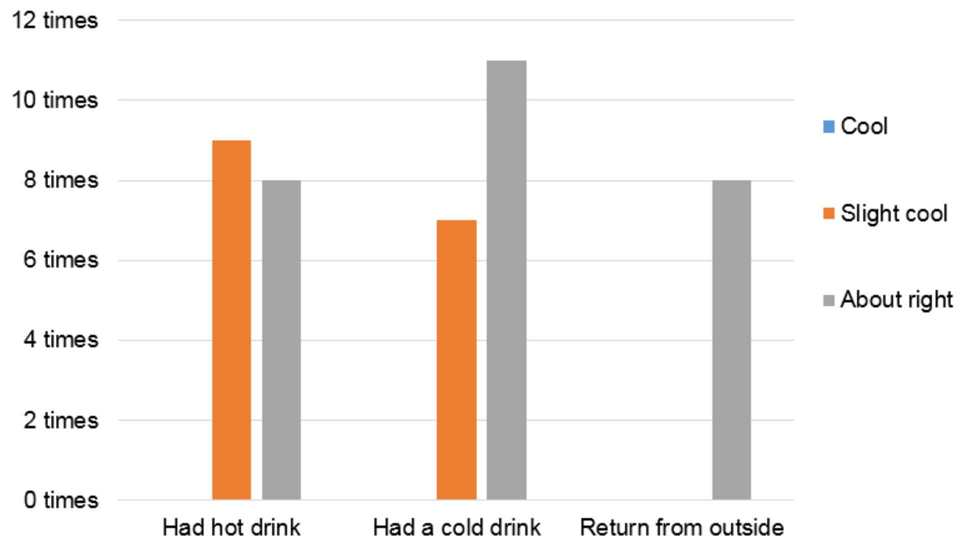


Figure 7.11: thermal satisfaction, beverage and recent thermal experience—dwelling 7

With regards to the thermal satisfaction and clothing level, despite the difference that dwelling 6 has more clothing choices and layers, thermal satisfactions appear not vastly different in each garment, except hoody, flip-flops and socks. In figure 7.12, occupant dwelling 6 never rate her thermal sensation as 'cool' if she had been wearing hoody or flip-flops. Occupant of dwelling 7 (figure 7.13) seems not felt 'cool' either if socks were worn. Occupants from both dwellings have their own preference of garment choices when they are at home and it seems to hard to find a pattern between clothing and thermal satisfaction, as usually it is considered that more clothe would be worn in order to restore thermal comfort.

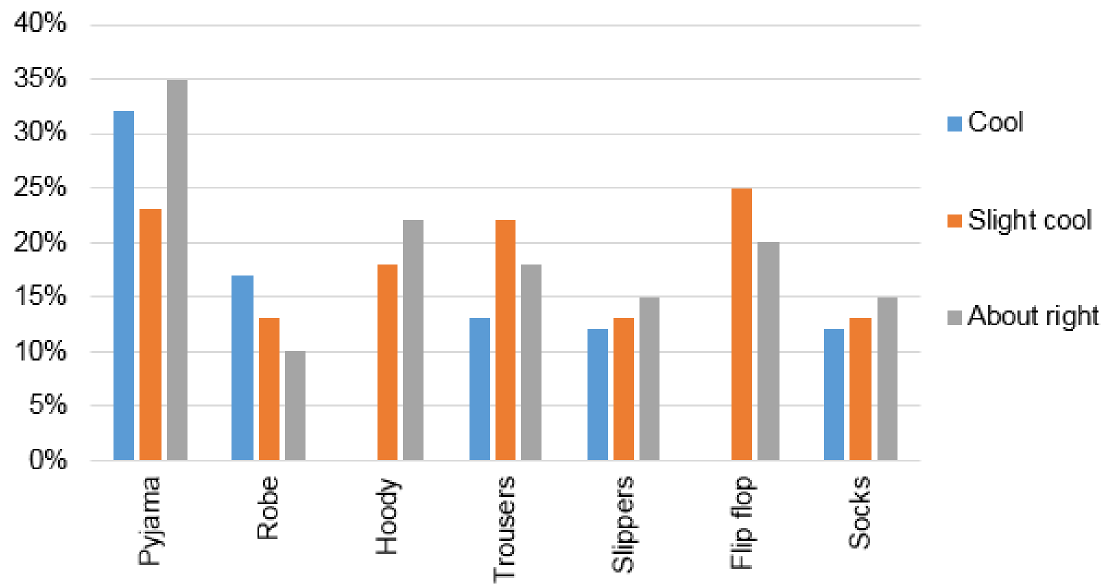


Figure 7.12: Thermal satisfaction and clothing level, dwelling 6

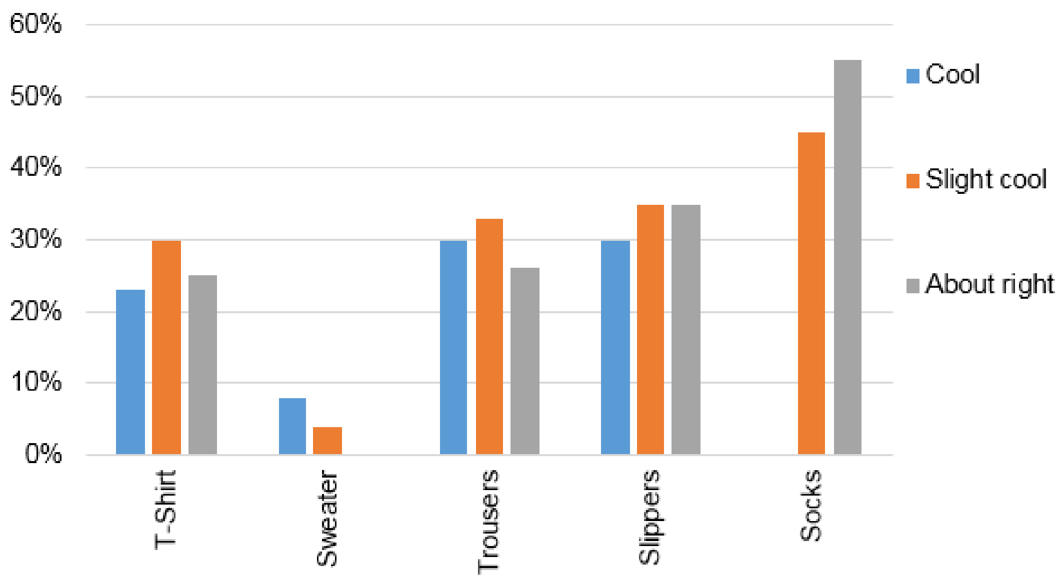


Figure 7.13: Thermal satisfaction and clothing level, dwelling 7

7.5 Calculated PMV and voted thermal satisfaction scale

Based on the samples from handhold anemometer, clothing level information from diaries and activity tracker data, the following assumptions have been made for the PMV calculation of dwelling 6 and 7 (table 7.4).

Table 7.4: Assumption for PMV calculation for dwelling 6 and 7

	Relative Air velocity	Clothing Insulation	Metabolic Rate
	(m/s)	(clo)	(met)
Dwelling 6	0.10	1.04	0.9
Dwelling 7	0.20	0.63	1.2

The results are presented in the following series of figures (Figure 7.14 to 7.21). Each figure contains actual thermal sensation rated by occupants and calculated PMV value based on physical indoor environmental monitoring results in the past 30 minutes.

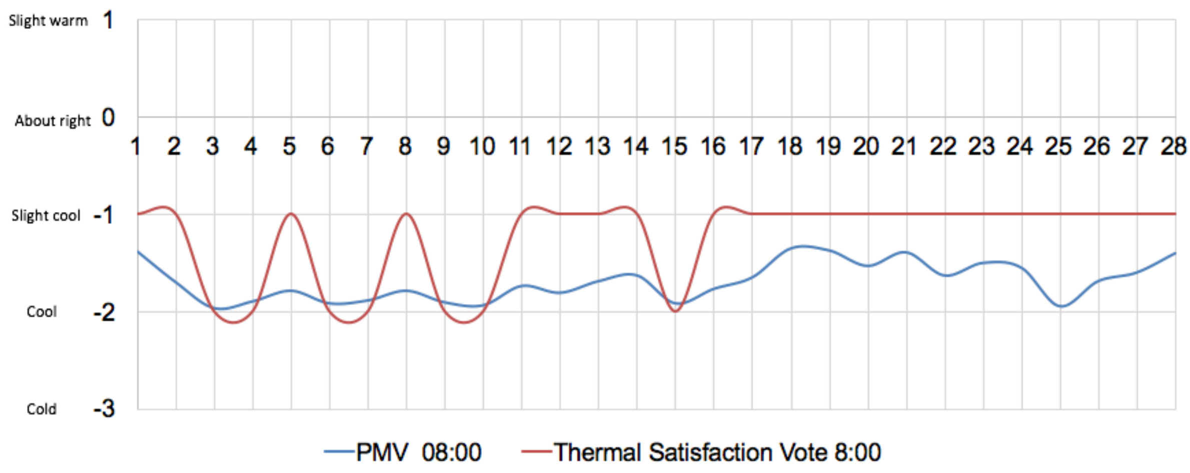


Figure 7.14: Calculated PMV and thermal satisfaction comparison at 8:00, dwelling 6

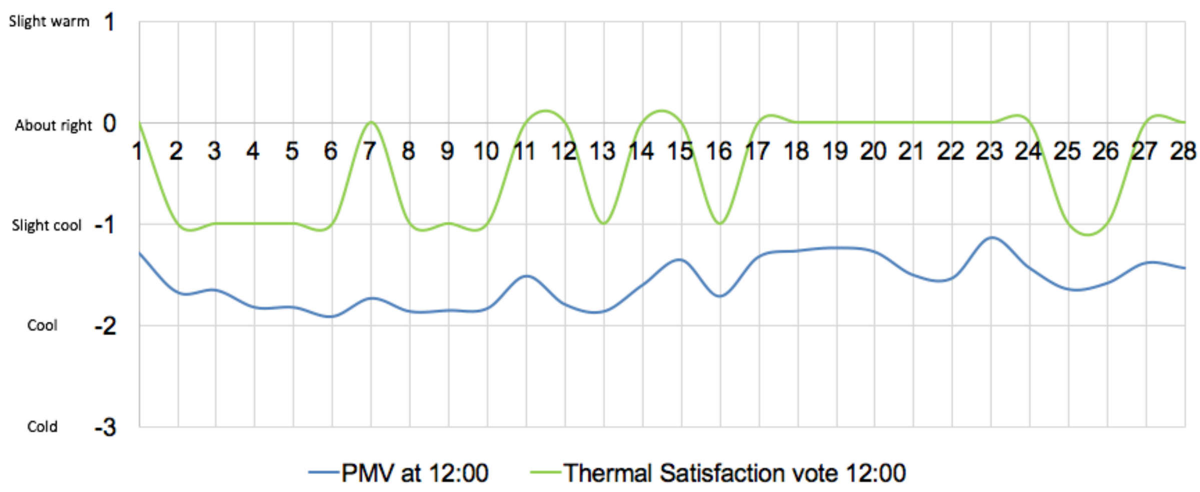


Figure 7.15: Calculated PMV and thermal satisfaction comparison at 12:00, dwelling 6

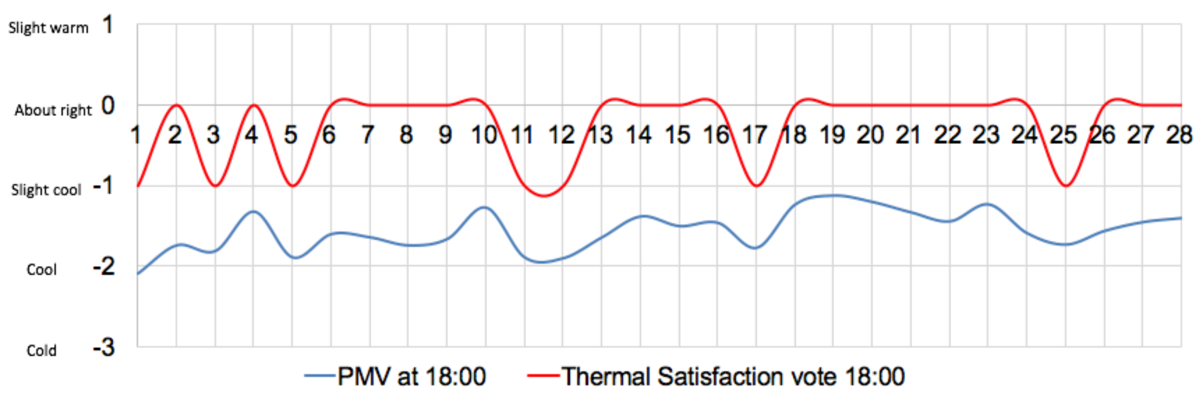


Figure 7.16: Calculated PMV and thermal satisfaction comparison at 18:00, dwelling 6

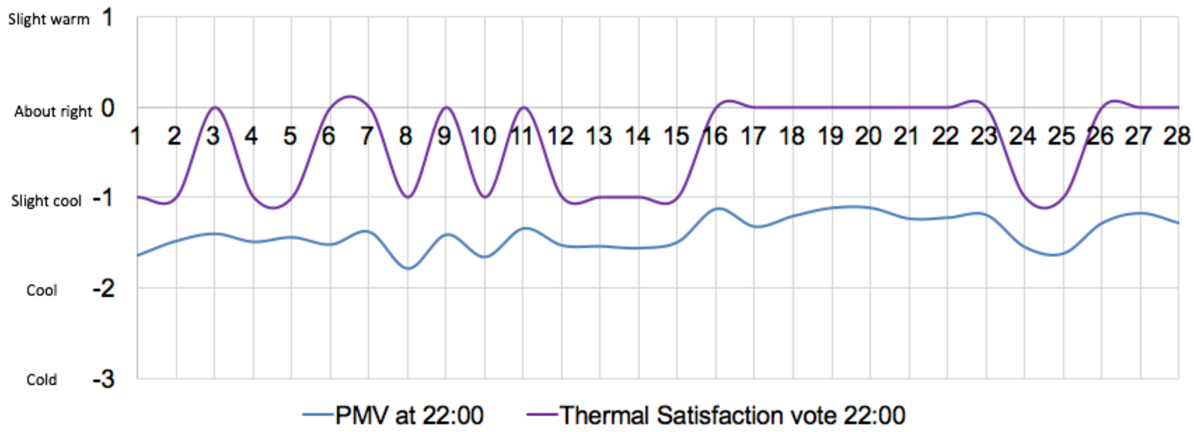


Figure 7.17: Calculated PMV and thermal satisfaction comparison at 22:00, dwelling 6

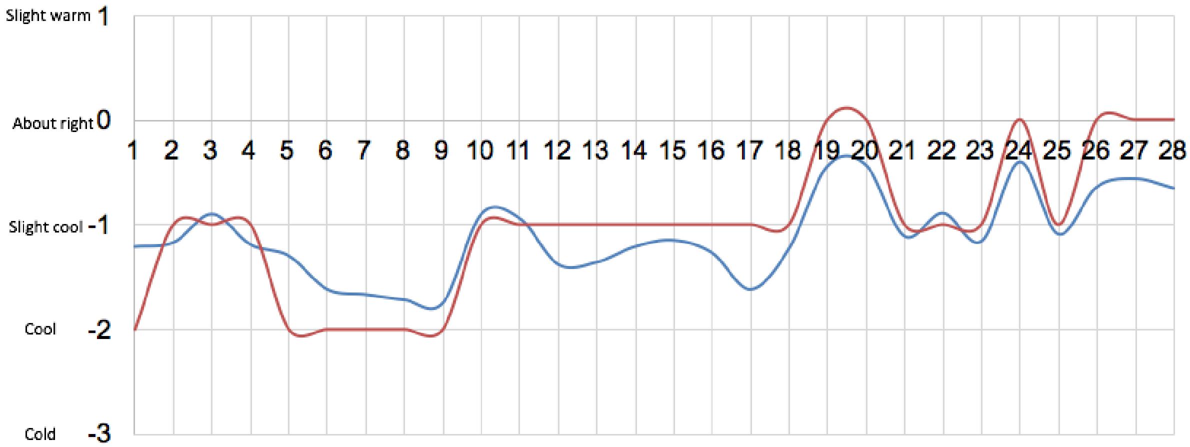


Figure 7.18: Calculated PMV and thermal satisfaction comparison at 8:00, dwelling 7

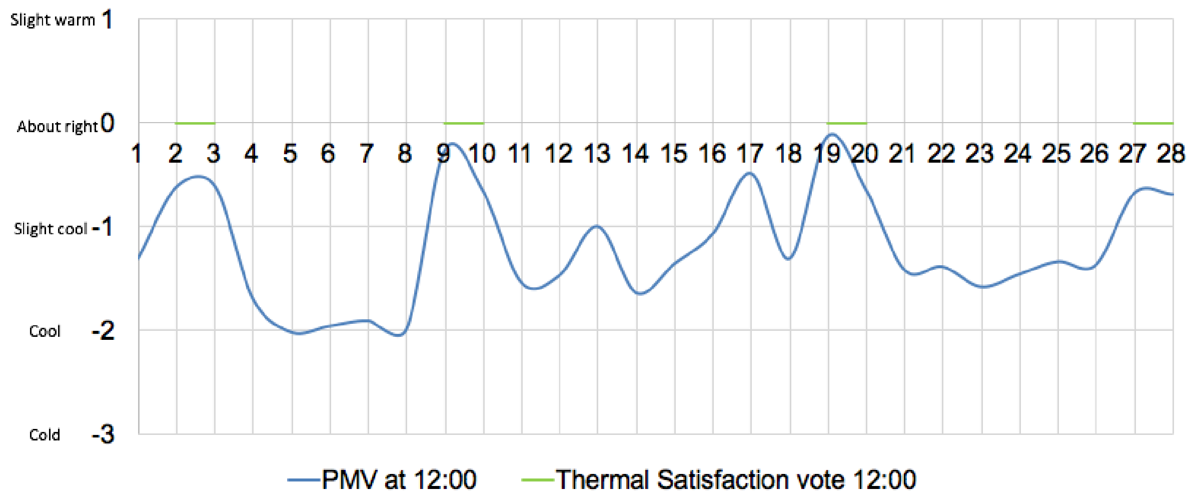


Figure 7.19: Calculated PMV and thermal satisfaction comparison at 12:00, dwelling 7

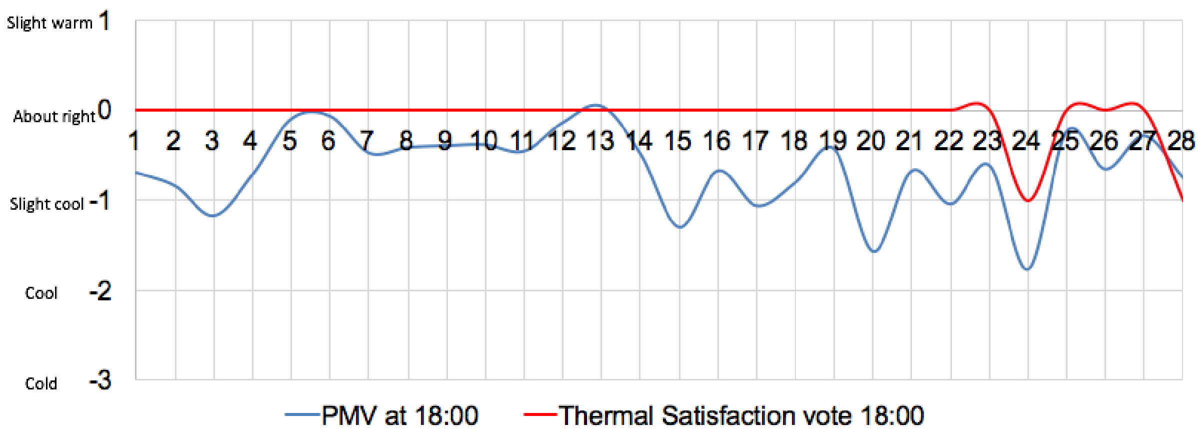


Figure 7.20: Calculated PMV and thermal satisfaction comparison at 18:00, dwelling 7

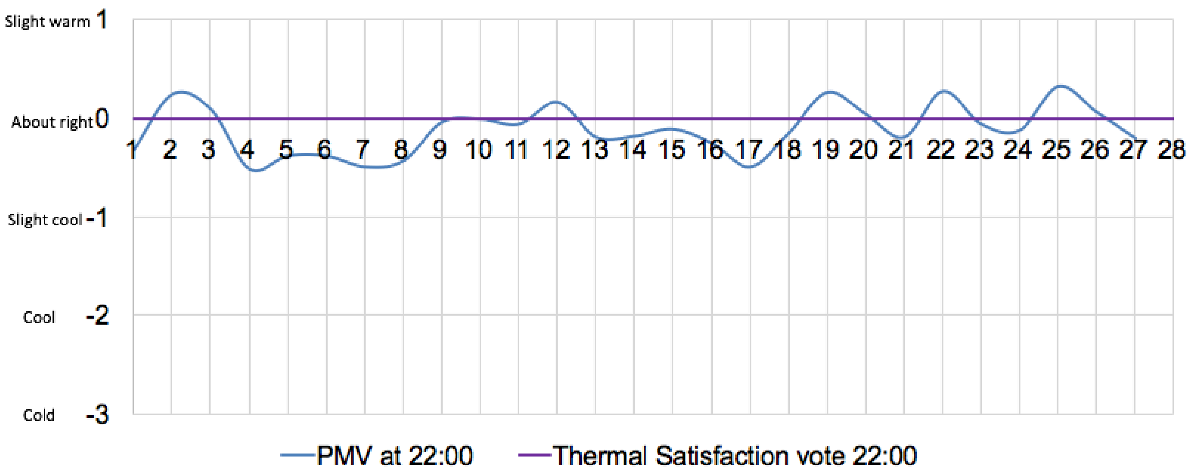


Figure 7.21: Calculated PMV and thermal satisfaction comparison at 22:00, dwelling 7

In general, the thermal satisfaction rated by occupant of dwelling 6 seems always higher than calculated PMV value of 30 minutes period before the the rating was given. In first fortnights, the fluctuation of both voted and calculated PMV match better than rest of diary keeping period. The self rated thermal sensation is closer to PMV value at 8:00 time than the other three diary time slots where most of thermal satisfaction votes are one level more comfortable than calculated PM.

Occupant of dwelling 7 seems always feel comfort at 18:00 and 22:00. The difference between rated thermal satisfaction and calculated PMV at dwelling 7 are much closer at the 8:00 and 22:00 than 12:00 and 18:00.

7.6 Application of monitoring methods

As part of informal contract with the housing association who provided access to some of the participated dwellings, it was agree to provide a brief report of energy comparison between dwelling 4 and 5, dwelling 6 and 7, and dwelling 8.

7.6.1 Identical occupants in different buildings: Dwelling 4 and 5

The family lives in dwelling and their total energy consumption are compared in table 5.36, where the mean gas and electricity consumption per house per day are compared between January and February of each year. The electricity consumption actually increased from 12.036 kWh to 14.181 kWh, equivalent to 18% rise. The gas consumption dropped from 13.604m^3 to 9.507m^3 which is 42% reduction. The increased electricity may be explained by the switch from gas cooker to electric hob.

Table 7.5: Energy consumption of occupants in dwelling 4 and 5

Mean daily consumption	Dwelling 4		Dwelling 5	
	Main Gas	Electricity	Main Gas	Electricity
Jan & Feb 2010	13.604 m3	12.036 kWh		
Jan & Feb 2011			9.563 m3	14.181 kWh

7.6.2 Identical buildings with different occupants: Dwelling 6 and 7

Comparing the total energy consumption, dwelling 7 always uses significantly more energy than dwelling 6. The differences between Dwelling 6 and 7 are listed in table 5.37.

In the percentage view, it can be seen that the biggest difference was September 2011 when dwelling 7 consumed 884 kWh which is 204% than Dwelling 6. Generallt dwelling 7's consumption is twice as high as dwelling 7. Interestingly, the difference is lower during winter but higher in summer. January and February 2011, dwelling 7 only used 27% and 23% more than dwelling 6. When entering heating season in October 2011, their difference dropped from 304% to 224% and then gradually decreased below 200% until February 2012.

Table: 7.6: Total energy consumption comparison

Monthly	Dwelling 6	Dwelling 7	Difference
Jan-2011	881.07 kWh	1,122.46 kWh	**127%**
Feb-2011	595.10 kWh	731.92 kWh	**123%**
Mar-2011	429.03 kWh	1,103.49 kWh	**257%**
Apr-2011	Missing	806.48 kWh	
May-2011	Missing	918.94 kWh	
Jun-2011	298.20 kWh	713.02 kWh	**260%**
Jul-2011	423.45 kWh	840.55 kWh	**199%**
Aug-2011	351.53 kWh	992.59 kWh	**282%**
Sep-2011	290.64 kWh	884.30 kWh	**304%**
Oct-2011	465.24 kWh	1,043.85 kWh	**224%**
Nov-2011	521.43 kWh	1,107.17 kWh	**212%**
Dec-2011	641.85 kWh	1,211.72 kWh	**189%**
Jan-2012	673.52 kWh	1,330.95 kWh	**198%**
Feb-2012	479.20 kWh	1,257.99 kWh	**263%**
Mar-2012	359.48 kWh	1,040.53 kWh	**289%**

Table 7.7: ASHP energy comparison

Monthly	ASHP Dwelling 6	ASHP Dwelling 7	Difference
Jan-2011	375 kWh	444 kWh	**118%**
Feb-2011	261 kWh	286 kWh	**110%**
Mar-2011	171 kWh	403 kWh	**236%**
Apr-2011	Missing	183 kWh	
May-2011	missing	197 kWh	
Jun-2011	55 kWh	108 kWh	**196%**
Jul-2011	77 kWh	136 kWh	**177%**
Aug-2011	90 kWh	156 kWh	**173%**
Sep-2011	88 kWh	184 kWh	**209%**
Oct-2011	145 kWh	251 kWh	**173%**
Nov-2011	223 kWh	343 kWh	**154%**
Dec-2011	344 kWh	435 kWh	**126%**
Jan-2012	226 kWh	449 kWh	**199%**
Feb-2012	180 kWh	530 kWh	**294%**
Mar-2012	111 kWh	343 kWh	**309%**

Electricity consumed by ASHP in two bungalows generally have the same curve. Starting from January 2011, ASHP consumptions in both bungalows are very similar for the first two months but in March dwelling 7 ASHP used twice as much as dwelling 6. From June to December, their tendencies are almost the same. dwelling 7's ASHP continued to work towards the maximum until February 2012 when dwelling 6's usage began to decrease two month ago after December 2011.

The similarity in curve suggests that both homes operate their ASHP the same way. But the higher usage at Dwelling 7 means occupants have warmer heat pump output setting.

Table 7.8: Immersion energy comparison

Monthly	Immersion Dwelling 6	Immersion Dwelling 7
Jan-2011	74 kWh	135 kWh
Feb-2011	49 kWh	87 kWh
Mar-2011	26 kWh	149 kWh
Apr-2011		138 kWh
May-2011		148 kWh
Jun-2011	10 kWh	103 kWh
Jul-2011	14 kWh	105 kWh
Aug-2011	3 kWh	181 kWh
Sep-2011	11 kWh	121 kWh
Oct-2011	17 kWh	156 kWh
Nov-2011	16 kWh	156 kWh
Dec-2011	12 kWh	180 kWh
Jan-2012	13 kWh	139 kWh
Feb-2012	12 kWh	125 kWh
Mar-2012	16 kWh	129 kWh

Immersion heater consumptions between two bungalows has significant difference. Occupants in Dwelling 6 had their immersion heater setting changed in June 2011 and they also adjusted their hot water consumption schedule such as avoid taking shower or bath at late night.

The impact of changed hot water demanding time and immersion heater setting is shown on Dwelling 6's immersion electricity consumption: after June, the immersion heater usage has dropped to 3 kWh for the whole August and staying around 10-14 kWh per month throughout the 2011-12 heating season. However, Dwelling 7 uses significantly much more just on immersion heater. Dwelling 7's immersion heater energy consumption is always 10 times of its neighbour. While Dwelling 6 has its lowest immersion heater consumption in August 2011, Dwelling 7's immersion heater actually used 181 kWh that is the highest usage.

Table 7.9: Cooker and Kitchen Sockets energy comparison

Monthly	Cooker Dwelling 6	Cooker Dwelling 7	Kitchen Socket Dwelling 6	Kitchen Sockets Dwelling 7
Jan-2011	22 kWh	38 kWh	130 kWh	190 kWh
Feb-2011	20 kWh	24 kWh	90 kWh	122 kWh
Mar-2011	20 kWh	31 kWh	81 kWh	156 kWh
Apr-2011	Missing	36 kWh	Missing	178 kWh
May-2011	Missing	45 kWh	Missing	225 kWh
Jun-2011	12 kWh	32 kWh	74 kWh	158 kWh
Jul-2011	24 kWh	39 kWh	128 kWh	194 kWh
Aug-2011	38 kWh	52 kWh	37 kWh	262 kWh
Sep-2011	31 kWh	39 kWh	43 kWh	194 kWh
Oct-2011	25 kWh	47 kWh	103 kWh	235 kWh
Nov-2011	33 kWh	46 kWh	73 kWh	232 kWh
Dec-2011	22 kWh	46 kWh	103 kWh	229 kWh
Jan-2012	24 kWh	62 kWh	130 kWh	311 kWh
Feb-2012	23 kWh	52 kWh	90 kWh	260 kWh
Mar-2012	21 kWh	43 kWh	81 kWh	216 kWh

Kitchen sockets and cooker electricity consumptions are compared together since they mainly hinged to the cooking, washing and drying activities. Overall, Dwelling 7 shows more energy consumption again either on Cooker and Kitchen Sockets. The higher electricity usage on kitchen sockets (include washing machine and dryer) in bungalow 2 suggests that it has more demand on kitchen appliance and laundering. Averagely dwelling 7 used around 50% to 319% more energy in Kitchen area includes Cooker and Kitchen sockets throughout the whole monitoring period.

Table 7.10: Other Sockets energy comparison

Monthly	Other Sockets Dwelling 6	Other Sockets Dwelling 7
Jan-2011	237 kWh	267 kWh
Feb-2011	138 kWh	172 kWh
Mar-2011	94 kWh	322 kWh
Apr-2011		249 kWh
May-2011		276 kWh
Jun-2011	43 kWh	294 kWh
Jul-2011	173 kWh	344 kWh
Aug-2011	175 kWh	317 kWh
Sep-2011	109 kWh	322 kWh
Oct-2011	158 kWh	317 kWh
Nov-2011	146 kWh	294 kWh
Dec-2011	119 kWh	276 kWh
Jan-2012	237 kWh	312 kWh
Feb-2012	138 kWh	269 kWh
Mar-2012	94 kWh	277 kWh

Dwelling 7's other sockets uses much more electricity again, according to the appliances auditing conducted in October 2011, every kid in Dwelling 7 has her own sets of game console, tablet, electric bike and etc. This would increase the energy consumption massively as these three kids can be more actively use more appliances comparing to the two adult children in Dwelling 6.

Lighting sub-circuit electricity consumption shows great similarity in winter. In the summer of 2011 from June to September, dwelling6 's Lighting electricity consumption is lower than 10 kWh per month, even dropped to 5 kWh per month in June. Comparing to 37 kWh in March, dwelling 6 consumed 87% less in June. Dwelling 7 used 42 kWh in March then it dropped down to 19 kWh in June 2011, which is 55% reduction in lighting electricity. From October, both bungalows began to use more electricity on lighting and reached the highest consumption in January 2012.

Table 7.11: Lighting energy comparison between dwelling 6 and 7

Monthly	Dwelling 6	Dwelling 7
Jan-2011	44 kWh	49 kWh
Feb-2011	37 kWh	42 kWh
Mar-2011	37 kWh	42 kWh
Apr-2011	missing	25 kWh
May-2011	missing	28 kWh
Jun-2011	5 kWh	19 kWh
Jul-2011	8 kWh	23 kWh
Aug-2011	9 kWh	24 kWh
Sep-2011	9 kWh	24 kWh
Oct-2011	18 kWh	38 kWh
Nov-2011	31 kWh	36 kWh
Dec-2011	41 kWh	46 kWh
Jan-2012	44 kWh	49 kWh
Feb-2012	37 kWh	42 kWh
Mar-2012	37 kWh	42 kWh

7.6.3 Identifying the cause of high energy usage Dwelling 8

Monitoring starts from 27th Mar and finished 26th April/2012. In 30 days, the total electricity usage is 1315.62 kWh, which is averagely 42.44 kWh per day. Table 5.43 lists all the electricity end uses by all the six sub circuits and illustrated in figure 5.89.

Table 7.12: Summary of sub-circuits electricity consumption.

Periods	Immersion	ASHP	Electric Shower	Sockets downstairs	Sockets Upstairs	Lighting and Kitchen Sockets
Week 1	0.00 kWh	27.99 kWh	24.60 kWh	64.33 kWh	6.21 kWh	34.82 kWh
Week 2	72.71 kWh	60.47 kWh	20.30 kWh	56.97 kWh	0.62 kWh	40.12 kWh

Periods	Immersion	ASHP	Electric Shower	Sockets downstairs	Sockets Upstairs	Lighting and Kitchen Sockets
Week 3	87.89 kWh	54.61 kWh	41.45 kWh	65.41 kWh	6.09 kWh	66.84 kWh
Week 4	150.07 kWh	12.98 kWh	39.67 kWh	73.68 kWh	2.82 kWh	70.07 kWh
Total	327.64 kWh	156.05 kWh	131.1 kWh	282.80 kWh	17.71 kWh	230.31 kWh

Highest daily consumption is 73.15 kWh and the lowest is 15.34 kWh. Electricity consumption at upstairs is the lowest comparing to downstairs and kitchen and lighting. The socket at ground floor contains all the appliances in the lounge and hallway where the washing machine and tumble dryer are located at the rear. The third sub circuit contains all the lighting in the house, oven and all the appliances in the kitchen. Ground floor sockets and kitchen sockets (plus lighting) are more close and similar in their trend.

Immersion heater uses significantly more than ASHPand electric shower. Daily average consumption of immersion heater is 10.92 kWh and highest is 39.48 kWh per day. The average ASHP usage is 5.20 kWh per day, which is about half of the immersion heater. Electric shower also uses similar amount of 4.37 kWh per day. There are few correlations between the immersion heater and the electric shower, but immersion heater runs much higher in later Aril while ASHP drops down. Occupant turned the ASHP completely off on 21 April and on that day immersion heater consumption reached the maximum.

Immersion heater was completely turned off by occupant in week 1. In the rest three weeks, immersion heater becomes a major end use. Since week 2, the electricity usage of ASHP becomes less and less while immersion heater raises from 29% to 43%. Throughout the 30days, it can bee seen that the largest part of electricity usage is immersion heater (29%). The second highest is socket downstairs (25%), but socket upstairs only takes 2%. The third place of electricity usage is taken by the circuit contains lighting, oven and kitchen sockets. This difference between sockets at ground and first floor is probably caused by the washing machine and tumble dryer at the rear of the hallway, plus the other appliances in the lounge such as plasma TV. ASHP consumption and Electric shower are 14% and 11% respectively.

Looking at ASHP and immersion heater, it can be seen that the ASHP only uses less than half of the immersion heater. This uneven usage ratio indicates that the less energy efficient immersion heater works a lot more than the ASHP. Considering the monitoring period was at the end of the heating season, high usage on immersion heater is most likely caused by the large amount of domestic hot water demand by the six children and one adult in the house.

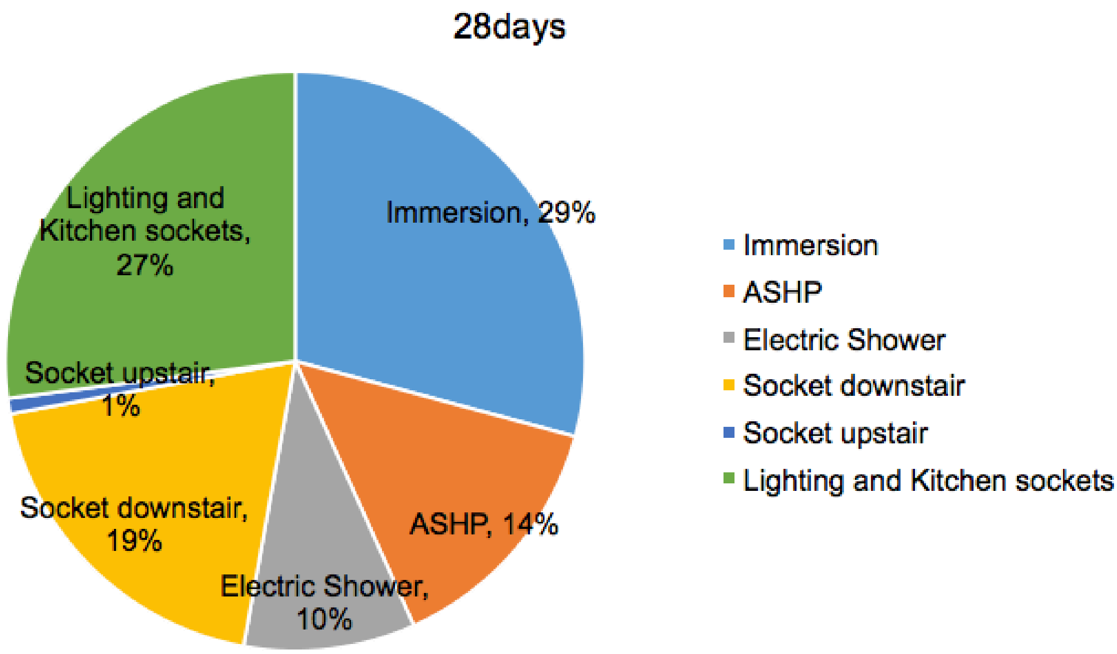


Figure 7.22: Percentage views of electricity consumption

Occupancy of seven people, especially with six you children, consequently leads to higher cooking, washing, drying and domestic hot water activities. However, the optimal energy efficiency cannot be achieved by satisfying such demand. This is reflected on the electricity consumption by ASHP and immersion heater.

7.7 Summary

This chapter presented the integration of physical measurement and social science survey results in order to explore the potential relationships which might become additional information of tested monitoring methods and instrumentation. In real cases, such methods have proven their usefulness with regards to the cause of high energy consumption.

As an exploratory attempt, there are some interesting relationships and interactions between these parameters but not conclusive. If the integration of measurements from different aspects had been planned before deployment of method and installation, a better result could be achieved on top of individual measurement and jointly provide additional information towards better interpretation of occupant behaviour in dwellings.

CHAPTER 8 DISCUSSION

8.1 Introduction

This chapter discusses the objectives outlined in Chapter 1 and addresses knowledge gaps listed in Chapter 2 in the light of the results from the fieldwork described in Chapters 5, 6 and 7. These objectives were developed in order to address the main aim of this thesis: *'to investigate methods of quantifying impact of occupant behaviour on domestic energy consumption, thermal comfort and indoor environmental conditions'*. Each objective is considered in turn and a final concluding statement is presented in relation to the main aims of this research. The final section of this chapter includes discussion of the aspects of the thesis where further work could be undertaken.

8.2 Contribution to knowledge gaps

The first and second knowledge gap, as stated in Chapter 2, are the lack of detailed description and specification of how relevant parameters were measured and what advantages and disadvantages a method or instrument may possess. This gap makes it is difficult for others to choose their tool when conduct similar studies. These gaps have been partially addressed by investigation of selected methods and sensors that focused on energy related parameters in domestic built environment. Each method and instrument has been studied and presented in table 8.1 in section 8.2.1 by five criteria, namely, level of invasiveness, accuracy, cost, ease of use and reliability.

The most commonly used method, such as questionnaire survey, interview, visit and observation have all been used for domestic built environment and occupants with several modifications. To begin with, one-off thermal comfort focused questionnaire has been replaced with self-administrated diary with repeatedly asked questions.

Regarding the gap of fewer studies in domestic sector, this research has been focusing solely on dwellings, especially on the comparisons of two pairs of sustainable homes in Wales (dwelling 4, 5, 6 and 7). The first pair, occupants moved from poor energy efficiency dwelling to a much better one actually reduced their energy consumption with slightly warm indoor environment. The second pair shows that even in identical dwellings with code level-4 sustainable home standard, the actually energy consumption can be significantly different due to the occupant's behaviours, especially during the heating season where energy demand peaks.

The high resolution metering investigating primarily focuses on bridging the gap between monitoring hardware and behavioural data analysis. Namely, the gas meter measurement and heating control pattern, electricity sub-circuit measurement and consumption profile, immersion heater energy consumption and domestic hot water demand events, windows status and their operation preferences. The positive feedback of purposely collected data and meaningful interpretation of occupant behaviour.

Minimising the level of invasiveness that monitoring method and instrumentations has been a priority in this research. The selected ones for investigate have been carefully thought of in order to avoid occupant feeling being monitored. Based on the feedback from occupants in field study, the invasiveness of each method and instrumentation have been rated (table 8.1).

The gap of how to integrate measurement has been attempted to fill by joining data from different sectors, namely, window opening CO2 concentration level and external air temperature, presence and CO2 concentration level, physical measurement based thermal satisfaction and subjectively rated thermal satisfaction. Given the relatively small number of field study dwellings, there are positive relationships between these parameters due to their interaction within dwellings which is also much smaller than commercial buildings. With more purposely designed and ethically permitted field study, it would be possible to reveal and quantify these interlinks more accurately.

8.3 Objectives of the research

The following objectives were developed:

1. To review and summarise current knowledge of method and instrumentations of measuring impact of behaviour on energy usage in the literature; **(8.2.1)**

2. To devise empirical studies to investigate people's behaviour in buildings and the resulting impacts on energy consumption and the environment; **(8.2.2)**

3. To monitor behaviour in actual buildings and to record its impact on energy consumption and the environment; **(8.2.3)**

8.3.1 Current monitoring methods and instrumentations

The energy and occupant behaviour-related parameters in the built environment have been studied broadly in existing literature. In general, monitoring methods and instrumentations can be classified into physical measurement and social science methods. With regards to the physical measurement, there is a lack of detail about how relevant parameters have been measured, especially the advantages and disadvantages of selected sensors and systems when deploying them in different buildings.

Social science methods, such as questionnaires and interviews, physical visits, direct and indirect observation are widely used in studies of the commercial built environment. Some cannot be applied in domestic dwellings due to the high level of invasiveness. Retrospective reporting of comfort and behaviour is often used, for example in the 'standard' Building Use Studies methodology (Bordass and Leaman REF), but can be inaccurate and may provide a false picture in occupant related parameters.

High resolution metering commonly focuses more on the technical side, and less on application and field test. In particular, there is very little information about test results to achieve optimal performance.

In conclusion, to bridge the gaps in terms of energy related behaviours study, there needs to be methods and instrumentations which are ethically accepted, minimally or completely non-intrusive, cost effective, and suitable for long-term study in domestic built environment. It is also interesting to integrate measured data together for better and more accurate interpretation of measured data.

8.3.2 Empirical studies to investigate monitoring methods and instrumentation behaviour in buildings

In general, methods and instrumentations are categorised into physical measurement and social science survey. The methods and instrumentations selected for investigation are listed in the Table 8.1 with regards to their invasiveness, cost, accuracy, ease of use and reliability. Specification of individual sensors can be found in the Chapter 3. This table focus on reviewing instrumentations and methods after they being been tested in the field study investigation.

Table 8.1: summary of monitoring methods and instrumentation

Type of parameter	Method and instrument	Invasiveness	Accuracy	Cost	Ease of use	Reliability
Space heating	Gas sub-meter and pulse counter	High, a gas sub-meter has to be installed into existing gas pipework	High, widely used with industrial standard	Low to medium, depends on size, gas sub meter cost between £40 to £70, plus £100 installation/dismantle cost, pulse counter costs £96	Requires specialist to install. Easy to operate once being installed.	High, works much the same as common gas meter, suitable for long-term study, almost maintenance free
	Gas boiler surface and temperature sensor	Low	Low to Medium, cannot differentiate space heating from domestic hot water	Low, Tinytag temperature sensor costs £56 per unit	Easy, place or attach sensor onto boiler surface	Medium. Can function as a rough indicator of boiler running status.
	ASHP boiler outdoor unit and temperature sensor	Low, could be installed from outside of the house	Medium to high, the temperature change marches with heat exchanger, therefore the ASHP	Low, Tinytag temperature sensor cost £56 per unit	Easy place or attach sensor onto ASHP extractor fan unit	Medium, Can function as a rough indicator of ASHP running status. Not able to separate space heating demand from domestic hot water
	Thermostat dial and resistance logger	Low, installation could be finished within15 minutes	High, it measures directly the rotary resistor inside thermostat which represents the temperature settings	Low, one resistance logger costs £55	Medium, the resistive component and corresponding positions (temperature settings) must be measured	High, and suitable for long term monitoring since it does not interfere with normal operation of thermostat (rotatory type)
	Individual radiator and fireplace and temperature logger	Low, a sensor could be place onto or nearby	Low to medium, as radiator remains warm for a while after being used, the lagging period	Low, Tinytag temperature sensor cost £56 per unit	Easy, researcher can installed sensors by oneself	Medium, effective enough to indicate state change from 'Off' to 'On', however, due to the lagging period, it is

Table 8.1: summary of monitoring methods and instrumentation

Type of parameter	Method and instrument	Invasiveness	Accuracy	Cost	Ease of use	Reliability
			varies and depends on its capacity			could not completely tell exactly when space heating is off since it stays warm short after.
Domestic hot water	Customised shower/bath diary	High, could only be completed by occupant who must remember to fill in	Medium to High, if well kept the hot water demand matches well with monitoring	Low, it is voluntary, but participant in this study was offered £20 incentive for keeping diary	Easy, can be tailored to the best fit to occupant's requirement	Low to Medium, in dwelling with multiple members of family, keeping track of every shower or bathing event may not be realistic
	Hot water inlet and return pipe surface and temperature logger	Low, not plumbing works required	Low, it only capture temperature shift from cold to hot well,	Low, Tinytag temperature sensor cost £56 per unit	Easy, simply attach sensor to pipe with good contact	Low, cannot provide details such as volume and temperature that inline heat and water meter can offer
	Boiler control panel display icon recognition	Medium, although it only points to the boiler, however it introduces visual recording device	High, once the tuning is completely, key activity icon change can be capture with time stamps	Medium, most cost goes to computer/laptop, customised webcam, infrared LED and tripod cost £40	Difficult, pictures of icon changes have to manually interpreted	Medium to High, it function as a footage of boiler's activity, lead to occupant's space heating and domestic hot water behaviour
Windows and door	Opening angle and Multiple contact switch board	Low to medium, the board needs to be installed either over the top or at bottom of the door,	High, the number of sensor could be increased for a higher resolution of angles	Low, reed switch cost £0.5 each and £45 for a 4 channelled event logger	Medium, need to measure the physical dimensions for best fit	Medium, it may needs inspection to ensure the right position securely. If reed switches could be fixed on the floor then less inspection would be required of long term measuring.
	Opening angle and Flexi	Low, the setting	High, bending	Low, £9-10 per	Easy, light	High, the only movable

Table 8.1: summary of monitoring methods and instrumentation

Type of parameter	Method and instrument	Invasiveness	Accuracy	Cost	Ease of use	Reliability
	resistive sensor	and small and low-profile	caused by a door matches well with resistance value	sensor and £55 for resistance logger	sensors setting can be attached with double sided sticky pad	piece is the flexi sensor which is designed up to 10000 times of bending
	Opening angle and Rotary resistive sensor	Low, the setting and small and low-profile	High, level of rotation represents physical angle of door	Low, £9-10 per sensor and £55 for resistance logger	Easy to medium, sensor has to be to the top of door	Medium to High, the rotary resistive sensor was not designed for rapid rotation
	Opened or closed status and single contact switch event logger	Low, the setting and small and low-profile	High, 'open' and 'closed' status of a door or window can be recorded accurately	Low, £5 per sensor, £45 for event logger with an 4 channels.	Easy, light-weighted contact switch can be installed externally with double sided sticky pad	High, the contact switch are designed for door status monitoring, can be maintained outside of dwelling.
Electrical appliance and lighting	Electricity sub-circuit and current transducer with and without voltage input	Low to Medium, depends the location of main consumer unit	Medium to High, error rate is proportionally greater without voltage input	High, every electrical sub-circuit needs a CT sensor the	Difficult, may need an electrician to install due to exposure of live wires.	High, suitable for long term monitoring, voltage import can improve its accuracy
	Individual appliance and socket electricity meter	Low, the setting and small and low-profile has appearance of normal socket	High, measures current and voltage	High, £40 for each sensor	Easy, plug and play	
Indoor physical environment	Temperature, humidity	Low, especially the battery powered stand-	High, it has been widely and commonly used in	Medium, £96 per sensor,	Easy, place and ready to record,	High, stand-alone logger can be retrieved up to with capacity of 10

Table 8.1: summary of monitoring methods and instrumentation

Type of parameter	Method and instrument	Invasiveness	Accuracy	Cost	Ease of use	Reliability
		along sensor with built-in logger	field study			month of data at 30 minutes interval
	CO_2 (Non Dispersive Infrared)	Low, the setting and small and low-profile	Medium, in domestic environment, location of CO2 sensor is restricted and must not interrupt daily activity	High, £200 per sensor	Easy, place and ready to record	Medium. It does not pick up significant amount of CO_2 concentration level while a room being occupied, requires additional parameters such as the ventilation rate and occupancy, CO_2 level data alone functions only as one aspect of indoor air quality
Occupant	Questionnaire and indoor condition satisfaction	Medium, will take 5 to 10 minutes of each participant	Medium, relies on personal, experience, judgement and understanding towards different types of comfort	N/A, mainly time of researcher and participant	Easy to medium, requires good understanding of questions and able to explain the terms and definitions if requires	Function as a glimpse of participants' memory and personal interpretation of comfort
	Self-reported recent thermal satisfaction, activity and clothing level	High, requires complete co-operation from occupants,	Medium to high, as the same set of questions are answered repeatedly with gradually strengthened	N/A, participant in this study was offered £20 incentive for keeping diary	Medium, feedback from field study was positive, it was difficult to keep for long term due to its	The pattern of activity level, clothing level, thermal comfort satisfaction,

Table 8.1: summary of monitoring methods and instrumentation

Type of parameter	Method and instrument	Invasiveness	Accuracy	Cost	Ease of use	Reliability
			understanding which provides consistence		frequency (four times a day)	
	Face to face interview	High, appointment need to be arranged	Medium to High, it offers in depth information of specific interest	N/A, mainly time of researcher and participant	Medium, communication and people skill	Better than questionnaire, can clear some doubts regarding occupant's understand of interviewed questions and topics
	Occupancy and PIR presence sensor	Medium to High, it need to point the area where occupant would usually be	Medium, varies with the setting, raw pulse generated by motion detection is more sensitive in than default 'error' filtered activity signal	Low to Medium, adjustable level of sensitivity requires customised PIR module with Arduino micro controller, cost £27 per set	Medium, requires basic programing skill with Arduino control and ability of building customised PIR module board	Medium, the position of PIR sensor affects its motion detection. In addition, it is important to measure the raw pulse instead of 'error' filtered activity signal
	Wearable activity tracker	High, total steps count while being worn	High, at least 3 accelerometers based tracker could detect movement accurately, mostly differ active level of wearer either being sedentary or walking around	Medium, tracker costs £30 to £50 each	Easy, wear on wrist, clip-on belt/clothe	Medium, It was found difficult in field study that wearer often forgot to take it off while not in home, this make it hard to estimate their activity level at home.

8.3.3 Monitor behaviour in actual buildings to record its impact on energy consumption and the environment

The field study contains two pairs of detailed monitoring studies for compassion. One selected two dwellings with different levels energy efficiency and occupied by the same participants. The other contains two different families who live in identical dwellings next to each other.

The family who moved into a higher energy efficient dwelling showed an improved mean indoor temperature that raised from 19.0 ˚C to 20.88˚C. The energy consumption also achieved substantial reduction, 24% less daily electricity and 44% less gas consumption. Electricity consumption is relatively stable but boiler gas consumption has very clear relationship with external temperature, higher boiler gas usage during cold days. Lifted indoor temperature doesn't alter her ventilation preferences according to the main bedroom window opening frequency. Occupants did not participate the self-administrated dairy, therefore very little is known regarding their behaviour change after moving to the new house.

The second comparison contains more detailed measurements in both physical and social science survey that have been conducted in dwelling 6 and 7 (off-gas properties). In comparison, dwelling 6 uses averagely 125% more electricity than dwelling 7, even up to 204% during heating season. However, dwelling 7's ASHP consumed averagely 90% more than dwelling 6 1 but its immersion water heater uses 1143% more electricity. Both physical measurement and social science survey results suggest that occupants of dwelling 7 prefer to have bath but their neighbour usually takes shower. Such different preference may explain the significant amount of domestic hot water energy consumption. It was found that ASHP cannot satisfy sudden domestic hot water demand and when it occurs, the much less energy efficient immersion heater would take over. This is proven by integrating shower/bathing diary and immersion heater which is always triggered after consecutive shower/bathing events.

Dwelling 7 has higher 174% energy on laundry appliances and often drying them inside house. On the other hand, in winter windows of dwelling 7 were operated 33% more frequently than dwelling 6 which suggest more active ventilation behaviour in winter. As a result, dwelling 7 has 25% lower CO_2 concentration level.

Higher number of window opening can also lead to heat loss and lower indoor temperature. Given the higher ASHP energy consumption in dwelling, mean indoor air temperature of dwelling 7 is only 0.33 ˚C warmer than dwelling 6.

Lighting energy usage shows matching tendency with daylight in both dwellings. Shorter day light time brings up lighting electricity consumption.

The social science survey found substantial differences between participants of Dwellings 6 and 7, namely activity level, clothing and thermal satisfaction. Participants who have high activity levels in past 30 minutes seems to wear fewer clothes, drink fewer hot beverage and rate thermal satisfaction better, given the 0.33 ˚C warmer indoor temperature.

In conclusion, energy consumption and indoor environment is directly affected by occupant who operates the house to satisfy various demands, life styles, habits and personally preferences. The investigation of impact of occupant behaviour on domestic energy consumption must consider all of those factors together in order to achieve a better understanding. Beside the measurement methods of each individual parameter, potential relationships between the followings are worth to be considered together for better data interpretation:

- Energy consumption for heating, space heating control behaviour and window operation (heat loss) behaviour.
- Domestic hot water energy usage, domestic hot water demands measurement, and immersion water heater (if any).
- CO2 concentration level, occupancy and window operation of the room and perhaps extend to the adjacent room’s windows/doors.
- Wearable activity tracker data, clothing level, calculated PMV and self-reported thermal satisfaction.
- Analysed measurement and post monitoring social science surveys that are tailored and targeted to verify findings.

CHAPTER 9 CONCLUSION

This chapter concludes the thesis by presenting the benefit of this research and recommendations for future studies.

9.1 Benefit of this research

The research explored a range of methods and instrumentations and studied several sustainable homes regarding their energy consumption and occupant behaviour. The results of tested method and sensors investigation provide first-hand experience, both pros and cons regarding their application in domestic buildings. Such experience may serve others who want to explore energy and occupant behaviour in the domestic built environment.

The study has developed four new methods for monitoring the domestic thermal environment. These are:

Thermostat adjustment behaviour

It was proven in field study that dial resistor based thermostat, which is also one of the most popular type, can be monitored by simply a resistance logger which both cost-effective and highly accurate with very little invasiveness. It captures all adjustments on space heating setting temperature made by occupant continuously even suitable for long term monitoring. Such method could be beneficial to detailed research on how occupant set space heating output and perhaps what circumstance might trigger them to make adjustment.

Optical gas meter reader

The test results optical sensor and existing gas meters, both dial and rotary type, are satisfying. Installation itself is non-intrusive and can provide accurate pulse readings as same as inline gas sub-meter does.

Self-administrated diary and wearable activity tracker

It was found that self-administrated diary kept at fixed intervals could provide more detailed subjective data and personal parameters than one-off questionnaire. Wearable activity tracker could also offer high quality data of activity level which usually replies on self-rated method via questionnaire.

Presence sensor's raw pulse

The finding of PIR presence sensor could be useful to occupancy monitoring. Commonly, PIR sensor contains manufacturer defined error filter which was designed to eliminate 'false' motion, however, such mechanism may not suit for domestic environment and the purpose of occupancy data collection. In commercial building, PIR presence sensor usually controls other functions, such like lighting, flush water or intruder detection alarm. In these occasions, PIR sensors are deliberately tuned less sensitive for ease of use. For example, three consecutive motion pulses within 5 seconds will be processed as an activity signal. However, in occupancy monitoring study, it would be ideal to measure the raw motion pulse than pre-filtered activity signal.

Indirect measurement

While directly measurement not applicable for some parameters, it worth to explore alternative parameters that might also be used to interpret occupant behaviour. Several new methods have been trialled with gas boiler surface temperature, ASHP compressor temperature, individual radiator surface temperature, exhaust vent temperature of gas fireplace, and hot water pipe surface temperature. Measurement taken from these spots are not exactly of study interest but come up as alternative option when permission or technical difficulty limits the direct monitoring method. Examples like fire place exhaust vent humidity and ASHP extraction fan temperature have shown clear relationship with their operating status. Indirect measurement methods often tend to be much less intrusive and more like to be accepted by occupant, however, at the cost of reduced accuracy. For example, testing result of hot water pipe surface temperature is proven to be only indicative of the start of domestic hot water demand only, whereas the more intrusive in-line heat meter would be able to differentiate and mark exactly a hot water demand start and finish.

Beside these new methods, energy consumption results indicate that higher energy efficiency can be achieved as a joint effort of best practice of HVAC system and behavioural adjustment. Energy reduction was found in the case study dwellings 4 and 5, the same family shows substantial amount of energy savings while being able keep the new house warmer during heating season.

It was also found that occupant behaviour, habit and life style could significantly affect the energy consumption even in dwellings with higher energy efficiency. Examples are dwelling 6, 7 and 8, where the lack of understanding regarding new space heating and hot water system, bathing choice and window ventilation preference together caused significant impact on energy consumption.

Data integration of energy consumption and behaviour measurement has been proven useful for local housing association to provide energy saving advice and to troubleshoot uncertain cause of high energy usage. In dwelling 6, 7 and 8, one common cause is mismatch between domestic hot water consumption habit and ASHP system. Occupants used to gas power condensing boiler which provide hot water as required, whereas ASHP could not provide if optimal energy efficiency is needed to be achieved. Have both sides understood, namely, ASHP system and occupant preference, can lead to target-oriented energy saving advice.

On a household scale, occupants and young one could be beneficial from a better understand of their indoor comfort need and best practice of maximising every unit of energy that used to provide such comfort. On a bigger canvas, better energy efficient while fulfilling occupant's requirement could be one of solution to battle against the worsening climate change, considering the time people spend at home and the number of dwellings.

9.2 Recommendation for further study

'All research work is incomplete – whether it be observational or experimental. All scientific work is liable to be upset or modified by advancing knowledge. That does not confer upon us a freedom to ignore the knowledge we already have or to postpone the action that it appears to demand at a given time'. (Bradford Hill, 1965)

This research has investigated a range of the methods and instrumentations which measure both physical and subjective parameters in domestic built environment in order to achieve a better understanding of occupant behaviour and its impact of energy consumption. The following considers a number of further research considerations that have resulted from this study.

Detailed space heating related control and automated method to record adjustment made by occupant has been considered. Given the increased popularity of digital control panel in boiler and heat pump manufacturing, it worth to investigate the possibility of monitor the internal signals. For example, a digital thermostat would send a signal of current room temperature and desired setting temperature to the boilers control module where a decision would be made regarding whether further heat output needs to be supplied. Same principle applies to domestic hot water, or even immersion heater which has a logic module to control when to start and stop water heating. This set of information can reveal the relationship between occupant demand pattern and system responses, which would be of mutual interest to both occupant who wants to know more and manufacturer who desires further product performance from tuning and commissioning existing system.

The current wide choice of parameters that could be measured in dwellings is likely to introduce consideration of integrated monitoring plans which can be targeted for different purpose. Measurement can serve better data interpretation, for example, window operation, room temperature, space heating energy, CO_2 concentration and occupancy are closed linked together. Individually, one parameter would be difficult to speculate how other parameters changes.

It is also considered that paper based subjective data collection method could be studied further and possibility of utilising handheld electronic equipment could be explored. A smartphone or tablet app may be able to provide a more friendly and convenient platform for participant to keep. The function is smart devices is also expandable, such as adding reminder feature to replace the alarm clock used in this study. Electronic device based social science survey also removes the physical boundary that limit the content per page.

Several customised sensor settings have been developed for door angle monitoring and all demonstrate good performance on invasiveness, cost, accuracy and reliability. In principle, these settings could be used for window monitoring. Angle of window could offer a much more enriched data set with regards to their exact level of being left open.

Occupants of dwelling 6 actively engaged with this study and made several changes to both HVAC system and their habits. Such intervention was found to have an impact on related energy consumption. It is considered further study could be focused on quantifying impact of behaviour change in dwelling with detailed monitoring set up. Experiments could lead to useful data that may be used to update the occupant input database of energy performance simulation software. It might be possible to compare the predicted performance with actual measurement in order to refine accuracy of simulation tool.

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